Salinity Characteristics of Gulf of Mexico Estuaries

NOAA's National Estuarine Inventory Series

Barataria Bay
Breton Sound
Mississippi Sound

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

Matrix showing time scales and forcing mechanisms important to the salinity structure and variability for Mobile Bay. A similar matrix has been developed for twenty-five other Gulf 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. Data from other strategic assessment projects have been adapted to the NEI framework to characterize important resource themes and 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 to 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)
National Ocean Service, NOAA
SSMC4
1305 East-West Highway
Silver Spring, MD 20910
(301) 713-3000

Salinity Characteristics of Gulf of Mexico Estuaries

Strategic Environmental Assessments Division
Office of Ocean Resources Conservation and Assessment
National Ocean Service
National Oceanic and Atmospheric Administration
Silver Spring, MD 20910

In Cooperation with:

Louisiana Universities Marine Consortium
Cocodrie, LA 70344

University of Texas
Austin, TX 78712

Florida State University
Tallahassee, FL 32306

Louisiana State University
Baton Rouge, LA 70803

July 1993

This report should be cited as: 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 Assessment. 209 pp.

Project Team

National Oceanic and Atmospheric Administration
S. Paul Orlando, Jr., C. John Klein, David A. Bontempo, Susan E. Holliday, Douglas E. Pirhalla, Karen C. Dennis, and Kim Keeter-Scott

Louisiana Universities Marine Consortium
Lawrence P. Rozas, Christopher G. Brantley, Brian T. Pollack, and Scott P. Longman

University of Texas
George H. Ward

Florida State University
Robert J. Livingston, Glen C. Woodsum, Jane M. Jimeian, and Laurie E. Wolfe

Louisiana State University
Erick M. Swenson

Acknowledgments

Many individuals contributed to the development and completion of this report. Within NOAA's Strategic Environmental Assessments (SEA) Division, Daniel J. Basta provided clear guidance on the content and design of the report. Mitchell J. Katz provided an editorial review. Farzad Shirzad provided data base and graphic support. Bart Chambers administered the cooperative agreements.

The authors would like to also thank the principle data sources for this report. *In Florida:* Tom Hudson, James Seagle, and Robert Thompson, regional offices of the FL Dept. of Natural Resources; Yvonne Stoker, USGS, St. Petersburg; David A. Flemer and William P. Davis of the USEPA Gulf Breeze Laboratory, Gulf Breeze; Robert A. Mattson, Suwannee River Water Management District, Live Oak; Susan Lowrey, Mote Marine Laboratory, Sarasota; James Barkuloo, USFWS, Panama City; Donald Ray, FL Dept. of Environmental Regulation, Tallahassee; Richard Boler, Hillsborough County Environmental Protection Commission, Tampa; Michael S. Flannery, Southwest Florida Water Management District, Brooksville; and John Taylor, Taylor Biological Company, Inc., Panama City Beach. *In Alabama:* Robert Perkins, AL Dept. of Public Health; Gary Halcomb, AL Dept. of Env. Mgmt., Mobile; and Dewayne Imsand, Mobile District USACOE. *In Mississippi:* Joanne Lyczkowski-Shultz, Thomas D. McIlwain, Larry Nicholson, Harriet Perry, and James "Tut" Warren of the Gulf Coast Research Laboratory, Ocean Springs. *In Louisiana:* Gerald Adkins, Barney B. Barrett, Jan Bowman, Philip Bowman, John Dameier, Ron Gouget, Vince Guillory, Conrad L. Juneau, Jr., Greg Linscombe, and Judd F. Pollard at LA Dept. of Wildlife and Fisheries regional offices; Matt Andrus, Kerry St. Pe', and Barbara Romanowsky, LA Dept. of Environmental Quality; Charles Demas, Charles Garrison, and Darwin Knochenmus at USGS regional offices; Kenneth Hemphill, LA Dept. of Health and Human Resources, New Orleans; H. Dickson Hoese, Univ. of Southwestern LA; Robert A. Muller, LA Office of State Climatology, Baton Rouge; Tony Drake, New Orleans District USACOE; and Al J. Levron, Terrebonne Parish Consolidated Government. *In Texas:* David A. Brock and Gary Powell, TX Water Development Board, Austin; Judie Lester, Galveston District USACOE; Kirk Wiles, TX State Dept. of Health, Austin; John Harrison, Dow Chemical USA, TX Division; Jeff Kirkpatrick and Craig McCulloch, Texas Water Commission in Corpus Christi and Austin; Thomas E. Czapla, NMFS, Galveston; and Billy Fuls and Al Green, TX Parks and Wildlife Dept., Austin.

Table of Contents

Page

Executive Summary

Introduction

Regional Overview

Salinity Characterization Summaries

Page

Concluding Comments

References

Appendices

Executive Summary

This report provides a comprehensive synthesis of salinity information for 26 principal Gulf estuaries. Besides being a critical factor that determines habitat, salinity provides a direct measure of estuarine transport behavior. An estuary's ability to retain, flush, and mix pollutants is determined by the same processes affecting how freshwater inputs combine with seawater, which is directly measured by salinity. 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.

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 information on both the spatial and temporal scales in which anthropogenic influences (e.g., freshwater diversions, dredged navigation channels, and inlet modifications) can be assessed. This is particularly important in the Gulf region where the coastal population is projected to increase by 22 percent to almost 18 million by 2010 (Culliton et al., 1990). Without this information, the impacts of these activities cannot be fully determined, as their influence on salinity is frequently misinterpreted when based on inappropriate averaging periods.

Area

Twenty-six estuaries were studied in detail in this report, including all the principal bays of the Gulf coast. The Mississippi River, the Rio Grande, several minor streams and distributaries flowing directly into the Gulf, and the south Florida systems have been excluded. Comparable information on the south Florida systems will be provided in a separate report due to the complexities associated with freshwater delivery to these estuaries.

The uniqueness and importance of these estuaries are primarily attributable to their morphology and the hydroclimatology of the Gulf region. The systems are dominated by an extensive wetland and shoreline habitat and correspondingly high biological productivity. However, the shallow nature of these systems makes them highly susceptible to both watershed and waterbody modifications, with the latter including channel dredging, dredged material disposal, filling of subtidal and tidal wetlands, and inlet stabilization.

The Gulf of Mexico watershed represents over 80% of the drainage of coterminous states into the coastal ocean. It encompasses nearly the full range of North American climates, with a corresponding range of inflows to the estuaries. Across the Gulf, inflow *volumes* range by more than two orders of magnitude, from the arid segments of the central Florida and south Texas coasts to the water-rich Mississippi delta. As importantly, the *time variation* of freshwater delivery to these estuaries ranges from seasonal dominance in the central Gulf to isolated, short-duration, high-intensity pulses in the arid areas of central Florida and south Texas. The timing and fluctuation of river flow are further modified by reservoirs constructed on most major rivers flowing to Gulf estuaries. The importance of freshwater inflow to salinity distributions, habitat, water-circulation patterns, and pollutant transport is, therefore, predicated on both the volume and timing of delivery, as well as its interaction with other physical forcing mechanisms. Accordingly, its influence varies between estuaries and within any given estuary.

Participants

This study required direct involvement with experts throughout the Gulf of Mexico region. In particular, experts from four institutions (i.e., Louisiana Universities Marine Consortium, the University of Texas at Austin, Florida State University, and Louisiana State University) worked cooperatively with NOAA to develop protocols, identify data sources and personal contacts, accurately synthesize and interpret information, and develop this report. In all, nearly 100 scientists from Federal, State, and local government agencies; academic institutions; and private organizations contributed data and information to this report. The time and effort dedicated by all participants are acknowledged and greatly appreciated.

Approach

Time series records of freshwater inflow and salinity, in conjunction with available background information on tides, wind, and other factors, were used to quantify salinity variability. For most U.S. estuaries, including those in the Gulf region, seasonal variation in freshwater inflow produces the most dramatic changes in bay-wide salinity patterns. Because a consistent time scale is necessary for comparisons among estuaries, seasonal salinity distributions were delineated for each estuary. *Representative* 3-month seasonal averaging periods were selected to reflect the normal range of high- and low-salinity regimes under *typical* and *present-day* hydrologic conditions. For both periods, the salinity structure was depicted by constructing isohalines at 5 parts-per-thousand (ppt) intervals from the head of tide to its ocean boundary for both the surface and bottom layers of the water column.

To put seasonal salinity variability into context, an analysis of temporal variability ranging from hours to years is provided. Additionally, the dominant, secondary, and modifying influences of the relevant processes affecting salinity variability have also been identified. This approach allows depiction of salinity behavior at various time scales, as well as a summary of the relevant mechanisms.

Summary of Results

Salinity Variability as a Management Tool. The dynamics of the physical environment have important consequences for estuarine resource and water-quality management. Because physical conditions in each estuary are uniquely governed by factors such as system morphology, freshwater inflow, and Gulf exchange, certain management alternatives are unlikely to elicit a common response across all estuaries. The variability of estuarine salinity inherently integrates the relative influence of the controlling factors and, therefore, is an indicator of the important temporal and spatial dynamics of the physical environment. Thus, it can be used to differentiate functional differences between estuaries and, ultimately, to develop a framework for evaluating the probable response to certain management alternatives.

Estuary Types. The classification of estuaries has traditionally been along jurisdictional boundaries, most often aligning to states or districts. Geographical proximity, however, often belies important functional differences between estuaries. Consequently, the effectiveness of research and management strategies is often reduced. Alternatively, a classification scheme, based on salinity behavior, provides a viable approach for grouping estuaries with similar physical processes affecting system dynamics. An proposed categorization uses average annual salinity and its intra-annual variability *under normal hydrologic conditions* to identify five estuarine types (see Figure 169, p. 178):

Type	Magnitude of Variability		Average Annual Salinity
	*Weekly**	*Seasonal**	
1	L	L	High (Seawater-dominated)
2	M	L	Intermediate
3	M	M	Intermediate
4	L	M	Intermediate
5	L	L	Low (Freshwater-dominated)

* L - low; M - medium

These types lie along a continuum, ranging from seawater-dominated (type 1) to freshwater-dominated (type 5) systems, with intermediate and overlapping conditions in types 2 through 4. Estuary types 1 and 5 lack any significant intra-annual variability, as they are each dominated by a single (but contrasting) forcing mechanism. Salinity in estuary types 2 through 4 depends on the relative influence of freshwater inflow, Gulf exchanges, and other controlling factors. In general, freshwater inflow increases and becomes more continuous from types 2 to 4, progressively suppressing seawater intrusion and shifting the dominant time scale of salinity variability from weekly to seasonal. Type 3 estuaries, however, experience the most variability over the widest range of time scales. Because the range of inflow defining types 2 through 4 overlaps, these estuaries may transition between types.

Management Implications. The time-space relationships of salinity across the Gulf region suggest that different research, management, and monitoring approaches may be required for specific estuarine types. For example, the susceptibility of an estuary to short-term, acute water-quality conditions versus longer-term chronic effects can be inferred from an understanding of the physical transport and mixing suggested by salinity behavior. For example, estuary types 1 and 2 are more likely to concentrate certain pollutants over longer periods than type 5 systems, as the latter are continually flushed by freshwater. In a similar sense, the success and distribution of many estuarine biota depend on preferred salinity concentrations, freshwater inflow regimes, or entrainment events that vary by estuary type. The migration of diadromous fish, for example, may coincide with the onset of a sustained tidal fresh environment, characteristic of estuary types 3 and 4.

Limited Salinity Data. An important conclusion of this study contradicts a common belief that an abundance of salinity data is available for the Nation's estuaries. Data availability varies widely from estuary-to-estuary; large data sets exist only for a few estuaries, while others go nearly unsampled for extended periods. Each sampling agency or institution has its own objectives that dictate the spatial and temporal sampling strategy. Few field sampling programs include a comprehensive survey of the estuary; most often programs are 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 certain time scales is limited or impossible. A greater cognizance of the need for and value of salinity data in estuary management is needed. Moreover, sampling programs must be optimized to monitor salinity so as to resolve the dominant time-space scales of variation.

What Remains?

This study focused on the relationship between forcing mechanisms and the response of the estuary's physical environment (i.e., spatial and temporal variability) under typical hydrologic conditions. It provides an *intermediate* step toward understanding the complex linkages between an estuarine environment's biotic and abiotic components. The proposed classification scheme, based on the temporal salinity variability, provides a framework that can be used to assess and prioritize certain strategic management and resource issues. However, further validation of the five estuary types as a viable classification scheme should be a prerequisite for expansion of this approach. This would require supplemental salinity data acquired through monitoring programs that provide this data at the appropriate temporal scale. Future studies should also address the effects of atypical or episodic events associated with the extremes in freshwater inflow that may be the dominant factor controlling salinity in an otherwise stable regime (e.g., Laguna Madre). Furthermore, a characterization at the appropriate spatial and temporal scales of the relative influence of other hydrographic variables (e.g., temperature and circulation) is required to further resolve habitat and water-quality issues inferred through salinity behavior.

Introduction

This report presents information on the spatial and temporal characteristics of salinity for 26 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 time-space 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), 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, 1985b). This atlas identified 92 of the Nation's estuaries and provided base-line estimates of certain physical and hydrologic data, including salinity. In addition, it identified the spatial framework for the consistent synthesis and depiction of physical, chemical, and biological attributes defining these estuaries. The framework contained 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, 1985b).

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 the 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), a mixing zone (>0.5-25 ppt), and a seawater zone (>25 ppt). Although it was 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 *mean* 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 brine discharges (e.g., Brazos River, TX), evaporation (e.g., Corpus Christi Bay, TX), density currents (e.g., Galveston Bay, TX), or inter-estuary exchanges (e.g., San Antonio Bay, TX).

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.

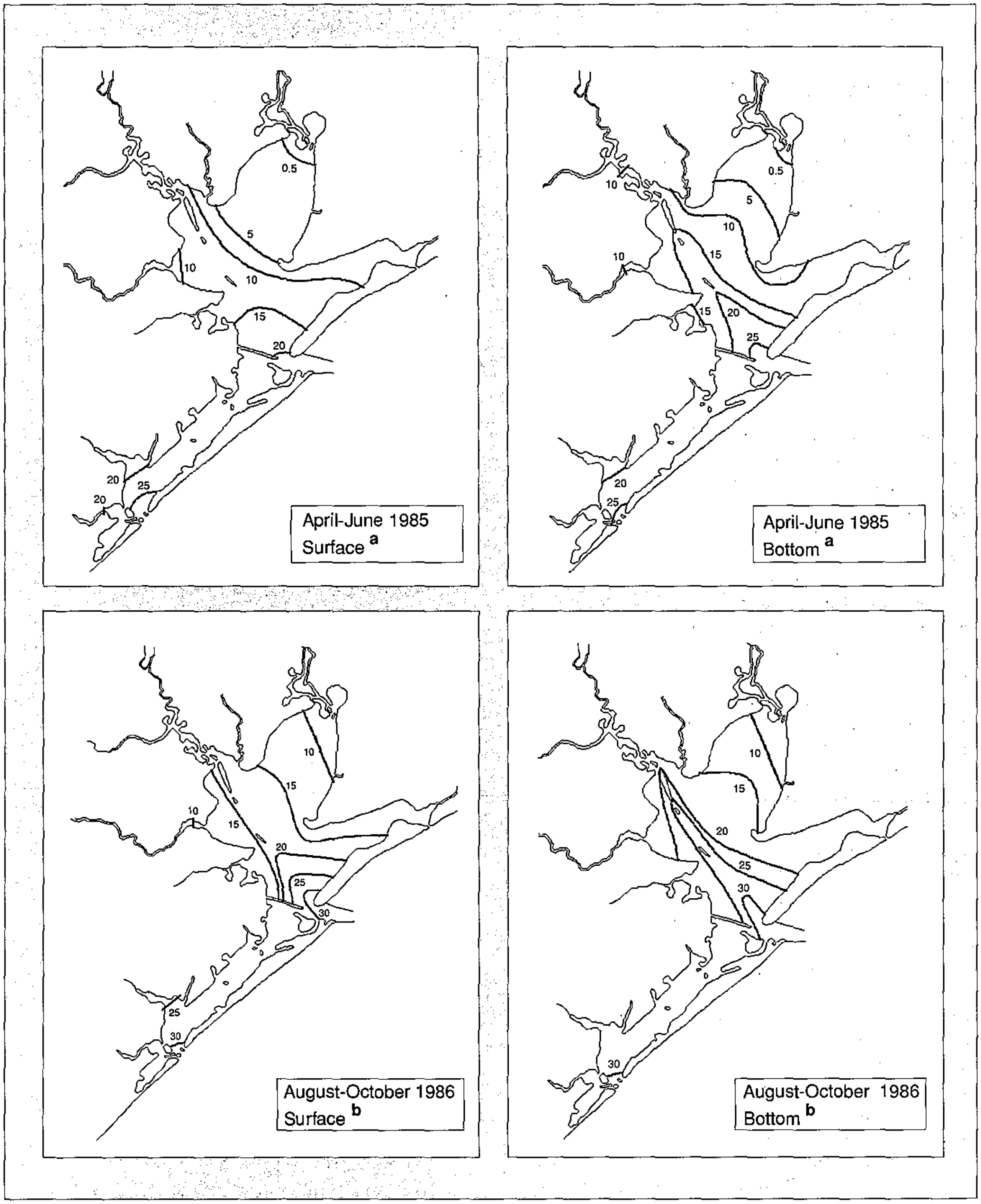
Although the magnitude of salinity variability experienced under normal conditions is often exceeded by low-frequency episodic events (e.g., a 100-year flood or 20-year drought), a characterization of variability at the episodic time scale is beyond the scope of this report. First, information for these 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. Because the latter is not a fundamental objective of this report, a characterization of these low-frequency events is only provided for those estuaries where it produces the only significant variability in an otherwise stable salinity structure (e.g., Corpus Christi Bay, TX).

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 the inlet; 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) cycle of tide, 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

Figure 1. *Refined spatial structure for Galveston Bay, Texas*



a. Data Sources: TSDH, 1991; TWC, 1991; TWDB, 1991a; TPWD, 1991
b. Data Sources: TSDH, 1991; TWC, 1991; TWDB, 1991a

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 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.

- *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 (e.g., the Bonnet-Carre Spillway into Lake Pontchartrain). 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.

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	

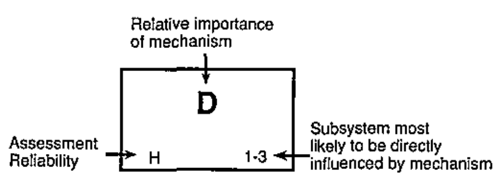
The Data

Data Availability. A common misconception 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

Figure 3. *Sample matrix summarizing time scales and forcing mechanisms important to salinity structure and variability*

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow					
Tides					
Wind					
Density Currents					
Shelf Processes					
Effect on Salinity Variability					

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 1 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 identifies the mechanisms most responsible for that variability.

extended periods. The amount of salinity data available for most estuaries lies somewhere between these two extremes.

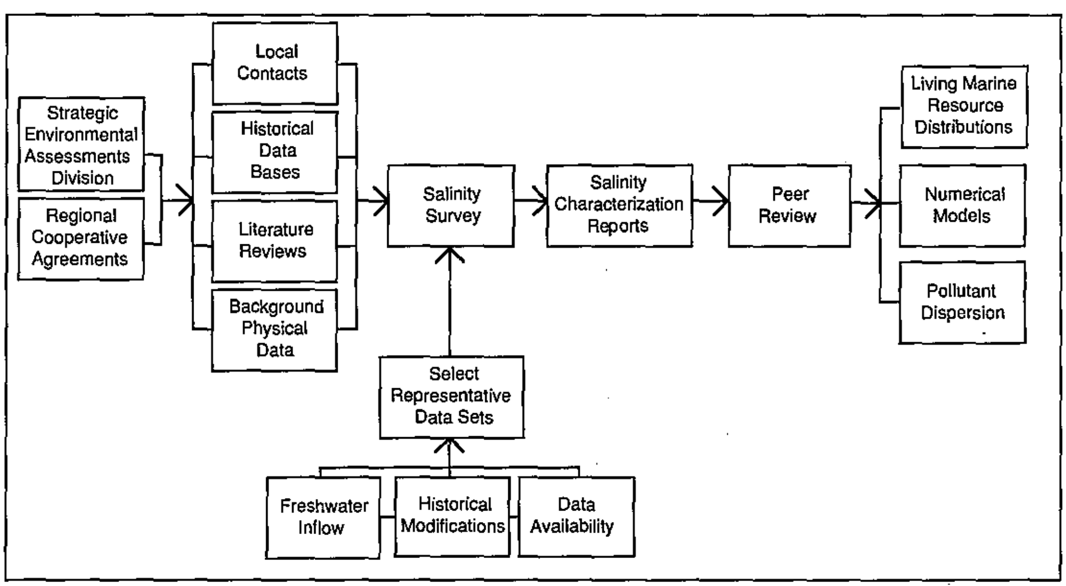
Given the disparate volume of information available, data sets cover an enormous range of spatial and temporal scales within any given estuary. Most often, the largest salinity data sets have been collected in support of long-term water-quality monitoring programs, usually administered by state regulatory 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). Appendices I and II describe the data bases and special studies 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 of these 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, merely that they pre-date existing conditions within the system.

Second, salinity data must be considered with respect to the physical, hydrographic, and meteorologic processes occurring before the salinity measurement (i.e., antecedent conditions). For example, if *typical* or *average* salinities are required, salinity measurements obtained before flood or drought periods should not be analyzed.

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 is supported by extensive documentation of the major physical processes, morphol-

Figure 4: *Project components*



ogy, natural features, and anthropogenic modifications that determine estuarine circulation and salinity. Furthermore, this study directly incorporated the knowledge base of experts who were solicited to provide guidance and interpretation. This information was 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

The salinity characterization summaries primarily focus on two 3-month periods extracted from historical data records. These *representative periods* were determined to: 1) have adequate data to reliably characterize salinity structure and variability; 2) be most representative of *typical* high- and low-salinity conditions; and 3) adequately represent the historical data records. However, the remaining historical records are not discarded in favor of the representative periods. Instead, historical records are used to: 1) verify the *representativeness* of the selected periods; 2) fill in important data gaps for the selected periods; and 3) quantify the magnitude of salinity variability at the identified time scales discussed on pages 2 and 4.

Three months were determined to be the appropriate duration for the representative periods because: 1) the seasonal freshwater inflow signal for most of the Nation's estuaries (i.e., variation on a 3-4 month time frame) was determined to be most important when compared to the other potential influences of astronomical tides and meteorology; 2) 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; and 3) three months was determined to be the shortest duration that ensured the availability of sufficient salinity data to examine structure and variability, given the data limitations discussed earlier.

Importance of Averaging Periods. Adequate characterization of salinity requires at least two representative periods to display the normal range in the system (i.e., a high-salinity and low-salinity period). The representative periods provide the most direct approach for examining the dynamics of salinity and its relevant physical processes. Using this approach, the real-time salinity records can be overlaid with the real-time freshwater inflow records (and tides and wind, where available) to examine salinity variability at time scales at and within the 3-month season (i.e., hours, days-to-weeks, and months-to-seasons). In contrast, an approach averaging an estuary's entire historical record would inherently limit the ability to characterize its salinity variability, and may actually misrepresent a system fluctuating between several states by depicting an intermediate condition that rarely, if ever, occurs. Other methodologies, including rigorous statistical techniques, are not appropriate due to the data limitations discussed earlier.

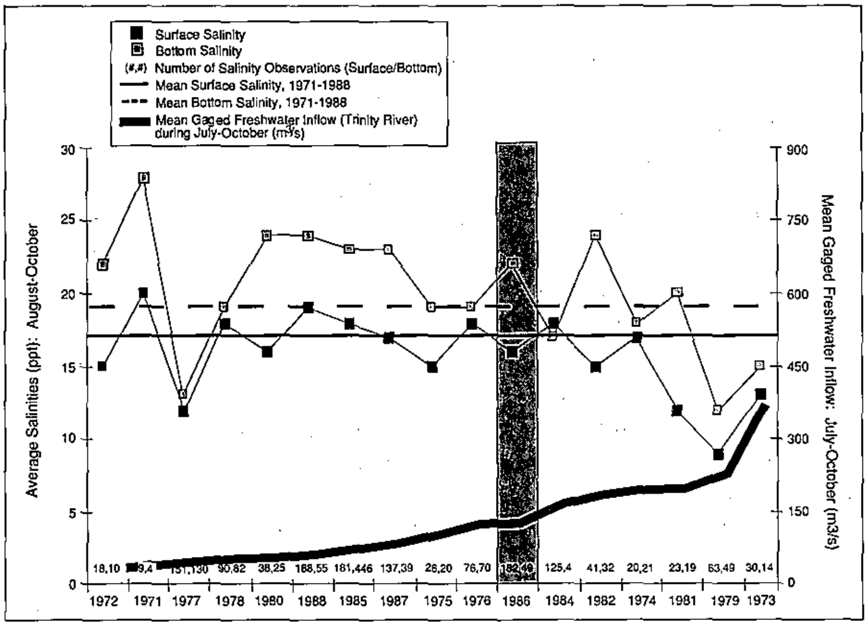
Comparison to Long-Term Averages. To determine the degree to which the selected periods represent the historical records (i.e., typical conditions), two analyses were conducted. First, the volume of freshwater inflow during the selected representative periods was compared to the historical records. Second, the average estuary-wide salinity during the selected representative periods was compared to the historical records. Figure 5 illustrates this comparison for August-October 1986 which represents the 3-month high-salinity period for Galveston Bay, Texas.

Selection of Representative Periods. The selection of representative periods is based on a methodology that consistently and objectively screens historical data sets that may yield salinities determined to be *typical* for the desired characterization period. This process examined the historical salinity record as discussed earlier, volume and timing of freshwater inflow, and historical modifications to an estuary and its watershed.

Volume and Timing of Freshwater Inflow. A two-step process was used to compare both the volume and timing of freshwater inflow during a potential 3-month representative period to the historical freshwater record. A 1-month antecedent period was included in the analysis to examine the influences associated with the possible lag effect of freshwater inflow on salinities. This process relied on freshwater inflow statistics, based on USGS gaged streamflow records, for major freshwater sources. Gages generally reflected 60-90% of the estuary's total drainage area. Where this percentage was lower (primarily in south Texas and in the Mississippi Delta region), the comparison was based on rainfall records and water budget analyses.

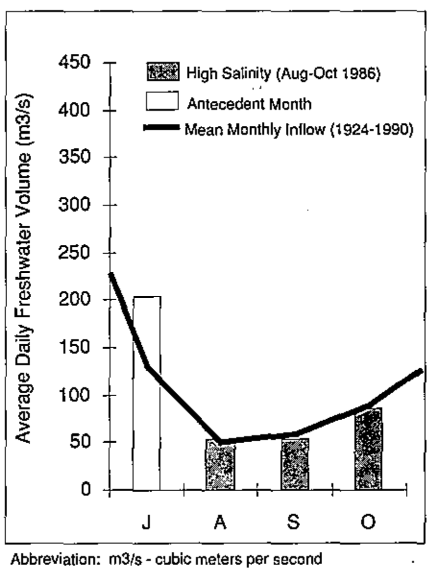
In Figure 6, the freshwater inflow volume to Galveston Bay during a potential representative high-salinity/low-inflow period (August-October 1986) is compared to the long-term average inflow. Freshwater statistics are given for the Trinity River, the major freshwater source to Galveston Bay, and include July as an indicator of antecedent conditions. The comparison indicates that the Trinity River discharge volume during July-October 1986 was consistent with long-term averages.

Figure 5. *Comparison of average salinity during August-October 1986 (the selected "representative period") to long-term average salinity for Galveston Bay, Texas*



Step two was conducted for potential representative periods that satisfy the freshwater volume criteria illustrated in Figure 6. The timing of peak freshwater events at durations of 1, 7, and 30 days was examined within the potential representative periods. This process ensured that the freshwater had been delivered to the system through a series of freshwater pulses typical of the 3-month period. For example, while the volume during a 3-month period may be consistent with the long-term record, this volume may have been determined by a typical freshwater surge (e.g., tropical storm) during an otherwise drier-than-normal period. In Figure 7, the timing of freshwater inflow during August-October 1986 for the Trinity River was consistent with long-term streamflow records, as defined by the 2-year return frequency. Peak discharges occurring less frequently than every 2 years (e.g., 5-year or 10-year return frequency) deliver higher-than-normal freshwater pulses to the estuary and are assumed to have an increased influence on estuarine salinities.

Figure 6. *Comparison of fresh-water volume to long-term averages for the Trinity River, Texas*

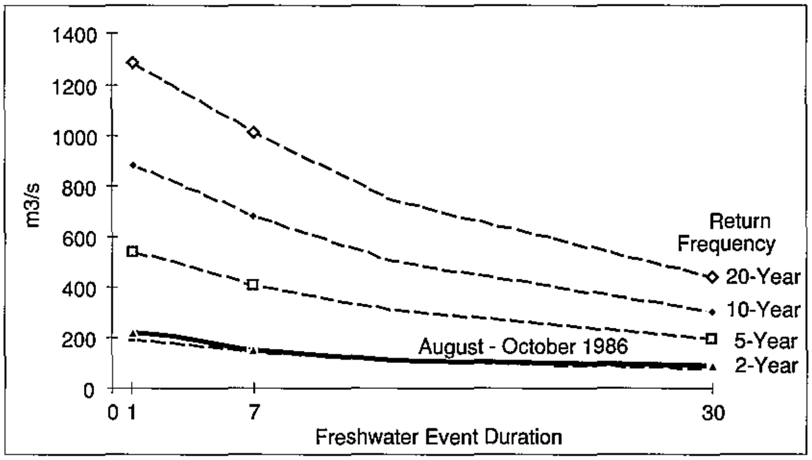


Abbreviation: m3/s - cubic meters per second

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., Mobile Ship Channel in Mobile Bay, AL)
- Diked disposal islands (e.g., North/South disposal area in Sabine Lake, TX/LA)
- Inlet creation (e.g., Sikes Cut in Apalachicola Bay, FL)
- Shoreline modification (e.g., Texas City Dike in Galveston Bay, TX)
- Reservoir construction (e.g., Choke Canyon Reservoir in Corpus Christi, TX)

Figure 7. *Comparison of peak freshwater events during a selected representative period to long-term averages*



- Saltwater control structures (e.g., at Lake Charles in Calcasieu Lake, LA)
- Freshwater diversions (e.g., Bayou Lamoque in Breton Sound, LA)

Selection Results. From the candidate representative periods meeting the freshwater and modifications criteria discussed earlier, data sets providing the best spatial and temporal salinity coverage were selected as the *representative periods.* For Galveston Bay, August-October 1986 was selected to represent present-day conditions typical of a high-salinity/ low-inflow period. A similar process identified April-June 1985 as the representative low-salinity/ high-inflow period for Galveston Bay. In limited cases (e.g., Aransas Bay, TX), the salinity information was so sparse that representative periods were based on the most abundant data sets which may have failed to meet the freshwater or modifications criteria. Salinity data was then obtained for these selected periods and isohalines were constructed. The results of this process are provided for each Gulf estuary in this report so that the user may also interpret this information.

Interpreting Salinity Characterization Summaries

The characterization summaries for all estuaries are consistently formatted and contain four sections: *Geographic Setting, Bathymetry, Salinity Patterns,* and *Factors Affecting Variability* (discussed below).

Geographic Setting

- Describes the physical boundaries of an estuary.
- Subdivides an estuary into sub systems to identify areas exhibiting similar responses to forcing mecha nisms (e.g., salinity variability).
- Identifies major freshwater sources to an estuary.
- Identifies major inlets (or passes) responsible for exchanges with the Gulf of Mexico.

Bathymetry

- States the average depth of the system and identifies naturally deep or shoal areas.
- Identifies major navigation channels in an estuary.
- Identifies major dredged material disposal areas and important shoreline modifications.
- Identifies important control structures or reservoirs in an estuary's watershed.

Salinity Patterns. This section identifies the representative periods selected as typical of the 3-month high-salinity period and 3-month low-salinity period during a year in which normal hydrographic conditions were occurring. These periods are considered to be consistent with long-term averages within the system and are expected to reflect present-day conditions, unless otherwise noted. Surface and bottom isohalines for the selected representative periods are provided for each estuary. A summary of freshwater inflow conditions, data availability, and salinity behavior during the representative periods accompanies the isohalines.

Factors Affecting Variability. This section highlights the most important physical processes that determine the salinity structure, and the most important time scales of salinity variability under normal conditions. This analysis is based on the entire historical record for each estuary.

A matrix (Figure 8) was developed to consistently summarize and quantify salinity variability for each estuary. The left-side of the matrix identifies the dominant processes (forcing mechanisms) affecting salinity. The upper portion of the matrix identifies the dominant time scales of variability. The lower portion of the matrix estimates the range (magnitude) of salinity variability at each time scale. For most U.S. estuaries, the matrix will indicate that salinity demonstrates its largest range of variability at the months-to-seasons time scale, primarily due to freshwater inflow (river discharge). For many of these estuaries, the matrix often quantifies the magnitude of variation at this time scale as *medium* (i.e., salinity is approximately 5-10 ppt higher during the low-inflow/high-salinity period than during the high-inflow/low-salinity period). This estimate may be used to compare salinity variability across estuaries.

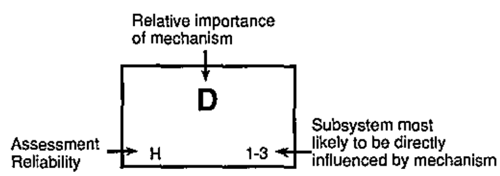
Subsystem discretion is available through the examination of the matrix *cells*. Each occupied cell:
1) defines the relative importance of a forcing mechanism on salinity variability at a given time scale;
2) identifies the subsystems of the estuary most likely to be directly affected by a forcing mechanism at a given time scale; and 3) indicates the quality of data to support 1) and 2) above. Cell characterization is based on available literature, the historical freshwater and salinity records, and guidance from locally recognized *experts*. An unoccupied cell indicates that salinity variability is unknown or not significant.

Figure 8 interprets the salinity variability for the Galveston Bay system. Referring to the lower portion of the matrix, Galveston Bay demonstrates the greatest range of variability (i.e., *medium*) at both the *months-to-seasons* and *year-to-year* time scales, while *low* variability occurs at the *days-to-weeks* time scale. Thus, for a normal range of hydrographic conditions, salinities in Galveston Bay are 6-10 ppt higher during the high-salinity season than the low-salinity season. The estuary also experiences important short-term (i.e., days-to-weeks) variability (2-5 ppt) and significant variability (6-10 ppt) from year-to-year. Further, the matrix indicates that freshwater inflow is the mechanism most responsible for salinity variability (denoted by *D* for dominant) at the months-to-seasons and year-to-year time scales; its influence is expressed throughout the estuary (see Figure 55, subsystems 1-5 for Pensacola Bay, FL). Shelf processes (river plumes discharged from adjacent estuaries) also affect salinity variability at the months-to-seasons and year-to-year time scales; their influence, however, is generally limited to subsystems nearest the inlets (subsystems 3 and 5). At the days-to-weeks time scale, salinity variability is determined by several mechanisms, although freshwater inflow and wind are most important; their influence extends throughout the entire estuary (subsystems 1-5). Over a period of hours, the variability of estuary-wide salinity is unknown, but is thought to be insignificant.

Figure 8. *Matrix summarizing time scales and forcing mechanisms important to salinity structure and variability for Galveston Bay, Texas*

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S L 1-5	D H 1-5	D H 1-5	
Tides		M LIT 3			
Wind		S LIT 1-5			
Density Currents		M LIT 2-3	S LIT 2-3		
Shelf Processes			S LIT 3,5	M LIT 3,5	
Effect on Salinity Variability	UNKNOWN	LOW	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 1 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 identifies the mechanisms most responsible for that variability.

Regional Overview

The U.S. Gulf coast extends from the Rio Grande to the Florida Keys, along which lies one of the most extensive estuary systems in the world (i.e., highly productive, supports the Gulf of Mexico fishery, and exhibits various estuary circulations and salinity regimes). In this report, 26 estuaries are studied in detail, including all of the principal bays of the Gulf coast except those of south Florida. Because south Florida systems are a coupled, highly controlled network of estuaries, wetlands, and bights, this complex region is studied in a separate report. Excluded are the Mississippi River (although Mississippi Sound is included), the Rio Grande (which has a very limited estuarine reach), and several minor streams and distributaries that flow directly into the Gulf of Mexico.

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., Gulf of Mexico circulation and the hydroclimatology of nearby states) of these estuaries are summarized below.

Coastal Zones

Florida Coastal Zone. This coastal zone completes the arc of the northern coastline. It extends northwest to southeast along 1000 km of coastline, from the tip of the Florida panhandle down to the Florida Keys. These estuaries generally have smaller drainage basins (175,000 km^2 collectively, only 5% of the entire Gulf of Mexico watershed) (Wilson and Iseri, 1969), with smaller proportions of fluvial sediments. The north Florida coastal zone extends from Perdido Bay in the western panhandle to the Suwannee River estuary in Florida's *Big Bend* region. Nine of the 13 major rivers and five of the seven major tributaries of Florida occur in this region. This portion of Florida's Gulf coast watershed encompasses about 135,000 km^2 of Florida, Alabama, and Georgia. Collectively, these estuarine systems comprise more than 2,100 km^2 of open water. The north Florida coastal zone is characterized by saltwater marshes, tidal creeks, intertidal flats, oyster reefs, seagrass beds, and subtidal and soft bottoms. Located between the Suwannee River and Tampa Bay is Florida's *Springs Coast* (Wolfe, 1990). This region, encompassing about 10,000 km^2, includes large expanses of marshes, wetlands, and seagrass beds. It also has numerous spring-fed rivers and streams along the coast, whose constant discharge provides unique, relatively stable estuarine environments (Wolfe, 1990). Located immediately south of the Springs Coast, the Tampa-Sarasota Bay watershed encompasses 11 major river basins or drainage areas, cumulatively occupying 7,700 km^2 of west central Florida (Wolfe and Drew, 1990). This region straddles the upper boundary of Florida's subtropical environment and supports a large and rapidly growing urban population. These estuaries and their watersheds have been extensively modified by ongoing water-supply, water-use, and land-use conflicts.

Louisiana-Mississippi-Alabama Coastal Zone. This coastal zone consists of a 900-km east-west line along the northern Gulf coast, which is distinguished from both the Texas and Florida coastal zones by a much greater influx of freshwater. The Louisiana coastal zone consists of an extensive wetland system (i.e., 25% to 41% of all U.S. coastal wetlands, depending on the classification system used) (Alexander, 1985; Turner and Gosselink, 1975). These marsh systems are characterized hydrologically by numerous interconnecting lakes, channels, and bayous that comprise the "blood vessels" of the marshlands (Murray, 1976). The flows through these channels are then coupled with extensive overland flooding, thus exchanging water between the marsh surface and the surrounding waterbodies. The Mississippi River, which drains about one-third of the contiguous U.S. (NOAA, 1990a), is a major freshwater source, as well as a boundary between the Louisiana coastal zone and the Mississippi-Alabama coastal zone. The Mississippi-Alabama coastal zone is characterized by a series of barrier islands and bays. However, these bays are surrounded only by fringing salt marshes as opposed to the extensive wetland systems found along the Louisiana coast.

Texas Coastal Zone. This coastal zone is oriented on a northeast-to-southwest arc of coastline on the northwestern Gulf of Mexico. It extends almost 600 km along a nearly continuous chain of barrier islands from Louisiana to the Mexican border, behind which lies one of the most extensive estuarine systems in the U.S. Its watershed encompasses approximately 500,000 km^2 of Texas, Louisiana, and New Mexico, as well as northern Mexico. These systems comprise more than 5,500 km^2 of open water and are bordered by tidal marshes and mud-sand flats. While they are hydrodynamically coupled in varying degrees, these estuaries readily separate into individual systems for detailed study and characterization (including all bays and principal rivers of the Texas coast, except the tidal reach of the Rio Grande and a few minor coastal drainageways discharging directly into the Gulf of Mexico).

Geomorphology and Bathymetry

Geomorphology. The geomorphology of Gulf estuaries is the cumulative expression of shoreline sculpting by Gulf waves and currents, transport and deposition of sediments by rivers, and erosion and reworking of sediments by currents within the bays. The rise in sea level associated with the retreat of ice-age glaciers has been accompanied by low-relief coastal flooding, the development of barrier islands, and filling the valleys and progradation of deltas with river sediments. This culminated 6,000 years ago as a series of shallow lagoons, in many cases isolated from the Gulf of Mexico by a barrier island string, except for occasional tidal inlets. These lagoons are overlaid with river deltas, in some cases extending across the lagoon to the sea and, in other cases, in the inland areas of the bay. The most extensive such system, by far, is the Mississippi Delta.

The Gulf estuaries combine the features of two basic geomorphologic types (Pritchard, 1952): the coastal plain estuary (or drowned-river valley) and the bar-built lagoon. Some Gulf estuaries represent pure examples of each type (e.g., the tidal reaches of the Brazos, Neches, Pascagoula and Suwannee rivers are drowned-river valleys, whereas the Laguna Madre and Apalachicola Bay are bar-built lagoons). Most Gulf estuaries, such as Galveston Bay, are intermediate geomorphologically, with various subtypes. For example, the Louisiana estuaries can be further divided into three broad classes: 1) barrier-built, 2) delta-front, or 3) delta-margin (Pilkey et al., 1989). Barrier-built estuaries are formed by delta abandonment (discussed later), delta-front estuaries by active sedimentation (e.g., the Atchafalaya River Delta complex), and delta-margin estuaries by deltaic entrapment or deltaic-plain submergence (Pilkey et al., 1989).

Bathymetry. An important physical characteristic of the Gulf estuaries is depth. Because of their lagoonal nature, these systems are generally shallow, approximately 1-5 m in depth. The exceptions are the drowned-river channels (comprised nearly of the entire Choctawhatchee Bay), and near tidal inlets where current scour is more operative and greater depths result. In addition, several estuaries have fluvial deposits, sand-bar accumulations, or natural reef formations (i.e., primarily oysters) which produce shoal areas, sometimes emergent. The broad, shallow nature of these systems determines their circulation, mixing processes, and man-induced activities.

Besides natural variations in bathymetry, these systems have been substantially altered by man. They have been transected by bridges and causeways, dredged, leveed, and revetted. Generally, the most important modification is dredging of navigation channels. A network of more than 7,000 km of navigational channels has been constructed along the Gulf coast, some with depths as great as 10-15 m and widths of 50-150 m (Christmas, 1973; Diener, 1975; LWFC, 1971; McNulty et al., 1972). These channels provide preferred avenues of flow and hydraulically connect bay sections that would otherwise be isolated. They also allow the development of density currents (i.e., the mean current directed from the mouth to the head of the estuary that is forced by the seaward gradient in salinity) that are an important mechanism for salinity intrusion (Ward, 1980). The intensity of density currents dramatically increases with water depth (Ward, 1983). Because dredged channels are relatively deep (e.g., in some estuaries three to four times the natural depth), they are very important conveyances for the intrusion of saline waters into upper estuaries.

Another hydrodynamic effect of navigational access is due to enlarging the cross section and increasing the controlling depths of inlets to the Gulf of Mexico. Many major inlets on the Gulf coast are now jettied, especially on the western (Texas) coastline (where only Pass Cavallo in the Matagorda system and San Luis Pass in the Galveston system remain unjettied). The inlet channels and jetties greatly affect the coupling of the estuary with the sea. In several instances, artificial navigational inlets have been created by cutting through barrier islands (e.g., Mansfield Pass in Laguna Madre and the Entrance Channel in Matagorda Bay). In other cases, river channels have been diverted to accommodate navigation. The net effect is that dredged channels are capable of modifying the internal circulation of estuaries to an extent greatly disproportionate to their (small) fraction of total estuarine volume.

Associated with channelization is the disposal of dredged material. Historically, most disposal has taken place within the Gulf estuaries. In some estuaries, such as Sabine Lake, substantial areas of the estuary have been replaced by dredged material islands. In most, the disposal areas are more modest in extent, but restrict or divert circulation, tides, and ultimately salinity. In Galveston Bay, for example, sediment disposal has created a 20-km longitudinal barrier that bifurcates the upper bay. Another example is the frequent disposal bars along the Gulf Intracoastal Waterway (GIWW) that impose an effective barrier to transverse flows.

Circulation and Salinity

The Gulf of Mexico is a Mediterranean sea, bounded on three sides by North America. The general circulation of the Gulf (Figure 9) is dominated by the dynamics of its eastern section, which is connected to the overall circulation of the North Atlantic. A limb of the westward-flowing equatorial current enters the Gulf between Yucatan peninsula and Cuba, penetrates the central Gulf as it turns clockwise, and exits between Cuba and Florida to feed the Florida Current (Nowlin, 1972; Nowlin and Hubertz, 1972). Within the Gulf, this strongly curved current, referred to as the *Loop Current,* is highly variable in position and configuration (Sturges and Evans, 1983). In general, the Loop Current grows northward into the Gulf to a maximum penetration, frequently producing the separation of an eddy or *ring,* followed by the westward drift of this ring leaving behind a Loop Current with reduced penetration into the Gulf (Behringer et al., 1977). The Loop Current has its greatest Gulf penetration in late summer and fall; hence, rings tend to pinch off in late fall and early winter (Ichiye et al., 1973).

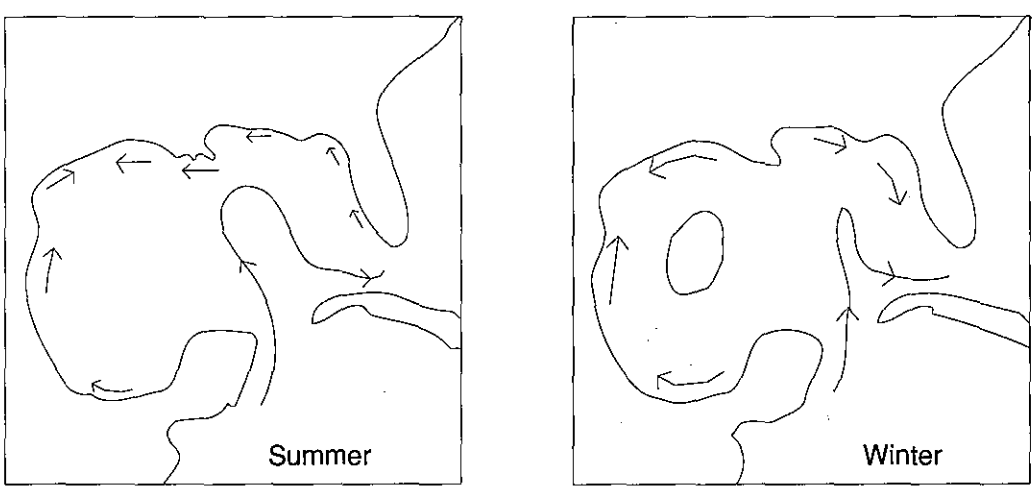
Eastern Gulf of Mexico Circulation. The nearshore currents along the Florida coast lack the well-defined average sets of wind-driven currents on the northwest coast, and exhibit a high degree of variability from spin-off eddies detaching from the southward limb of the Loop Current (Niiler, 1976). These eddies are due to shear instability (resulting from the frictional drag of the West Florida Shelf on the Loop Current) and, therefore, tend to be much smaller in spatial scale than the detached rings of the Western Gulf. Small cyclonic gyres may be situated in the bight of the panhandle (with Apalachee Bay at its apex) and out from Florida Bay that combine to force a weak northward-setting current along the coast (Austin and Jones, 1974).

Central Gulf of Mexico Circulation. The circulation in the Mississippi Sound is quite variable and is strongly influenced by local bathymetry, river flow, and winds. Chuang et al. (1982) concluded that the mean summertime alongshore motion off the Alabama coast is wind-driven, with a net longshore motion possible in either direction. The cross-shelf motion appears to be negligible when the longshore motion is to the west, but it exhibits a persistent offshore motion during the summer when the longshore motion is to the east (Chuang et al., 1982). In general, the tidal flows in the Mississippi Sound are quite complex, although three general zones can be described (USACE, 1982):

- The *eastern portion* of the sound is strongly influenced by flows through Petit Bois Pass and from Mobile Bay and the east passage of the Pascagoula River.

- The *central portion* of the sound is influenced by tidal flows through Dog Keys and Ship Island Passes.

Figure 9. *General circulation of Gulf of Mexico*



- The *western portion* of the sound is influenced by flows through Cat Island Pass and Chandeleur Sound, as well as from Lake Borgne and the Pearl River.

Western Gulf of Mexico Circulation. The Gulf's western section is relatively more quiescent. Its circulation is dominated by an anticyclonic gyre in the southwestern Gulf (probably fed by accumulated warm core rings) (Vidal et al., 1990), with a relatively narrow eastward-flowing current at its northern limit. On the inner shelf, the Texas coast is a convergence zone of a current flowing north along the western shore of the Gulf, and a westward or southwestward flowing current from the north. The westerly current is stronger during the winter, and the convergence zone is displaced to the south along the Mexican coast. During summer, the northward current strengthens and the convergence zone migrates northward to the Texas coastal bend. This semipermanent offshore current, westerly on the Louisiana and upper Texas coast and northerly on the lower Texas coast, is subject to many variations, besides its seasonal fluctuation per se. Tidal currents are superposed, of course, and transient wind-driven currents are common. For example, current meter data from the Buccaneer Field, 50 km south of Galveston (Harper, 1977), showed predominantly westerly currents between March and June, but easterly between July and September. Nonetheless, the westerly current, especially when closer to shore, is dependable enough to be used by vessels and small craft (Blackford, 1977). This nearshore circulation is wind-driven, and is probably directly related to longshore wind stress (Etter et al., 1985).

Salinity and Temperature. The distribution of salinity and temperature in the Gulf is influenced primarily by high salinity and warm temperatures injected into the Gulf by the Yucatan current and the influx of low salinity and cool temperatures by runoff from the northern shoreline. These influences result in a core of high salinities aligned with the northerly limb of the Loop Current, and a band of lower salinities extending along the continental shelf from Florida to the Texas coastal bend (Nowlin, 1972). Lower salinities from the Louisiana coast, including the Mississippi plume, are transported to the upper Texas coast by the westerly current. This fresher water varies substantially in salinity, depending on inflow. For example, data from the Buccaneer Field in 1976 (Martin, 1977) showed a monthly mean varying from 27 to 36 ppt. The seasonal periods of minimum salinity correspond to the maximum freshwater influx, usually in May and October (Cochrane and Kelly, 1986). The Florida coast, in contrast, exhibits little seasonal variation in salinity due to the limited influence of freshwater. For example, summer-to-winter salinities range from 35.8 to 36.0 ppt (Austin and Jones, 1974; Niiler, 1976; Nowlin, 1972).

Currently, the most important aspect of circulation in the Gulf of Mexico is the potential influence it has on the estuaries, most significantly the salinity regimes characterizing the seaward boundary of the estuaries, and the exchange between the estuaries and Gulf shelf waters.

Tides

Tidal interaction between the Atlantic Ocean and the Gulf of Mexico occurs through Yucatan Strait and Florida Strait (two ports to the Gulf), and greatly favors the diurnal rather than the semidiurnal tides. The net effect is a predominance of diurnal tides in the Gulf. Semidiurnal tides are more directly forced and, therefore, are limited in amplitude. Diurnal tides increase in amplitude from Florida to Texas, and are nearly synchronous west of the Mississippi River (Grace, 1932; Zetler and Hansen, 1972). A semidiurnal tide exhibits a marked change in phase across the Gulf midline, from the Mississippi Delta to Yucatan Peninsula, with a minimal amplitude around Louisiana (Zetler and Hansen, 1972). The mean tidal range along the upper Gulf coast is on the order of 0.5 m, about three-quarters of which is diurnal.

Diurnal tides vary substantially with the moon's declination. At small declination, tides become nearly semidiurnal. Tides range from 0.8 m at maximum declination to about 0.2 m at minimum declination (Rezak et al., 1983; Ward et al., 1980; Zetler and Hansen, 1972). While they are important in local coastal areas, tides are significantly feeble, augmenting the importance of nontidal water-level variations.

As they propagate through tidal passes and into estuaries, tides significantly change, lagging in phase and attenuating in amplitude. Semidiurnal tides are usually filtered, relative to diurnal, and transform from progressive waves to standing waves (Ward, 1980). Because their amplitude and characteristics are modified by factors such as estuary bathymetry and inlet configuration, tides vary among Gulf estuaries and even in areas of the same estuary.

Saline waters enter estuaries in tidal pulses and, during the subsequent ebb, retreat to the seaward areas. The net effect is a general long-term increase in estuary salinity, with all other factors being equal. However, this *tidal dispersion* of salinity in Gulf estuaries is much smaller in magnitude than other U.S. estuaries. Significant changes to the horizontal or vertical salinity structure are generally not caused by tides, but instead are related to river discharges and wind (Ward, 1973).

The tide's effect on salinity transported to an estuary is directly measured by the tidal excursion (i.e., the total distance a water parcel is moved on the flooding current). Tidal excursions in Gulf systems are quite small (e.g., on the order of 10 km near the passes) and decline to 1-2 km or less in the upper segments of the bays. Near large, energetic tidal inlets, excursions may approach 15 km at great lunar declination. In systems with highly constricted Gulf exchanges, tidal excursions may be only a few kilometers or less, even in the open bay. Notably in Louisiana estuaries west of the Mississippi and in the Florida bight near Apalachee Bay, local bathymetric forcing increases tidal excursions.

Climatology

This section presents an overview of the regional climate pertinent to the hydrography of the Gulf estuaries. More detail and data concerning the climate may be found in the literature on national and state climatography (Bomar, 1983; Rezak et al., 1983). The Gulf watershed (1.7 million square miles) represents over 80% of the drainage of coterminous states into the coastal ocean (a portion of the U.S. does not drain to the coastal ocean) (Wilson and Iseri, 1969). It is subject to nearly the full range of North American climates. The nature of this climate dictates the hydrographic characteristics of Gulf estuaries.

Air Masses. In general, the movement and interaction of airstreams, strongly modulated by the topography of the land surface and its radiation budget, determines the climate of the coterminous U.S. The western section of the Gulf estuaries lies in the rainshadow of the North American cordillera, which impedes and deflects the impingent westerlies. East of the cordillera (i.e., the Great Plains), the interior highlands and the coastal plains present vast low-relief areas that allow the relatively unhindered north-south movement of airstreams (where polar air can thrust deep into Mexico and the Gulf), while warm and moist tropical air from the Gulf can flow into the north central plains.

The Gulf of Mexico region acts as an air-mass source (i.e., air that is tropical in character, warm and moist, with a high degree of potential instability). A persistent onshore flow from the southerly limb of the circulation about the Bermuda High transports Gulf air into the southern and eastern states. Climates of states immediately near the Gulf can be described as Gulf flows interrupted by mid-latitude disturbances, the frequency and duration of which vary with season. Cold fronts generally traverse the southeastern states from the north or northwest. Their southward penetration depends on the energy and track of the synoptic system. These systems typically weaken in the latitudes of the Florida and Texas estuaries in response to ground-surface contact modifications, to outrunning the main baroclinic energy source, and to encountering the onshore Gulf flow.

Precipitation and Evaporation. A central parameter affecting estuarine salinity is precipitation and the associated runoff. Of the mechanisms producing organized convection and precipitation, frontal disturbances and tropical storms (including hurricanes) are the most important. Figure 10 depicts the annual precipitation across the Gulf estuaries, and displays the general precipitation increase from west to east. The maximum precipitation season varies substantially across the region. Most of the coast exhibits maxima in the equinoctial seasons. In summer, a large quantity of moisture is available, but the reduced frequency of frontal passages makes frontal-induced precipitation infrequent. In contrast, frontal disturbances in winter are most frequent, but the Gulf's onshore flow is much weaker and less persistent, so frontal-induced precipitation is minimal. In the fall and spring, however, the interplay between frontal intrusions and the Gulf's return flow generates storms and rainfall. The fall maximum is reinforced by tropical storms entering the Gulf in the tropical easterlies. In south Florida and south Texas, frontal penetration is limited and the tropical system's effect is more pronounced, hence the fall maximum in precipitation. The Florida peninsula is especially prone to summer air-mass thunderstorms; in fact, this area has the highest thunderstorm frequency in the coterminous states.

Not only does precipitation decrease from east to west across the Gulf estuaries, but surface evaporation increases because of the subsidence in the lee of the Rockies (Figure 11). A comparison of Figures 10 and 11 shows an annual evaporative deficit for the western part of the Gulf of Mexico, as well as the southern part of the Florida peninsula; thus, a marked climate gradient exists along the Gulf coast, passing literally from humid to arid in a few hundred kilometers. This is reflected in the controlling hydrology of the Gulf estuaries. Some estuaries on the north coast (e.g., Sabine Lake and Mobile Bay) receive the highest freshwater inflow per-unit-estuary-volume of any estuarine embayment systems in the U.S. (Ward, 1980). In southern Texas, Laguna Madre is the classical example of a hypersaline estuary, in which salinities over three times that of seawater are routinely encountered.

Meteorological Forcing

Because astronomical tides are so feeble along the Gulf coast, meteorological forcing is the primary

Figure 10. *Average annual precipitation (cm) for the Gulf of Mexico*

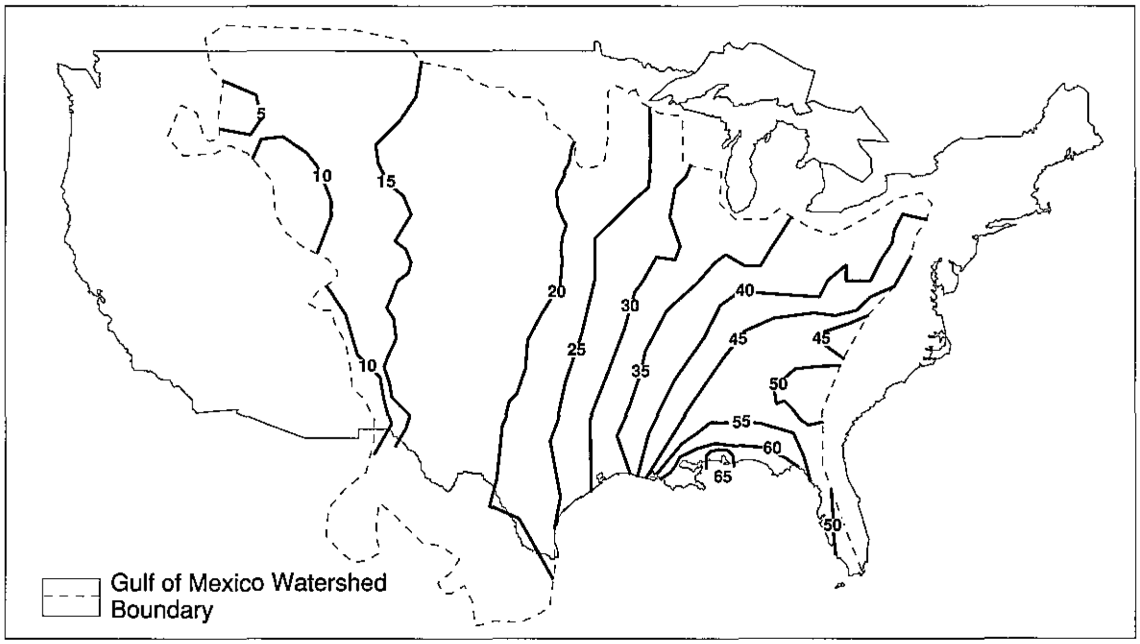
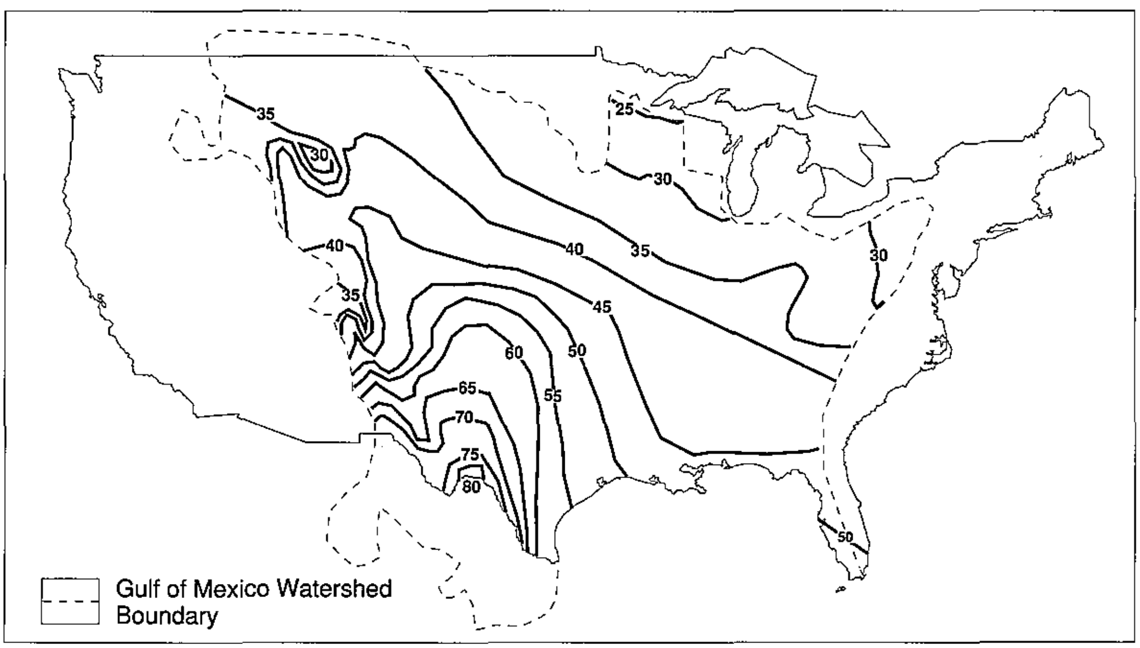


Figure 11. *Average annual lake surface evaporation rates (cm)*



mechanism driving the water exchange between estuaries and the Gulf. The most immediate index to this forcing is the variation in water levels. Seasonal wind shifts over the Gulf of Mexico influence nearshore and estuarine water levels, and can affect the water exchange between estuaries and the Gulf. On an annual basis, winds from the southeast predominate (Rezak et al., 1983). However, summer and winter wind patterns are very different; they have mainly southern and eastern components between June and August. From December to February, north winds dominate and alternate with weak south or east winds. These north winds are due to frontal passages and continental high-pressure systems. Cold fronts occur primarily from October to March, and are most frequent from December to February.

Gulf of Mexico Water Level Variation. The seasonal variation in meteorology leads to a characteristic annual variation in water levels along the nearshore Gulf of Mexico. This variation is generally bimodal with maxima in spring and fall, and minima in winter and summer (Chew, 1964). The winter minimum and fall maximum predominate, with a net range on the order of 0.3 m. The winter minimum is associated with the depression of nearshore waters by north winds, in combination with the maximum density due to cold temperatures. As the year progresses, additional heat yields a steric sea-level change of about 0.15 m. The early fall maximum corresponds to the maximum in the Gulf's heat storage. Increased onshore flow during this period adds to the water-level elevation. The July minimum, which is most pronounced on the Gulf's western coast (Blaha and Sturges, 1981), remains unexplained, although mechanisms such as the Ekman convergence (Chew, 1964) and curl-driven dynamic sea-level response (i.e., detachment of a western boundary current) (Sturges and Blaha, 1976) have been proposed. On a shorter time frame, water-level variations occurring every few days have been shown to be highly coherent with trans-Gulf atmospheric pressure (Smith, 1979), a combined response to both winds and inverse barometer effects.

Currents on the inner shelf of the Texas-Louisiana coast, as discussed earlier, are westerly on the north coast, and southerly on the south, creating a convergence zone that migrates north with strengthening southerly currents in summer. These inner-shelf currents are most likely the result of direct wind stress, whose longshore component is to the west on the upper coast and to the north on the lower coast (Etter et al., 1985), a consequence of the coast's curvature in this area. The littoral transport is similar (Carothers and Innis, 1960), with a convergence zone on the south Texas coast caused by wave crests generated by wind stress.

Effect on Gulf Estuaries. Meteorological forcing in the estuaries is even more dramatic than in the open Gulf, partially due to the morphology of these bays being broad, shallow systems with long over-water fetches. Abrupt wind shifts and barometric pressure changes associated with frontal passages can dramatically affect water levels in the estuary, obliterate any tidal effect, and ultimately lead to the flushing of estuarine waters (Ward, 1980; Wermund et al., 1989). As the cold front approaches, the low-level atmospheric convergence augments the southerly winds over the estuaries and northwest Gulf. With the frontal passage, winds shift suddenly to the north and water levels that increased during the front's approach abruptly decrease due to the northerly winds and rising barometric pressure. In the upper estuary, water levels can decrease by more than 1 m in a few hours. Currents in the inlets are swift and are frequently augmented by large bay-to-Gulf differences in water elevation across the barrier islands due to their increase on the bay-side and decrease in the Gulf. Half of the volume for some estuaries can be evacuated within 24 hours of a frontal passage by intense systems (Ward, 1980).

Estuarine-coastal exchange processes resulting from wind forcing also result in the formation of buoyant effluent plumes, which in turn influence shelf chemistry, biology, and physics, especially along the central portion of the Gulf coast (Wiseman, 1986). These exchanges are bi-directional, with significant mass and momentum transfers, as well as chemical and geological constituents also occurring between the shelf and the estuary (Wiseman, 1986). Ekman convergence/divergence may be driven by the alongshore wind stress, thereby controlling estuarine-shelf exchanges at longer time scales (Schroeder and Wiseman, 1986).

Frontal Passages. Frontal passages can greatly stimulate the exchange between the estuary and the Gulf, thereby greatly influencing the salinity in an estuary. An additional long-term effect exists due to the seasonal frequency of these events. Therefore, winds may affect the salinity regime over periods ranging from days to months. Sustained northerly winds generally decrease estuarine volume, diminish tidal height, and reduce salinity. In contrast, southerly winds generally increase water levels in the upper segments of the estuaries and accelerate the salinity intrusion.

Tropical Storms. Tropical storms and hurricanes are episodic events that can have pronounced effects on estuarine salinity, depending on the storm's proximity to the estuary. Hurricanes occur in the Gulf of Mexico primarily from June to October, but are most common in late summer and early fall (Henry et al., 1975) when the easterly circulation about the Bermuda High is strongest and water temperatures are maximal. Winds are most dramatically expressed as storm surges affecting coastal water levels. Depending on the direction of approach, storm surges can either inject large water volumes into the estuary or flush water from the estuary through existing inlets, breaches, or overwashes through the barrier islands.

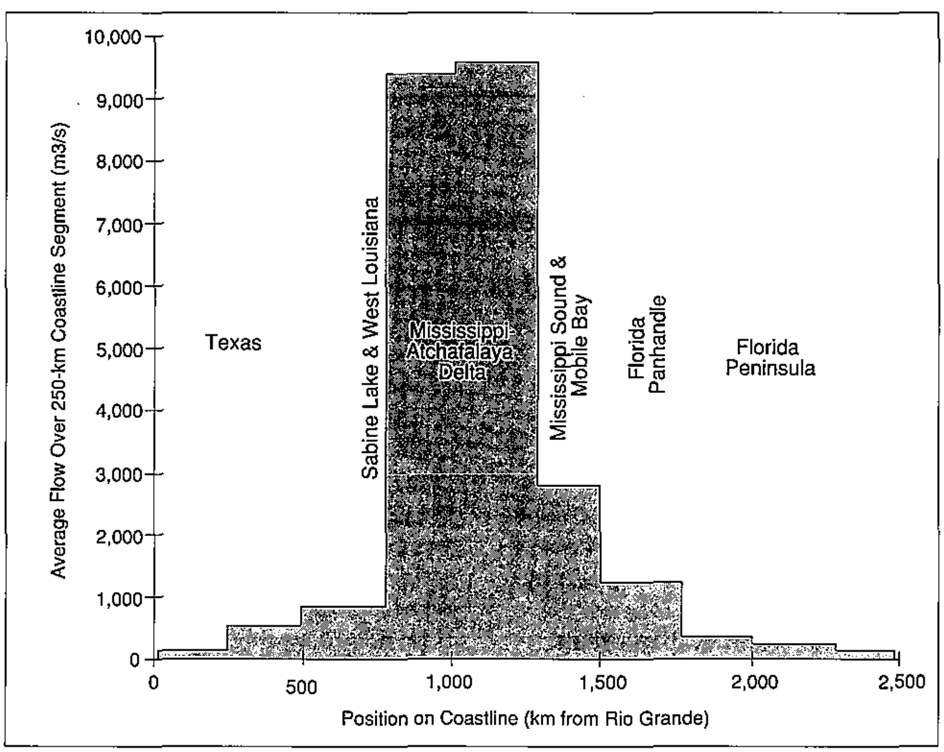
Besides the dynamic mechanisms of wind and pressure, meteorological systems also directly affect estuarine salinity through precipitation. As discussed earlier, frontal passages and tropical storms are the principal rain-producing systems for most of the Gulf of Mexico region. Cold fronts accompanied by intense rainfall can dramatically reduce salinities throughout an estuary (McFarlane et al., 1989). Many tropical storms and hurricanes bring torrential rains, which generate large freshwater volumes. However, rain falling in this region and draining into the estuaries are far more important determinants of estuary salinity than rain falling directly on the water surface.

Freshwater Inflow

Over half of the freshwater discharge to the sea from the coterminous U.S. enters the Gulf of Mexico, with three-quarters carried by the Mississippi River system. The Gulf's various climates entail corresponding inflow ranges. Figure 12 shows the inflow variation with distance around the Gulf coast. This inflow is roughly symmetric, centered, of course, on the Mississippi River Delta, with a range of over two orders of magnitude, from the arid segments of the Florida and Texas coasts to the water-rich Mississippi Delta. (Figure 12 depicts the general variation of the Gulf's river flow but should not mislead one into inferring that the inflow is a smooth function of coastline position. River flow is, of course, concentrated in the principal drainageways and would appear as spikes of inflow, separated by large distances with no inflow. Figure 12 greatly smooths this variation by averaging over 250-km segments.)

Temporal Variation. The monthly and seasonal cumulative variation in freshwater inflow produces the most dramatic changes in bay-wide salinities in most Gulf estuaries. For most of the coast, the summer or fall is the low-flow season (Geraghty et al., 1973). The high-flow season depends on the situation of the Gulf estuaries with large-scale

Figure 12. *General variation of river flow around the Gulf*



climatological controls. For most of the Texas coast, spring is the high-flow season, driven by direct precipitation on the Gulf estuaries by the equinoctial interaction of continental and marine air. For the northern coast from Louisiana to the Florida panhandle, the winter and early spring are the high-flow seasons, due to precipitation, snow melt, and river-channel transport in the great Midwestern watersheds. In Florida, summer and early fall are the high-flow seasons, due to air-mass thunderstorms in the peninsula's small watersheds. Also in Florida, spring is frequently the low-flow season.

Year-to-year variability in freshwater input to Gulf estuaries is great, responding to the large-scale climate fluctuations that produce flooding and drought. In some years, the high-flow period is pronounced and lengthy; in other years, it may be completely absent. Although river discharges in the low-flow period are less variable than those in the high-flow period, annual variability does occur. In some years, the low-flow period is shortened or eliminated by unusual runoff; in other years, it is prolonged.

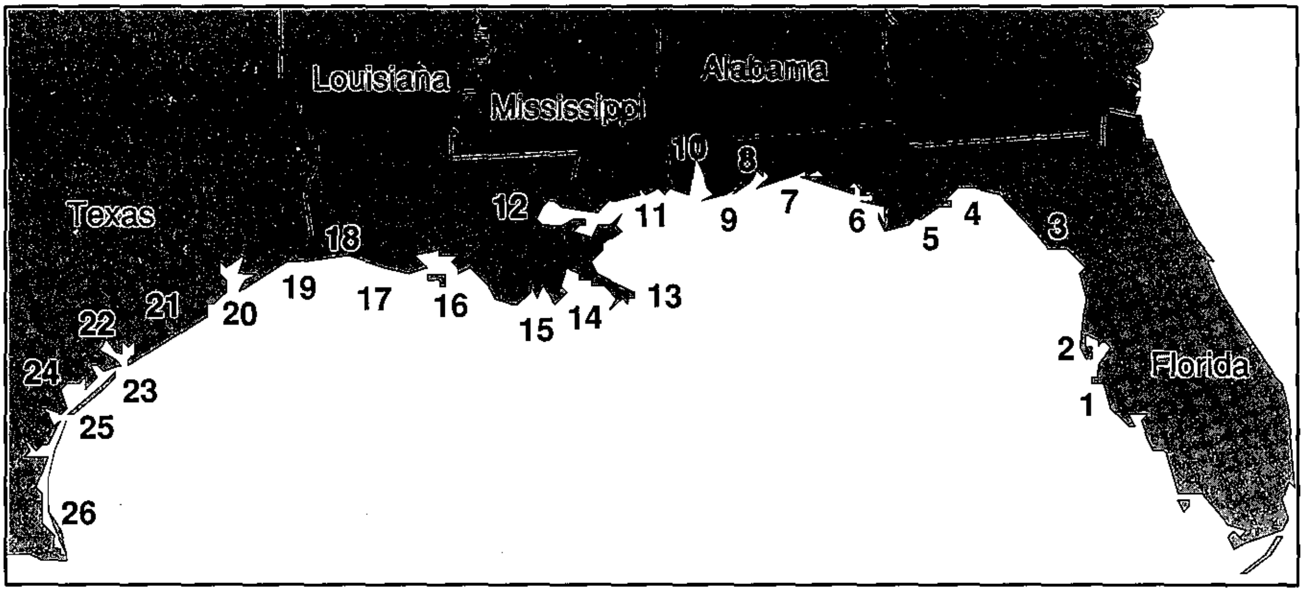
Inflow to the Central Gulf. The Louisiana estuaries on the west side of the Mississippi River are a series of bar-built systems in which freshwater is generally dispersed by numerous small channels or bayous. The freshwater input to these systems is not well known. To the east of the Mississippi River, two major freshwater sources entering Mississippi Sound on the western end include the Pearl and the Pascagoula rivers, which supply about equal volumes of mean flow (USACE, 1983c). Additional freshwater is also supplied by several smaller rivers in Mississippi, as well as several rivers entering Lake Pontchartrain, thus supplying freshwater to Lake Borgne through the tidal passes at the east end of Lake Pontchartrain. The picture is quite different on the eastern end of the Sound where Mobile River supplies freshwater at an average rate of about 1800 m^3/s (Isphording et al., 1983). The impact of these rivers on the salinities in both the estuaries and Mississippi Sound is large and, in general, follows a seasonal pattern, with highest salinities in summer and fall during low-river flows, and lowest in winter and spring during high-river flows.

Inflow to the Eastern and Western Gulf. In the more arid sections of the Gulf coast (i.e., Texas and Florida), river flow is governed by surface runoff generated by storms and, therefore, is highly variable, causing rivers to exhibit large, sudden excursions in flow. The greater frequency and intensity of precipitation in estuaries of the upper Texas and Florida panhandle coasts, along with the detention created by reservoirs, lead to considerable overlap in individual storm impulses. Hence, the freshwater inflow hydrography in these estuaries is typically manifested as a seasonal runoff surge of several weeks to a few months in duration. Further south in Texas and Florida, runoff impulses become more isolated in time, and the inflow appears as a series of nearly discrete flood pulses.

Effect on Estuarine Salinities. Freshwater river plumes discharging into the northern Gulf of Mexico reduce salinities of nearshore Gulf waters, especially in May and October (Cochrane and Kelly, 1986). These low-salinity waters generally drift westward, driven by southeasterly winds and pressure gradients. The degree to which salinities in Texas estuaries are affected by these low-salinity waters depends on their proximity to major river plumes and on the year-to-year variability in river discharges, especially those of the Atchafalaya and Mississippi Rivers. These plumes are also responsible for the high variability in shelf salinity off the Texas coast, compared to those off the Florida coast (discussed earlier).

Watershed Modifications. Reservoirs are located on most major rivers flowing into Gulf estuaries. Operation of these structures generally does not affect annual mean inflows, because their volumes are small compared to river-flow volumes, but can affect timing and fluctuations of river flow. The flow variation is smoothed by reservoirs, as peak flows are lagged and attenuated. In specific low-flow periods (i.e., summer), the relative effect of the reservoirs may be much greater, since the low-river flow is even further reduced. For rivers in the more arid segments of the Gulf, it is arguable whether the natural river flow at low-flow levels would have any impact on salinities, even without reservoirs. The effect of these reservoirs on average estuarine salinities is controversial, but it is believed to be less important than other factors (e.g., seasonal variation in marine and terrestrial climates, or the presence of navigation channels connecting estuaries with the Gulf). However, the presence of reservoirs indicates the diversion of water for human use, which may be important to the freshwater inflow budget of an estuary.

Salinity Characterization Summaries



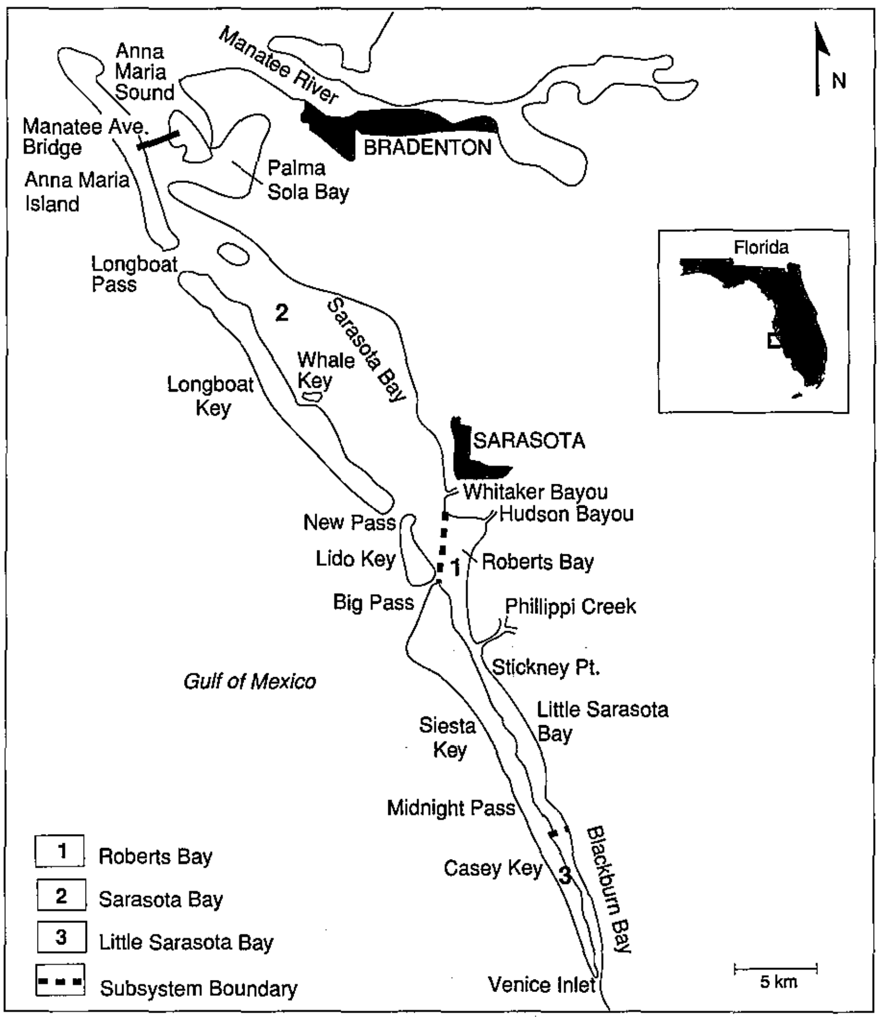
Eastern Gulf of Mexico		Central Gulf of Mexico		Western Gulf of Mexico	
1	Sarasota Bay	11	Mississippi Sound	19	Sabine Lake
2	Tampa Bay	12	Lakes Pontchartrain/ Borgne & Chandeleur Sound	20	Galveston Bay
3	Suwannee River	13	Breton Sound	21	Brazos River & San Bernard Rivers/Cedar Lakes
4	Apalachee Bay Estuaries	14	Barataria Bay	22	Matagorda Bay
5	Apalachicola Bay	15	Terrebonne/Timbalier Bays	23	San Antonio Bay
6	St. Andrew Bay	16	Atchafalaya/ Vermilion Bays	24	Aransas Bay
7	Choctawhatchee Bay	17	Mermentau River	25	Corpus Christi Bay
8	Pensacola Bay	18	Calcasieu Lake	26	Laguna Madre
9	Perdido Bay				
10	Mobile Bay				

Geographic Setting

The Sarasota Bay estuary is an elongated bar-built coastal lagoon, occupying just 114 km² (NOAA, 1990a) south of Tampa Bay. Extending south from the Manatee Avenue Bridge at Anna Maria Sound to Venice Inlet, this estuary includes Sarasota Bay, Little Sarasota Bay, and four smaller bays (i.e., Palma Sola Bay, Roberts Bay, Anna Maria Sound, and Blackburn Bay) (Figure 13). It has four direct openings to the Gulf of Mexico: Longboat Pass, New Pass, Big Pass, and Venice Inlet. A fifth inlet, Midnight Pass, has been closed since 1983. Exchange between Anna Maria Sound and the Gulf of Mexico occurs through Tampa Bay (Sheng and Peene, 1992). Tidal flows at the major passes govern circulation patterns within the estuary, although winds cause significant short-term fluctuations. The water volume flowing through each pass varies significantly during each tidal cycle, although the largest water volume generally enters through Big Pass. Strong currents exist at the passes; weak currents or null zones occur south of Stickney Point, west of Hudson Bayou, north of Whale Key, and in Palma Sola Bay (Sheng and Peene, 1992).

Freshwater inflow to the estuary is derived from several small tributaries and storm-water drains, the largest of which (Whitaker Bayou and Phillippi Creek) enter Roberts Bay (Flannery, 1989). USGS freshwater gage records for this watershed are incomplete; therefore, inflow must be estimated using precipitation records. Although recent watershed development has increased runoff to the estuary, inflow remains low and has little effect on bay circulation, salinity, or temperature except near the mouths of freshwater sources (Walton and Gibney, 1988). Under certain conditions, salinities near Anna Maria Sound may be affected by flows from the Manatee River. This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 13).

Figure 13: *Location map and subsystem identification*



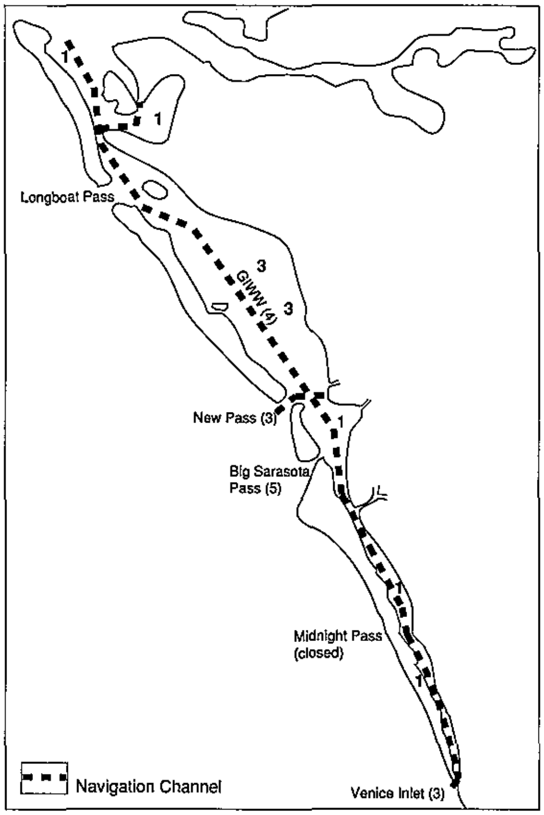
Bathymetry

The average depth of the estuary is approximately 2 m at mid-tide level (NOAA, 1990a). Naturally deep areas exist at the passes and within central Sarasota Bay (Figure 14). Shoals and shoreline constrictions occur throughout the estuary, but are most prominent in Palma Sola and Roberts Bays. The estuary's shoreline and bottom morphology have been subject to extensive modifications, including numerous small navigation channels, dredge disposal sites, and canals.

Salinity Patterns

The Data. April-June 1986 and August-October 1990 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions because no major modifications

Figure 14. *Bathymetry (meters)*



were made to this estuary or its watershed since the natural closing of Midnight Pass in 1983. A summary of freshwater inflow conditions (precipitation) and salinity data for these periods is given in Figure 15. Figure 16 compares the total precipitation during each month of the selected periods to long-term averages and suggests that both periods experienced relatively typical inflow conditions. Figure 17 presents salinity distributions for the selected periods. This structure experiences little variability as indicated in Figure 18.

High-Inflow/Low-Salinity Period (August-October 1990). During this selected period and including July 1990, total precipitation at Bradenton, FL was approximately 15% lower than long-term averages (Figures 15 and 16). Most precipitation occurred from mid-July to early September. The largest events occurred during mid-July (14 cm), early August (8 cm), late September (5 cm), and mid-October (16 cm).

Throughout Sarasota Bay, salinities were generally highest during early August and before the late August and early September freshets. By mid-September, salinities had been depressed by 1-3 ppt, then remained relatively constant through October. Salinities were relatively stable throughout the estuary, with some variability in Roberts Bay. Weak vertical stratification briefly occurred in Roberts Bay, with the remainder of this estuary vertically homogeneous. Salinity data for Little Sarasota and Blackburn Bays were limited to August. Blackburn Bay salinities were consistent with Gulf values, but concentrations in Little Sarasota Bay were approximately 3 ppt less.

Low-Inflow/High-Salinity Period (April-June 1986). During this selected period and including March 1986, total precipitation at Bradenton, FL was approximately 20% above long-term averages (Figures 15 and 16). Most precipitation occurred during mid-March (8 cm) and mid-June (21 cm).

In Sarasota Bay, salinities were very stable, vertically homogeneous, and approximately 3 ppt higher than during the low-salinity period (Figure 17). A weak response (depressed salinities) to the mid-June freshet occurred in Roberts Bay. Salinity data for Anna Maria Sound and Palma Sola Bay were limited to early May and were approximately 3 ppt lower than salinities in Sarasota Bay. Salinity data for Little Sarasota and Blackburn Bays were not available for this period.

Factors Affecting Variability

The salinity structure in Sarasota Bay is primarily determined by seasonal patterns of precipitation and evaporation. The highest estuarine salinities generally occur in spring, coinciding with periods of low precipitation and high evaporation rates. In contrast, lower salinities coincide with the summer wet season (Flannery, 1989). However, mean salinities during both periods differ by only 2-3 ppt. Vertical stratification is uncommon, but may briefly occur in areas near freshwater sources following a significant inflow event.

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 18. This estuary is among the most stable in the Gulf of Mexico, experiencing only limited variability due to isolated and intense precipitation. Under these conditions, salinities may be temporarily depressed and may experience weak vertical stratification in areas near the mouths of freshwater sources (especially within Roberts and Little Sarasota Bays). Salinities in Anna Maria Sound are susceptible to conditions within the Manatee River system. In addition, intense winds (especially when associated with winter cold fronts) may enhance estuarine circulation and vertical mixing.

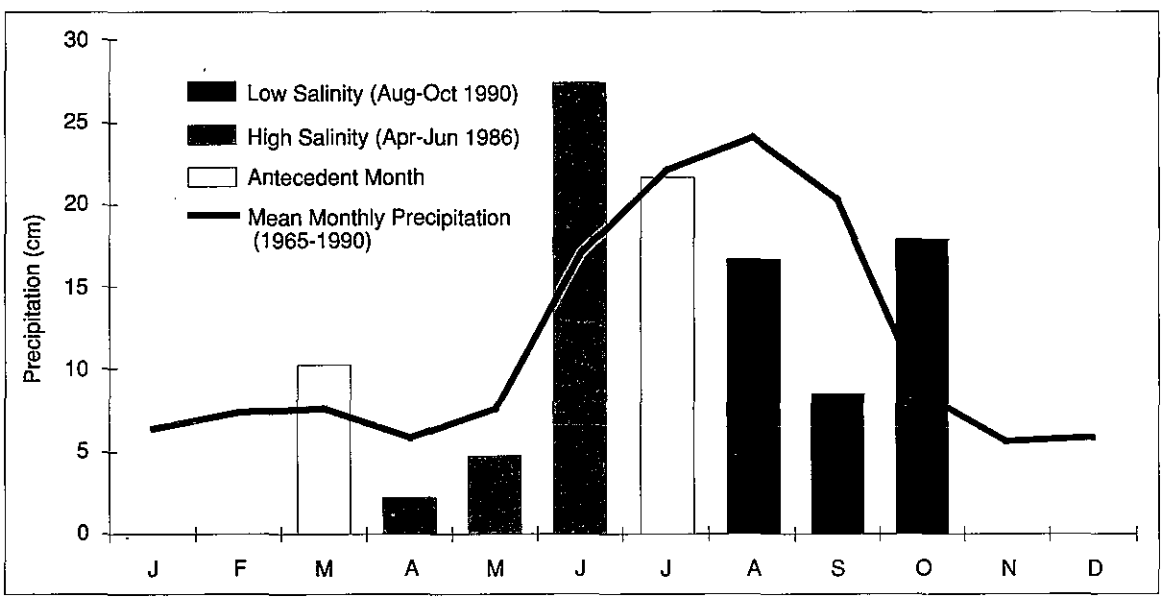
*Figure 15. Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods**

	August-October 1990 (High Inflow/Low Salinity)	April-June 1986 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	328	384
Sampling Distribution [a]	1-3	1-2
Sampling Frequency	monthly	biweekly
Average Salinity (ppt)	31.9	33.7
Bottom Salinity		
# of Observations	142	345
Sampling Distribution [a]	1-3	1-2
Sampling Frequency	monthly	biweekly
Average Salinity (ppt)	33.0	34.0
Precipitation		
Bradenton	15% below average [b]	20% above average [c]

* Return frequencies were unavailable for this system since no streamflow was used.
Abbreviation: ppt - parts per thousand

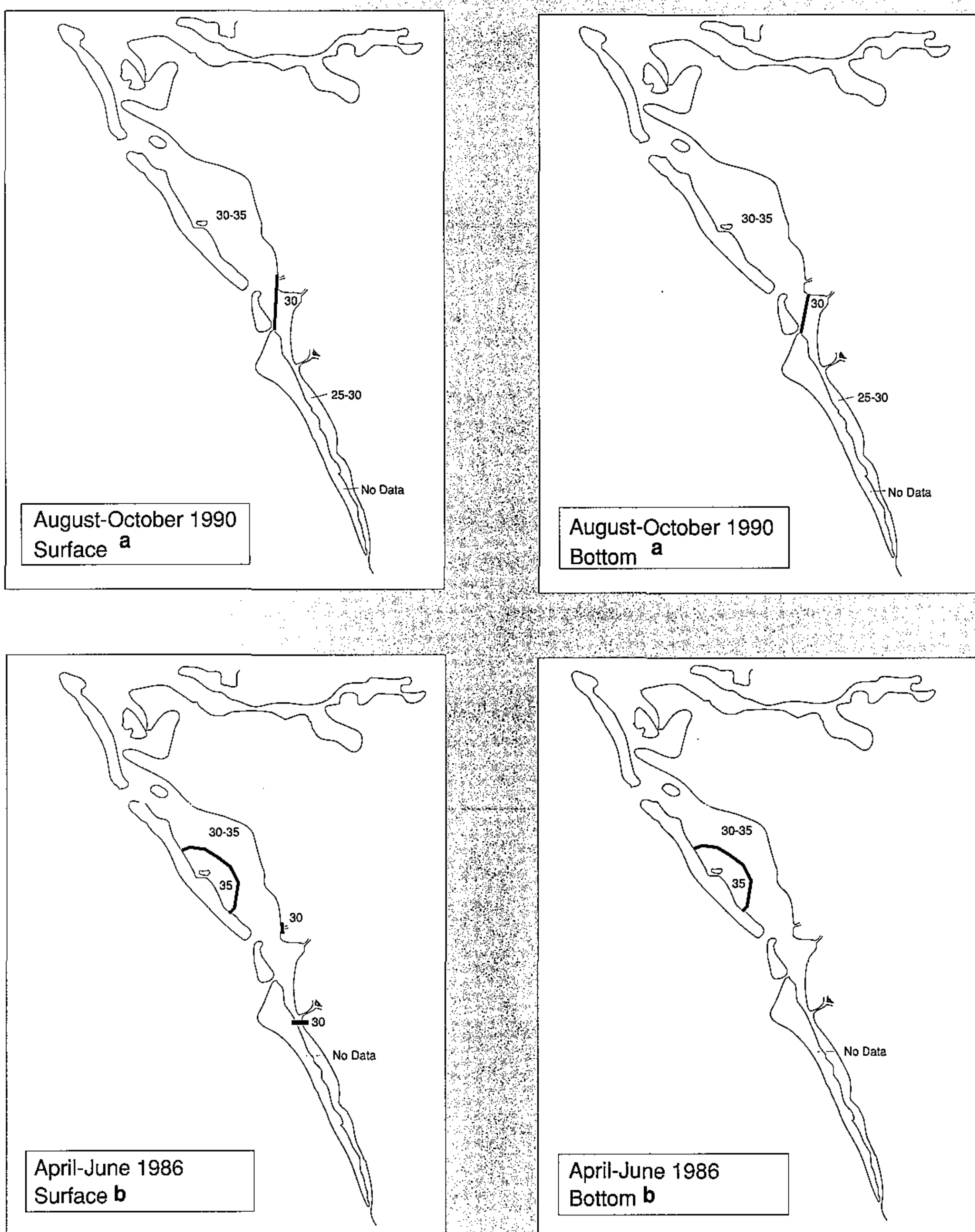
a. Subsystem(s) with high sampling density
b. Includes July 1990
c. Includes March 1986

Figure 16. Comparison of total precipitation (cm) at Bradenton, FL during periods of salinity depiction to period-of-record averages



Abbreviation: cm - centimeters

Figure 17. *Surface and bottom salinities during low- and high-salinity periods*

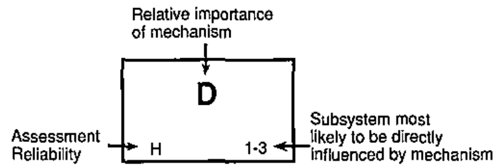


a. Data Sources: FDNR, 1991; Mote Marine Laboratory, 1991
b. Data Sources: FDNR, 1991

Figure 18. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		**S** M 1,3	**S** M 1-3	**D** M 1-3	**D** LIT 1-3
Tides		**M** LIT 2,3			
Wind		**S** LIT 1-3			
Evaporation			**S** LIT 1-3		
Effect on Salinity Variability	UNKNOWN	VERY LOW	VERY LOW	VERY LOW	HIGH

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 17 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 structure and variability, primarily in Roberts and Little Sarasota Bays.

Months-Seasons. Secondary influence on salinity structure, primarily in Roberts and Little Sarasota Bays. The inflow volume is extremely limited for both high- and low-salinity periods; thus, seasonal salinity differences are small and probably due to higher evaporation rates and less-frequent freshwater pulses during spring than summer.

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

Episodic. Dominant influence on salinity structure and variability throughout the estuary. Hurricanes and tropical storms produce significantly greater than normal rainfall and, therefore, reduce salinities to nearly fresh values.

Tides

Days-Weeks. Minor influence on salinity variability, primarily near the passes, but are an important forcing mechanism of circulation. Tides are mixed, but primarily semi-diurnal. The average, spring, and neap ranges are 0.4, 0.7, and <0.1 m, respectively (Walton and Gibney, 1988).

Wind

Days-Weeks. Secondary influence on salinity stability throughout the estuary. Wind, especially when associated with winter cold fronts, enhances vertical and horizontal mixing in the water column (Sheng and Peene, 1992). Cold fronts are most common during January-March (Flannery, 1989).

Evaporation

Months-Seasons. Secondary influence on salinity structure throughout the estuary. Evaporation from open waterbodies in the region is between 122-132 cm per year, which is only slightly less than the average annual rainfall. Highest evaporation rates occur in spring (Flannery, 1989).

* Data Sources: See data sources listed in Appendix II for Florida.

Geographic Setting

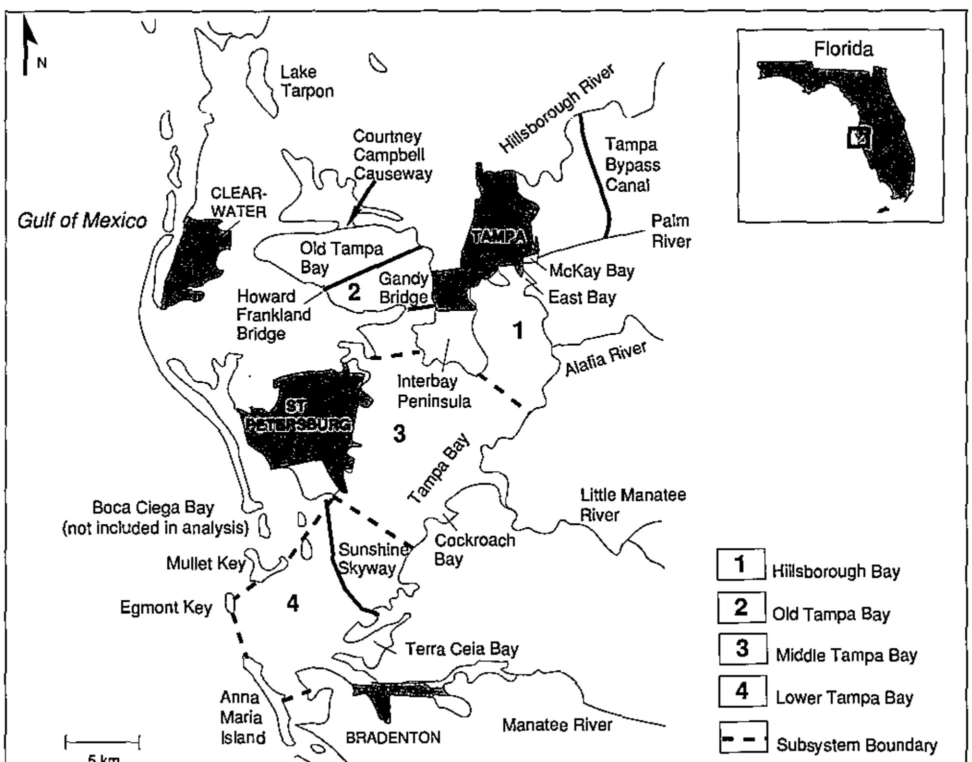
The Tampa Bay estuary is a shallow, Y-shaped embayment located at the northern periphery of south Florida's subtropical environment (Lewis and Estevez, 1988). Occupying 896 km², it is Florida's second largest Gulf coast estuarine system (NOAA, 1990a). This estuary includes the Tampa Bay main stem and its two major embayments (Hillsborough and Old Tampa Bays) separated by the Interbay Peninsula (Figure 19). Its boundaries are defined from the head of tide on its four principal tributaries (the Alafia River at kilometer 16.0, Hillsborough River at km 17.7, Little Manatee River at km 24.0, and the Manatee River at km 30.0 [Lewis and Estevez, 1988]) to its terminus with the Gulf near Egmont Key. Gulf waters are transported at a diminishing rate toward Old Tampa Bay, extending as far as the Courtney Campbell Causeway (Lewis and Estevez, 1988). Transport into Hillsborough Bay is minimal and its circulation poor (Lewis and Estevez, 1988). This estuary has been divided into four subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 19). Boca Ciega Bay is not considered in this analysis because it is not included in NOAA's National Estuarine Inventory (1990a).

The Tampa Bay watershed is among the smallest (6,700 km²) in the Gulf of Mexico (NOAA, 1990a) and contains no single large river source. Approximately 85% of all freshwater inflow to the estuary is derived from its four principal tributaries; three-quarters of this volume is delivered to Hillsborough Bay (Flannery, 1989). The Hillsborough River is normally the largest single freshwater source to Hillsborough Bay, but during dry periods, flow is predominantly from the Alafia River (Giovannelli, 1980). Artesian springs provide an important source of baseflow during the dry season to the Hillsborough and Alafia Rivers (Flannery, 1989). Freshwater is delivered to Old Tampa Bay by several small creeks that may also be supplemented by groundwater (Hutchinson, 1983). Inflow to the estuary peaks from June to September due to thunderstorm activity and is at a minimum during May and June when solar radiation and evaporation rates are highest (Flannery, 1989).

Streamflow in each of the four principal tributaries is impacted by withdrawals and diversions for municipal or industrial purposes. Collectively, withdrawals are equivalent to less than 10% of the annual streamflow to the estuary, but their impact may be very important seasonally (Flannery, 1989). Impoundments exist on all but the Little Manatee River; withdrawals from three in-stream reservoirs have caused significant reduction of dry season flows in these rivers and, periodically, the virtual elimination of flows past the dams entirely. Additionally, the refilling of reservoir storage can markedly increase flow reductions during recovery after low-inflow periods (Flannery, 1989). Withdrawals from the Little Manatee River support power plant cooling operations. These withdrawals occur only when the river exceeds pre-determined seasonal levels and are highest during mid-to-late summer (Flannery, 1989).

The estuary also receives freshwater from several flood control canals operated intermittently during high-inflow

Figure 19. *Location map and subsystem identification*



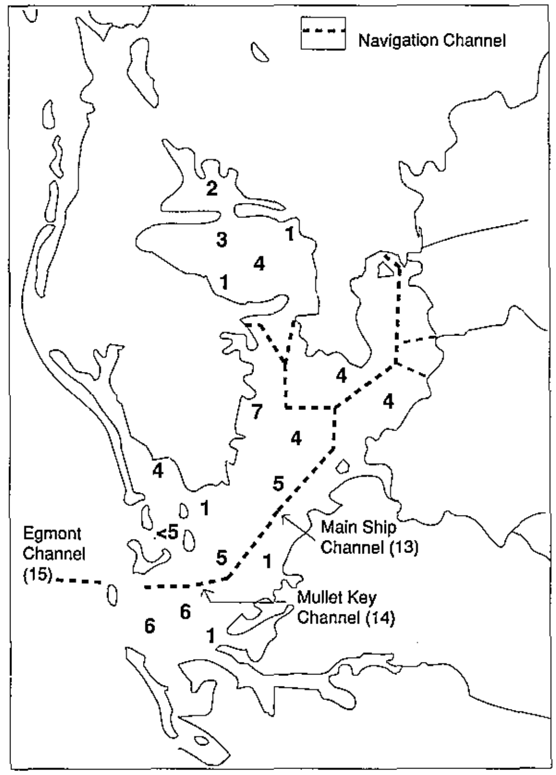
periods. The largest is the Tampa Bypass Canal (completed in 1983) which diverts water from the Hillsborough River and empties into McKay Bay (Flannery, 1989).

Bathymetry

The average depth of this estuary is about 4 m at mid-tide level (NOAA, 1990a) and 90% of its area is shallower than 7 m (Lewis and Estevez, 1988). Naturally deep areas are located at the passes, within lower Tampa Bay, and south of the Interbay Peninsula (Figure 20).

During the past century, the estuary's physical structure has undergone extensive modification that have significantly altered historical circulation and transport processes. These features include tens of kilometers of dredged channels, numerous islands, submerged dredged material disposal sites, four major causeways, and numerous residential and commercial shoreline landfills (Goodwin, 1987). Most modifications occurred before 1972 due to early channel projects, although important changes (e.g., the main ship channel expansion completed in 1985 and the dredging of circulation-inducing cuts within Hillsborough Bay) have occurred subsequently. The main ship channel (13 m) extends from the Egmont Channel to the Hillsborough River; a branch of this channel (>10 m) extends into the lower portions of Old Tampa Bay. Channelization may increase tidal-induced flushing and facilitate intrusion of saline Gulf waters through most of the estuary (Goodwin, 1987). Earthen causeways have restricted the natural cross-section available for water transport, particularly in Old Tampa Bay.

Figure 20. *Bathymetry (meters)*



Salinity Patterns

The Data. April-June 1980 and August-October 1983 were selected to represent high- and low-salinity periods, respectively. These periods do not include the main ship channel expansion in 1985 or the completion of the Tampa Bypass Canal in 1983. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 21. Figure 22 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and indicates that inflow during both periods was below average. Figure 23 presents salinity distributions for the selected periods, illustrating a modest influence of seasonal freshwater discharge on salinity structure. This structure experiences variability at other time scales as indicated in Figure 24.

High-Inflow/Low-Salinity Period (August-October 1983). During this selected period and including July 1983, total inflow was approximately 20% below long-term averages (Figures 21 and 22). Discharge from the principal tributaries was consistent with long-term averages during July and September, but below average during August and October. In general, peak discharge events occurred in these tributaries during early July, mid-August, and late September. Within this period, daily base flow on the Hillsborough River remained below 20 m^3/s except during mid-June (30 m^3/s), early July (45 m^3/s), early September (60 m^3/s), and late September (45 m^3/s).

A modest, short-term salinity reduction occurred during September, following the mid-August and September freshets. Salinities decreased by 3-5 ppt throughout most of the estuary, although the response was nearly double in McKay Bay, East Bay, and the Tampa Bay main stem near Little Manatee River and Cockroach Bay. Moderately stratified conditions existed in these watersheds during September while salinities in the remaining estuary were vertically homogeneous.

Low-Inflow/High-Salinity Period (April-June 1980). During this selected period and including March 1980, total inflow was approximately 20% below long-term averages (Figures 21 and 22). Discharge from the principal tributaries was slightly above average during April and May, but below average during March and June. The timing of peak discharges varied by river basin, but often included mid-March, mid-April, and late May. Within this period, the daily base flow on the Alafia River remained below 10 m^3/s, except during early March (14 m^3/s), early April (14 m^3/s), mid-April (12 m^3/s), late May (28 m^3/s), and late June (13 m^3/s).

During this period, salinities were approximately 5 ppt higher than during the low-salinity period (August-October 1983) (Figure 23). Salinity response to freshwater events varied throughout the estuary, ranging from very stable salinities in lower Tampa Bay (subsystem 4 in Figure 19) to moderately variable salinities in Old Tampa Bay. During late May, salinities in Old Tampa Bay were nearly 10 ppt lower than during late April, temporarily extending into the northwestern portion of the Tampa Bay main stem. Vertically homogeneous conditions prevailed throughout the estuary.

Figure 21. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	August-October 1983 (High Inflow/Low Salinity)	April-June 1980 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	265	272
Sampling Distribution [a]	1-4	1-4
Sampling Frequency	monthly	monthly
Average Salinity (ppt)	23.8	27.4
Bottom Salinity		
# of Observations	175	182
Sampling Distribution [a]	1-4	1-4
Sampling Frequency	monthly	monthly
Average Salinity (ppt)	23.3	26.3
Freshwater Inflow		
Volume [1]	20% below average [b]	20% below average [c]
Return Frequency of Peak Events [2]		
1-day duration	1.9-year	1.8-year
7-day duration	1.5-year	1.8-year
30-day duration	1.7-year	2.0-year

Abbreviation: ppt - parts per thousand

1. Based on Hillsborough River near Tampa, Little Manatee River near Wimauma, Alafia River at Lithia, and Manatee River near Myakka Head.
2. Based on Hillsborough River near Tampa

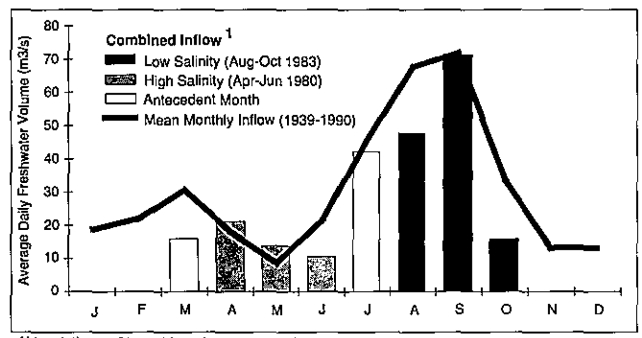
a. Subsystem(s) with high sampling density
b. Includes July 1983
c. Includes March 1980

Factors Affecting Variability

The salinity structure in the Tampa Bay estuary is determined, primarily, by seasonal freshwater discharge. Highest estuarine salinities generally occur in spring, coinciding with periods of low precipitation, high evaporation rates, and extensive in-stream withdrawals. In contrast, lower salinities coincide with the summer wet season (Flannery, 1989), which may include short-term freshwater diversions from flood control canals. Mean salinities during these two periods most often differ by less than 5 ppt. Vertical stratification is uncommon, but may briefly occur in areas near principal freshwater sources following a significant inflow.

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 24. This estuary is relatively stable, experiencing little variability due to limited freshwater inflow. Under peak inflow conditions, salinities may be temporarily suppressed in areas near the mouths of freshwater sources and may experience weak-to-moderate vertical stratification. Salinity variability and vertical stratification are usually short-lived, as wind and tides re-establish pre-event conditions.

Figure 22. *Comparison of gaged freshwater volume during periods of salinity depiction and period-of-record averages* *

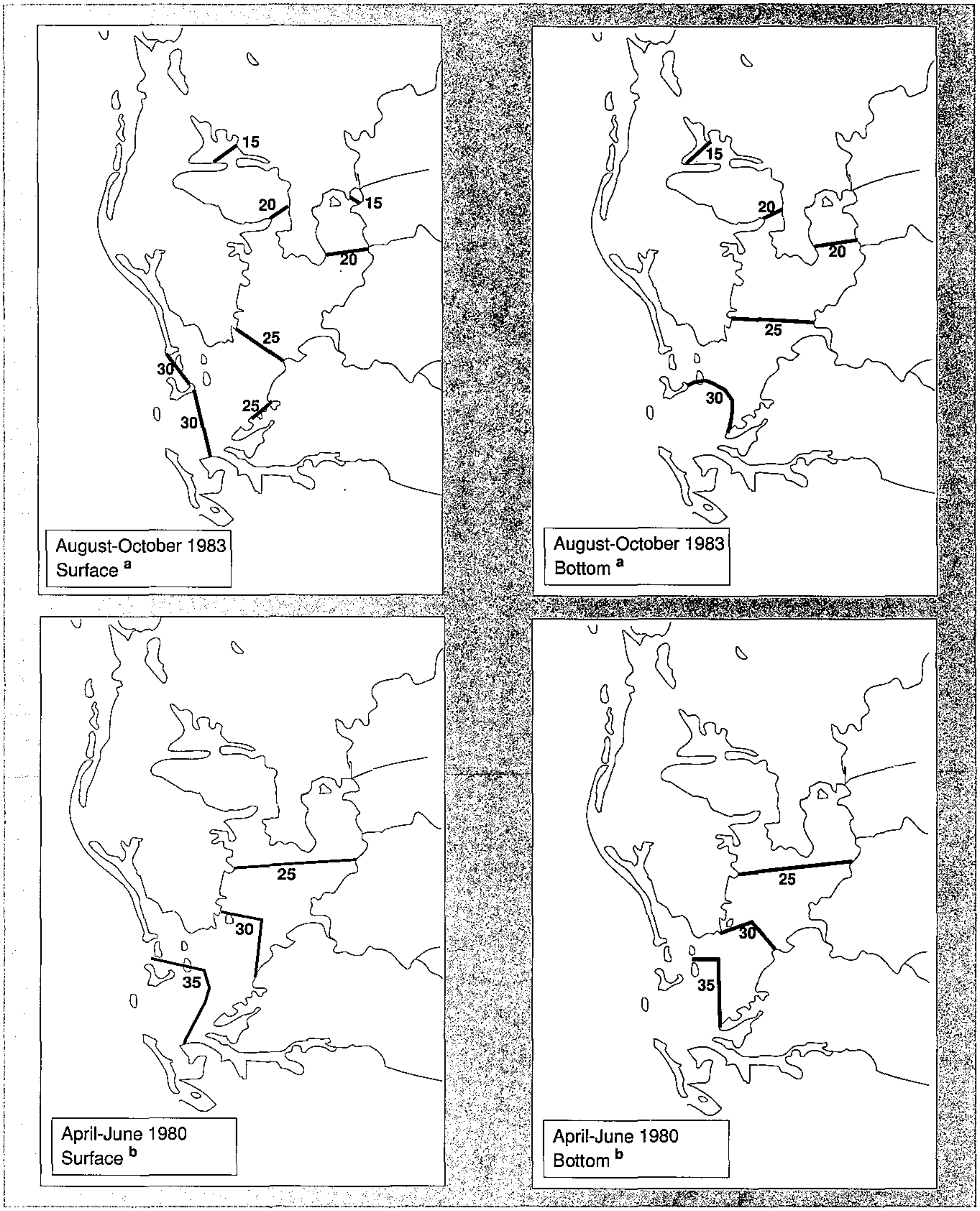


Abbreviation: m3/s - cubic meters per second

1. Based on Hillsborough River near Tampa, Little Manatee River near Wimauma, Alafia River at Lithia and Manatee River near Myakka Head

* USGS gages reflect inflow from 46% of the estuary's total watershed (6,734 km2) (USGS, 1990)

Figure 23. *Surface and bottom salinities during low- and high-salinity periods*

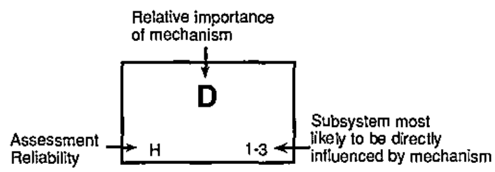


a. Data Sources: FDNR, 1991; HCEPC, 1991
b. Data Sources: FDNR, 1991; HCEPC, 1991

Figure 24. *Time scales and forcing mechanisms important to salinity structure and variability* *

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

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 23 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, primarily near the mouths of the principal freshwater sources. Freshets may temporarily produce weak-to-moderate vertical stratification in these areas.

Months-Seasons. Dominant influence on salinity structure throughout the estuary. Highest salinities occur during spring when precipitation is low, evaporation high, and in-stream withdrawals common.

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

Episodic. Dominant influence on salinity structure and variability throughout the estuary. Hurricanes and tropical storms produce significantly greater than normal rainfall and, therefore, reduce salinities to nearly fresh values.

Tides

Days-Weeks. Minor influence on salinity variability, primarily in the Tampa Bay main stem. Tides are mixed, but predominantly diurnal and range 0.7 m near Egmont Key (NOAA, 1990b). Tides enhance water-column mixing.

Wind

Days-Weeks. Secondary influence on salinity stability throughout the estuary. Wind, especially when associated with winter cold fronts, enhances vertical mixing and flushing of bay waters (Sheng and Peene, 1992). North winds associated with cold fronts can reduce water levels by 1.0-1.5 m (Lewis and Estevez, 1988). Cold fronts are most common during January-March (Flannery, 1989).

Density Currents

Months-Seasons. Minor influence on salinity structure during peak freshwater discharges, especially in the Main Ship Channel.

Evaporation

Months-Seasons. Secondary influence on salinity structure throughout the estuary. Evaporation from open waterbodies is between 122-132 cm/yr, which is only slightly less than the average annual rainfall. Highest evaporation rates occur in spring (Flannery, 1989).

* Data Sources: See data sources listed in Appendix II for Florida.

Geographic Setting

The Suwannee River estuary lies within the Big Bend region of the Florida coast. The estuary consists of Suwannee Sound, the Suwannee River delta, and extensive tidal wetland areas (Figure 25). The estuary is defined from the head of tide on the Suwannee River, approximately 53 km upstream of its terminus at Suwannee Sound (Mattson and Rowan, 1989). Suwannee Sound is bounded by the sand and oyster bars of Suwannee Reef, but includes waters from Horseshoe Point to Cedar Key.

The Suwannee River is the second largest discharging river in Florida and the major freshwater source to the estuary. The river originates in the Okefenokee Swamp of southern Georgia; its discharge pattern is more closely correlated with climatological conditions in this region than in coastal Florida (Leadon, 1979). River flow is greatly enhanced by the substantial groundwater contributions of numerous springs along its banks and from aquifer base flow (Wolfe and Wolfe, 1985). The Suwannee River divides at the Gulf coast into two major branches: East Pass and West Pass; the latter is further divided into the North, Alligator, and Wadley passes. Approximately 70% of river discharge occurs through West Pass (Wolfe and Wolfe, 1985). The estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 25).

Figure 25. *Location map and subsystem identification*

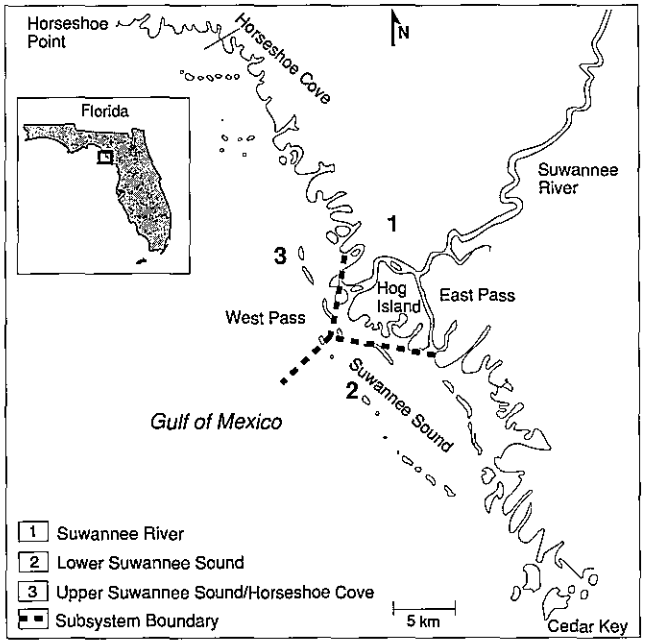
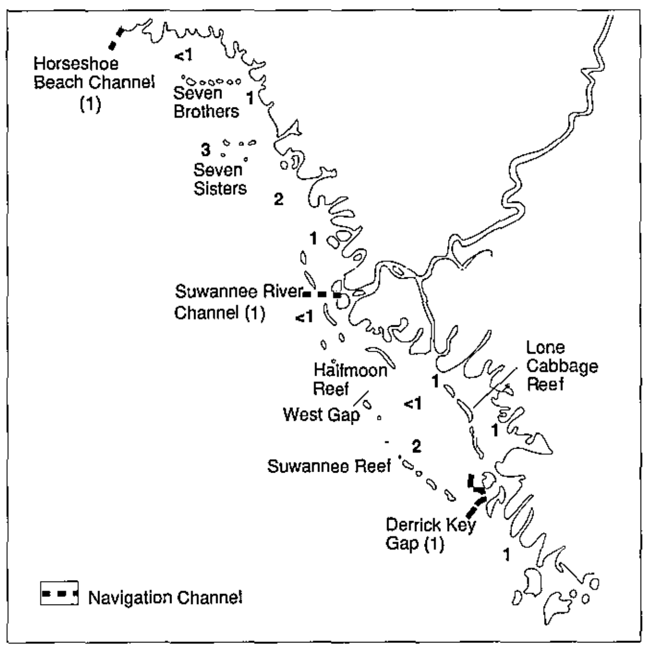


Figure 26. *Bathymetry (meters)*



Bathymetry

The average depth of this estuary is approximately 2 m at mid-tide level (NOAA, 1990a). Suwannee Sound is a relatively shallow and open embayment. Numerous reef and shoal areas exist within the sound, but apparently offer little resistance to circulation and exchanges (Wolfe and Wolfe, 1985). Naturally deep areas are limited to portions of East Pass and West Pass (3-6 m) and the West Gap of Suwannee Reef (3-6 m) (Figure 26). Few navigation channels exist; these are generally narrow and very shallow (1 m).

Salinity Patterns

The Data. October-December 1984 and February-April 1988 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions, as the estuary and its watershed are relatively unmodified. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 27. Figure 28 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that both periods experienced typical inflow conditions. Figure 29

Figure 27. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	February-April 1988 (High Inflow/Low Salinity)	October-December 1984 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	164	244
Sampling Distribution [a]	1-3	1-3
Sampling Frequency	weekly (no April)	daily-monthly (no October)
Average Salinity (ppt)	6.0	18.5
Bottom Salinity		
# of Observations	105	177
Sampling Distribution [a]	1-3	1-3
Sampling Frequency	biweekly (no April)	monthly (no October)
Average Salinity (ppt)	7.7	19.9
Freshwater Inflow (Suwannee River)		
Volume	average [b]	10% below average [c]
Return Frequency of Peak Events		
1-day duration	3.3-year	1.7-year
7-day duration	3.2-year	1.6-year
30-day duration	3.4-year	1.6-year

Abbreviation: ppt - parts per thousand
a. Subsystem(s) with high sampling density
b. Includes January 1988
c. Includes September 1984

presents salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure, however, experiences significant variability as indicated in Figure 30.

High-Inflow/Low-Salinity Period (February-April 1988). During this selected period and including January 1988, total inflow from the Suwannee River was consistent with long-term averages (Figures 27 and 28), but highly variable within the period. Discharge remained between 170-210 m^3/s from January through mid-February. Inflow rapidly increased to a peak of 710 m^3/s by mid-March and gradually returned to 340 m^3/s by late April.

Inflow dominated salinities in the Suwannee River and its delta. March inflows sharply reduced salinities within Suwannee Sound, although this influence was most persistent within the southern portion of the sound. Salinities were most stable within the delta region and most variable in the northern portions of Suwannee Sound. In general, the system was vertically homogeneous, although weak-to-moderate stratification occurred in the northern portion of Suwannee Sound during peak discharges.

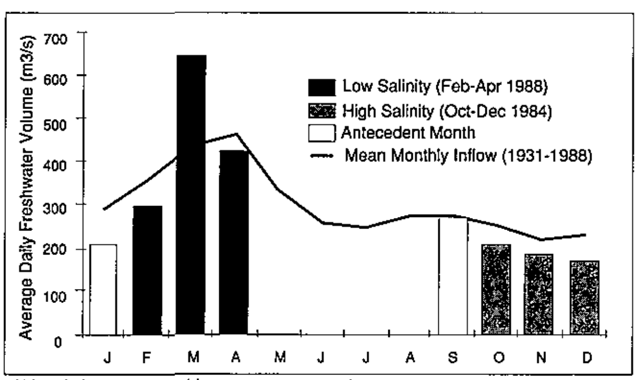
Low-Inflow/High-Salinity Period (October-December 1984). During this selected period and including September 1984, total inflow from the Suwannee River was 10% below long-term averages (Figures 27 and 28). Daily inflow peaked near 340 m^3/s in early September and steadily declined to 200 m^3/s by late December.

Salinities were 10-20 ppt higher throughout most portions of Suwannee Sound than during the low-salinity period (February-April 1988) (Figure 29). In contrast, delta salinities remained surprisingly low, producing a sharp gradient from the delta to the adjacent sound. Vertical stratification (surface-to-bottom differences about 5 ppt) was limited to the marsh and sound areas near the Suwannee delta. Salinities were relatively stable throughout the estuary, with most variability occurring near the Suwannee delta.

Factors Affecting Variability

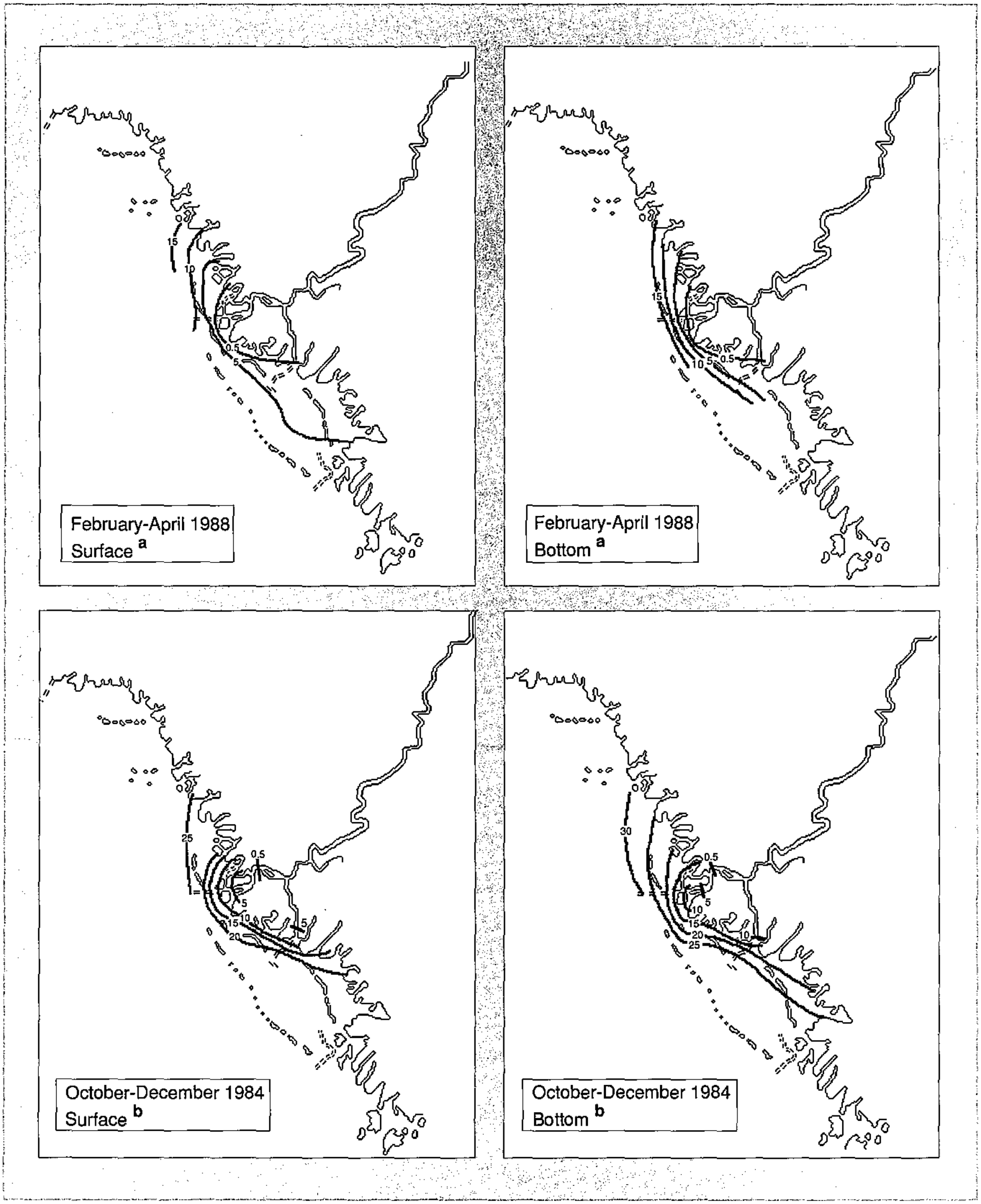
The salinity structure is dominated by the seasonal freshwater discharge from the Suwannee River. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 30. Variability is most apparent within Suwannee Sound during the high-inflow periods, but this variability zone moves toward the river delta during low-inflow conditions. Winds associated with frontal passages and daily tides are also responsible for significant variability, primarily within Suwannee Sound.

Figure 28. *Comparison of gaged freshwater volume for the Suwannee River near Wilcox, FL, during periods of salinity depiction to period-of-record averages **



Abbreviation: m3/s - cubic meters per second
* USGS gages reflect inflow from 94% of the estuary's total watershed (26,400 km2) (USGS, 1990)

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

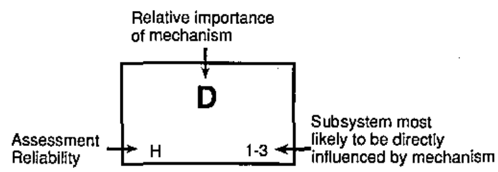


a. Data Source: FDNR, 1991
b. Data Source: FDNR, 1991

Figure 30. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		**S** M 1	**D** M 1-3	**D** M 1-3	
Tides	**D** LIT 2-3				
Wind		**S** LIT 2-3	M LIT 2-3		
Effect on Salinity Variability	LOW	MEDIUM	HIGH	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 29 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, primarily limited to the marsh regions near the river delta (Wolfe and Wolfe, 1985).

Months-Seasons. Dominant influence on salinity structure throughout the estuary. Inflows during the low-flow season remain sufficient to control salinities within the river and delta. The influence of freshwater expands during the high-flow period and is more persistent in the southern portions of the Suwannee Sound than its northern portions. The zone of vertical stratification is pushed toward the Gulf from the delta during the high-inflow period. Groundwater is an important contributor to river flow.

Year-Year. Dominant influence on salinity structure.

Tides

Hours. Dominant influence on salinity variability. Tidal range (0.6-1.0 m) is high relative to average depth of Suwannee Sound; thus, a large portion of sound waters is displaced significantly offshore on a single outgoing tide. Tide destratifies water column within the sound.

Wind

Days-Weeks. Secondary influence on salinity variability primarily within the Suwannee Sound. Cold fronts penetrate the region from November-March, altering circulation patterns and destratifying the water column.

Months-Seasons. Minor influence on salinity structure, primarily in Suwannee Sound. Prevailing winds during both high- and low-salinity periods are northerly, enhancing the effect of river flow on salinity.

* Data Sources: See data sources listed in Appendix II for Florida.

Geographic Setting

Apalachee Bay is an open-water estuarine system within Florida's Big Bend region whose boundaries are not consistently defined. This area is a bight and, therefore, lacks the semi-enclosed characteristics of a *bonafide* estuary. It consists of may small estuaries around its periphery that are considered collectively in this analysis. This system separates the lagoonal estuarine systems of the Florida Panhandle from the *Springs Coast* (Wolfe, 1990) of west-central Florida, from Lighthouse Point to Cedar Keys. Apalachee Bay is lined by numerous small streams that comprise springs, lakes, freshwater swamps, and coastal marshes near a broad marine shelf. This study characterizes the Ochlockonee/Oyster Bay and Econfina/Fenholloway River systems (Figure 31) which are typical of estuaries in Florida's Big Bend region (R.J. Livingston, Pers. Comm.), and for which the salinity data base is sufficient for characterization. This estuary has been divided into five subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 31).

Ochlockonee Bay is a small shallow drowned river valley estuarine system. Its boundaries are defined from the head of tide on the Ochlockonee River, 19 km upstream of its confluence with Ochlockonee Bay (Wolfe et al., 1988), to its terminus west of Apalachee Bay. Ochlockonee River and its major tributary, the Sopchoppy River, are the principal freshwater sources to Ochlockonee Bay. These rivers drain approximately 5,800 km² of Florida and southern Georgia (Wolfe et al., 1988). Since 1985, Lake Talquin's Jackson Bluff Dam (not shown) on the Ochlockonee River has been used for hydroelectric power and is responsible for significant short-term drops in lake elevation (Wolfe et al., 1988), with a corresponding influx to the estuary.

The Econfina and Fenholloway Rivers are small tributary systems, located approximately 11 km apart, northeast of Apalachee Bay. The rivers share similar climatic, sedimentary, and watershed characteristics, and discharge comparable freshwater volumes to the bay (Livingston, 1975). The Econfina and Fenholloway River boundaries are defined from the head of tide, approximately 6 and 5 km, respectively, upstream from the mouth to their terminus in northeast Apalachee Bay (USFWS, 1982d; Dujardin, Pers. Comm.).

Bathymetry

The estuary, which includes the broad shelf of Apalachee Bay, is approximately 3 m deep at mid-tide level (NOAA, 1990a). The small, marshy embayments and riverine systems near Apalachee Bay are typically 1-2 m deep. Navigation channels exist only in lower Oyster Bay and St. Marks River, and are small and shallow (Figure 32).

Large portions of the Ochlockonee and Oyster Bay systems average less than 1 m deep, although both contain isolated areas that approach 4 m. The Econfina and Fenholloway River systems are very shallow and are navigable only for a few kilometers above their mouths (NOAA, 1991). Numerous shoals and oyster bars exist at the mouth of each system.

Figure 31. *Location map and subsystem identification.*

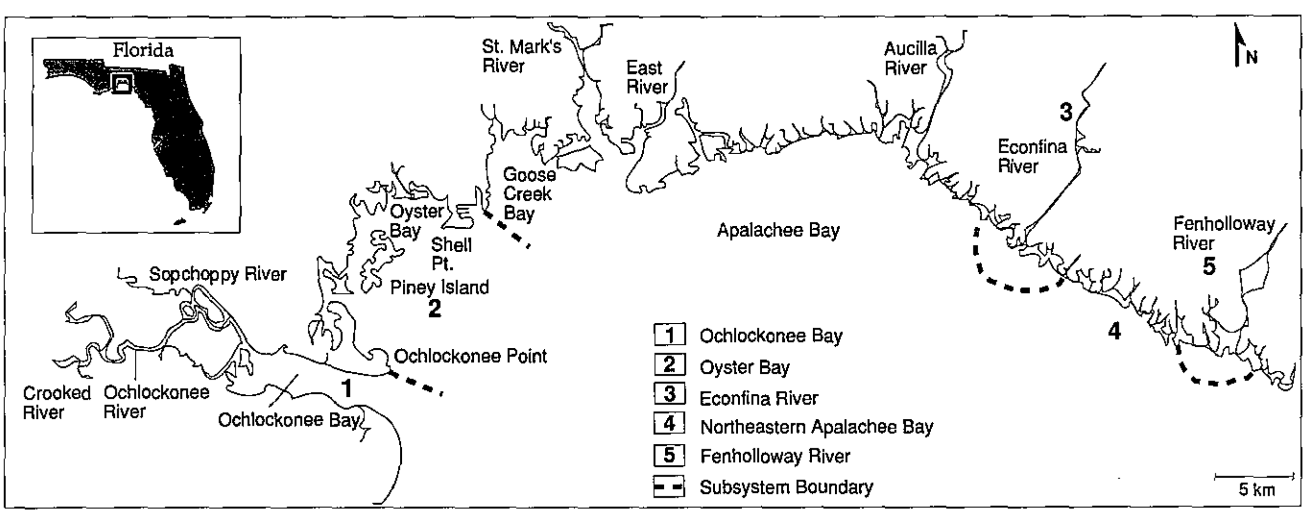
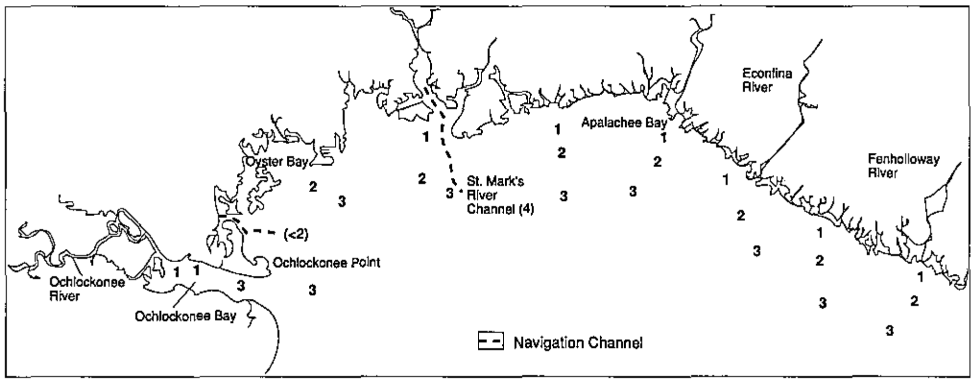


Figure 32. *Bathymetry (meters)*



Salinity Patterns

The Data. For Ochlockonee/Oyster Bays, September-November 1989 and February-April 1990 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions as no major modifications to the estuary or its watershed have occurred since the reactivation of the Jackson Bluff Dam hydroelectric generation plant in 1985. For the Econfina and Fenholloway Rivers, September-November 1975 and February-April 1978 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions as their watersheds are relatively unmodified. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 33; data for Ochlockonee Bay is very limited. Figure 34 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages. Figure 35 presents salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on salinity structure. This structure, however, experiences significant variability as indicated in Figure 36.

High-Inflow/Low-Salinity Period

Ochlockonee/Oyster Bays (February-April 1990). During this selected period and including January 1990, total combined inflow from the Ochlockonee and Sopchoppy Rivers was consistent with long-term averages (Figures 33 and 34). Steady flows from the Ochlockonee River (55-85 m^3/s) were interrupted by peak discharges during mid-January (160 m^3/s) and late February (195 m^3/s) and a dry period (<15 m^3/s) in late April. Discharge from the Sopchoppy River was less than 10 m^3/s, except during late February (30 m^3/s).

In Oyster Bay, salinities were lowest in February and increased throughout this period. Salinities were relatively unstable along the shoreline, but more stable near Apalachee Bay. Vertical stratification was generally absent, but infrequently occurred near Shell Point. Salinity data for Ochlockonee Bay was only available for March and indicated weak stratification in the navigation channels.

Econfina/Fenholloway Rivers (February-April 1978). During this selected period and including January 1978, total combined inflow was approximately 15% above long-term averages (Figures 33

Figure 33. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	February-April (High Inflow/Low Salinity)		September-November (Low Inflow/High Salinity)	
	1978 [1]	1990 [2]	1975 [1]	1989 [2]
Surface Salinity				
# of Observations	95	138	72	128
Sampling Distribution [a]	3,5	1,2	3,5	2
Sampling Frequency	weekly-monthly	monthly	monthly	monthly
Average Salinity (ppt)	14.7	18.3	19.2	19.7
Bottom Salinity				
# of Observations	95	135	66	120
Sampling Distribution [a]	3,5	1,2	3,5	2
Sampling Frequency	weekly-monthly	monthly	monthly	monthly
Average Salinity (ppt)	16.1	19.6	22.5	22.3
Freshwater Inflow				
Ochlockonee/Sopchoppy River Volumes	NA	average [b]	NA	30% below average [d]
Econfina/Fenholloway River Volumes	15% above average [c]	NA	35% below average [e]	NA
Return Frequency of Peak Events	Econfina River	Ochlockonee River	Econfina River	Ochlockonee River
1-day duration	3.0-year	2.0-year	1.8-year	1.4-year
7-day duration	3.0-year	2.2-year	1.5-year	1.5-year
30-day duration	3.3-year	2.1-year	1.8-year	1.5-year

Abbreviation: ppt - parts per thousand

1. Econfina/Fenholloway Rivers
2. Ochlockonee/Oyster Bays

a. Subsystem(s) with high sampling density
b. Includes January 1990
c. Includes January 1978
d. Includes August 1989
e. Includes August 1975

and 34). Discharge from both rivers steadily increased from early January to early March, then decreased through April. Econfina and Fenholloway River inflows peaked in early March (18 and 11 m³/s, respectively).

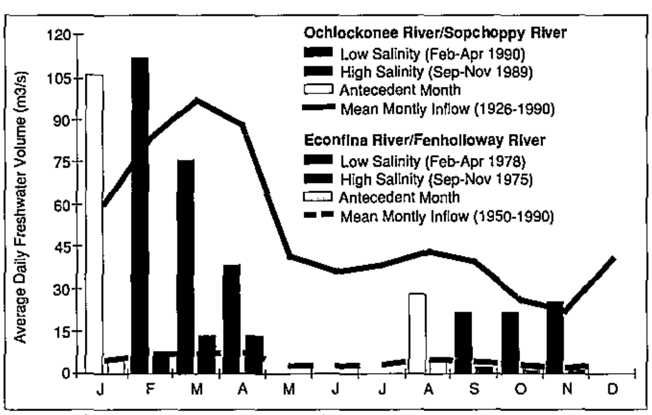
In both estuaries, salinities were relatively constant throughout this period. Most variability occurred in the lower Econfina and Fenholloway Rivers and near Apalachee Bay. Salinities in these areas experienced a modest decrease during mid-March and a modest increase during late April. Also, these areas were moderately stratified during early February and late March; the remainder of the estuary was generally vertically homogeneous.

Low-Inflow/High-Salinity Period

Ochlockonee/Oyster Bays (September-November 1989). During this selected period and including August 1989, total combined inflow from the Ochlockonee and Sopchoppy Rivers was approximately 30% below long-term averages (Figures 33 and 34). Inflow from both rivers was highly variable. Steady flows from the Ochlockonee River (10 m³/s) were frequently interrupted by short-term discharges near 40 m³/s, with a peak discharge (100 m³/s) during early August. Baseline flow (1 m³/s) on the Sopchoppy River was interrupted by several small discharges, with the largest (35 m³/s) occurring in late September.

In Oyster Bay, the average salinity structure was relatively unchanged when compared to February-April 1990. Bottom salinities, however, were much more stable than between February-April 1990. Weak-to-moderate vertical stratification was common in northern Oyster Bay. Salinity data for Ochlockonee Bay was only available for October and indicated weak-to-moderate stratification in the navigation channels.

Figure 34. *Comparison of gaged freshwater volume for Ochlockonee River near Bloxham, FL; Sopchoppy River near Sopchoppy, FL; Econfina River near Perry, FL; and Fenholloway River at Foley, FL during periods of salinity depiction to period-of-record averages **



Abbreviation: m3/s - cubic meters per second

Econfina/Fenholloway Rivers (September-November 1975). During this period and including August 1975, total combined inflow was approximately 35% below long-term averages (Figures 33 and 34). Fenholloway River discharge was nearly constant (2-3 m³/s), except for drier conditions in late August (<1 m³/s). Econfina discharge peaked in early August (8 m³/s) and late August (5 m³/s), then remained between 2-3 m³/s through November.

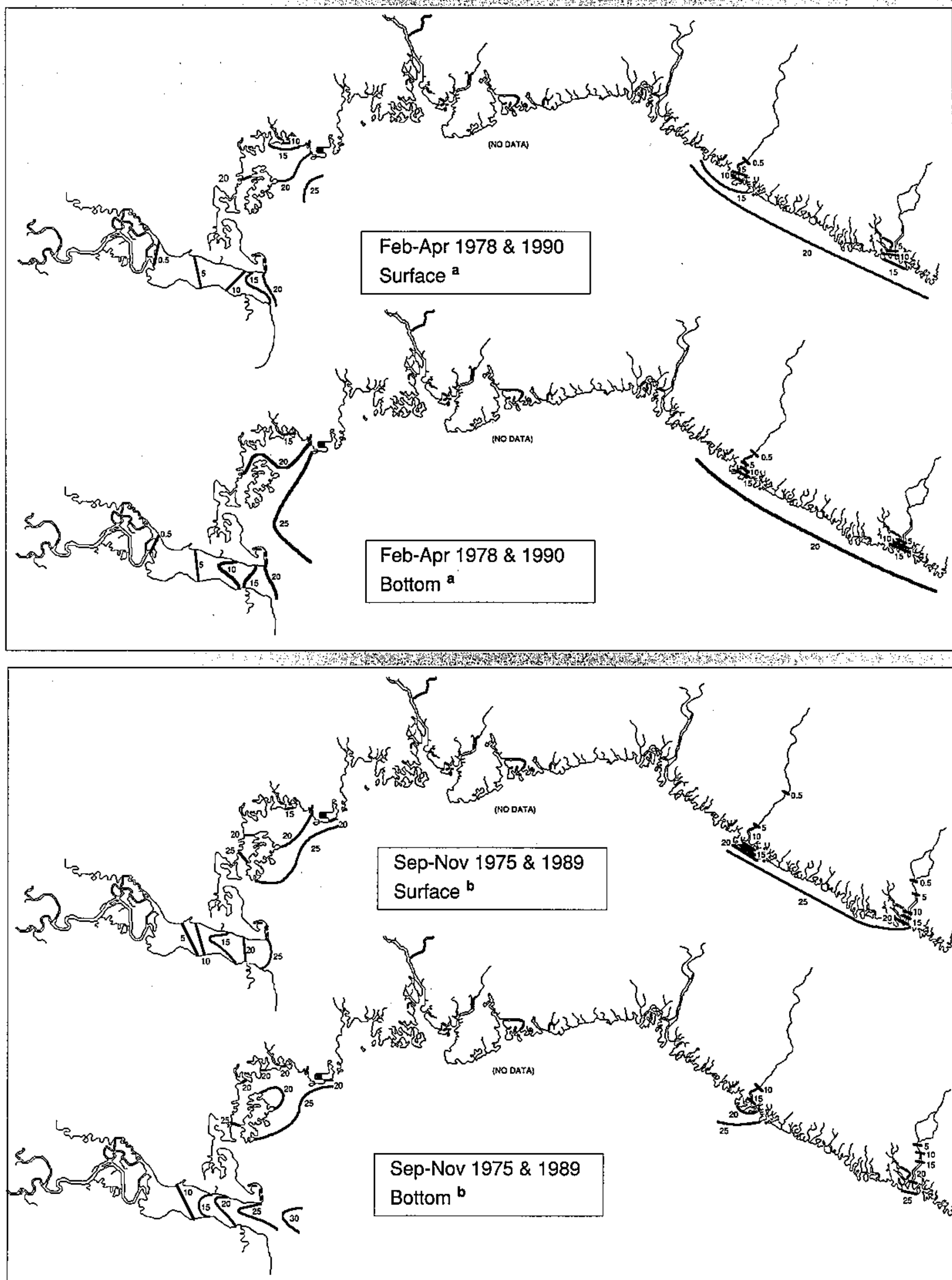
In both estuaries, salinities were nearly 10 ppt higher than during the low-salinity period (February-April 1978). Salinities in the Econfina system were lowest in September and increased throughout this period. Most variability occurred in the lower Econfina River and near Apalachee Bay. This estuary was often highly stratified, the remainder of which experienced little variability or vertical stratification. In the Fenholloway River, salinities remained relatively constant throughout this period, with most variability apparent in the lower river and near Apalachee Bay. This estuary experienced moderate-to-high vertical stratification.

Factors Affecting Variability

The salinity structure is primarily determined by seasonal freshwater discharge from major rivers, but is subject to frequent short-term variation. The Econfina, Fenholloway, and Ochlockonee Rivers are relatively similar, demonstrating intense horizontal salinity gradients in their lower reaches (i.e., near the Gulf). The relative position of the gradient is determined primarily by freshwater discharge. Open-water areas of Apalachee Bay, not immediately near principal river sources, likely reflect conditions in the Gulf of Mexico. Vertical stratification is uncommon throughout these estuaries, but occasionally exists in the lower reaches of major rivers and in navigation channels.

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 36. Variability is most often associated with short-term freshwater discharges and wind.

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

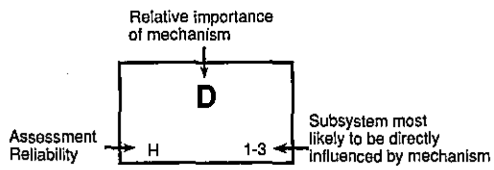


a. Data Sources: FDNR, 1991; Livingston, 1975 &1990
b. Data Sources: FDNR, 1991; Livingston, 1975 & 1990

Figure 36. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		S (L 1-5)	D (L 1-5)	D (L 1-5)	
Tides		M (LIT 1-5)			
Wind		S (LIT 1-5)			
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 35 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 the salinity structure, especially in lower Econfina, Fenholloway, and Ochlockonee Rivers.

Months-Seasons. Dominant influence on the salinity structure throughout the estuary, including nearshore Apalachee Bay.

Year-Year. Dominant influence on the salinity structure.

Tides

Days-Weeks. Minor influence on the salinity structure, extending into the lower reaches of the major river systems only during spring tide. Astronomical tides are primarily semi-diurnal and typically range 0.66 m at entrances to major rivers (NOAA, 1990b).

Wind

Days-Weeks. Secondary influence on the salinity structure. During the winter, 15-20 frontal systems pass this estuary. Prolonged north winds reduce water levels by 0.33-0.66 m (NOAA, 1991).

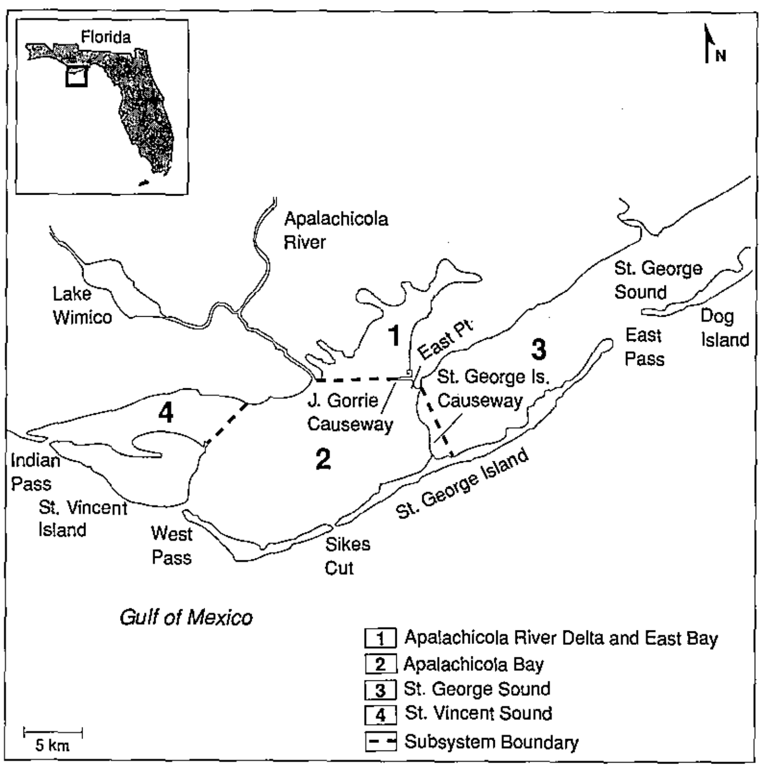
* Data Sources: Livingston, Pers. Comm.; also see data sources listed in Appendix II for Florida.

Geographic Setting

The Apalachicola Bay estuary is a broad, shallow lagoonal system. It is the largest of the Florida panhandle estuaries, encompassing 554 km^2 (NOAA, 1990a). This estuary consists of the Apalachicola River delta and several major embayments, whose boundaries are conveniently defined by earthen causeways or prominent physiographic features (Figure 37). The estuary is defined from the head of tide on the Apalachicola River, located 40 km up-stream of its terminus at East Bay (Gorsline, 1963; Livingston, 1984c), and is separated from the Gulf by three major barrier islands. Because information for the eastern portions of St. George Sound and Alligator Harbor is limited, these areas are not considered in this analysis.

The Apalachicola River is Florida's largest discharging river and the primary source of freshwater to the estuary (Livingston, 1984c). Because 85% of the estuary's watershed (53,135 km^2) (NOAA, 1990a) is located in Georgia, Apalachicola River discharges (and its effect on salinity) more closely follow the Georgia rainfall cycle (peak rainfall January-April) than that of coastal Florida (peak rainfall July-September) (Livingston, 1984c; Meeter et al., 1979).

Figure 37. *Location map and subsystem identification*



The river process is thought to extend toward West Pass as it merges with waters moving west from St. George Sound. Thus, the influence of freshwater tends to be greatest in East Bay and Apalachicola Bay.

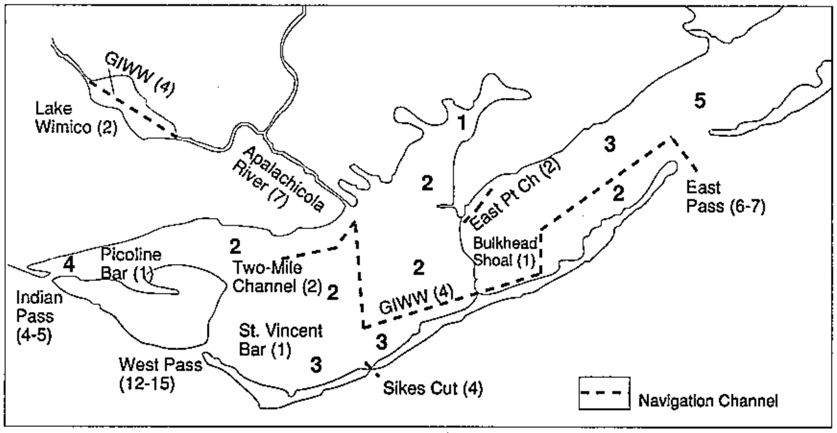
This estuary has four natural openings to the Gulf of Mexico: Indian Pass, West Pass, East Pass, and a pass between Alligator Harbor and Dog Island. Sikes Cut, a man-made opening, was established in the western portion of St. George Island in 1954. Long-shore currents and tidal phasing at the passes produce a net east-to-west water movement through the estuary (Graham et al., 1979). West Pass appears to be a major outlet for estuarine water discharged to the Gulf, especially when influenced by long-duration or high-intensity east winds. More than 66% of the total bay discharge occurs through West Pass and Indian Pass, although they account for only 10% of the inlet area (Gorsline, 1963). 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 2 m at mid-tide level (NOAA, 1990a). Naturally deep areas include portions of Indian Pass (4-5 m), West Pass (12-15 m), East Pass (6-7 m), and the Apalachicola River (7 m) (Figure 38). Oyster reefs cover about 7% of the estuary and create numerous shoal areas that significantly impede water exchange. The largest shoals are located at Bulkhead Shoal and near both West Pass and Indian Pass. Numerous open water disposal sites are associated with navigation channels and may also limit exchanges within the bay. The most significant of these disposal sites is the bulkhead shoal near the St. George Island causeway (Graham et al., 1979).

The GIWW and Sikes Cut are the deepest channels within the estuary (Figure 38). Channels are important corridors for seawater intrusion because of density currents maintained by the steep horizontal salinity gradient within this estuary (Livingston, 1984b). Increased bay-wide salinities have been associated with the intrusion of bottom waters through Sikes Cut (Livingston, 1979). Incoming saline

Figure 38. *Bathymetry (meters)*



increased from near-freshwater conditions at the Apalachicola River delta to near-Gulf salinities at Sikes Cut. An east-west gradient resulted in Gulf salinities in St. George and St. Vincent Sounds but brackish conditions within the central basin. Strong vertical stratification persisted throughout the estuary except in East Bay. Peak discharges were sufficient to displace saline bottom waters to lower Apalachicola Bay, producing strong vertical stratification in this region. Simultaneously, salinities and stratification decreased in the upper and middle portions of Apalachicola Bay. Salinities were most stable within the Apalachicola River delta, East Bay, and at the passes.

waters may be trapped within a relatively deep basin near Sikes Cut and transported into the upper bay by density currents operating within the north-south extension of the GIWW.

Salinity Patterns

The Data. September-November 1983 and February-April 1984 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions as the only recent modification to the estuary or its watershed was a minor expansion of Sikes Cut in 1986. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 39. Figure 40 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that both periods experienced typical inflow conditions. Figure 41 presents salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 42.

High-Inflow/Low-Salinity Period (February-April 1984). During this selected period and including January 1984, total inflow from the Apalachicola River was approximately 15% above long-term averages (Figures 39 and 40). Within this period, daily inflow generally remained between 750-1,250 m^3/s, but peaked in late January (2,000 m^3/s) and mid-March (2,300 m^3/s).

Salinities generally declined in February, reached their lowest concentrations by late March or early April, and increased by late April. A north-south salinity gradient through the central basin gradually

Low-Inflow/High-Salinity Period (September-November 1983). During this selected period and including August 1983, total inflow from the Apalachicola River was 5% below long-term averages (Figures 39 and 40). Within this period, daily inflow remained relatively constant (310-370 m^3/s), except for minor peaks during mid-August (450 m^3/s), mid-September (430 m^3/s), and a larger peak in late November (775 m^3/s).

Although this volume of inflow was three times less than during the high flow period, it considerably influenced the salinity structure and variability. Salinities generally increased through the period except for a modest response to the mid-September freshet, primarily in the northern portions of the estuary. Salinity concentrations were more uniform throughout the estuary, although a north-south gradient was still apparent. Moderate stratification existed throughout most of the estuary. The most stable salinities were found near the passes. The most variable salinities were found in the northern portions of Apalachicola Bay, the eastern portions of St. Vincent Sound, and near St. George Island.

Factors Affecting Variability

The salinity structure is determined by the seasonal freshwater discharge, primarily from the Apalachicola River. The freshwater plume merges with waters moving east-to-west from St. George Sound and is most influential in upper and central Apalachicola Bay, western St. Vincent Sound, and eastern St. George Sound. These same regions may experience a wide range of stratification conditions depending on the magnitude of the freshwater plume. Highest stratification occurs in lower Apalachicola Bay during high-inflow periods, but migrates toward East Bay with decreasing freshwater volume (Livingston, 1990). Prevailing seasonal winds usually enhance vertical stratification.

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 42. The most significant short-term variation is attributable to frontal passages which encourage mixing and may interrupt the net east-to-west transport. In addition, freshets dampen salinities in areas near the freshwater source and may inhibit saltwater intrusion to the upper estuary. Inter-annual variability was greatest within central Apalachicola Bay, at West Pass, and near East Point; little inter-annual variability occurred near the Apalachicola River delta and at Sikes Cut.

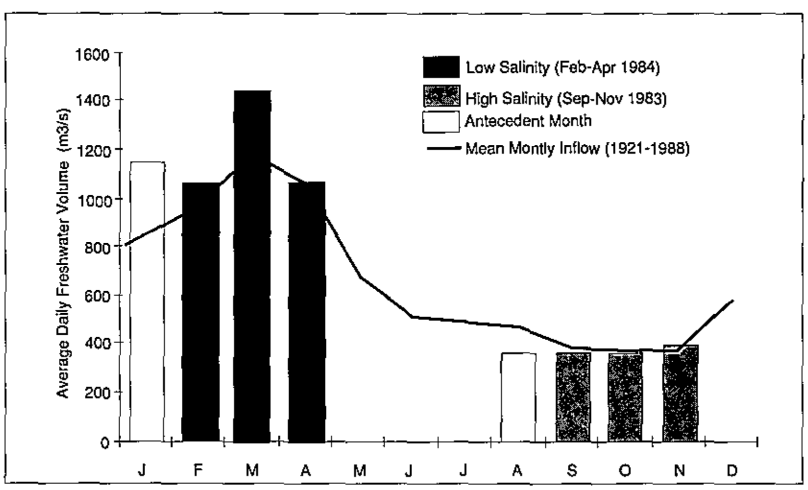
Figure 39. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	February-April 1984 (High Inflow/Low Salinity)	September-November 1983 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	662	202
Sampling Distribution [a]	1-4	1-4
Sampling Frequency	weekly - monthly	weekly - monthly
Average Salinity (ppt)	8.2	18.1
Bottom Salinity		
# of Observations	382	133
Sampling Distribution [a]	1-4	1-4
Sampling Frequency	weekly - monthly	weekly - monthly
Average Salinity (ppt)	13.2	22.1
Freshwater Inflow		
Volume	15% above average [b]	5% below average [c]
Return Frequency of Peak Events		
1-day duration	1.9-year	2.6-year
7-day duration	2.2-year	1.8-year
30-day duration	2.4-year	1.9-year

Abbreviation: ppt - parts per thousand

a. Subsystem(s) with high sampling density
b. Includes January 1984
c. Includes August 1983

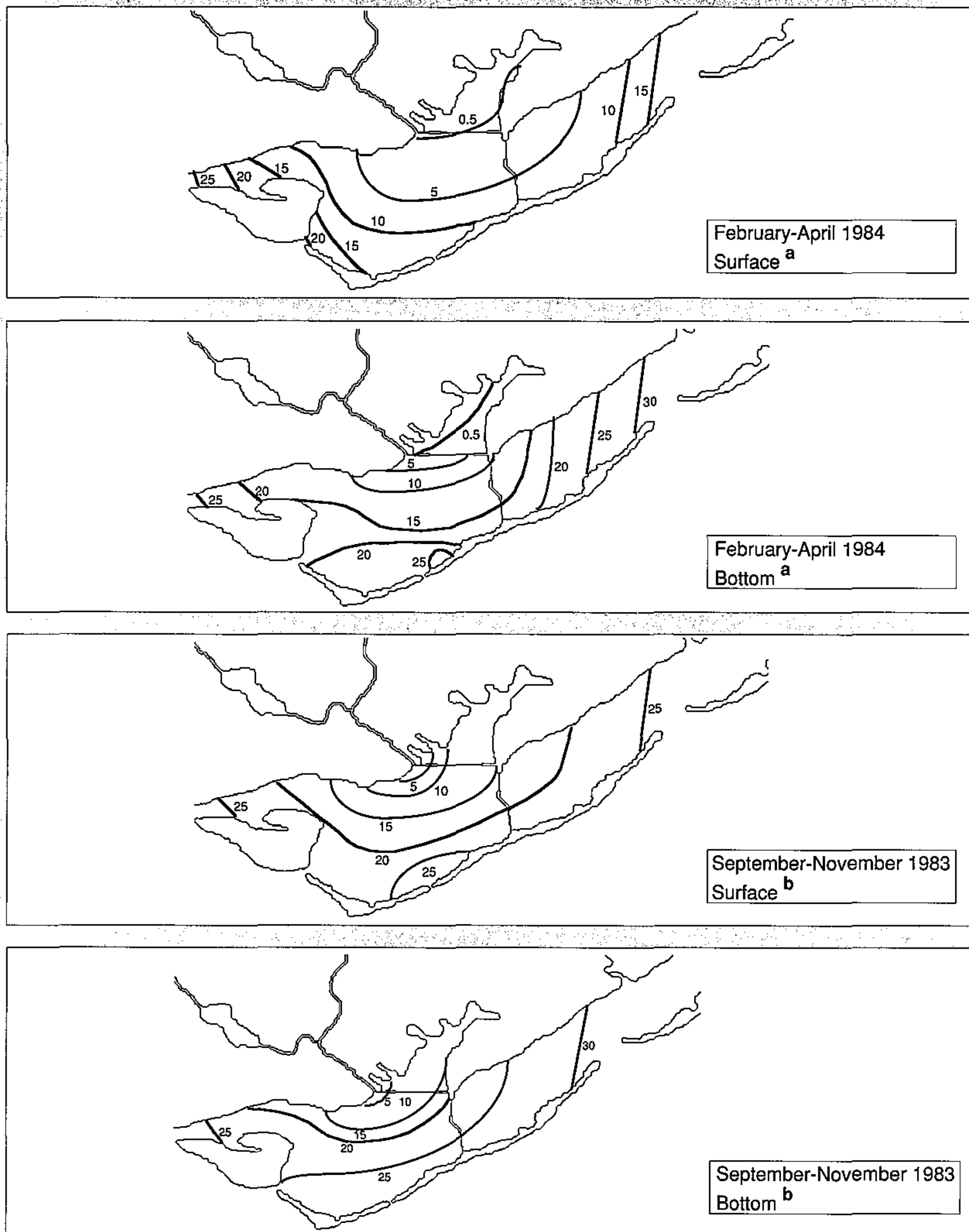
Figure 40. *Comparison of gaged freshwater volume for the Apalachicola River near Blountstown, FL, during periods of salinity depiction and period-of-record averages **



Abbreviation: m3/s - cubic meters per second

* USGS gages reflect inflow from 86% of the estuary's total watershed (53,135 km2) (USGS,1990)

Figure 41. *Surface and bottom salinities during low- and high-salinity periods*

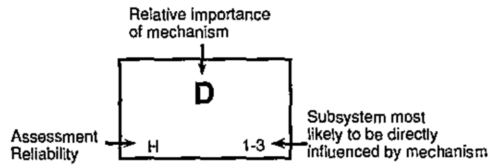


a. Data Sources: FDNR, 1991; Livingston, 1990; USACE, 1984a
b. Data Sources: FDNR, 1991; Livingston, 1990; USACE, 1984a

Figure 42. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S (H, 1-2)	D (H, 1-4)	D (H, 1-4)	
Tides	D (LIT, 2-3)				
Wind		S (LIT, 1-4)	S (LIT, 1-4)		
Density Currents			S (LIT, 1-2)		
Effect on Salinity Variability	UNKNOWN	MEDIUM	HIGH	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 41 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 structure, particularly in East Bay and upper Apalachicola Bay. Freshets displace saline bottom waters to lower Apalachicola Bay, resulting in vertically homogeneous conditions in the upper bay and stratified conditions in the lower bay.

Months-Seasons. Dominant, estuary-wide influence on salinity structure. Freshwater volume from the Apalachicola River is three times greater during February-April than during September-November and displaces isohalines by 10 ppt throughout most of the estuary. Groundwater may have locally important effects on salinities inside St. George Island between Sikes Cut and Bulkhead Shoal [Livingston, unpublished data].

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

Tides

Hours. Dominant influence on salinity variability, primarily near the passes, causing modest salinity increases and destratifying water columns. Tides are generally semi-diurnal, but frequently have a diurnal component. Tide range is approximately 0.5 m near the passes. Tidal phasing at the passes produces a net east-to-west water movement through the estuary (Graham et al., 1979).

Wind

Days-Weeks. Secondary, estuary-wide influence on salinity structure. From November-March, about 30-40 polar air masses penetrates this region which induces vertical mixing. Flushing and current generation at the inlets is wind-dominated (Weisberg, 1989).

Months-Seasons. Secondary, estuary-wide influence on salinity structure. Prevailing winds are generally from the north or northeast during September-February, southeast during March-May, and southwest-to-west during June-August and generally favor increased mixing and flushing of bay waters. Wind is three times more effective than tides when determining current strength and direction (Conner et al., 1981).

Density Currents

Months-Seasons. Secondary influence on salinity structure, primarily in Apalachicola and East Bays. The extent of bottom water intrusion and its effect on vertical stratification depends on river discharge and wind.

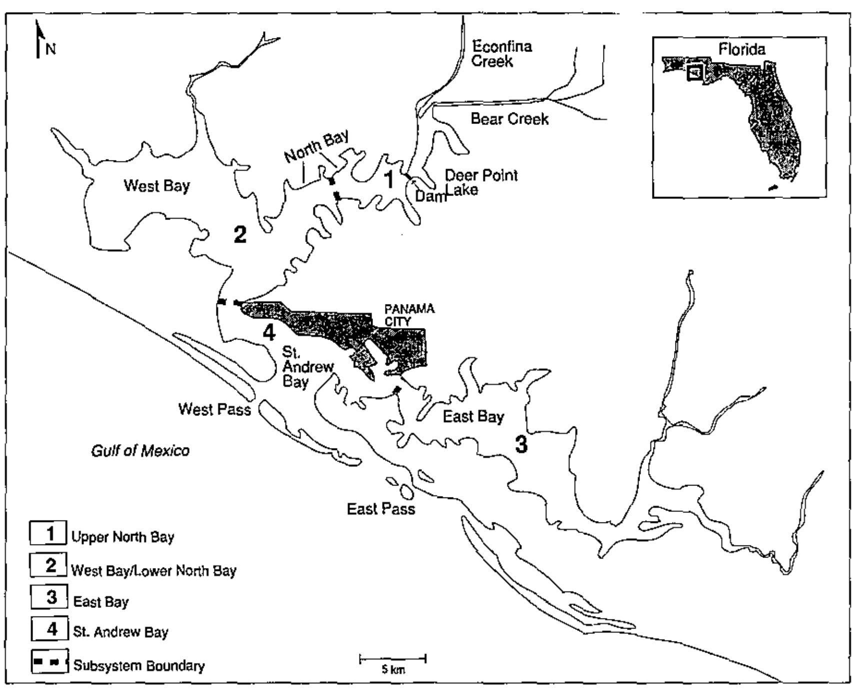
* Data Sources: See data sources listed in Appendix II for Florida.

Geographic Setting

The St. Andrew Bay estuary is a relatively deep, Y-shaped embayment, occupying 245 km² (NOAA, 1990a) behind Shell Island and a peninsular spit. This estuary includes St. Andrew, West, North, and East Bays (Figure 43). It is defined from the head of tide on the Econfina Creek at the Deer Point Lake Dam to its terminus with the Gulf of Mexico at the East and West Passes. West Pass was artificially cut in 1934 as the principal navigation channel through the estuary. However, most exchanges between the estuary and the Gulf occur through East Pass (Ichiye and Jones, 1961). Long-shore currents and tidal phasing at the passes produce net east-to-west water movement through the estuary (Ichiye and Jones, 1961).

Although the estuary receives minimal freshwater inflow due to its small drainage basin, discharge is sufficient to maintain a *positive* salinity structure. North Bay receives about 60 percent of the total inflow through Econfina Creek and Bear Creek across the Deer Point Lake Dam. Discharge in the Econfina Creek is continually supplied by groundwater springs from the Floridan Aquifer (Musgrove et al., 1964). West Bay and East Bay receive 7 and 22 percent of the total inflow to the estuary, respectively. The remainder enters directly into St. Andrew Bay through small tributaries and as sheet flow (Rodriguez and Wu, 1990). This estuary has been divided into four subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 43).

Figure 43. *Location map and subsystem identification*



Bathymetry

The average depth of this estuary is approximately 4 m at mid-tide level, among the deepest of the Gulf systems (NOAA, 1990a). Naturally deep areas exist throughout St. Andrew Bay and the lower parts of North, West, and East Bays (Figure 44). Parts of West Pass (10 m) and East Pass (9 m) are also naturally deep, although the latter is unstable and constantly shoals. The Panama City Harbor Entrance Channel is maintained at West Pass (10 m); the GIWW is maintained only in upper East and West Bays.

Salinity Patterns

The Data. September-November 1991 and February-April 1990 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions since no major modifications to the estuary or its watershed have occurred since the construction of Deer Point Dam in 1961. A summary of freshwater inflow conditions (precipitation) and salinity data for these periods is given in Figure 45. Figure 46 compares the total precipitation during each month of the selected periods to long-term averages and suggests that freshwater inflow was below normal during both periods. Figure 47 presents salinity distributions for the selected periods, illustrating the influence of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 48.

High-Inflow/Low-Salinity Period (February-April 1990). During this selected period and including January 1990, total precipitation measured at Panama City was approximately 25% below long-term averages (Figures 45 and 46). Significant precipitation occurred in early January (4 cm), late February (10 cm), mid-March (8 cm) and late March (5 cm).

Throughout the estuary, salinities were generally highest during February and lowest during April. They were most stable in St. Andrew Bay and West Bay, and were most variable in upper North Bay due to precipitation and possibly dam releases from Deer Point Lake. Less variability occurred in East Bay. Moderate vertical stratification occurred in the upper reaches of both North and West Bays. No bottom salinity data was available for East Bay and St. Andrew Bay during this period.

Low-Inflow/High-Salinity Period (September-November 1991). During this selected period and including August 1991, total precipitation measured at Panama City was approximately 15% below long-term averages (Figures 45 and 46). Significant precipitation occurred in early August (8 cm), mid-August (8 cm), early October (8 cm), early November (4 cm), and late November (4 cm).

Salinities were approximately 5 ppt higher during this period than during the low-salinity period. Throughout the estuary, salinities were generally lowest during September and highest during November. Salinities in the upper reaches of North Bay, however, were reduced by 5-10 ppt following the late November freshet. They were most stable in West Bay and St. Andrew Bay, but most variable in North Bay. Weak vertical stratification occurred throughout the estuary except in West Bay where salinities were vertically homogeneous.

Factors Affecting Variability

The salinity structure is determined by seasonal freshwater discharge, primarily due to direct precipitation to the estuary and discharges from Econfina Creek. A horizontal salinity gradient is most pronounced in upper North Bay and East Bay. This estuary commonly experiences weak vertical stratification, particularly within upper North Bay following freshets.

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 48. Salinities are most variable in upper North Bay due to direct precipitation and short-term releases from Deer Point Lake Dam. Vertical stratification is weakened by tides and wind.

Figure 44. *Bathymetry (meters)*

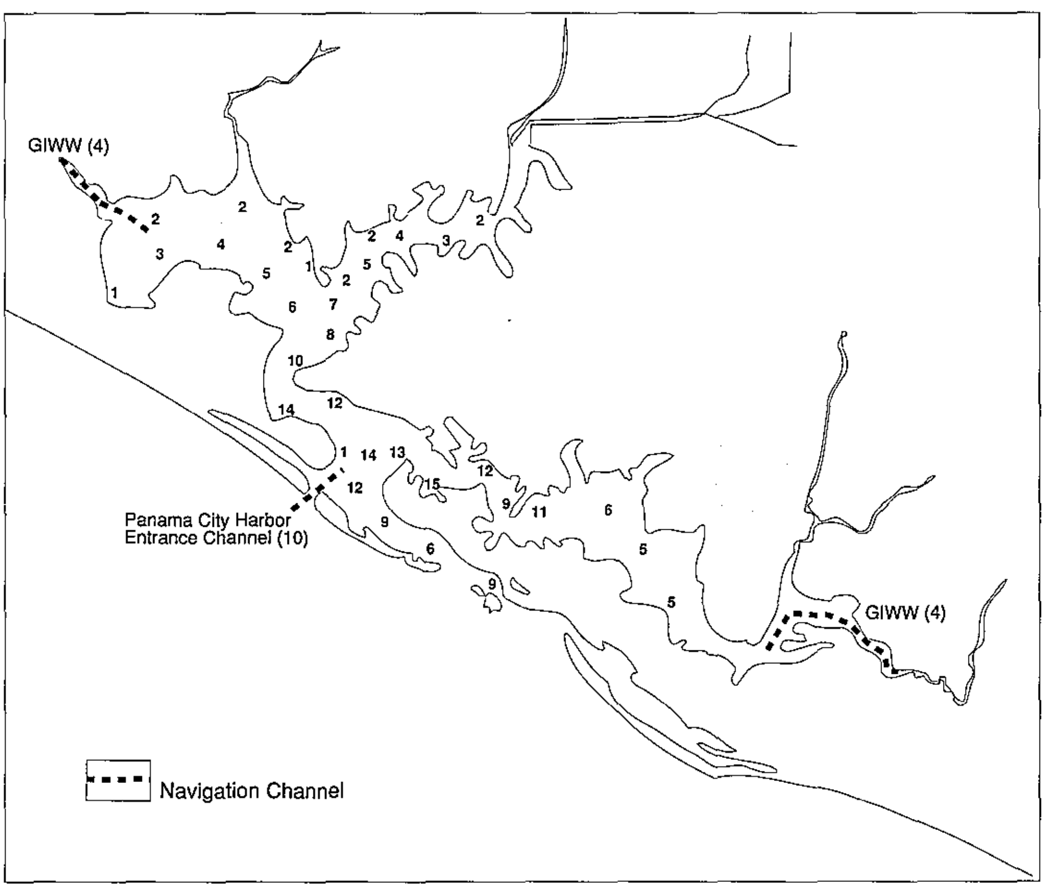


Figure 45. *Precipitation, salinity sampling, and average salinity during low- and high-salinity periods**

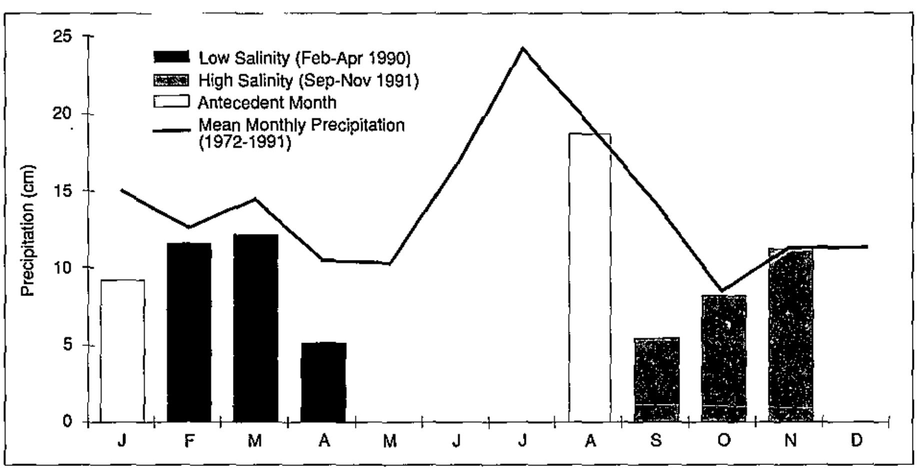
	February-April 1990 (High Inflow/Low Salinity)	September-November 1991 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	359	319
Sampling Distribution [a]	1-2	1-2
Sampling Frequency	biweekly-monthly	biweekly-monthly
Average Salinity (ppt)	16.6	24.2
Bottom Salinity		
# of Observations	235	236
Sampling Distribution [a]	1-2	1-2
Sampling Frequency	biweekly-monthly	biweekly-monthly
Average Salinity (ppt)	23.3	26.8
Precipitation		
St. Andrew Bay	25% below average [b]	15% below average [c]

Abbreviation: ppt - parts per thousand

* Return frequencies were unavailable for this system since no stream flow was used.

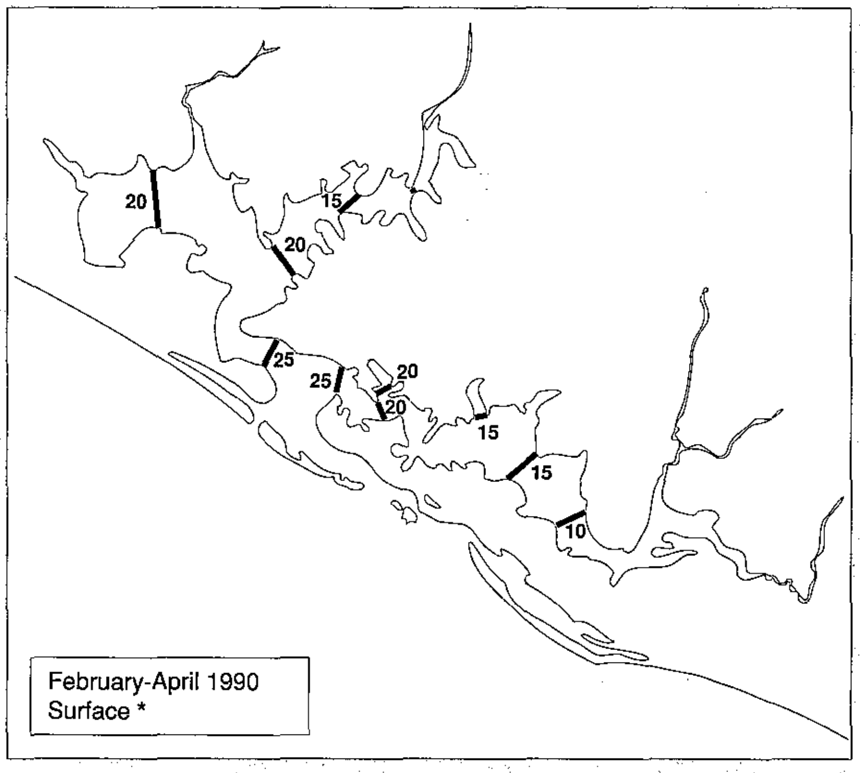
a. Subsystem(s) with high sampling density
b. Includes January 1990
c. Includes August 1991

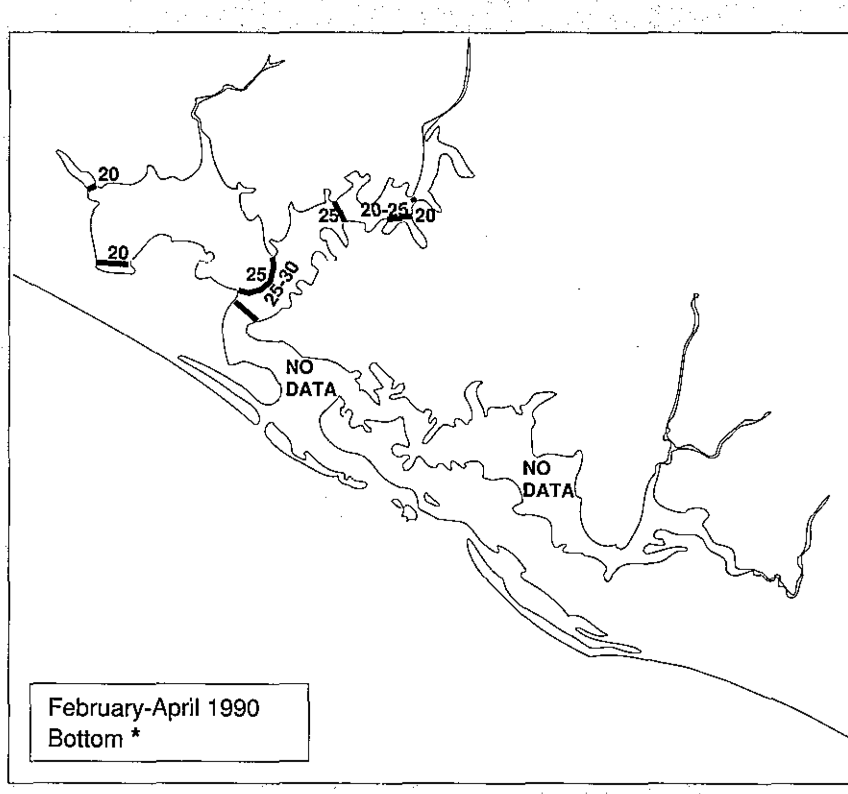
Figure 46. *Comparison of total precipitation (cm) at Panama City, FL during periods of salinity depiction and period-of-record averages*



Abbreviation: cm - cubic meters

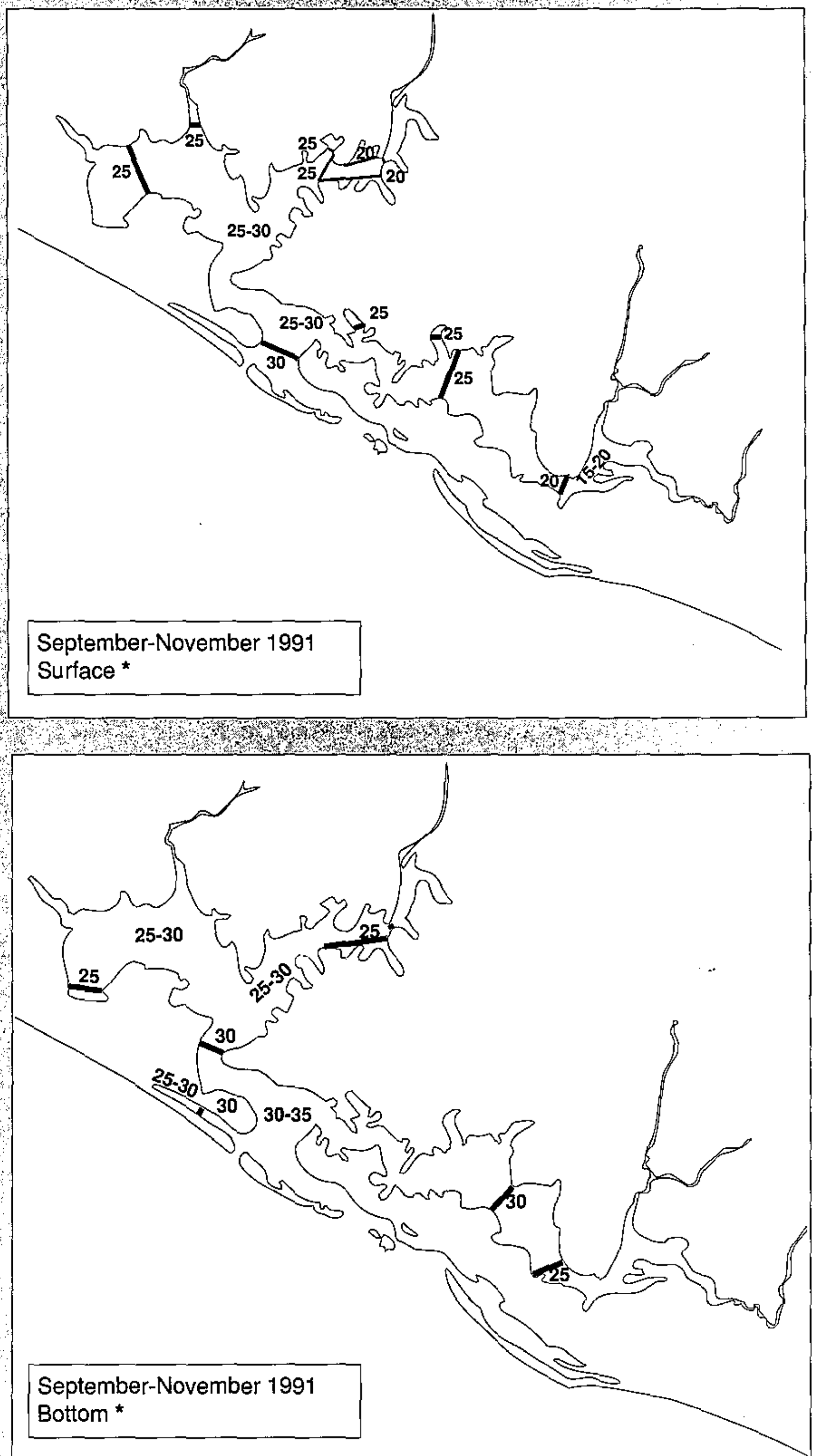
Figure 47. *Surface and bottom salinities during low- and high-salinity periods*





* Data Sources: FDNR, 1991; Taylor Biological Company, Inc., 1991

Figure 47. *Surface and bottom salinities during low- and high-salinity periods (continued)*

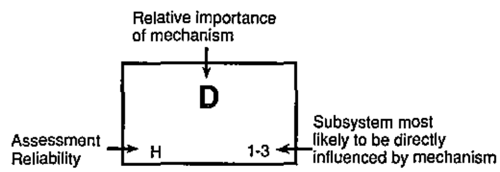


* Data Sources: FDNR, 1991; Taylor Biological Company, Inc., 1991

Figure 48. *Time scales and forcing mechanisms important to salinity structure and variability**

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 1-4)	D (L 1-4)	
Tides		M (LIT 4)			
Wind		S (LIT 1-4)			
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 47 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 structure and stability, primarily in upper North Bay due to releases from Deer Point Lake Dam.

Months-Seasons. Dominant influence on salinity structure, primarily in North and East Bays where salinities are approximately 5 ppt higher during September-November than February-April.

Year-Year. Dominant influence on salinity structure throughout this estuary.

Tides

Days-Weeks. Minor influence on salinity stability, primarily in St. Andrew Bay (Ichiye and Jones, 1961).

Wind

Days-Weeks. Secondary influence on salinity stability throughout this estuary. Wind associated with cold fronts enhances water-column mixing (Salsman and Ciesluk, 1978).

* Data Sources: See data sources listed in Appendix II for Florida.

Geographic Setting

The Choctawhatchee Bay estuary is a relatively deep and narrow lagoon located between the St. Andrew Bay and Pensacola Bay systems. Occupying 334 km^2 (NOAA, 1990a), the estuary includes Choctawhatchee Bay, the Choctawhatchee River delta complex, and several secondary embayments. (Figure 49). The estuary is defined from the head of tide on the Choctawhatchee River approximately 7 km upstream of the delta complex and on Alaqua Creek near Portland, Florida. The estuary is separated from the Gulf by a barrier spit along its southern shore; exchange occurs solely through East Pass. Limited exchange with the Santa Rosa Sound occurs in the western portion of Choctawhatchee Bay.

The Choctawhatchee River is the fourth largest discharging river in Florida and the major freshwater source to the estuary. This river lies primarily in Alabama (69%) and receives significant input from the Floridan Aquifer System (Wolfe et al., 1988). The estuary also receives secondary inflows from several bayous located primarily in northern sections of the bay (Livingston, 1986) which may derive more than 90% of their base flow from the shallow sand and gravel aquifer (Wolfe et al., 1988). Transport of the Choctawhatchee River plume is somewhat restricted by the US 331 causeway in eastern Choctawhatchee Bay. A second causeway, spanning the middle bay from White Point to Piney Point, is currently under construction (Bartel, Pers. Comm.). The potential impacts of this construction depend on the type of bridge built and the extent of the associated causeway, but are expected to reduce flushing in the western basin under intense frontal passages (Livingston, 1986). This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 49).

Bathymetry

The average depth of this estuary is approximately 4 m at mid-tide level (NOAA, 1990a), although natural depths decrease from west to east (Figure 50). Depths exceed 10 m in the western basin, but are approximately 3 m in the eastern basin due to intense sediment deposition from the Choctawhatchee River. The La Grange Bayou Channel and GIWW, the only navigation channels within the system, encourage the development of density currents and the intrusion of saline bottom waters.

Despite repeated attempts since 1988 to stabilize the entrance at East Pass, the inlet retains tendencies for migration and shoaling (Morang, 1992). This shallow region effectively forms a sill that tends to trap saline bottom waters within the deep western basin of Choctawhatchee Bay. East Pass requires continuous dredging to maintain its 3.6 m deep channel.

Salinity Patterns

The Data. September-November 1985 and February-April 1987 were selected to represent high- and low-salinity periods, respectively. These periods precede construction of a spur jetty at East Pass in 1977 and the mid-bay causeway. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 51. Figure 52 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that February-April 1987 experi-

Figure 49. *Location map and subsystem identification*

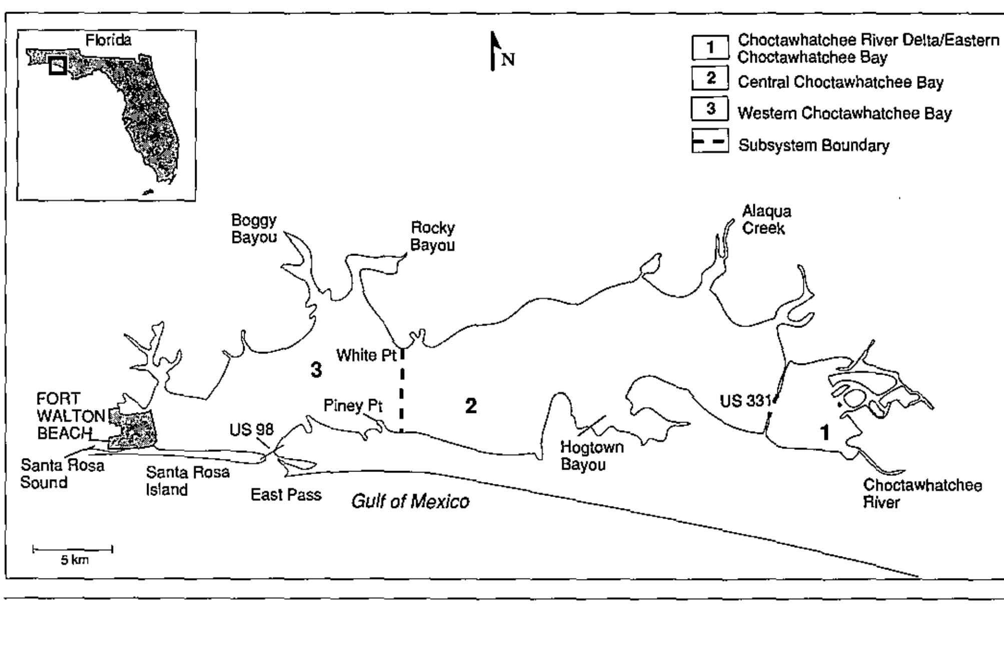
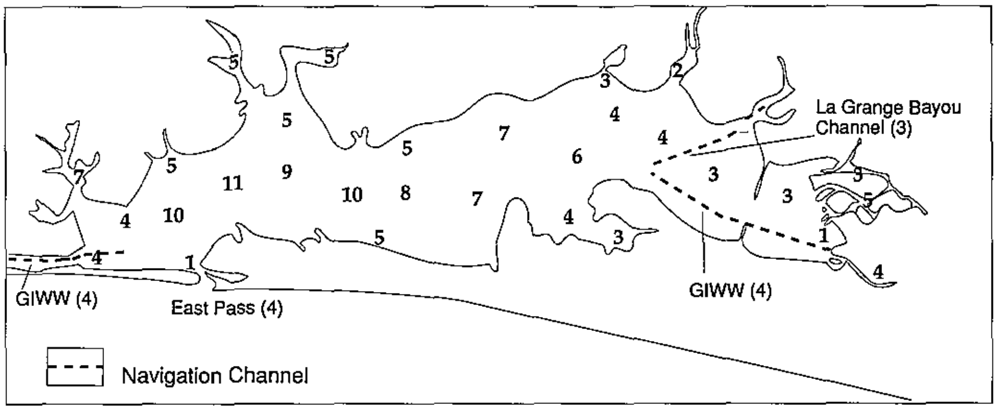


Figure 50. *Bathymetry (meters)*



Salinities during this period were approximately 10 ppt higher than during the low-salinity period. Surface and bottom salinities were relatively stable throughout the period and demonstrated little horizontal gradient. The November freshets produced modest surface salinity reductions in the eastern basin. High vertical stratification existed in the river delta and eastern basin, while moderate stratification existed in the remainder of the estuary.

enced near typical inflow conditions, while September-November 1985 was drier than normal. Figure 53 presents salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 54.

High-Inflow/Low-Salinity Period (February-April 1987). During this selected period and including January 1987, total inflow from the Choctawhatchee River was 10% below long-term averages (Figures 51 and 52), but was highly variable within this period. Base flow (175-250 m^3/s) from the Choctawhatchee River was interrupted by three peaks occurring in late January (480 m^3/s), mid-March (510 m^3/s), and mid-April (460 m^3/s).

Inflows were sufficient to maintain tidal-fresh (0 ppt) conditions within the delta and dominate surface waters throughout most of the estuary. Bottom waters, especially within the eastern and central basins, also responded to the freshwater signal but quickly rebounded to pre-freshet conditions. Moderate-to-high vertical stratification persisted throughout the estuary. Surface salinities within the eastern and central basins were relatively stable. Surface salinities within the western basin and bottom salinities throughout the estuary were less stable.

Low-Inflow/High-Salinity Period (September-November 1985). During this selected period and including August 1985, total inflow from the Choctawhatchee River was approximately 20% below long-term averages (Figures 51 and 52). Daily inflow typically ranged from 55 to 110 m^3/s from August-October, except for a minor surge (155 m^3/s) in early September. Freshwater discharge peaked in early November (300 m^3/s) and late November (250 m^3/s).

Factors Affecting Variability

The salinity structure is determined by the seasonal freshwater discharge, primarily from the Choctawhatchee River. The plume may dominate the eastern basin, but its influence was severely reduced in the western basin. Moderate-to-high vertical stratification is predominant throughout the system. Prevailing seasonal winds often enhance vertical stratification.

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 54. Variability was much less from September-November than during February-April. Variability is most often associated with frontal passages which may temporarily disrupt the salinity structure and stability. Runoff from the north-shore tributaries has limited influence within the secondary embayments.

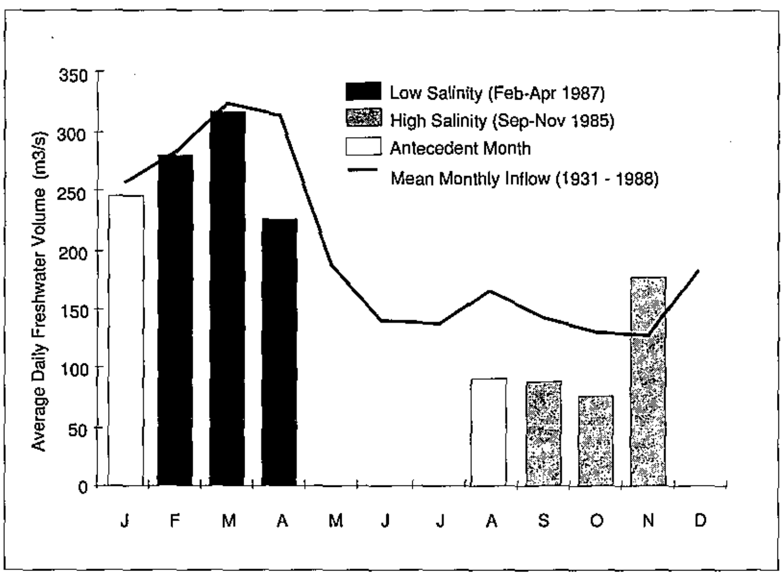
Figure 51. *Freshwater inflow, salinity sampling, and average salinity during during low- and high-salinity periods*

	February-April 1987 (High Inflow/Low Salinity)	September-November 1985 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	105	455
Sampling Distribution [a]	1-2	1-3
Sampling Frequency	monthly	weekly - monthly
Average Salinity (ppt)	5.9	17.3
Bottom Salinity		
# of Observations	54	303
Sampling Distribution [a]	1-2	1-3
Sampling Frequency	monthly	weekly - monthly
Average Salinity (ppt)	13.6	22.8
Freshwater Inflow		
Volume	10% below average [b]	20% below average [c]
Return Frequency of Peak Events		
1-day duration	2.2-year	2.5-year
7-day duration	1.3-year	2.5-year
30-day duration	1.4-year	2.7-year

Abbreviation: ppt - parts per thousand

a. Subsystem(s) with high sampling density
b. Includes January 1987
c. Includes August 1985

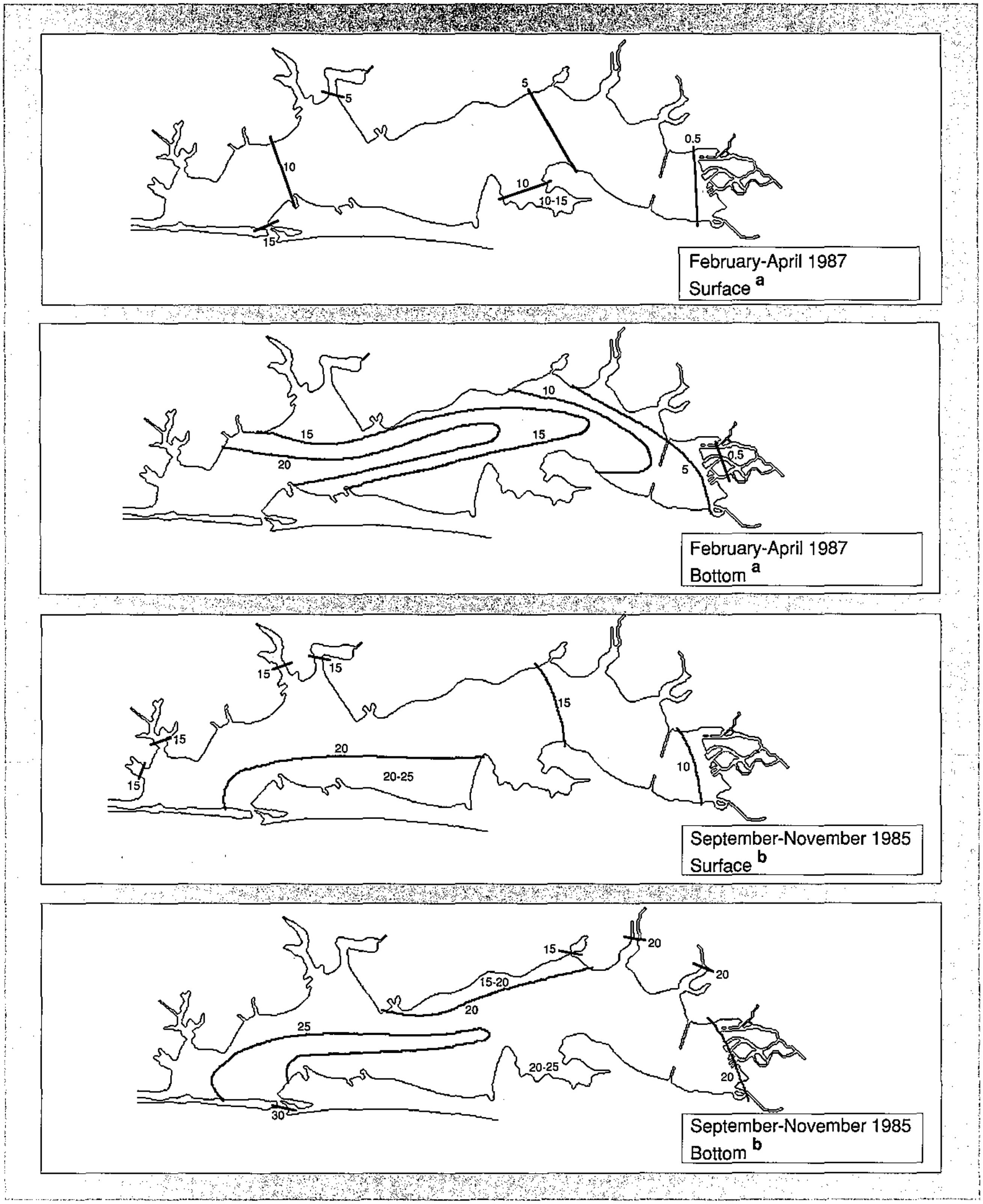
Figure 52. *Comparison of gaged freshwater volume for the Choctawhatchee River during periods of salinity depiction to period-of-record averages**



Abbreviation: m3/s - cubic meters per second

* USGS gages reflect inflow from 81% of the estuary's total watershed (13,985 km2) (USGS, 1990)

Figure 53: *Surface and bottom salinities during low- and high-salinity periods*



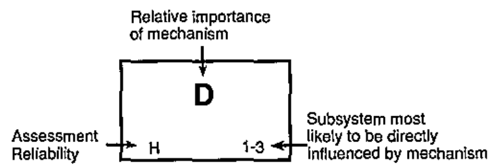
a. Data Sources: FDNR, 1991; Livingston, 1986
b. Data Sources: FDNR, 1991; Livingston, 1986

Figure 54. *Time scales and forcing mechanisms important to salinity structure and variability **

Mechanism	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		M LIT 3			
Wind		S LIT 1-3	M LIT 1-3		
Density Currents		M LIT 1-2			
Shelf Processes			M LIT 3		
Effect on Salinity Variability	UNKNOWN	LOW	MEDIUM	LOW	UNKNOWN

Time Scale of Salinity Response

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 53 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 stability and stratification, especially near the Choctawhatchee River delta, eastern bay, and north-shore embayments.

Months-Seasons. Dominant influence on salinity structure throughout the estuary. Inflow decreases estuary-wide stability and increases vertical stratification.

Year-Year. Dominant parameter influencing salinity structure throughout the estuary, although year-to-year variation is relatively low.

Tides

Days-Weeks. Minor influence on salinity stability and stratification in the western basin.

Wind

Days-Weeks. Secondary influence on salinity stability and stratification throughout the estuary, especially when associated with cold fronts.

Months-Seasons. Minor influence on salinity structure throughout the estuary. Prevailing winds enhance stratification during the winter months.

Density Currents

Days-Weeks. Minor influence on salinity structure and stability, primarily within the eastern basin. Density currents promote saline bottom water intrusion toward the delta.

Shelf Processes

Months-Seasons. Minor influence on salinity structure, primarily in the western basin. River plumes from adjacent estuaries may lower shelf-water salinities.

* Data Sources: See data sources listed in Appendix II for Florida.

Geographic Setting

The Pensacola Bay estuary is a drowned river estuary and lagoon covering approximately 370 km² (NOAA, 1990a). It includes Pensacola Bay, Escambia Bay, East Bay, Blackwater Bay, and Santa Rosa Sound, although the latter is not considered in this analysis (Figure 55). The boundaries of this estuary are defined from the head of tide on the Escambia River near Quintette (Bass and Hitt, 1978), on the Blackwater River approximately 5 km north of US Highway 90 (Yeager et al., 1989), and the Yellow River near its juncture with Blackwater Bay (Bass et al., 1979). The estuary is separated from the Gulf by Santa Rosa Island and direct exchange is limited to the Pensacola Inlet. Limited exchange occurs with the Perdido system through Big Lagoon, and the Choctawhatchee system through Santa Rosa Sound.

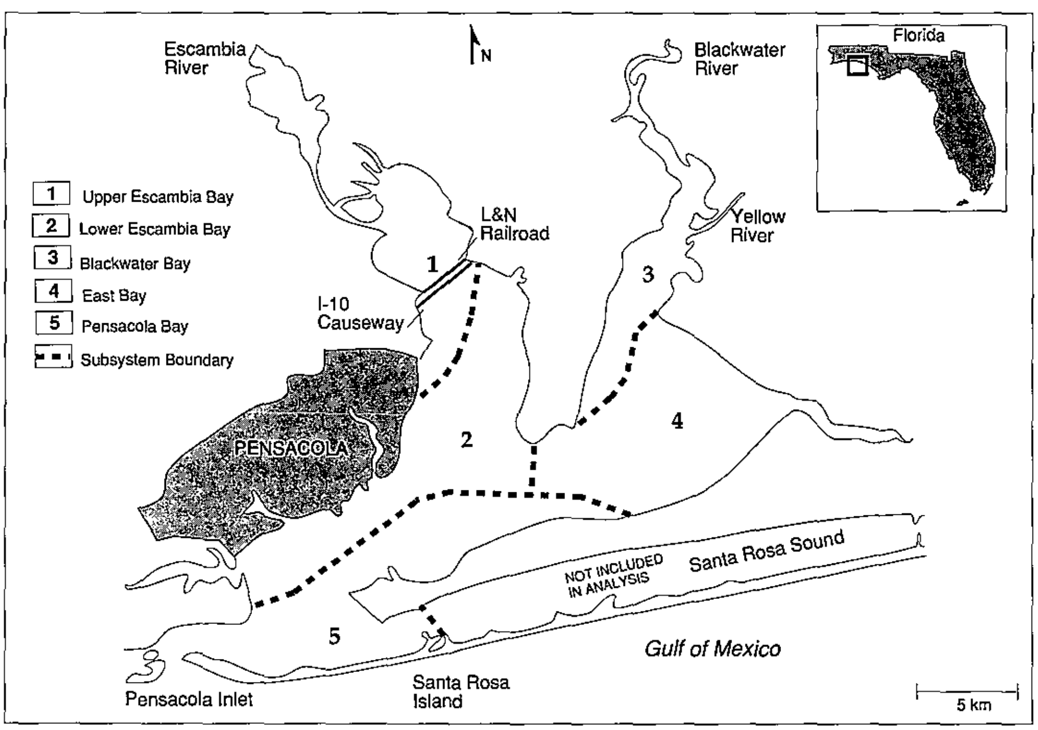
The Escambia River discharges to Escambia Bay and is the primary source of freshwater to this estuary. The Yellow and Blackwater Rivers are major contributors to Blackwater and East Bays, discharging approximately one-half the flow as the Escambia River. Circulation in Escambia Bay is dominated by a counterclockwise flow during both high- and low-inflow periods, resulting from the movement of freshwater along the western shoreline and saline bottom water intrusion along the eastern shoreline (Hopkins and Schomer, undated; Wolfe et al., 1988). This estuary has been divided into five subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 55). Santa Rosa Sound is not considered in this analysis because it is not included in NOAA's NEI (NOAA, 1990a).

Bathymetry

The average depth of this estuary is approximately 4 m at mid-tide level (NOAA, 1990a). Depth increases uniformly from the Escambia River toward the Pensacola Inlet (Figure 56). East and Blackwater Bays are comparatively shallow, except for a significant depression in lower East Bay.

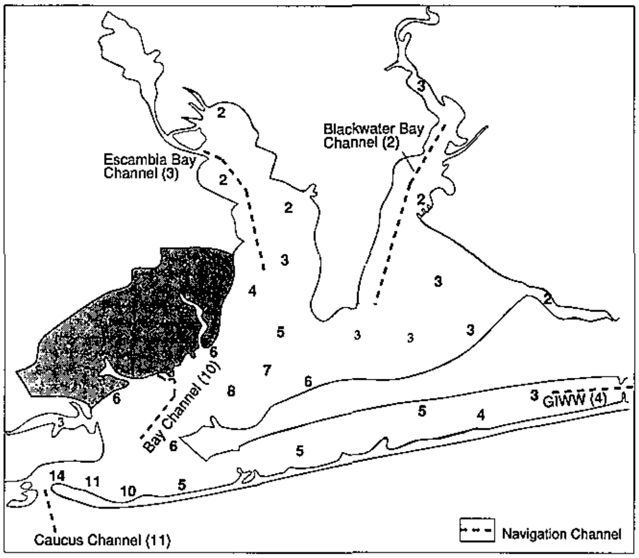
Navigation channels exceeding 11 m exist throughout lower Pensacola Bay and the Pensacola Inner Harbor. Smaller channels (2-3 m) within Escambia Bay, the lower Escambia River, and Blackwater Bay are important conduits for the intrusion of saline bottom waters through the estuary. In Escambia Bay, vertical stratification is greatest within the channel, along the east of the bay, and within the river delta. A *salt-wedge* may extend 18 km upstream in the Escambia River during low-flow conditions (Wolfe et al., 1988). Tidal flow into East Bay occurs consistently along the southern shoreline with the greatest tidal influence occurring May-July (Hopkins and Schomer, undated).

Figure 55. *Location map and subsystem identification*



Exchange between upper and lower Escambia Bay was thought to be somewhat restricted historically by the support pilings associated with the L&N Railroad bridge. Its densely spaced pilings were estimated to constrict the natural cross-sectional area by 11%, thus retarding the freshwater release to the lower estuary (Hopkins and Schomer, undated; Wolfe et al., 1988). This problem was amplified by the I-10 causeway located <0.5 km

Figure 56. *Bathymetry (meters)*



south of the L&N Railroad. Use of the railroad was discontinued and its pilings removed during the early-to-mid 1970s (Hopkins, Pers. Comm.).

Salinity Patterns

The Data. September-November 1973 and February-April 1988 were selected to represent high- and low-salinity periods, respectively. These periods should represent present-day conditions, although both periods pre-date the 1990 inlet channel dredging through lower Pensacola Bay. In addition, the 1973 data set may pre-date the removal of the L&N Railroad pilings. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 57. Figure 58 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that September-November 1973 experienced relatively typical inflow conditions, while February-April 1988 was drier than normal. Figure 59 presents salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 60.

High-Inflow/Low-Salinity Period (February-April 1988). During this selected period and including January 1988, total inflow from the Escambia, Blackwater, and Yellow Rivers was approximately 20% below long-term averages (Figures 57 and 58). Discharge from the Escambia River peaked during mid-March at 760 m^3/s. Three other significant discharge events (greater than 425 m^3/s) occurred in late January, late February, and late March. Discharge from the Yellow and Blackwater Rivers followed a similar pattern, with combined peak inflows occurring late February (110 m^3/s) and mid-March (110 m^3/s).

Surface and bottom salinities throughout the estuary were unstable, due to the frequency of the freshwater pulses. Salinities decreased significantly during the freshwater events, but rapidly recovered as the signal weakened. Highly stratified waters within the Escambia Bay channel and lower East Bay were temporarily displaced into Pensacola Bay, but were also quickly re-established. During peak discharges, Escambia River waters extended into lower East Bay, temporarily creating a reverse salinity gradient within this bay. Vertically homogeneous and moderately stratified conditions prevailed throughout the remainder of the estuary.

Low-Inflow/High-Salinity Period (September-November 1973). During this selected period and including August 1973, total inflow was consistent with long-term averages but was approximately three times lower than during February-April 1988 (Figures 57 and 58). Peak discharges in the Escambia River occurred in early August (200 m^3/s), mid-September (210 m^3/s), and late November (165 m^3/s). Peak inflows from the Yellow and Blackwater Rivers also occurred in early August (45 m^3/s), mid-September (60 m^3/s), and late November (35 m^3/s).

Throughout the estuary, salinities were lowest during late-September, increased through mid-November, and exhibited a modest decrease by mid-November. The lowest surface salinities occurred along the western shoreline of both Escambia and East Bays. These subsystems also exhibited the highest variability. Intrusion of high-salinity bottom waters within the Escambia Bay channel and lower East Bay persisted throughout the averaging period. Inflows during September and November did little to displace the Escambia Bay channel *salt-wedge*. Highly stratified conditions existed within upper- and mid-Escambia Bay, while the remainder of the bay was moderately stratified.

Factors Affecting Variability

The salinity structure is determined by the seasonal freshwater discharge, primarily from the Escambia River. River waters usually move seaward along the western shoreline, but may dominate Escambia Bay and the lower portions of East Bay during peak seasonal discharges. The highest vertical stratification occurs within the Escambia Bay channel. Escambia Bay is often moderately stratified, while East Bay is most often vertically homogeneous or moderately stratified.

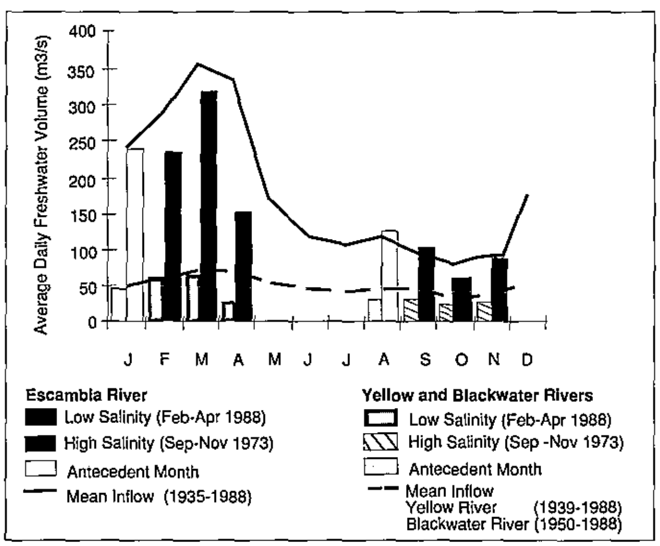
The important time scales of salinity variability and responsible mechanisms are summarized in Figure 60. The highest variability occurred within Escambia Bay and western East Bay, due to river-flow fluctuations. Tidal variation was found to have modest importance within Pensacola Bay and lower Escambia Bay (Olinger et al., 1975). Variability attributable to wind is limited to surface water mixing and lowering of the halocline (Hopkins and Schomer, undated). The most stable salinities usually occurred within lower East Bay and lower Pensacola Bay, particularly within the bottom layer of the water column.

Figure 57. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	February-April 1988 (High Inflow/Low Salinity)	September-November 1973 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	333	286
Sampling Distribution [a]	1,2,4	1,2,4
Sampling Frequency	weekly - monthly	monthly
Average Salinity (ppt)	8	18.1
Bottom Salinity		
# of Observations	300	323
Sampling Distribution [a]	1,2,4	1,2,4
Sampling Frequency	weekly - monthly	monthly
Average Salinity (ppt)	12.1	24.1
Freshwater Inflow		
Escambia River Volume	25% below average [b]	10% below average [c]
Yellow/Blackwater River Volume	15% below average [b]	30% below average [c]
Return Frequency of Peak Events		
1-day duration	1.6-year	1.8-year
7-day duration	1.5-year	1.8-year
30-day duration	1.3-year	2.2-year

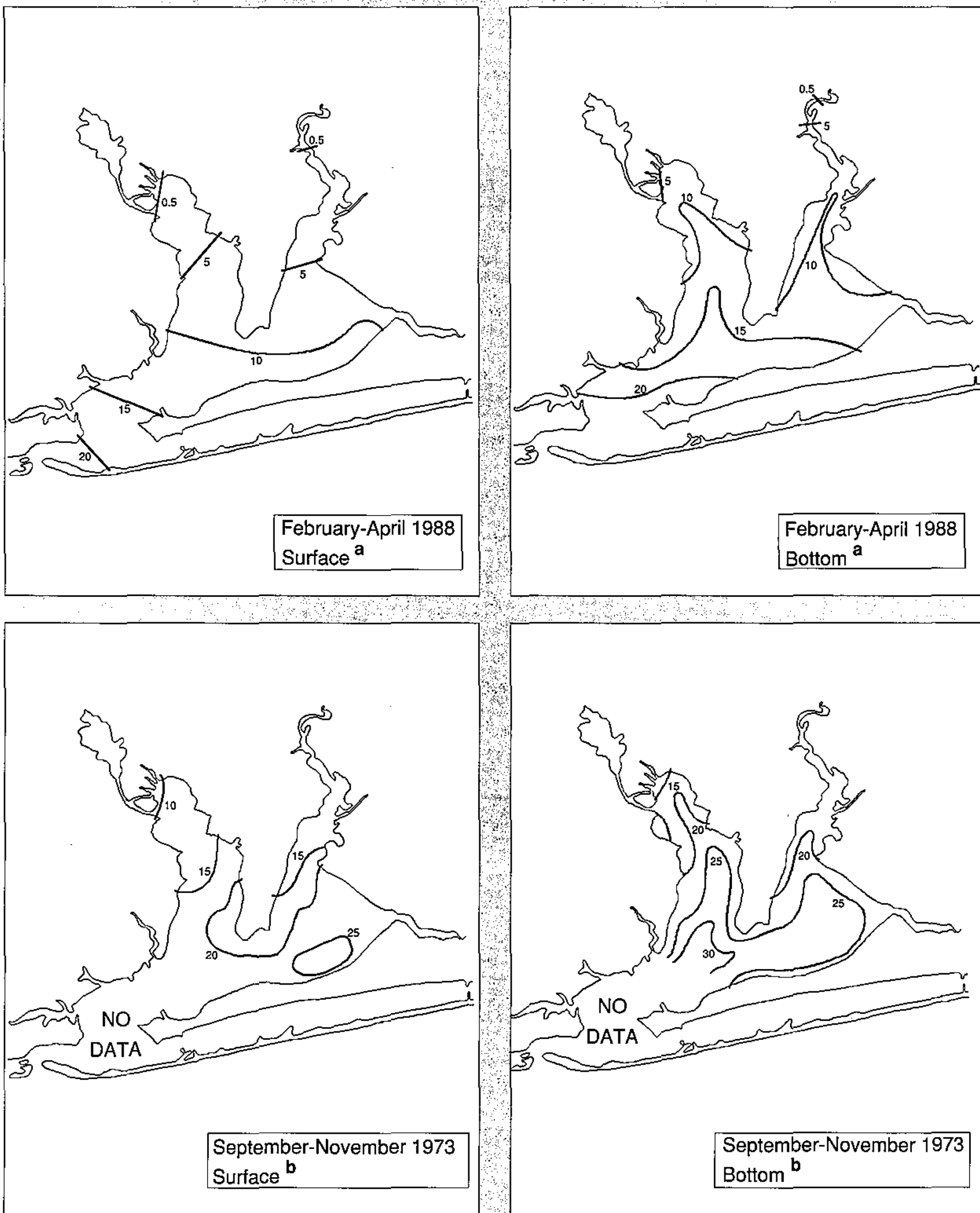
Abbreviation: ppt - parts per thousand
a. Subsystem(s) with high sampling density
b. Includes January 1988
c. Includes August 1973

Figure 58. *Comparison of gaged freshwater volume for the Escambia, Yellow, and Blackwater Rivers during periods of salinity depiction and period-of-record averages* *



Abbreviation: m3/s - cubic meters per second
* USGS gages reflect inflow from 66% of the estuary's total watershed (18,100 km2) (USGS, 1990)

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

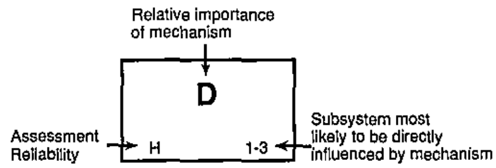


a. Data Sources: FDER, 1991; FDNR, 1989-90
b. Data Source: Hopkins and Schomer, undated

Figure 60. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		D M 1-3	D M 1-5	D M 1-5	
Tides	D LIT 2, 5				
Wind		M LIT 1-5	M LIT 1-5		
Density Currents		S LIT 1-3	S LIT 1-5		
Effect on Salinity Variability	UNKNOWN	MEDIUM	HIGH	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 59 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 stability and stratification, especially in upper and middle Escambia Bay and upper western East Bay.

Months-Seasons. Dominant influence on salinity structure throughout the estuary. Inflow decreases estuary-wide stability and increases vertical stratification. Peak discharges during February-April displace high-salinity bottom waters from upper Escambia Bay to Pensacola Bay.

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

Tides

Hours. Dominant influence on salinity stability and stratification within Pensacola Bay and lower Escambia Bay (Olinger et al., 1975). Tides are diurnal, varying from 1 m at the mouth of the bay to 0.3 m in upper Escambia Bay (Bass and Hitt, 1978).

Wind

Days-Weeks. Minor influence on salinity stability and stratification throughout the estuary, especially when associated with cold fronts.

Months-Seasons. Minor influence on salinity structure throughout the estuary. Prevailing winds enhance stratification during the winter months.

Density Currents

Days-Weeks. Secondary influence on salinity structure and stability, especially within upper and middle Escambia Bay.

Months-Seasons. Secondary influence on salinity structure and stability throughout the estuary.

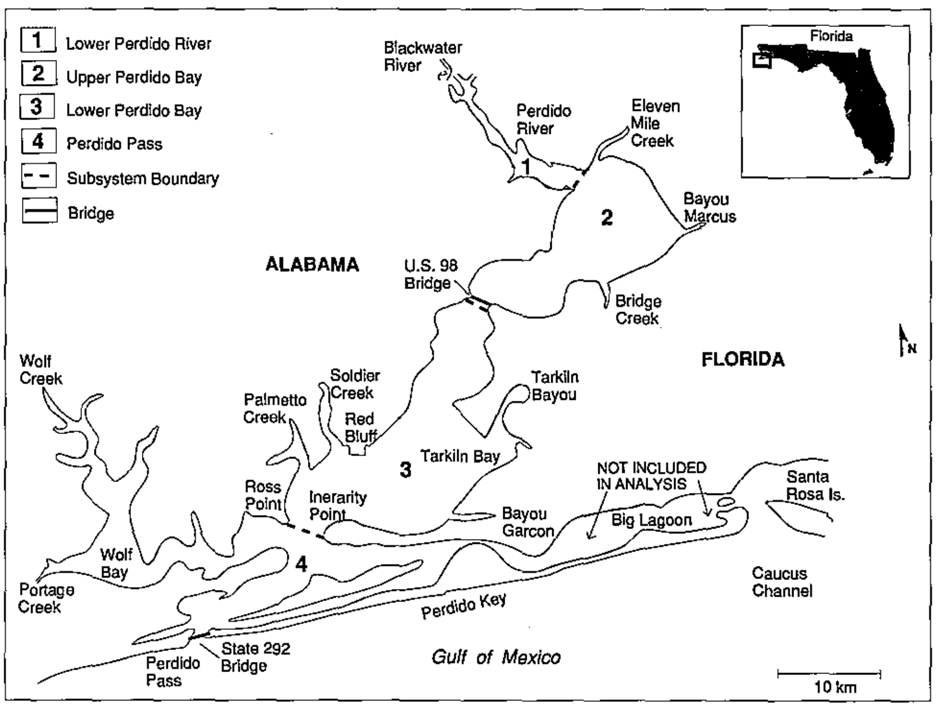
* Data Sources: See data sources listed in Appendix II for Florida.

Geographic Setting

The Perdido Bay estuary occupies just 130 km^2 and is the fifth smallest estuarine system on the Gulf coast (NOAA, 1990a). Its boundaries are defined from the head of tide on the Perdido River at Highway 112, approximately 19 km upstream of its confluence with Perdido Bay to its terminus with the Gulf of Mexico at Perdido Pass (Figure 61) (USFWS, 1982e). The estuary's northeast-southwest axis is highly convoluted and contains several constricting points along its length. The estuary is separated from the Gulf by Perdido Key and direct exchange is restricted to Perdido Pass. Limited exchange occurs with the Pensacola system through Big Lagoon and the Mobile system through the GIWW.

The Perdido River and its principal tributaries (Styx [not shown] and Blackwater Rivers) are the primary freshwater sources to this estuary. The transport of the Perdido River plume is restricted to the upper bay due, in part, to shoreline constrictions. Freshwater dominance of the lower bay occurs only during periods of extreme inflow. This estuary has been divided into four subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 61). No salinity data are available for Big Lagoon and it is not included in this analysis.

Figure 61. *Location map and subsystem identification*



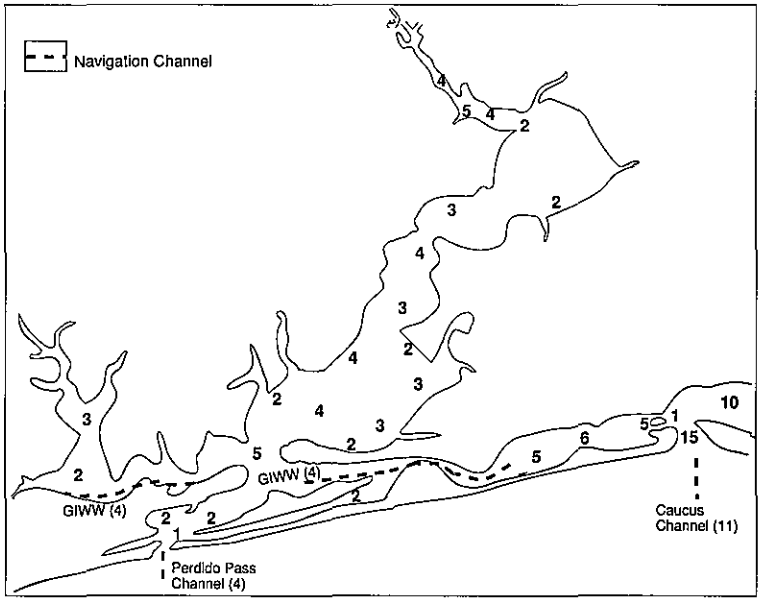
Bathymetry

The average depth of this estuary is 2 m at mid-tide level (NOAA, 1990a), but contains important irregularities throughout the system. Naturally deep areas are located near the mouth of the Perdido River, in Caucus Channel, south of the US 98 bridge, and below Ross Point (Figure 62). These areas effectively trap saline bottom waters, enhancing and prolonging vertical stratification. The entrance at Perdido Pass is subject to shoaling and requires continual dredging to maintain a 4 m channel. These shoals act as a sill to trap saline bottom waters and maintain moderately-to-highly stratified conditions. Upper Perdido Bay is shallow compared to other subsystems, but frequently alternates between vertically homogeneous and highly stratified conditions.

Salinity Patterns

The Data. October-December 1988 and February-April 1988 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions since no recent major modifications to the estuary or its watershed are known to have occurred. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 63. Limited salinity information was available for Wolf Bay and Perdido Pass. Figure 64 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that the low-salinity period experienced relatively typical inflow conditions, while the high-salinity period was preceded by an unusually wet September. Figure 65 presents salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 66.

Figure 62. *Bathymetry (meters)*



High-Inflow/Low-Salinity Period (February-April 1988). During this selected period and including January 1988, total inflow from the Perdido River was approximately 20% below long-term averages (Figures 63 and 64). Daily inflow was consistent with long-term averages during January-March, but was below normal in April. Base flows near 15 m^3/s were frequently interrupted by short-duration events. Inflows peaked (90 m^3/s) in early March with secondary peaks occurring in mid-February (80 m^3/s), mid-January (60 m^3/s), early April (55 m^3/s), and late March (35 m^3/s).

Salinity data were limited during this period, but indicated a significant freshening of the estuary when compared to the October-December 1988 period, despite only a modestly higher freshwater volume. In contrast to the October-December 1988 period, inflow events occurred in rapid succession allowing continued influence throughout the upper bay and extending into the lower bay region. Surface salinities had been reduced to <10 ppt near Inerarity Point by mid-March, and gradually increased during April. Bottom salinities throughout the bay were relatively stable until mid-April, suggesting a response-lag with respect to the freshwater event or the influence of meteorological activity. Highly stratified conditions persisted south of the US 98 bridge, while vertically homogeneous conditions occurred in the upper bay.

Low-Inflow/High-Salinity Period (October-December 1988). During this selected period and including September 1988, total inflow from the Perdido River was approximately 20% above long-term averages (Figures 63 and 64). Inflows remained near 10 m^3/s throughout the period, except during short-duration peaks in early September (60 m^3/s), late September (110 m^3/s), mid-September (110 m^3/s) and early October (45 m^3/s).

Salinity response was generally limited to the surface layer above the US 98 bridge where surface salinities were reduced through October. Surface concentrations had recovered by early November and were relatively stable throughout the remainder of the period. Bottom salinities remained relatively stable and appeared unaffected by the freshwater event, especially within the lower bay. Highly stratified conditions persisted within lower Perdido River, lower Eleven Mile Creek, and the upper bay nearest these freshwater sources. Moderately stratified conditions occurred within the remainder of the upper bay. The lower bay was moderately-to-highly stratified throughout the period.

Factors Affecting Variability

Salinity structure is determined, primarily, by the seasonal freshwater discharge from the Perdido River system. The plume may dominate surface salinities within the lower Perdido River and upper bay under normal conditions, but has limited influence on bottom salinities or surface salinities below the US 98 bridge. The estuary is rarely unstratified, with vertically homogeneous conditions occurring primarily in the shallow areas of the upper bay. Moderately-to-highly stratified conditions persist throughout the lower bay and lower Perdido River. Stratification may be enhanced by sustained northerly winds.

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 66. Variability is most often associated with short-duration freshwater events, although its influence is generally confined to the upper bay. Here, surface salinities are reduced and vertical stratification increased. Meteorological events are important modifiers of salinity throughout the estuary. These events may destratify the water column and enhance exchanges with shelf waters.

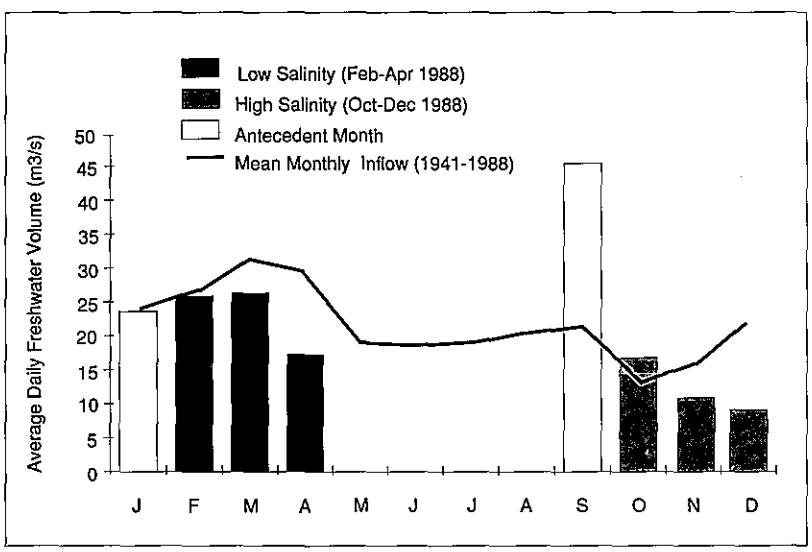
Figure 63. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	February-April 1988 (High Inflow/Low Salinity)	October-December 1988 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	20	159 (Dec. only)
Sampling Distribution [a]	1-3	1-3
Sampling Frequency	monthly	monthly
Average Salinity (ppt)	5.6	9.8
Bottom Salinity		
# of Observations	20	156 (Dec. only)
Sampling Distribution [a]	1-3	1-3
Sampling Frequency	monthly	monthly
Average Salinity (ppt)	12.1	17.5
Freshwater Inflow		
Volume	20% below average [b]	20% below average [c]
Return Frequency of Peak Events		
1-day duration	1.5-year	2.4-year
7-day duration	1.3-year	2.0-year
30-day duration	1.5-year	1.4-year

Abbreviation: ppt - parts per thousand

a. Subsystem(s) with high sampling density
b. Includes January 1988
c. Includes September 1988

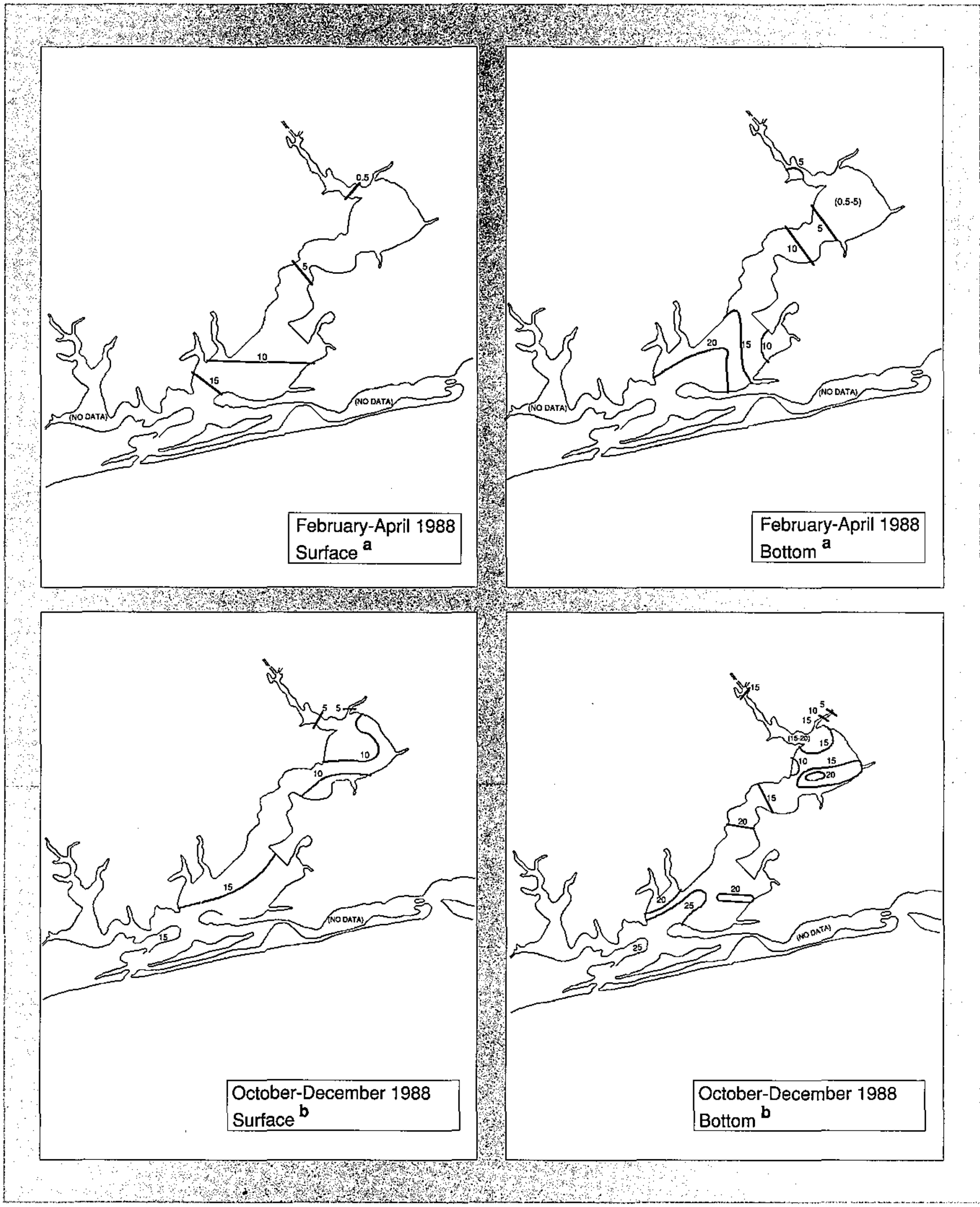
Figure 64. *Comparison of gaged freshwater volume for the Perdido River at Barrineau Park, FL during periods of salinity depiction and period-of-record averages**



Abbreviation: m3/s - cubic meters per second

* USGS gage reflects inflow from 54% of the estuary's total watershed (3,100 km2) (USGS, 1990)

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

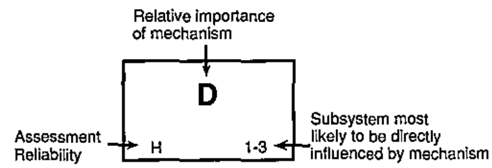


a. Data Source: USEPA, 1991
b. Data Sources: ADEM, 1993; EP&A, 1991; USEPA, 1991b

Figure 66. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S M 1	D M 1-3	D M 1-3	
Tides		M LIT 4			
Wind		S LIT 1-4	M LIT 1-4		
Shelf Processes			M LIT 4	M LIT 4	
Effect on Salinity Variability	LOW	MEDIUM	HIGH	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.

Freshwater Inflow

Days-Weeks. Secondary influence on salinity variability and stratification, primarily in the lower Perdido River and upper bay. Freshets affect the surface layer, generally having limited influence on bottom salinities, except within the lower Perdido River. Freshets may briefly displace stratified waters in the lower Perdido River and intensify vertical stratification in the upper bay.

Months-Seasons. Dominant influence on salinity structure in the upper estuary, but limited influence south of Inerarity Point. Typical peak seasonal discharges (October-December) primarily affect the surface layer, but may depress salinities in the upper bay for several weeks.

Year-Year. Dominant influence on salinity structure throughout the upper and middle bay. Lower bay salinities become dominated by freshwater only during floods.

Tides

Days-Weeks. Minor influence on salinity variability and stratification within the lower estuary, generally promoting water-column mixing. Tides are diurnal and range <0.5 m.

Wind

Days-Weeks. Secondary influence on salinity variability and stratification throughout the estuary, especially when associated with cold fronts. This influence is less pronounced than in other estuaries because of the system's north-south alignment and limited fetch (Niedaroda, Pers. Comm.).

Months-Seasons. Minor influence on salinity structure throughout the estuary. Sustained northerly winds may increase estuarine salinities and stratification. Sustained southerly winds elevate shelf water levels and increase the transport of high-salinity bottom waters into the lower and middle bay (Niedaroda, Pers. Comm.).

Shelf Processes

Months-Seasons. Minor influence on salinity structure within the lower bay due to peak discharges from the Mobile and Pensacola systems.

Year-Year. Minor influence on salinity structure within the lower bay due to peak discharges from the Mobile and Pensacola systems.

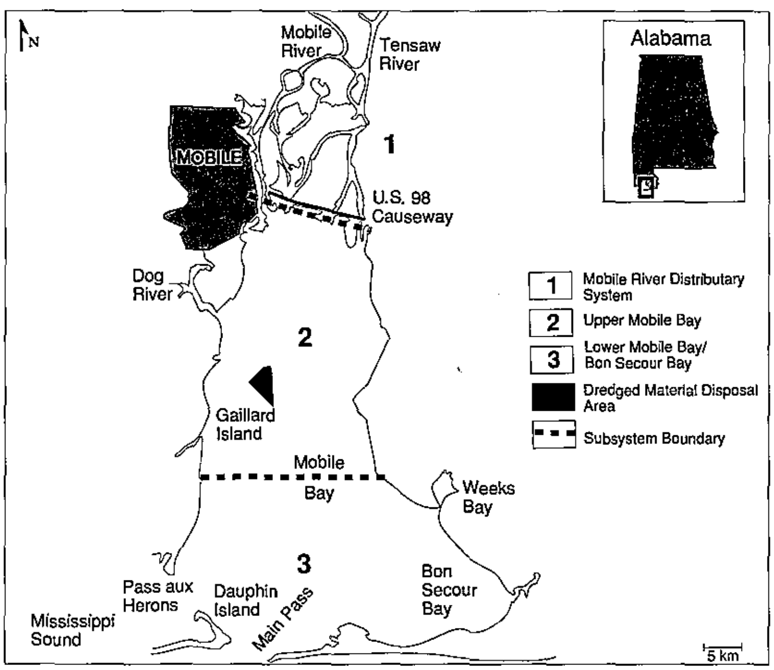
* Data Sources: See data sources listed in Appendix II for Florida.

Geographic Setting

Mobile Bay is a drowned river valley estuary located on the Alabama coast between the Mississippi Sound and Perdido Bay systems. Occupying 1,070 km^2 (NOAA, 1990a), it includes Mobile Bay, the Mobile River distributary system, and several secondary embayments (Figure 67). Its watershed (115,510 km^2) includes two-thirds of Alabama and portions of Mississippi, Georgia, and Tennessee (Crance, 1971). The estuary extends inland to the heads of tide on the Alabama River at Claiborne, AL and the Tombigbee River at Coffeeville, AL. Exchanges with the Gulf occur primarily through Main Pass (85%). Exchanges through Mississippi Sound at Pass aux Herons are partially obstructed by oyster reef shoals and the Dauphin Island causeway.

The distributary system is the terminus of the Mobile, Tombigbee-Black Warrior, and the Alabama-Coosa-Tallapoosa river systems. Together, these systems provide more than 95% of the estuary's freshwater. Exchanges between Mobile Bay and the distributary system, however, are limited by an earthen causeway that restricts freshwater inflow to the mouths of the four distributaries and two small viaducts under the causeway. This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 67).

Figure 67. *Location map and subsystem identification*



Bathymetry

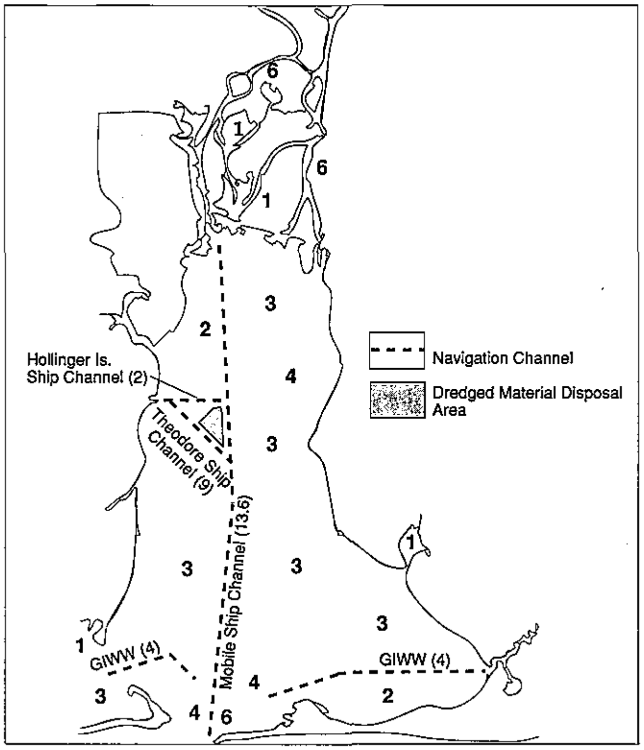
The average depth of Mobile Bay and its distributaries is approximately 3 m and 6 m at mid-tide level, respectively (Figure 68) (NOAA, 1990a). Oyster reefs create numerous shallow areas throughout the bay that may significantly affect water circulation and exchanges. In addition, dredged material disposal areas near the Mobile Ship Channel (MSC) and the Hollinger Island Ship Channel hinder east-west exchanges within the bay (Schroeder and Lysinger, 1979).

The navigation channels throughout this estuary assist in the development of density currents, an important mechanism for salinity intrusion. In particular, the MSC extends from Main Pass to the Port of Mobile and allows saline Gulf bottom waters to extend beyond the Port of Mobile. On rare occasions (during periods of very low freshwater inflow and high tides), high-salinity bottom waters may reach more than 30 km upstream from the mouth of the Mobile River (Smith, 1984).

Salinity Patterns

The Data. August-October 1968 and February-April 1969 were selected to represent high- and low-salinity periods, respectively. Although limited salinity information exists for this estuary, the selected data sets are unique in providing estuary-wide coverage. These periods do not include any alteration to the salinity structure that may be associated with the deepening of the MSC from 12.0 to 13.6 m in 1990 or the construction of the Gaillard Island disposal area and Theodore Ship Channel in 1975. The latter had caused locally important increases in bottom salinities (Lawing et al., 1975). This estuary's watershed has, however, remained relatively unaffected by modifications since 1969. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 69. Figure 70 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that August-October 1968 experienced relatively typical inflow conditions, while February-August 1969 was drier than normal. Figure 71 presents salinity distributions for the selected periods,

Figure 68. *Bathymetry (meters)*



illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 72.

High-Inflow/Low-Salinity Period (February-April 1969). During this selected period and including January 1969, total inflow from the Alabama and Tombigbee Rivers was approximately 25% below long-term averages (Figures 69 and 70), but highly variable within this period. Inflow peaked (5,900 m^3/s) during late April, with secondary peaks occurring in late January (3,600 m^3/s), mid-February (4,000 m^3/s), and late March (4,500 m^3/s). Isohalines presented in Figure 71 reflect February and March salinities only.

Salinities demonstrated a longitudinal gradient spanning from near freshwater conditions in the distributaries and upper bay, to brackish conditions in the lower bay. Seawater conditions only occurred in bottom waters near Main Pass and in the lowest portion of the MSC. Surface salinities throughout the estuary decreased throughout the period but were relatively stable except near Main Pass. Bottom salinities within the distributaries were stable, but those within the bay were highly variable. Vertical stratification persisted within the MSC and occurred in the lower bay following the February-March freshet.

Low-Inflow/High-Salinity Period (August-October 1968). During this selected period and including July 1968, total inflow from the Alabama and Tombigbee Rivers was approximately 15% below long-term averages (Figures 69 and 70). Inflow peaked (1,900 m^3/s) during mid-July, with secondary peaks during mid-August (850 m^3/s), early September (500 m^3/s), and mid-October (400 m^3/s).

Salinities increased throughout the period, reaching their highest levels in August. The water column was more unstable than during the low-salinity period. A longitudinal gradient was again apparent, although isohalines were shifted landward by 10 ppt. Brackish salinities penetrated deep into the distributary system, affecting both surface and bottom layers, and producing a 25-ppt vertical gradient in the Mobile River near Mobile. Moderate stratification persisted in the open bay.

Factors Affecting Variability

The salinity structure is determined by the seasonal freshwater discharge, which is almost exclusively transported by the Mobile River system. A longitudinal gradient exists in the bay, but varies due to freshwater inflow, prevailing winds, and density currents. Thus, the open bay may range from near-fresh to near-Gulf salinities under typical hydrodynamic conditions. However, the distributary system remains fresh or near-fresh, except in the Mobile River. Despite its shallow depths, the bay is moderately stratified throughout the year, with the strongest gradients during the spring due to increased river discharge. The strongest vertical stratification is likely to occur under conditions of (1) moderate-to-high river discharge and weak winds, or (2) persistent northerly winds and low river discharge (Schroeder, 1979).

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 72. Variability is most common in the open bay and is most frequently associated with freshets and meteorological events. Winds of sufficient magnitude and direction may result in near-homogeneous conditions throughout the estuary, although the system requires only a few days to restratify (Schroeder et al., 1988b). Tidal influence is usually restricted to the lower bay, but may be enhanced during low-inflow conditions.

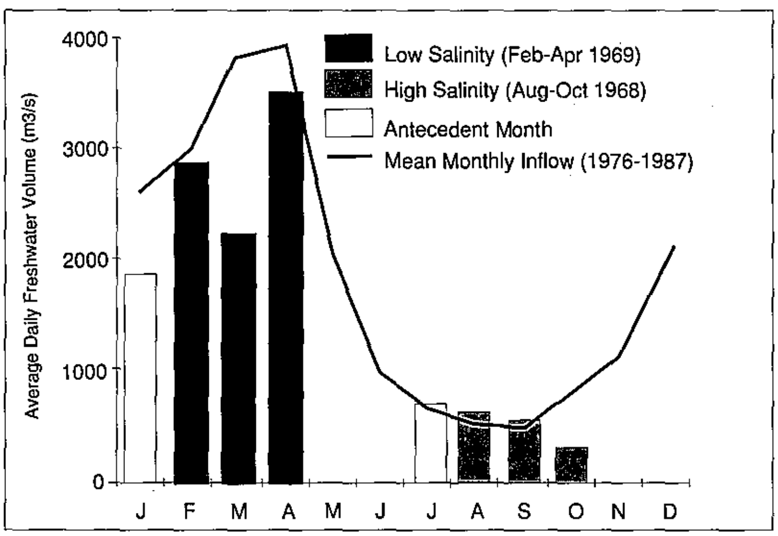
Figure 69. *Freshwater inflow, salinity sampling, and average salinity during low - and high-salinity periods*

	February-April 1969 (High Inflow/Low Salinity)	August-October 1968 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	32	48
Sampling Distribution [a]	1-3	1-3
Sampling Frequency	No April	monthly
Average Salinity (ppt)	4	13
Bottom Salinity		
# of Observations	32	48
Sampling Distribution [a]	1-3	1-3
Sampling Frequency	No April	monthly
Average Salinity (ppt)	11	20
Freshwater Inflow		
Alabama/Tombigbee Rivers Volume	25% below average [b]	15% below average [c]
Return Frequency of Peak Events		
1-day duration	1.2-year	1.2-year
7-day duration	1.2-year	1.3-year
30-day duration	1.2-year	1.5-year

Abbreviation: ppt - parts per thousand

a. Subsystem(s) with high sampling density
b. Includes January 1969
c. Includes July 1968

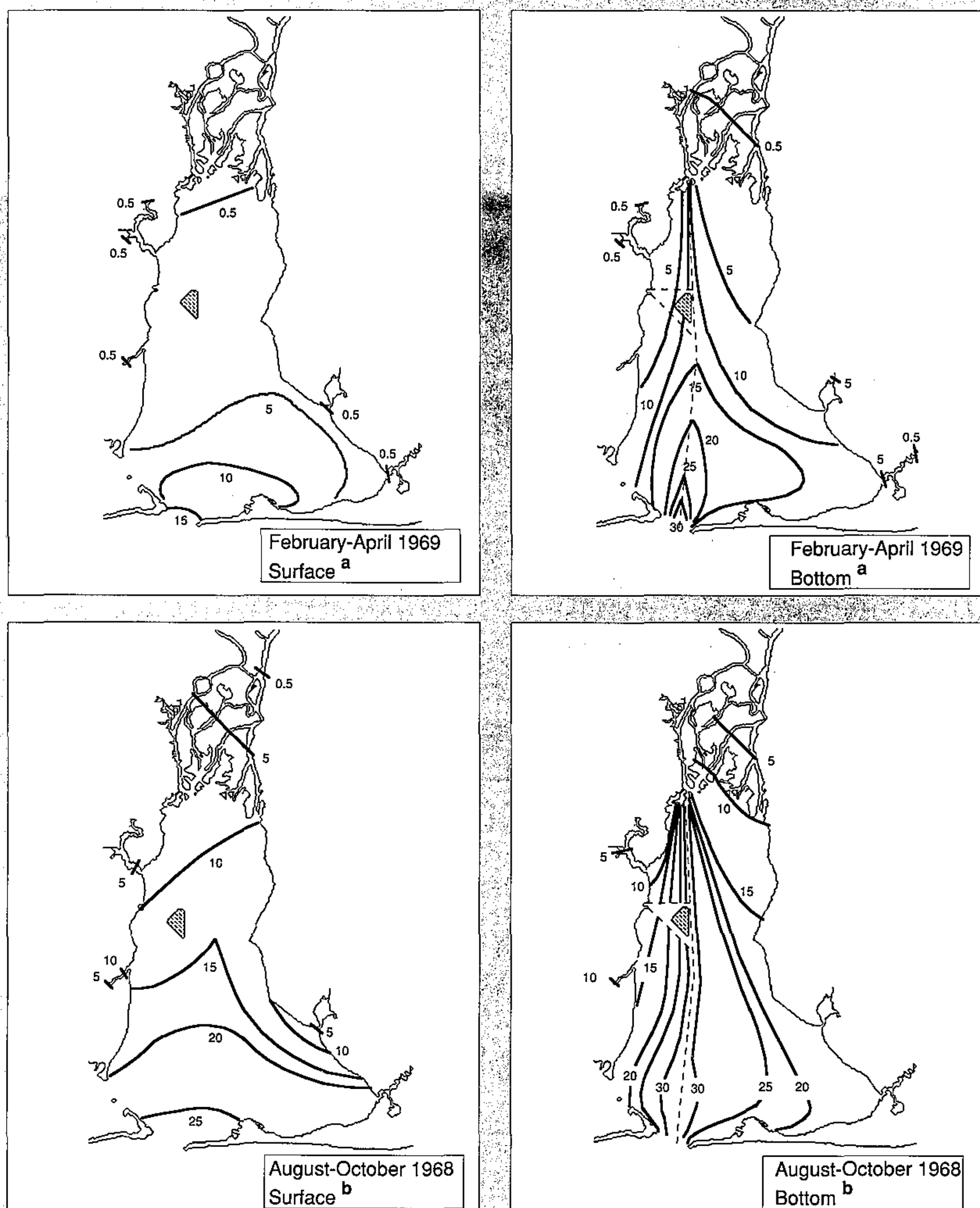
Figure 70. *Comparison of gaged freshwater volume for the Alabama River at Claiborne, AL and Tombigbee River at Coffeeville, AL during periods of salinity depiction and period-of-record averages **



Abbreviation: m3/s - cubic meters per second

*USGS gages reflect inflow from 95% of the estuary's total watershed (115,510 km2) (USGS, 1990)

Figure 71. *Surface and bottom salinities during low- and high-salinity periods*

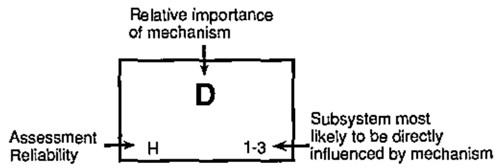


a. Data Source: Bault, 1972
b. Data Source: Bault, 1972

Figure 72. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S (L, 1-3)	D (H, 1-3)	D (H, 1-3)	
Tides		M (LIT, 3)			
Wind		S (LIT, 2-3)	M (LIT, 2-3)		
Density Currents			S (LIT, 1-3)		
Shelf Processes			M (LIT, 3)		
Effect on Salinity Variability	UNKNOWN	LOW	HIGH	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 71 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, primarily in the upper portions of Mobile Bay, that may cause a temporary retreat of bottom waters within the MSC.

Months-Seasons. Dominant influence on salinity structure throughout the estuary. Inflow maintains near-fresh conditions in distributaries, but allows significant Gulf influence under low-inflow conditions.

Year-Year. Dominant influence on salinity structure throughout the estuary. High inflow produces near-fresh conditions except in the lower portion of the MSC, in portions of Bon Secour Bay, and at Main Pass (Schroeder and Lysinger, 1979).

Tides

Days-Weeks. Minor influence on salinity variability, primarily in lower Mobile Bay.

Wind

Days-Weeks. Secondary influence on salinity variability throughout the system. In particular, cold fronts produce abrupt changes in the bay and generally favor the "flushing" of bay waters. These events typically occur five times per month during October-March (Schroeder et al., 1988a). Northerly winds <4 m/s generally have no effect on vertical stratification; winds 4-8 m/s enhance stratification; and winds >8 m/s encourage mixing (Schroeder and Wiseman, 1985).

Months-Seasons. Minor influence on salinity structure throughout the bay. Sustained northerly winds decrease system volume, dampen tidal ranges, and push surface isohalines toward the mouth of the estuary (Imsand, Pers. Comm.; Schroeder and Lysinger, 1979).

Density Currents

Months-Seasons. Secondary influence on salinity structure throughout Mobile Bay and Mobile River. Navigation channels facilitate intrusion of high-salinity waters into the upper estuary and enhance vertical stratification.

Shelf Processes

Months-Seasons. Minor influence on salinity structure in lower Mobile Bay. River plumes, especially from the Pascagoula River may lower salinities entrained through the passes.

* Data Sources: See data sources listed in Appendix II for Alabama.

Geographic Setting

The Mississippi Sound estuary, located along the north-central coast of the Gulf of Mexico, includes three adjoining estuarine systems: St. Louis Bay, Biloxi Bay, and the Pascagoula River delta complex (Christmas, 1973) (Figure 73). The estuary extends from the heads of tide on the Jourdan River 1 km west of Highway 43, on the Wolf River 3 km south of I-10, on the Biloxi River 5 km north of I-10, and on the Pascagoula River 3 km north of its confluence with the West Pascagoula River to its terminus with the Gulf. This estuary is separated from the Gulf by a series of barrier islands: Cat, Ship, Horn, Petit Bois, and Dauphin. Most tidal exchange between the Mississippi Sound and Gulf occurs through Dog Keys Pass, Horn Island Pass, and Petit Bois Pass. This estuary also exchanges waters with Mobile Bay (through Pass aux Herons), Lake Borgne (through Grand Island Pass), and Chandeleur Sound (through Ship Island Pass).

The Pascagoula and Pearl Rivers are the major freshwater sources to the system, although the Mobile River may also contribute a significant freshwater volume to the eastern portion of the Mississippi Sound (Austin, 1954; Eleuterius, 1979; Kjerfve, 1983). The Mississippi River can contribute significant freshwater volumes to the system through Lake Pontchartrain and Lake Borgne, especially when the Bonnet Carre Spillway is opened to relieve flooding on the lower stem of the river (Kjerfve, 1983). This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 73).

Bathymetry

The average depth of this estuary is approximately 3 m at mid-tide level (NOAA, 1990a), with 99% less than 6 m deep (Higgins and Eleuterius, 1978) (Figure 74). Depths in the Sound change very gradually, except in navigation channels and island passes. Maximum depths in the Gulfport and Pascagoula Ship Channels are 9.1 and 11.5 m, respectively (USACE, 1983b). These channels allow the intrusion of saline waters into the upper estuary (Eleuterius, 1978c). The GIWW traverses the entire length of the Mississippi Sound and periodic dredging is required to maintain the project depth only in the shallow east and west ends of the Mississippi Sound. Natural scouring has deepened the inlets along the western tips of the barrier islands; maximum depths range 4-13.4 m.

Figure 73. *Location map and subsystem identification*

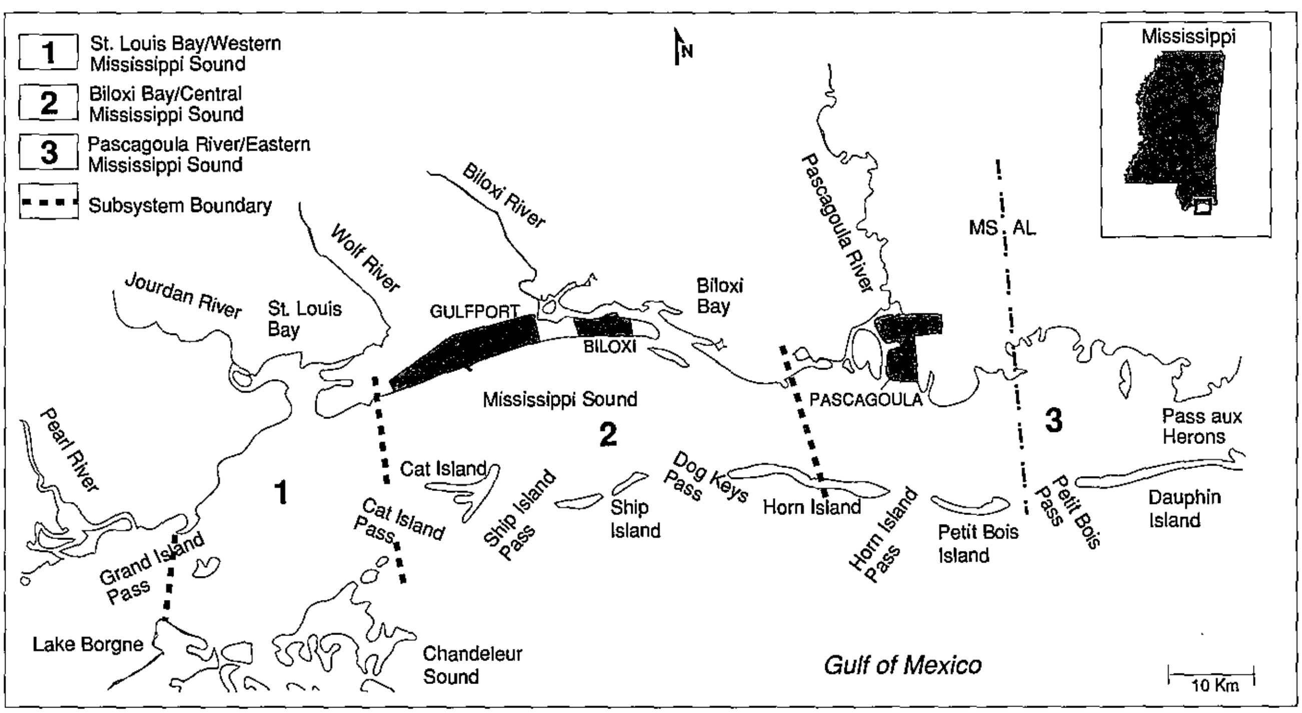
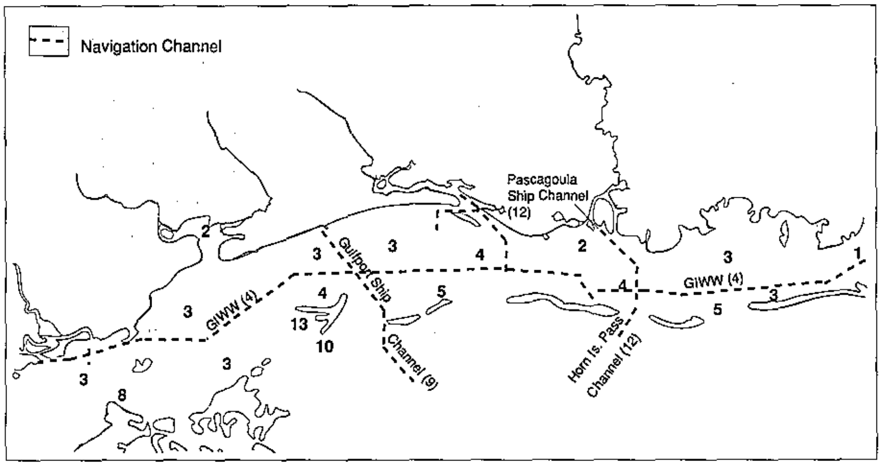


Figure 74. *Bathymetry (meters)*



Average salinities in Mississippi Sound were highest in its central basin, where a tongue of high-salinity water extended northward to Biloxi Bay. Salinities decreased toward Lake Borgne and Mobile Bay where they were moderated by the Pearl and Mobile River discharges, respectively. Salinities were relatively unstable, particularly within the adjoining estuarine systems. Bottom salinities were generally higher than surface salinities throughout the system, although waters were occasionally well mixed. Vertical stratification occurred most frequently in the central basin.

Salinity Patterns

The Data. August-October 1980 and February-April 1984 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions as no major modifications to the estuary or its watershed have occurred since improvements to the Biloxi Channel in 1975 (USACE, 1983b). A summary of freshwater inflow conditions and salinity data for these selected periods is given in Figure 75. Bottom salinity data were limited, but available for most areas of the estuary. Figure 76 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests February-April 1984 experienced typical inflow conditions, while August-October 1980 was drier than normal. Figure 77 presents salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 78.

High-Inflow/Low-Salinity Period (February-April 1984). During this selected period and including January 1984, total inflow from the Pearl, Pascagoula, and Mobile River systems was generally above-normal in January and near-normal during February-April when compared to the long-term averages (Figures 75 and 76). Within the period, peak flows on the Pearl and Pascagoula Rivers occurred in mid-March, with secondary peaks in early January, late February, and mid-April. The Mobile River system peaked (>3,000 m^3/s) in early January, with secondary peaks in early March and mid-April.

Low-Inflow/High-Salinity Period (August-October 1980). During this selected period and including July 1980, total inflow from the Pearl, Pascagoula, and Mobile River systems were generally below normal, except for above-normal flows for the Pearl River during July, when compared to the long-term averages (Figures 75 and 76). Within the period, peak and secondary discharges were approximately four times lower than during the low-salinity period and occurred during early July, early October, and late October.

Average surface salinities in the Mississippi Sound exhibited a pattern similar to the February-April 1984 period, with the lowest salinities (<15 ppt) in the west and highest salinities (>25 ppt) near passes in central Mississippi Sound. Salinities in the adjoining estuarine systems were noticeably higher and brackish waters intruded upstream several kilometers into embayment tributaries. In contrast to February-April 1984, salinities throughout the system were generally stable and stratification was less common.

Factors Affecting Variability

The salinity structure is determined by the seasonal freshwater discharge. The lowest salinities are typically set up in the western basin, due to the Pearl River plume. Mobile River discharges contribute to reduced salinities in the eastern basin. The highest salinities occur in the central basin where freshwater discharge is lowest. Navigation channels facilitate the development of density currents and the intrusion of high salinity waters into the upper estuary

(Eleuterius, 1978c). Because most of the estuary is shallow, winds and tides probably prevent salinity stratification under most conditions (Eleuterius, 1978a/b). Stratification is most likely to occur in the navigation channels during periods of high freshwater inflow (Eleuterius, 1978a/b).

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 78. Variability is most common in the western basin of the Mississippi Sound and in the adjoining estuarine systems, and less common in the Sound's central basin. Meteorological forcing, especially when associated with cold fronts, dramatically affects water levels, circulation, and salinity. Kjerfve (1983) found that meteorological events with periods of approximately 1 week were most important in controlling water exchanges between this estuary and the Gulf. Winds could cause large net displacements of lagoonal waters, while tidal currents accounted for essentially zero net displacement (Kjerfve, 1983).

Figure 75. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	February-April 1984 (High Inflow/Low Salinity)	August-October 1980 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	94	231
Sampling Distribution [a]	1-2	1-3
Sampling Frequency	biweekly-monthly	monthly
Average Salinity (ppt)	13.0	16.0
Bottom Salinity		
# of Observations	59	111
Sampling Distribution [a]	2	2
Sampling Frequency	biweekly-monthly	monthly
Average Salinity (ppt)	17.0	24.0
Freshwater Inflow		
Pearl River Volume	average [b]	10% below average [c]
Pascagoula River Volume	5% below average [b]	20% below average [c]
Return Frequency of Peak Events for Pearl River		
1-day duration	2.2-year	1.4-year
7-day duration	2.2-year	1.3-year
30-day duration	2.3-year	1.3-year
Return Frequency of Peak Events for Pascagoula River		
1-day duration	1.5-year	1.9-year
7-day duration	1.4-year	1.5-year
30-day duration	1.5-year	1.4-year

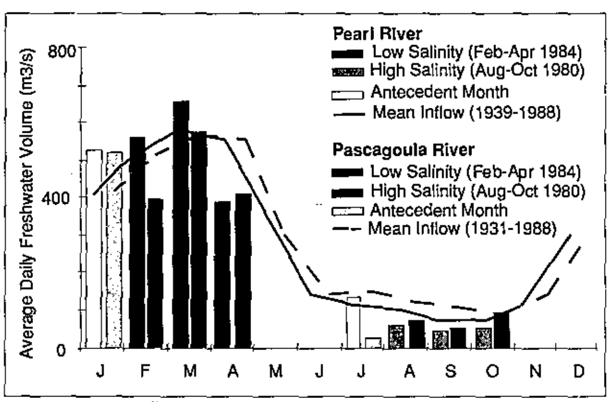
Abbreviation: ppt - parts per thousand

a. Subsystem(s) with high sampling density

b. Includes January 1984

c. Includes July 1980

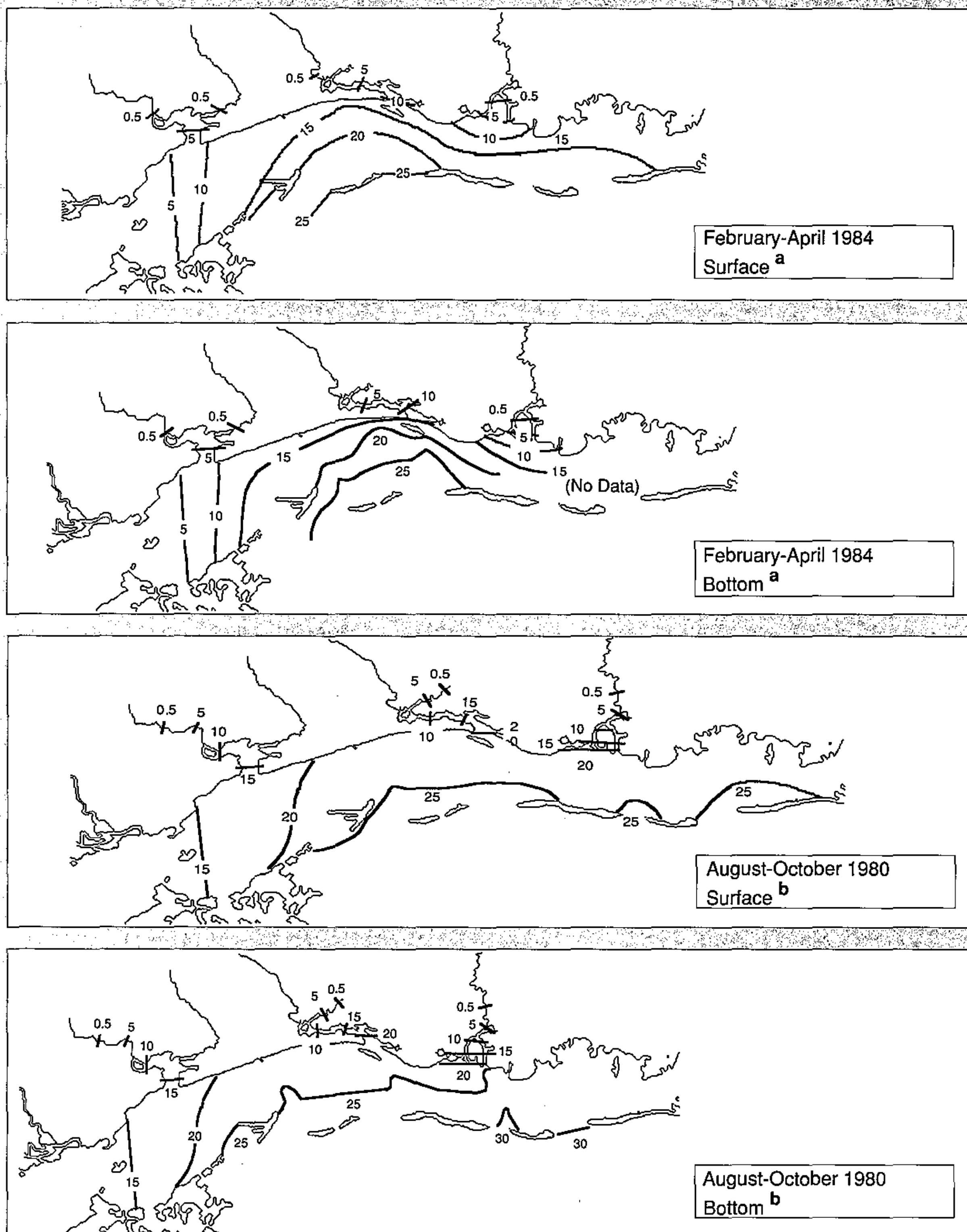
Figure 76. *Comparison of gaged freshwater volume for the Pearl River at Bogalusa, LA, and the Pascagoula River at Merrill, MS, during periods of salinity depiction to period-of-record averages* *



Abbreviation: m3/s - cubic meters per second

*USGS gages reflect inflow from 50% of the estuary's total watershed (69,668 km2), which includes Lake Pontchartrain and Lake Borgne watersheds (USGS, 1990)

Figure 77. *Surface and bottom salinities during low- and high-salinity periods*

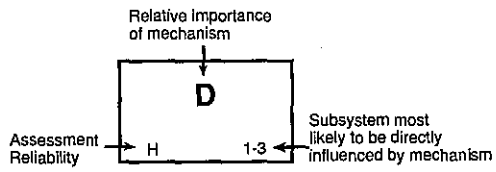


a. Data Sources: ADPH, 1991; Gulf Coast Research Laboratory, 1991
b. Data Sources: ADPH, 1991; Gulf Coast Research Laboratory, 1991

Figure 78. *Time Scales and forcing mechanisms important to salinity structure and variability.**

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		S (M 1-3)	S (H 1-3)	S (H 1-3)	
Tides					
Wind		S (LIT 1-3)			
Density Currents			M (LIT 2-3)		
Inter-estuary Exchanges		S (LIT 1-3)	D (LIT 1-3)	S (LIT 1-3)	
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 77 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, primarily near freshwater sources in the St. Louis Bay, Biloxi Bay, Pascagoula River, and western Mississippi Sound.

Months-Seasons. Secondary influence on salinity structure. Inflow from Pascagoula, Wolf, Biloxi, and Jourdan Rivers primarily affect the adjacent estuarine systems.

Year-Year. Secondary influence on salinity structure. Bottom salinities, in particular, are relatively constant from year-to-year.

Wind

Days-Weeks. Secondary influence on salinity structure throughout the estuary.

Density Currents

Month-Seasons. Minor influence on salinity structure, primarily near the Pascagoula and Biloxi channels. These channels facilitate the intrusion of high-salinity waters into the upper estuary and may result in increased average salinities in this area (Eleuterius, 1978c). Favorable stratification conditions are enhanced by deep navigation channels.

Inter-estuary Exchanges

Days-Weeks. Secondary influence on salinity variability caused by Pearl River and Mobile River systems within the western and eastern basins of Mississippi Sound, respectively.

Months-Seasons. Dominant influence on salinity structure in western and eastern basins of Mississippi Sound. Freshwater inflow from the Pearl River and Mobile Bay systems was approximately four times greater during the low-salinity period than high-salinity period which dilutes salinity by more than 5 ppt in most of the estuary.

Year-Year. Secondary influence on salinity structure or stability, but locally important in eastern and western basins of Mississippi Sound.

* Data Sources: See data sources listed in Appendix II for Mississippi.

Lakes Pontchartrain/Borgne and Chandeleur Sound, LA

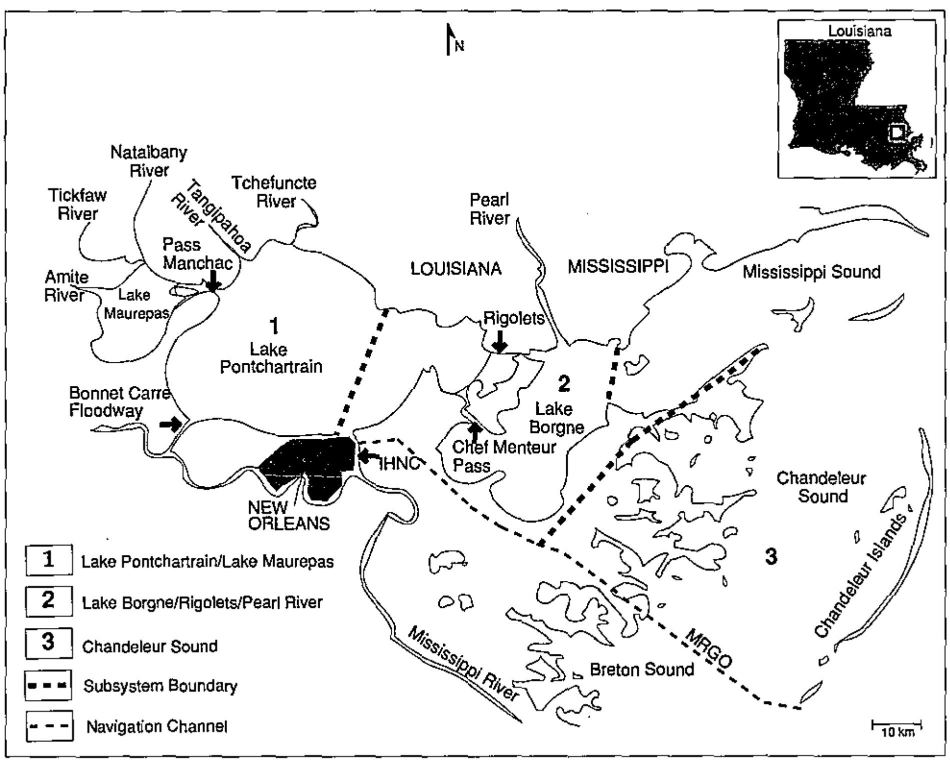
Geographic Setting

The Lakes Pontchartrain/Borgne and Chandeleur Sound estuarine system is located in the Mississippi River deltaic plain. Its boundaries include a Pleistocene coastal terrace to the north and the natural levee of the Mississippi River and dredged disposal material areas near the Mississippi River Gulf Outlet (MRGO) on the south. The estuarine boundaries extend from the head of tide on the Pearl River at the I-10 causeway, and the heads of tide on the principal Pontchartrain drainages to the Gulf and Mississippi Sound (Figure 79).

Historically, the estuary received freshwater from the Mississippi River's over-bank flooding. By the 1930s, the Mississippi River had been completely leveed; its discharge to Lake Pontchartrain occurred only when the Bonnet Carre Floodway was opened in 1937, 1945, 1950, 1973, 1975, 1979, and 1983. During most years, the floodway remains closed and Lake Pontchartrain salinities are dominated by seasonal flows, primarily from the Amite-Comite and Tangipahoa Rivers (Swenson, 1980a). The Pearl River is the major freshwater source to Lake Borgne and the Chandeleur Sound. As a result, water entrained to Lake Pontchartrain is significantly freshened and may maintain very low salinities within the lake, even under low-flow conditions from the Amite-Comite and Tangipahoa Rivers. Direct precipitation contributes less than 10% of the freshwater to the system as stream flow. Stormwater runoff pumped into Lake Pontchartrain from New Orleans composes 4% of the total freshwater input to the lake (Sikora and Kjerfve, 1985).

Two major inlets, Chef Menteur Pass and the Rigolets, connect Lake Pontchartrain with Lake Borgne and the Mississippi Sound. The Rigolets account for 60% of the tidal exchange in Lake Pontchartrain, and Chef Menteur accounts for 30% (Swenson and Chuang, 1983); the remaining 10% occurs through the man-made Inner Harbor Navigation Canal (IHNC), which allows intrusion of Gulf waters into Lake Pontchartrain through the MRGO (Swenson and Chuang, 1983). Most tidal exchange between the lower estuarine system and the Gulf occurs near the Chandeleur Islands. This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 79).

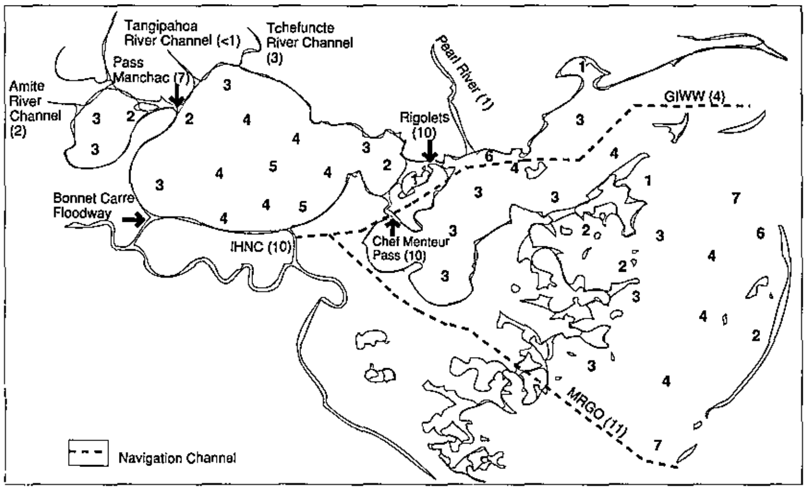
Figure 79. *Location map and subsystem identification.*



Bathymetry

The average depth of the estuary is less than 4 m at mid-tide level (NOAA, 1990a). The deepest areas are in the Rigolets, Chef Menteur Pass, MRGO, IHNC, and near the north end of the Chandeleur Islands (Figure 80). Construction of the MRGO and IHNC increased salinity to Lake Borgne and eastern Lake Pontchartrain (Fagerburg, 1990; Hawes and Perry, 1978; Sikora and Kjerfve, 1985; Wiseman et al., 1990b). Dugas (1979) observed the effects of the IHNC on lake salinities as far west as Pass Manchac. However, increases in mean salinity (2 ppt in the eastern part of Lake Pontchartrain and much less to the west) are less than the overall salinity variability and the seasonal range in salinity (Sikora and Kjerfve, 1985). Salinities in Lake Borgne have also been impacted by the MRGO construction and other channels connecting

Figure 80. *Bathymetry (meters)*



the lake with the Breton and Mississippi Sounds (Hawes and Perry, 1978). Salinity stratification commonly occurs in the MRGO (Gagliano et al., 1973). Stratification also occurs in Lake Pontchartrain near the entrance to the IHNC, but the frequency and duration of stratification decrease due to mixing, with increasing distance from the channel entrance (Poirrier, 1978).

Other primary bathymetric features are the GIWW, Amite River Channel, Tchefuncte River Channel, Tangipahoa River Navigation Channel, and Bonnet Carre Floodway. When opened, the floodway conveys Mississippi River water into the southern end of Lake Pontchartrain. The freshwater plume reduces both the temperature and salinity of estuarine waters. Lake Pontchartrain becomes fresh within a few days after the floodway is opened, and freshwater conditions may persist for as long as two months (Sikora and Kjerfve, 1985; Swenson, 1981).

Salinity Patterns

The Data. August-October 1980 and February-April 1984 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions as no major modifications to the estuary or its watershed have occurred since the MRGO alteration in 1968 (USACE, 1984b). A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 81. Freshwater statistics reflect inflow from the Pearl and Amite Rivers. Figure 82 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that both periods experienced relatively typical inflow conditions. Figure 83 presents surface salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure experiences relatively little variability as indicated in Figure 84. Bottom salinity data were not available for these selected periods.

High-Inflow/Low-Salinity Period (February-April 1984). During this selected period and including January 1984, total inflow from the Pearl River was consistent with long-term averages (Figures 81 and 82). Within this period, Pearl River discharge peaked at 1,130 m^3/s in mid-March. Secondary peaks (900-1,000 m^3/s) occurred in early January, late February, and early April. Peak inflows on the Amite River occurred in mid-February (500 m^3/s) and early March (400 m^3/s). The Tangipahoa River peaked (>200 m^3/s) in early March.

Salinities generally maintained a west-to-east gradient, increasing from freshwater conditions west of the Lake Pontchartrain causeway to more than 25 ppt in the Chandeleur Sound. Salinities were lowest in February and March and highest in late April. Salinities in Lake Borgne were most responsive to changes in freshwater input from the Pearl River. Lake Maurepas, Lake Pontchartrain, and the northern portion of Lake Borgne exhibited the most stable salinities. Salinities were unstable in Lake Borgne near the MRGO and in the embayments near the Chandeleur Sound. Although vertical stratification could not be examined in this analysis, it is typically not observed in Lakes Borgne and Pontchartrain except near the IHNC (Poirrier, 1978; Sikora and Kjerfve, 1985; Swenson, 1980b). Salinities in Lake Borgne, however, were noticeably higher and less stable near the MRGO.

Low-Inflow/High-Salinity Period (August-October 1980). During this selected period and including July 1980, total inflow from Pearl River was consistent with long-term averages (Figures 81 and 82). Discharge from the major tributaries was also below normal. Pearl River inflows were <100 m^3/s, except for peaks during late July (300 m^3/s) and late October (140 m^3/s). Discharges from the Amite River exceeded a base flow of 25 m^3/s in late July, early September, and on three occasions in October; the highest flows (>100 m^3/s) were observed in late October. Flows on the Tangipahoa River exceeded 25 m^3/s only in late October (50 m^3/s).

The west-to-east salinity gradient existed during this period, but isohalines were shifted westward when compared to the low-salinity period. Average salinities in Lake Pontchartrain were approximately 5 ppt higher than during the low-salinity period. In Lake Borgne and the wetlands to the east, salinities were 10 ppt higher. Lower salinities occurred in August and gradually increased to a peak in mid-October. In contrast to the low salinity period, salinities throughout the system were generally stable. Variability was most apparent near the Rigolets and Chef Menteur Pass. Bottom salinity data were not available to examine vertical stratification.

Factors Affecting Variability

The salinity structure is determined by the seasonal freshwater discharge. Inflow primarily from the Amite-Comite and Tangipahoa basins is sufficient to override the tidal prism volume and maintain very low salinity concentrations within Lake Pontchartrain. Entrained waters to the system, however, are considerably diluted by the Pearl River plume which dominates the Lake Borgne profile. Salinities in Chandeleur Sound demonstrate limited association with the Pearl River and Lake Pontchartrain discharges. Because the estuarine system is shallow, winds and tidal action prevent salinity stratification under most conditions (Sikora and Kjerfve, 1985; Swenson, 1980b). Stratification may occur in the deeper areas of the estuary, especially in and near the MRGO and IHNC (Gagliano et al., 1973; Poirrier, 1978; Swenson, 1980b).

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 84. The most significant variation is attributable to freshwater inflow and winds, especially when associated with frontal passages (Chuang and Swenson, 1981). Density currents within the MRGO which conveyed high-salinity waters in the upper estuary are also important (Dugas, 1979).

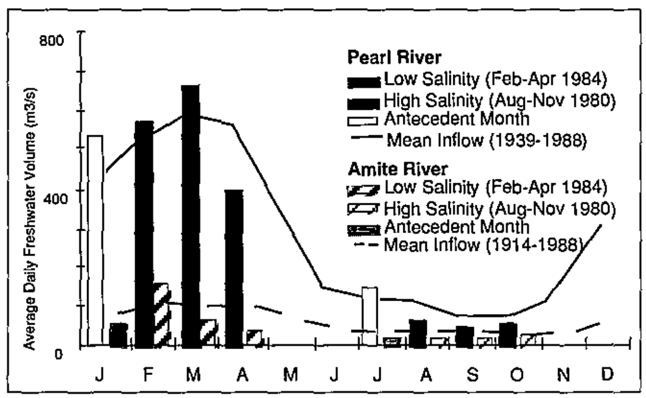
Figure 81. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	February-April 1984 (High Inflow/Low Salinity)	August-October 1980 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	576	274
Sampling Distribution [a]	2-3	1-3
Sampling Frequency	weekly - monthly	weekly - monthly
Average Salinity (ppt)	7.0	10.7
Bottom Salinity		
# of Observations	0	0
Sampling Distribution [a]	NA	NA
Sampling Frequency	NA	NA
Average Salinity (ppt)	NA	NA
Freshwater Inflow		
Pearl River Volume	average [b]	10% below average [c]
Amite River Volume	15% below average [b]	20% below average [c]
Return Frequency of Peak Events (Pearl River)		
1-day duration	2.2-year	1.4-year
7-day duration	2.2-year	1.3-year
30-day duration	2.3-year	1.3-year

Abbreviations: ppt - parts per thousand; NA - not available

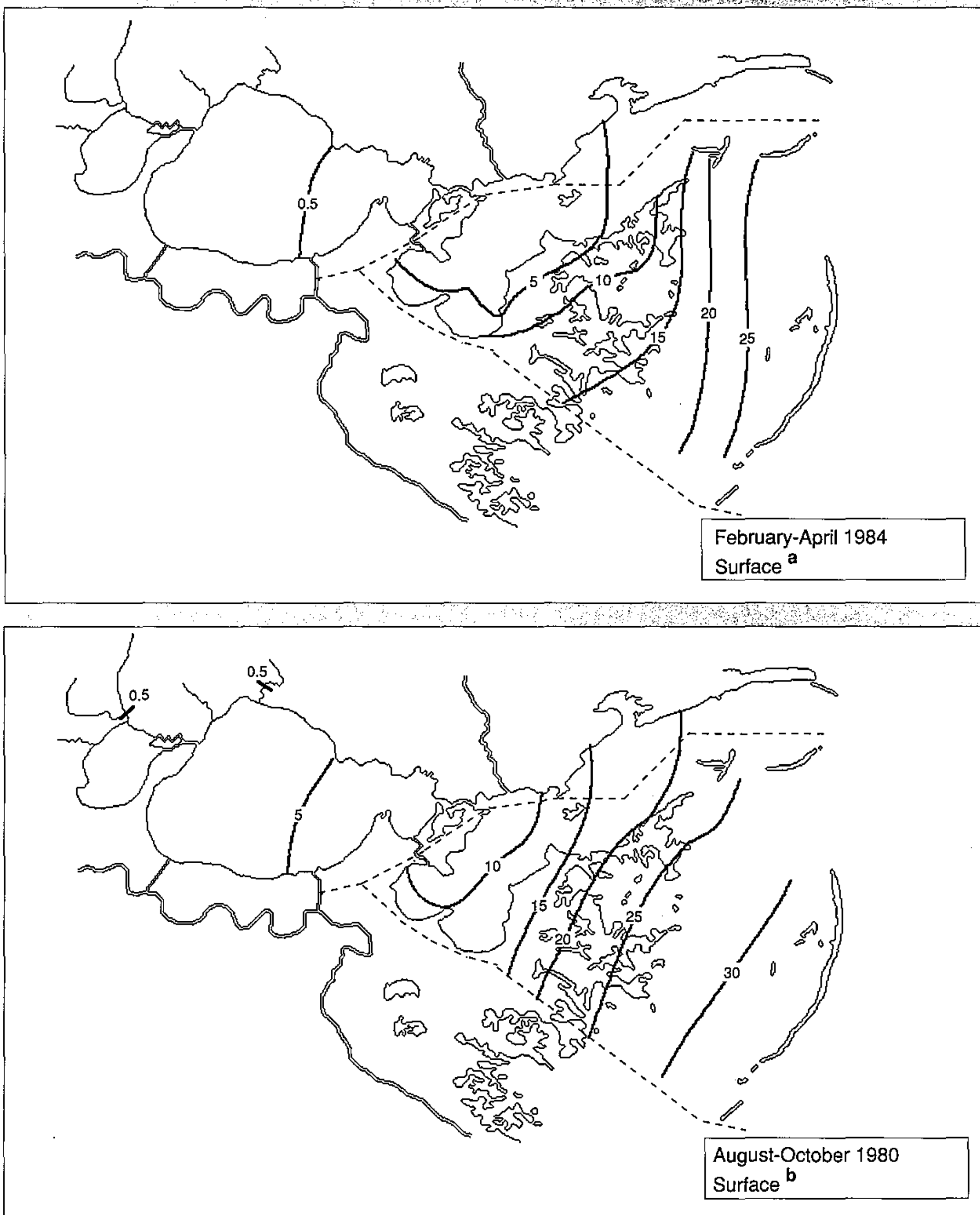
a. Subsystem(s) with high sampling density
b. Includes January 1984
c. Includes July 1980

Figure 82. *Comparison of gaged freshwater volume for the Pearl River at Bogalusa, LA, and the Amite River near Denham Springs, LA, during periods of salinity depiction to period-of-record averages* *



Abbreviation: m3/s - cubic meters per second
* Percentage of watershed reflected by USGS gages is unknown

Figure 83. *Surface salinities during low- and high-salinity periods*

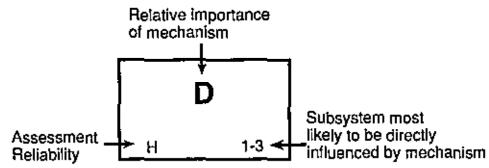


a. Data Sources: Gulf Coast Research Lab, 1991; LDEQ, 1991; LDHHR, 1991; LDWF, 1991
b. Data Sources: LDEQ, 1991; LDHHR, 1991; LDWF, 1991

Figure 84. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow			**D** H 1-3	**D** M 1-3	
Tides	**D** LIT 3				
Wind		**D** LIT 1-3	M LIT 1-3		
Density Currents			**S** LIT 3		
Shelf Processes		**S** LIT 1-3			
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 83 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

Months-Seasons. Dominant influence on salinity structure. Reduced salinities in Lakes Pontchartrain and Borgne maintained by basin discharges and by the influence of Pearl River on shelf salinities.

Year-Year. Dominant influence on salinity structure. Increased inflow may produce freshwater conditions throughout Lake Pontchartrain (Swenson, 1980a).

Tides

Hours. Dominant influence on salinity structure in Chandeleur Sound. Tidal phasing at Chandeleur Islands produces north-south currents through Chandeleur Sound (Hart, 1976).

Wind

Days-Weeks. Wind events with a strong east-west component, especially cold fronts, have a dominant effect on estuarine water levels and salinity (Chuang and Swenson, 1981; Schroeder et al., 1985; Gael, 1980). Cold fronts move over the estuary most frequently from December through February, with a frequency of approximately 6/month (Baumann, 1987). Winds exceeding 3 m/s predominate over tides in the estuary (Swenson, 1980a).

Months-Seasons. Minor influence on salinity structure, but an important force on driving circulation in the system.

Density Currents

Months-Seasons. Secondary influence on salinity structure. Density currents in the MRGO convey high-salinity waters into the upper reaches of the estuary (Dugas, 1979). Construction of the MRGO and other navigation channels connecting Lake Pontchartrain and Lake Borgne with the saline waters of Mississippi and Breton Sounds has undoubtedly increased average salinities in these areas (Fagerburg, 1990; Hawes and Perry, 1978; Sikora and Kjerfve, 1985).

Shelf Processes

Days-Weeks. Secondary influence on the salinity structure throughout the estuary.

* Data Sources: See data sources listed in Appendix II for Louisiana.

Geographic Setting

The Breton Sound estuary is in the Mississippi River deltaic plain between Lakes Pontchartrain and Borgne, and the Mississippi River systems. The estuary's boundaries are defined by the Mississippi River levees to the west and south, the Violet Canal to the north, and the Mississippi River Gulf Outlet (MRGO) to the east (Figure 85). Its seaward boundary is defined along a transect from Breton Island to Grand Bay. The upper estuary consists of tidal marshes separated by tidal creeks, bayous, and shallow lakes. Bayou Terre aux Boeufs and River aux Chenes are the major streams in the basin; Lake Lery, Big Mar, and Grand Lake are major inland waterbodies. Breton Sound encompasses most of the lower estuary, although numerous bays are present along the marsh-sound interface (i.e., Black Bay, American Bay, California Bay, Bay Gardene, Bay Crabe, Quarantine Bay, and Grand Bay).

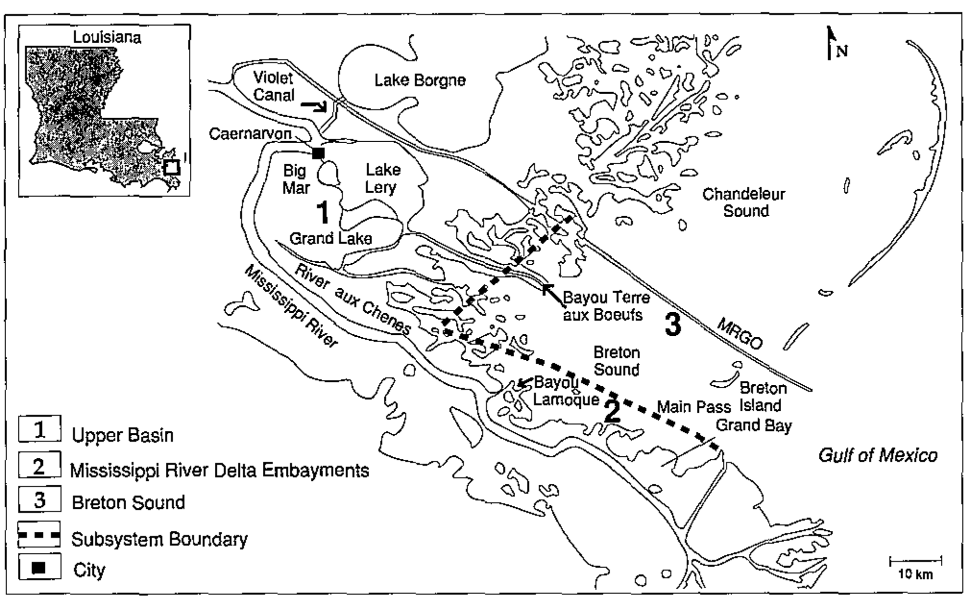
Historically, the estuary received freshwater from over-bank flooding of the Mississippi River. Construction of the Mississippi River levees in the 1930s restricted inflow into the upper estuary and converted it to a precipitation-dominated system. However, a substantial amount of freshwater is provided to the lower estuary by several diversion structures and through numerous breaks in the lower Mississippi River levees (USACE, 1984b). Bayou Lamoque, for example, conveys approximately 1% of the annual flow of the Mississippi River into Breton Sound (USACE, 1984b). A second diversion structure, originating at Caernarvon and extending through Big Mar and Lake Lery, was completed in 1991. Its purpose was to moderate salinities in Breton Sound and adjacent marshes during periods of high salinity by diverting Mississippi River water into the estuary. As a result, salinities will not exceed a predetermined level under most conditions. In addition, the Pearl River plume may be an important freshwater source to Breton Sound under certain hydrodynamic conditions.

Tidal exchange occurs near Breton Island and through the MRGO. This estuary is influenced by net north-to-south circulation through Chandeleur Sound, the result of tidal phasing around the Chandeleur Islands (Hart, 1976). This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 85).

Bathymetry

The average depth of the upper basin is less than 1 m at mid-tide level, while the open bay increases from 1 m near the upper basin to about 7 m near Breton Island (Figure 86) (NOAA, 1990a). The MRGO is the deepest area of the estuary and is often highly stratified (Gagliano et al., 1973). Its construction disrupted the hydrology of the estuary and is responsible for increased salinity, especially within the upper basin (Dugas, 1979; Rounsefell, 1964). Exchanges across the MRGO are often reduced by adjacent dredged material disposal areas.

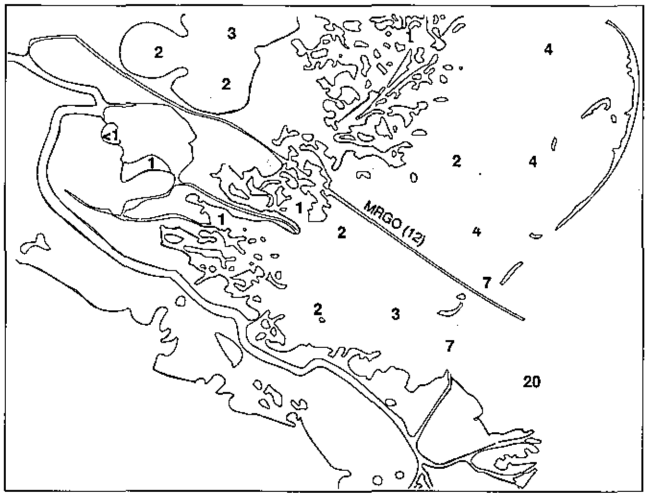
Figure 85. *Location map and subsystem identification*



Salinity Patterns

The Data. September-November 1982 and March-May 1987 were selected to represent high- and low-salinity periods, respectively. These periods do not include any alteration of the salinity structure associated with the completion of the Caernarvon diversion in 1991. A summary of freshwater inflow condi-

Figure 86. *Bathymetry (meters)*



tions and salinity data for these periods is given in Figure 87. Freshwater statistics reflect Mississippi River inflow gaged at Vicksburg, MS and basin runoff determined by the Thornwaite Water Budget (LOSC, 1989). Mississippi River flows are used as a proxy indicator of advective exchange of diluted shelf water, not as a direct inflow to the estuary. Figure 88 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that both periods experienced relatively typical inflow conditions. Figure 89 presents salinity distributions for these selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure, particularly in the lower estuary. This structure, however, experiences variability as indicated in Figure 90.

High-Inflow/Low-Salinity Period (March-May 1987). During this selected period and including February 1987, total inflow from Mississippi River was approximately 10% below the long-term averages (Figures 87 and 88). Mississippi River discharge averaged 14,000 m^3/s during February, then rapidly increased to a peak of 27,600 m^3/s in mid-March. Inflow steadily declined to less than 10,000 m^3/s by the end of the period, but was interrupted by a modest freshet (20,000 m^3/s) in late April. Precipitation measured at Boothville and St. Bernard occurred consistently throughout the period, except for a relatively dry period in April. Inflow from the Pearl River was above the long-term average during February-March but was lower than average from April-May.

Salinity patterns in the upper basin were most responsive to precipitation, whereas Mississippi River inflows influenced salinities within the embayments along the delta. In the upper basin, salinities generally remained between 5-10 ppt, were very stable, and were infrequently stratified. The delta embayments averaged 5-10 ppt and were unstable. Salinities were particularly low east of Bayou Lamoque (<5 ppt) and in Grand Bay (<2 ppt). Because salinity data for Breton Sound were limited, isohalines were based on salinities of the embayments adjoining the sound.

Low-Inflow/High-Salinity Period (September-November 1982). During this selected period and including August 1982, total inflow from Mississippi River was consistent with long-term averages (Figures 87 and 88). Mississippi River inflows peaked at 12,700 m^3/s in early August, then generally remained between 7,500-10,000 m^3/s during the remainder of the period. Secondary peaks of 11,400 m^3/s were recorded in mid-September and late November. Precipitation was greatest in mid-September and late November. Little or no rainfall was recorded from mid-October to early November. Pearl River inflows were above average in August and September, near the long-term average in October, and below average in November.

Salinities averaged 5-10 ppt higher than during the low-salinity period (Figure 89). Salinities were generally lowest in September and highest in November, except in the delta embayments where they were highly variable. Salinity patterns in the upper basin were again most responsive to precipitation; salinities were stable and averaged 10-15 ppt. Breton Sound salinities were also relatively stable and averaged 20-25 ppt. Salinities in the delta embayments were suppressed relative to Breton Sound, although fluctuations were not coincident with either periods of increased Mississippi River inflows or heavy precipitation. Stratification was uncommon, except in the delta region where waters were occasionally highly stratified.

Factors Affecting Variability

The salinity structure is determined by the seasonal freshwater discharge, although the dominant freshwater source is different for the upper basin and most portions of Breton Sound than within embayments near the Mississippi River Delta. Salinities in these embayments are most influenced by seasonal discharge diversions from the Mississippi River, whereas the remaining estuary is usually regulated by local precipitation. Throughout the estuary, salinities are generally lowest during March-

May when precipitation and river discharges are high. Salinities usually peak from September-November, when local precipitation and river discharge are low, evaporation is high, Gulf water levels are high, and currents and winds favor onshore transport of high-salinity Gulf waters. Salinities were relatively stable in the upper estuary and Breton Sound, whereas those near the Mississippi River Delta were quite variable. Stratification was uncommon in most of the estuary; it was most frequently observed within the MRGO and embayments of the Mississippi River Delta during the low-inflow period.

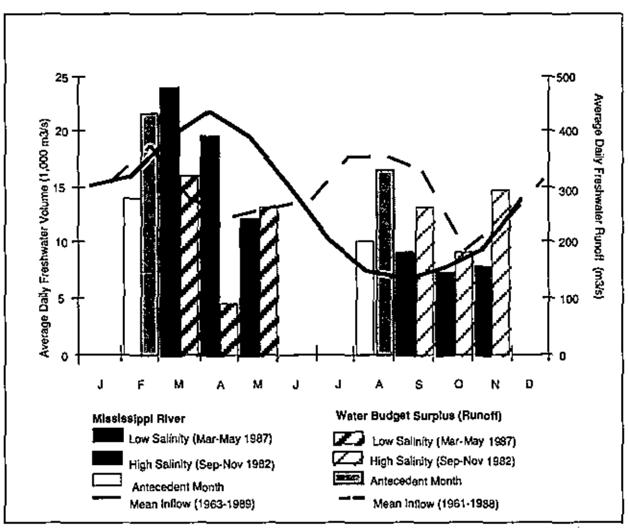
The important time scales of salinity variability and responsible mechanisms are summarized in Figure 90. The most significant variation is attributable to frontal passages, local precipitation, shelf processes (i.e., Pearl River), and density currents.

Figure 87. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	March-May 1987 (High Inflow/Low Salinity)	September-November 1982 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	415	432
Sampling Distribution [a]	1-2	1-2
Sampling Frequency	weekly - monthly	weekly - monthly
Average Salinity (ppt)	8.6	15.0
Bottom Salinity		
# of Observations	73	64
Sampling Distribution [a]	1-2	1-2
Sampling Frequency	weekly - monthly	weekly - monthly
Average Salinity (ppt)	11.2	18.8
Freshwater Inflow		
Mississippi River Volume	10% below average [b]	average [c]
Water Budget Surplus (Runoff)	5% below average [b]	average [c]
Return Frequency of Peak Events		
1-day duration	2.1-year	1.8-year
7-day duration	2.1-year	2.0-year
30-day duration	2.1-year	2.2-year

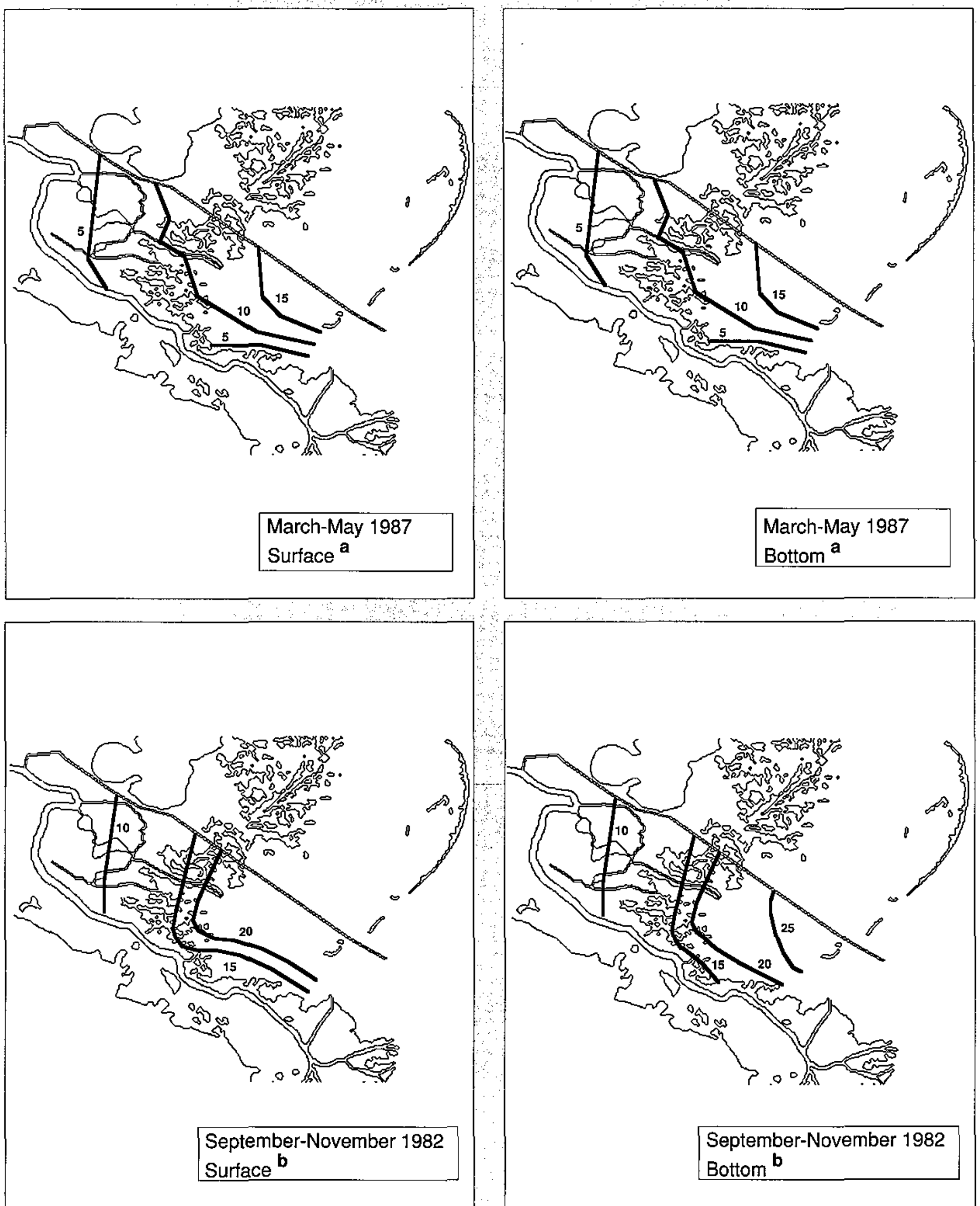
Abbreviation: ppt - parts per thousand
a. Subsystem(s) with high sampling density
b. Includes February 1987
c. Includes August 1982

Figure 88. *Comparison of gaged freshwater volume for the Mississippi River at Tarbert Landing, MS and estimated basin runoff during periods of salinity depiction to period-of-record averages* *



Abbreviation: m3/s - cubic meters per second
* Determined by the Thornwaite Water Budget (LOSC, 1989)

Figure 89. *Surface and bottom salinities during low- and high-salinity periods*

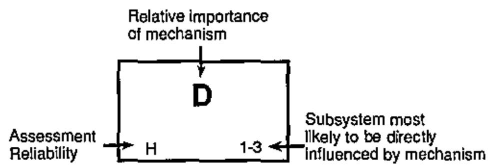


a. Data Sources: LDHHR, 1991; LDWF, 1991
b. Data Sources: LDHHR, 1991; LDWF, 1991

Figure 90. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S (M 1)	D (M 1)	M (M 1)	
Tides	D (LIT 2)				
Wind		S (LIT 2)	M (LIT 2)		
Density Currents			M (LIT 1-2)		
Shelf Processes		S (LIT 2)			
Effect on Salinity Variability	UNKNOWN	LOW	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 89 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, short-term modification of salinity structure in the upper basin.

Months-Seasons. Dominant influence on salinity structure. Precipitation events and Mississippi River discharges produce salinities 5-10 ppt lower in March-May than during September-November. Precipitation dominates the upper basin and the Mississippi River dominates delta embayments.

Year-Year. Minor influence on estuary-wide salinity structure, but most important in the Mississippi River Delta embayments.

Tides

Hours. Dominant influence on salinity structure in the lower estuary. Tidal phasing at Chandeleur Islands produces north-to-south currents through Chandeleur Sound with indirect effects on Breton Sound (Hart, 1976).

Wind

Days-Weeks. Secondary influence on salinity structure throughout the estuary. About 15-20 cold fronts occur during November-March and may reverse prevailing north-to-south circulation through this estuary (Hart, 1976; Schroeder et al., 1985; USACE, 1984b). Winds inhibit vertical stratification under most conditions.

Months-Seasons. Minor influence on salinity structure. Prevailing southerly and easterly winds induce entrainment of Gulf waters between spring and fall. Prevailing northerly winds may enhance vertical stratification near MRGO.

Density Currents

Months-Seasons. Minor influence on the salinity structure near MRGO. MRGO facilitates saltwater intrusion into the upper reaches of the estuary. Vertical stratification may occur during periods of high Pearl River discharge and northerly winds.

Shelf Processes

Days-Weeks. Secondary, short-term modification of salinity structure within Breton Sound during increased Pearl River discharges and strong northerly winds.

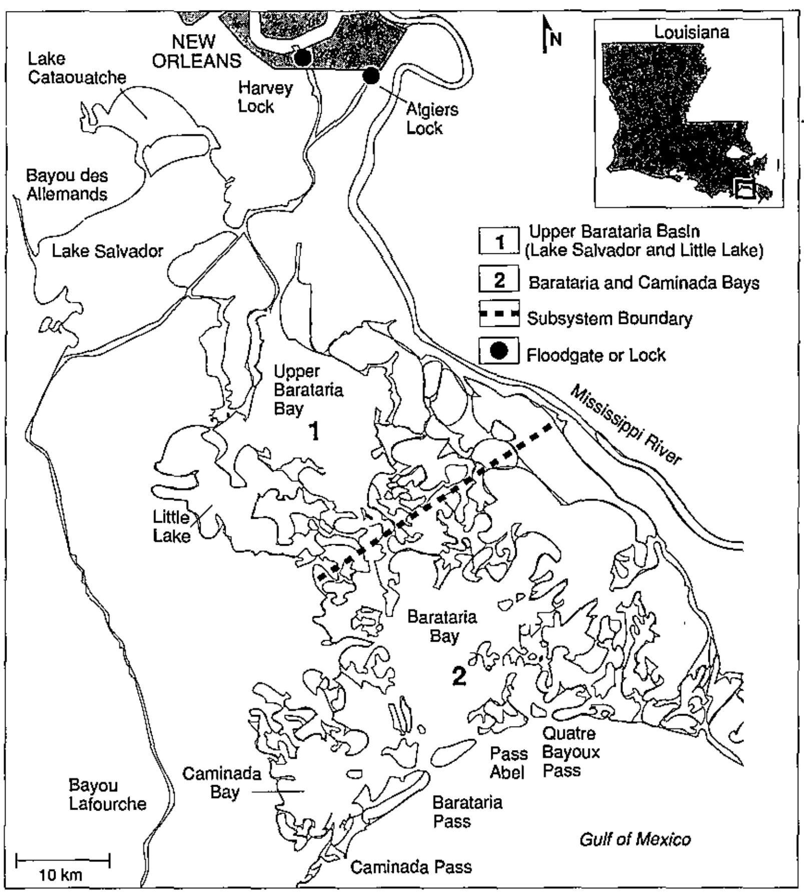
* Data Sources: See data sources listed in Appendix II for Louisiana.

Geographic Setting

The Barataria Bay estuary is an interdistributary estuarine-wetland system of the Mississippi River deltaic plain. Its boundaries consist of the Mississippi River on the east and the Bayou Lafourche on the west (Conner and Day, 1987) (Figure 91). The inland boundary is defined from the head of tide on Bayou des Allemands at des Allemands (Byrne et al., 1976). Caminada and Barataria Bays occupy most of the lower estuary and form a shallow, wide area of open water interspersed with numerous marsh islands. The upper estuary is composed of tidal marshes separated by tidal creeks, bayous, ponds, and shallow lakes.

Historically, this estuary received most of its freshwater inflow from over-bank flooding of the Mississippi River and Bayou Lafourche, a major distributary of the Mississippi. Construction of the Bayou Lafourche dam in 1904 and the Mississippi River levees in the 1930s restricted inflow to the upper estuary, so that only minor discharges occur today through the Harvey and Algiers locks. Although salinity in the lower estuary is still greatly influenced by Mississippi River water entering from the Gulf, the upper estuary was changed from a system dominated by seasonal over-bank flooding to one dominated by local precipitation. Most tidal exchange (66%) occurs through Barataria Pass; the remainder occurs through Quatre Bayoux Pass (18%), Caminada Pass (13%), and Pass Abel (3%) (Marmer, 1948). The estuary has been divided into two subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 91).

Figure 91. *Location map and subsystem identification*



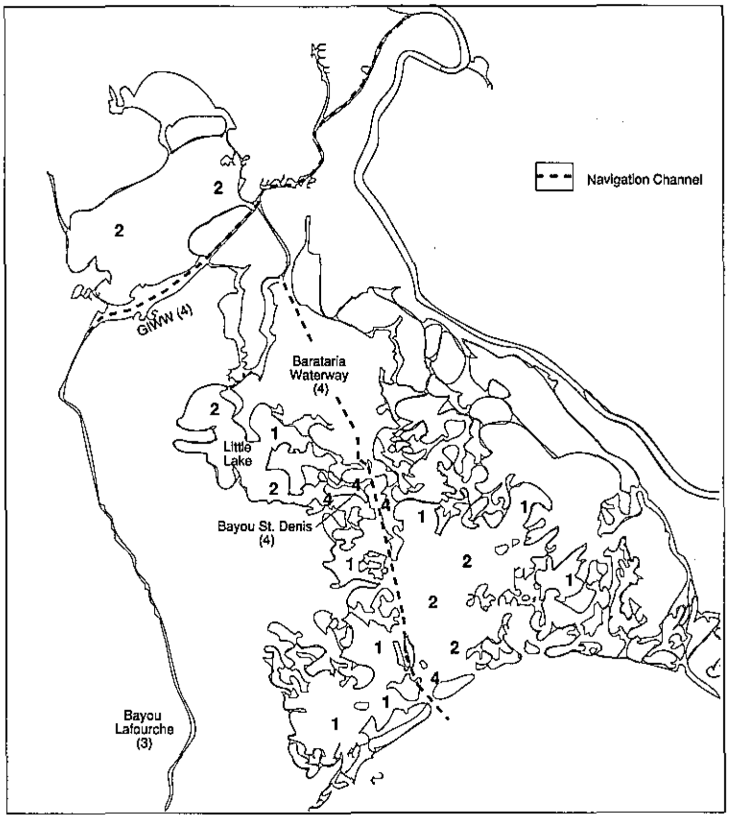
Bathymetry

The depth of open water areas within the estuary is relatively uniform and averages 2 m at mid-tide level (NOAA, 1990a). Naturally deep areas exist within Bayou St. Denis and the inlets (Figure 92). The Barataria Waterway and GIWW are the major navigation channels. An extensive network of smaller navigation, oil field, and drainage canals exists throughout the basin and has significantly altered the estuary's hydrology. Channels and deep areas of the bay are generally more saline and vertically stratified than adjacent areas.

Salinity Patterns

The Data. September-November 1978 and April-June 1978 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions as no major modifications to the estuary or its watershed have occurred since the construction of the Barataria Waterway in 1963. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 93. Freshwater statistics reflect Mississippi River inflows gaged at Vicksburg, MS and basin runoff determined by the Thornwaite Water Budget (LOSC, 1989). Mississippi River flows are used as a proxy indicator of advective exchange of diluted shelf water, not as a direct inflow to the estuary. Figure 94 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that both periods experienced relatively typical inflow conditions. Figure 95 presents salinity distributions for the selected periods, illustrating the dominance of seasonal

Figure 92. *Bathymetry (meters)*



freshwater discharge on the salinity structure of the lower estuary. This structure, however, experiences variability as indicated in Figure 96.

The low-salinity period does not represent the lowest salinity period for the entire estuary since the timing of freshwater and method of delivery to the two areas do not coincide. The lowest salinities in the upper bay actually occur during December-February, a period of increased rainfall and runoff. Freshwater from the Mississippi River advected into the estuary by near-shore circulation patterns during the spring greatly influences salinities in the lower estuary. Because it was desirable to capture the more pronounced variability associated with salinity in the lower bay during the low-salinity period, a simultaneous assessment of the upper bay is presented. However, salinities for the upper estuary during this period are probably higher than average winter salinities.

High-Inflow/Low-Salinity Period (April-June 1978). During this selected period and including March 1978, total inflow from the Mississippi River was approximately 10% above long-term averages (Figures 93 and 94). Mississippi River discharge rapidly increased from 12,000 m^3/s in early March to 38,000 m^3/s in early April. Discharge decreased to 23,000 m^3/s in early May before reaching 30,000 m^3/s in late May. Flow returned to about 12,000 m^3/s by late June. Precipitation, measured at New Orleans, Boothville, and Paradis, LA occurred throughout the period, but its frequency was greatest in June. The highest 1-day precipitation event occurred May 3 when more than 15 cm of rainfall was recorded at both New Orleans and Paradis.

Salinities in the lower estuary (Barataria and Caminada Bays) generally decreased when the Mississippi River inflow increased. The timing of this response in lower Barataria Bay coincided with discharges, but lagged by two weeks in upper Barataria Bay. Salinities were most variable near the Barataria waterway and the inlets. This estuary generally remained vertically homogeneous, but occasionally exhibited weak vertical stratification. Moderate stratification occurred near the passes during the Mississippi River's peak discharges.

Salinities in the upper estuary did not seem to respond to changes in the Mississippi River discharge, but were more closely related to precipitation. Salinities upstream of Little Lake were stable and remained less than 2 ppt; however, Little Lake salinities were more variable. Vertical stratification was uncommon, but surface-to-bottom differences of 2 ppt occasionally occurred.

Low-Inflow/High-Salinity Period (September-November 1978). During this selected period and including August 1978, total inflow from the Mississippi River was consistent with long-term averages (Figures 93 and 94). Mississippi River discharge remained between 8,500 and 12,500 m^3/s during August and September. Discharge increased to 16,000 m^3/s by late October before falling to 11,000 m^3/s in early November. Flows steadily increased to 20,000 m^3/s by late November. Precipitation was most frequent in August and September. Very little precipitation was recorded in October and early November, although heavy rainfall was recorded in late November at Paradis and Boothville.

Throughout the estuary, the lowest salinities were recorded in September and early October; highest salinities occurred in November. Salinities were more related to local precipitation than Mississippi River discharges. Saline water intrusion increased in the lower estuary and was detectable (1-2 ppt) in central Lake Salvador. Surface salinities in the lower estuary were approximately 5 ppt greater during this period than during the low-salinity period; salinities in the upper estuary were relatively unchanged. Stratification was seldom observed, although weak stratification occasionally occurred. Moderate stratification was infrequently observed in eastern Barataria Bay and near the Barataria Waterway. Although salinities remained relatively unstable below Little Lake, the estuary was less variable during this period than during the low-salinity period.

Factors Affecting Variability

Salinity structure is determined by the seasonal freshwater discharge, although the freshwater source and timing of delivery differ for the upper and lower portion of the estuary. The lowest salinities occur in the lower estuary from April-June and are related to the advection of inflow from the Mississippi River and the seasonal water-level cycle (Byrne et al., 1976; Baumann, 1987). However, this signal is weakened during the low-inflow period of the Mississippi River when local precipitation becomes more significant. In the upper estuary, the lowest salinities occur from December-February due to seasonal precipitation. Salinity reductions in the lower estuary (i.e., Barataria Bay) caused by advected river water are of greater magnitude, occur later in the spring, and than decreases in the upper estuary due to local precipitation (Baumann, 1987).

Because Barataria Bay is so shallow, winds and tides prevent salinity stratification under most conditions. Stratification was seldom observed during the two periods depicted in this study. However, stratification may occur in the deeper portions of the estuary, especially in major navigation channels and tidal passes. Circumstances most likely to produce stratification are: (1) advection of Mississippi River water into the estuary during high-river discharge; and (2) persistent northerly winds, accompanied by little or no precipitation, that push freshwater stored in the upper estuary into the lower estuary (Barrett, 1971; Baumann, 1987).

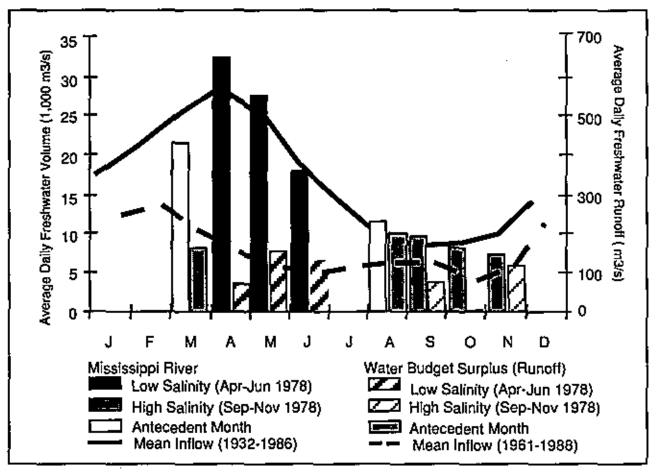
The important time scales of salinity variability and responsible mechanisms are summarized in Figure 96. The most significant variation is attributable to local precipitation and frontal passages. Precipitation is most important during periods of reduced Mississippi River discharge. Astronomical tides produce minor variability in the lower estuary, although their effect may be enhanced by prevailing winds.

Figure 93. Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods

	April-June 1978 (High Inflow/Low Salinity)	September-November 1978 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	159	115
Sampling Distribution [a]	2	2
Sampling Frequency	weekly - monthly	weekly - monthly
Average Salinity (ppt)	13.5	16.6
Bottom Salinity		
# of Observations	145	106
Sampling Distribution [a]	2	2
Sampling Frequency	weekly - monthly	weekly - monthly
Average Salinity (ppt)	13.5	16.6
Freshwater Inflow		
Mississippi River Volume	10% below average [b]	average [c]
Water Budget Surplus (Runoff)	average [b]	40% below average [c]
Return Frequency of Peak Events		
1-day duration	3.0-year	6.0-year
7-day duration	3.0-year	1.8-year
30-day duration	2.3-year	2.0-year

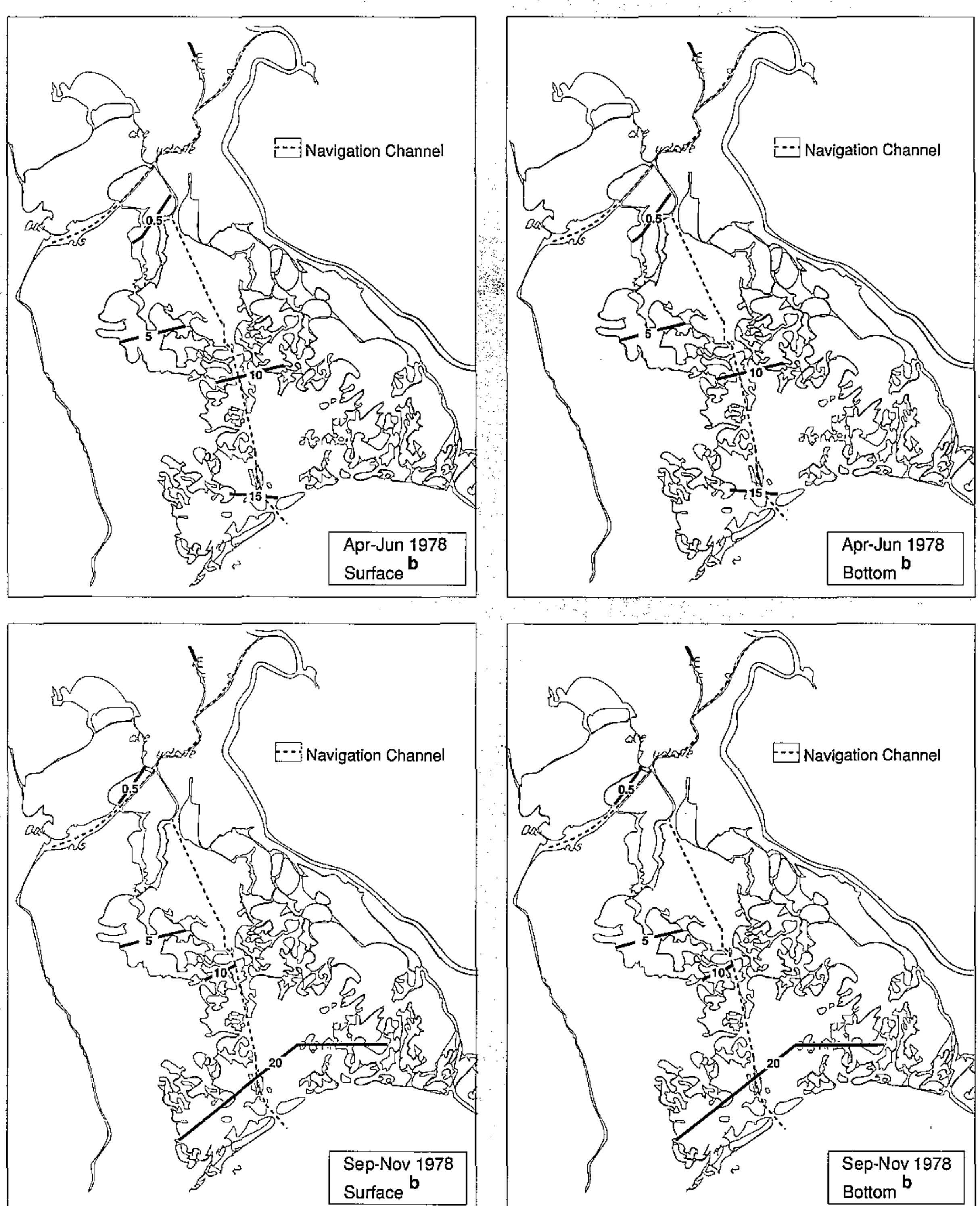
Abbreviation: ppt - parts per thousand
a. Subsystem(s) with high sampling density
b. Includes March 1978
c. Includes August 1978

*Figure 94. Comparison of gaged freshwater volume for the Mississippi River at Vicksburg, MS and estimated basin runoff during periods of salinity depiction to period-of-record averages **



Abbreviation: m3/s - cubic meters per second
*Determined by the Thornwaite Water Budget (LOSC, 1989)

Figure 95. *Surface and bottom salinities during low- and high-salinity periods*

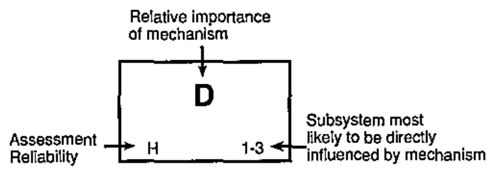


a. Data Source: LDWF, 1991
b. Data Source: LDWF, 1991

Figure 96. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		**S** M 1	**S** H 1	**S** M 1	
Tides		**M** LIT 2			
Wind		**S** LIT 2	**M** LIT 2		
Density Currents			**M** LIT 1-2		
Shelf Processes			**D** LIT 2	**S** 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 95 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, short-term modification of salinity structure.

Months-Seasons. Secondary influence on salinity structure, but more important during periods of low Mississippi River inflow.

Year-Year. Secondary influence on estuary-wide salinity structure, but most important in upper Barataria Bay.

Tides

Days-Weeks. Minor, short-term alteration of salinity structure in the lower estuary.

Wind

Days-Weeks. Secondary, short-term alteration of salinity structure throughout the estuary. Cold fronts average six per month during December-February (Baumann, 1987). Winds inhibit vertical stratification under most conditions.

Months-Seasons. Minor influence on salinity structure. Prevailing southerly and easterly winds induce entrainment of Gulf waters from spring-fall. Prevailing northerly winds may enhance vertical stratification.

Density Currents

Months-Seasons. Minor influence on salinity structure near Barataria Waterway. Density currents enhance vertical stratification during periods of high Mississippi River discharge.

Shelf Processes

Months-Seasons. Dominant influence on salinity structure during high Mississippi River inflow (spring-summer), but less influential during low-inflow periods. This influence is more apparent in the open bay than in the upper basin.

Year-Year. Secondary influence on salinity structure.

* Data Sources: See data sources listed in Appendix II for Louisiana.

Geographic Setting

The Terrebonne/Timbalier Bays estuary is a major interdistributary basin within the Mississippi River Deltaic plain. Occupying 1,760 km² (NOAA, 1990a), it is bounded on the east by the natural levees of Bayou Lafourche; the Bayou du Large drainage basin forms its western boundary (Figure 97). The upper estuary is composed of tidal marshes separated by tidal creeks, bayous, ponds, and shallow lakes. The estuary extends seaward from the heads of tide on Bayou Terrebonne approximately 1 km north of Point Barre, on Bayou Pointe au Chien 7 km south of its confluence with Bayou Terrebonne, on Bayou Grand Caillou 1 km north of Lake Boudreaux, and on Bayou Penchant 6 km south of its confluence with Bayou Copasaw (USFWS, 1982c). However, head of tide locations are inconsistent with available salinity data used in this study, suggesting that tidal influence extends further inland (Figure 101).

Historically, this estuary received most of its freshwater inflow from over-bank flooding of Bayou Lafourche and its major distributary, Bayou Terrebonne. Construction of the Bayou Lafourche dam in 1904 and Mississippi River levees in the 1930s restricted inflow to the upper estuary and converted it to a precipitation-dominated system. Most basin runoff is channeled to coastal wetlands and small embayments near the Houma Navigation Canal (HNC) in upper Terrebonne Bay (Figure 98). The lower estuary, however, continues to receive a substantial amount of freshwater from the Mississippi River each spring and summer when nearshore water diluted by river water is advected into the estuary (Dinnel and Wiseman, 1986; Wiseman et al., 1982). Wiseman et al. (1990b) demonstrated that Mississippi River discharge could account for 30-50% of the explained variance in weekly mean salinity at two locations within the estuary (Cocodrie and Caillou Lake). The lower estuary may also receive periodic freshwater fluxes across Bayou du Large during flooding of the Atchafalaya River. Most tidal exchange occurs through Little Pass Timbalier, Cat Island Pass, Wine Island Pass, and Whiskey Pass. Limited tidal exchange occurs through several narrower passes. This estuary has been divided into four subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 97).

Bathymetry

The depth of open water areas within the estuary is relatively uniform, averaging less than 2 m at mid-tide level (Figure 98) (NOAA, 1990a). Naturally deep areas exist within Terrebonne Bay and in the passes connecting Caillou Bay with Caillou Lake and Lake Pelto.

The HNC, which connects Terrebonne Bay with the GIWW near Houma, is the major navigation channel (Figure 98). Because the HNC is deep relative to the estuary, its construction has facilitated saltwater intrusion into the basin and it has been blamed for causing salinity concentrations near Houma to double (Bahr et al., 1983; Gagliano et al., 1973).

Figure 97. Location map and subsystem identification

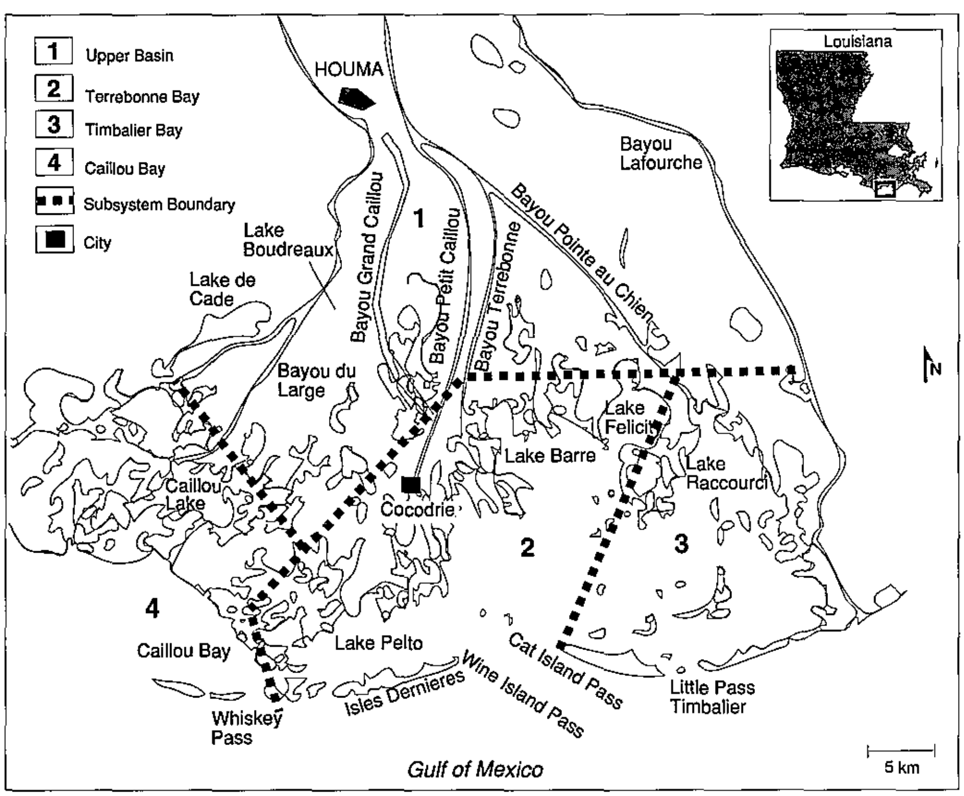
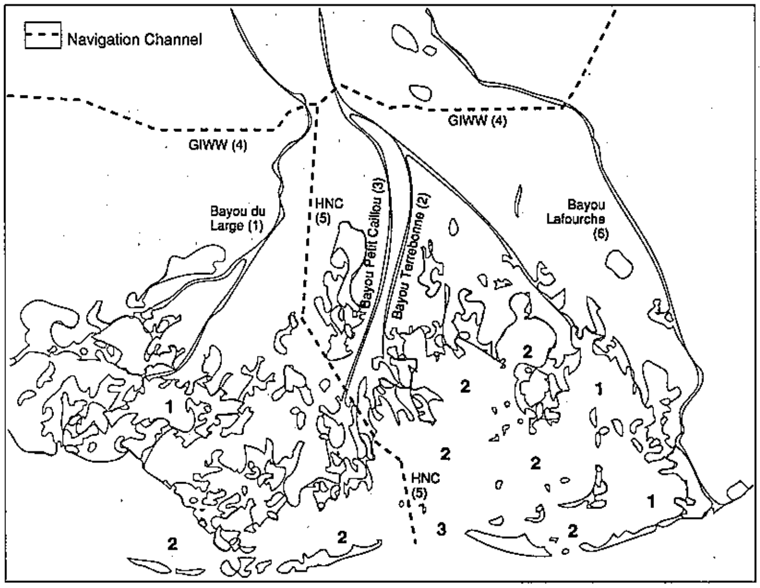


Figure 98. *Bathymetry (meters)*



Vertical stratification is most often exhibited in the HNC, but diminishes as inflow increases (Wang, 1988). Other important bathymetric features include the GIWW, and Bayou Petit Caillou. These channels, along with numerous smaller navigation, oil field, and drainage canals, have significantly modified the natural hydrology of the basin.

Salinity Patterns

The Data. September-November 1983 and January-March 1984 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions as no major modifications have occurred to this estuary or its watershed since the dredging of the HNC in 1962 and Bayou Lafourche in 1968. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 99. Freshwater statistics reflect Mississippi River inflows gaged at Tarbert Landing, MS and basin runoff determined by the Thornwaite Water Budget (LOSC, 1989). Mississippi River flows are used as a proxy indicator of advective exchange of diluted shelf water, not as a direct inflow to the estuary. Figure 100 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that both periods experienced typical inflow conditions. Figure 101 presents salinity distributions for the selected periods, illustrating modest differences of the salinity structure in the lower estuary between these two seasons. Although bottom salinity data were extremely limited, the estuary is very shallow and often experiences little or no vertical stratification except in the HNC and at tidal passes. Therefore, bottom salinities probably closely resemble the surface layer. The salinity structure experiences variability as indicated in Figure 102.

High-Inflow/Low-Salinity Period (January-March 1984). During this selected period and including December 1983, total inflow from the Mississippi River was approximately 15% above long-term averages (Figures 99 and 100). Mississippi River discharge peaked near 40,000 m^3/s in mid-December, but rapidly fell to 21,000 m^3/s by January. Inflows were below 17,000 m^3/s through mid-February, then steadily increased to almost 34,000 m^3/s by late March. Precipitation recorded at Houma was infrequent but intense during late December, February, and March. Frequent, low-magnitude rainfall occurred in January.

The lowest salinities occurred during January in Timbalier Bay, during February in Terrebonne Bay, and during March in Caillou Bay. The latter was probably the result of increased flows from the Atchafalaya River. In the lower estuary, average salinities generally decreased from east to west, but variability increased. The most stable conditions occurred in upper Timbalier Bay and Lake Raccourci; the most variable conditions occurred in lower Terrebonne Bay and Caillou Bay. Bottom salinity data was limited but indicated vertically homogeneous conditions, except for infrequent weak-to-moderate stratification at the passes.

Low-Inflow/High-Salinity Period (September-November 1983). During this selected period and including August 1983, total inflow from the Mississippi River was 10% below long-term averages (Figures 99 and 100). Mississippi River discharge steadily decreased from 13,000 m^3/s in early August to near 5,700 m^3/s in late September. Flow remained between 5,700 and 11,300 m^3/s from October to mid-November. Flows peaked at 17,000 m^3/s during late November. Most rainfall occurred in early August, early September, and late November. Salinities were generally lowest in early September, highest in October, and reduced in late November.

Average salinities were approximately 5 ppt higher than during the low-salinity period. Salinities were lowest in upper Terrebonne and Timbalier Bays, and in Caillou Bay, but highest near the passes and in lower Terrebonne Bay. Salinities were most stable in Timbalier Bay and most variable in Caillou Bay. Salinities in northwest Terrebonne Bay were very responsive to local precipitation, but this trend was not apparent in Timbalier Bay. Bottom salinity data was limited but indicated vertically homogeneous conditions.

Factors Affecting Variability

The salinity structure is determined by the seasonal freshwater discharge, although the source differs for the upper and lower portions of the estuary. Lowest salinities in the lower estuary are related to the advection of inflow from the Mississippi River. However, this signal is weakened during the low-inflow period of the Mississippi River when local precipitation becomes more significant. The lowest salinities in the upper estuary are related to seasonal precipitation. Because advection of Mississippi River water to the lower estuary occurs when freshwater input from precipitation is low (i.e., late spring and summer), the river's effect on estuary-wide salinities at this time is diminished. The lowest estuary-wide salinities occur in late winter and early spring when high precipitation coincides with high Mississippi River inflows. Because the estuary is shallow, winds and tides prevent salinity stratification under most conditions. Stratification was seldom observed during the two periods depicted in this study; however, stratification is likely to occur in the HNC and near tidal passes. Wang (1988) has shown that density currents are present in the HNC.

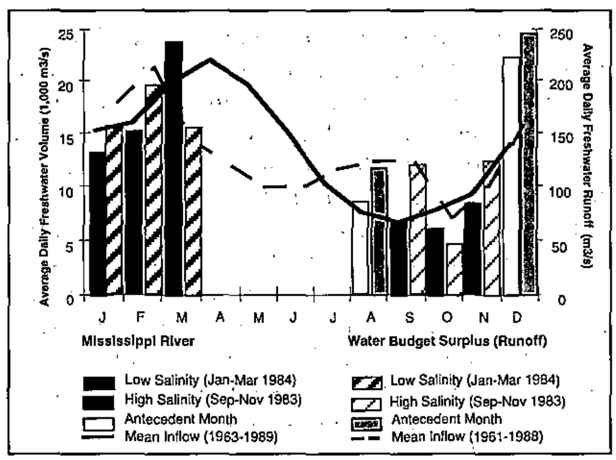
The important time scales of salinity variability and responsible mechanisms are summarized in Figure 102. The most significant variation is attributable to frontal passages, exchanges with the Atchafalaya basin, Mississippi River inflows, and local precipitation. The latter is most important during reduced Mississippi River discharges. Astronomical tides produce modest variability in the lower estuary, although its effect may be enhanced by prevailing winds.

Figure 99. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	January-March 1984 (High Inflow/Low Salinity)	September-November 1983 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	1,322	679
Sampling Distribution [a]	1,2,4	1,2,4
Sampling Frequency	weekly - monthly	weekly - monthly
Average Salinity (ppt)	8.5	15.3
Bottom Salinity		
# of Observations	18	2
Sampling Distribution [a]	4	4
Sampling Frequency	weekly - monthly	NA
Average Salinity (ppt)	13.7	15.7
Freshwater Inflow		
Mississippi River Volume	15% above average [b]	10% below average [c]
Water Budget Surplus (Runoff)	average [b]	10% below average [c]
Return Frequency of Peak Events		
1-day duration	1.8-year	2.5-year
7-day duration	1.8-year	2.8-year
30-day duration	3.0-year	1.5-year

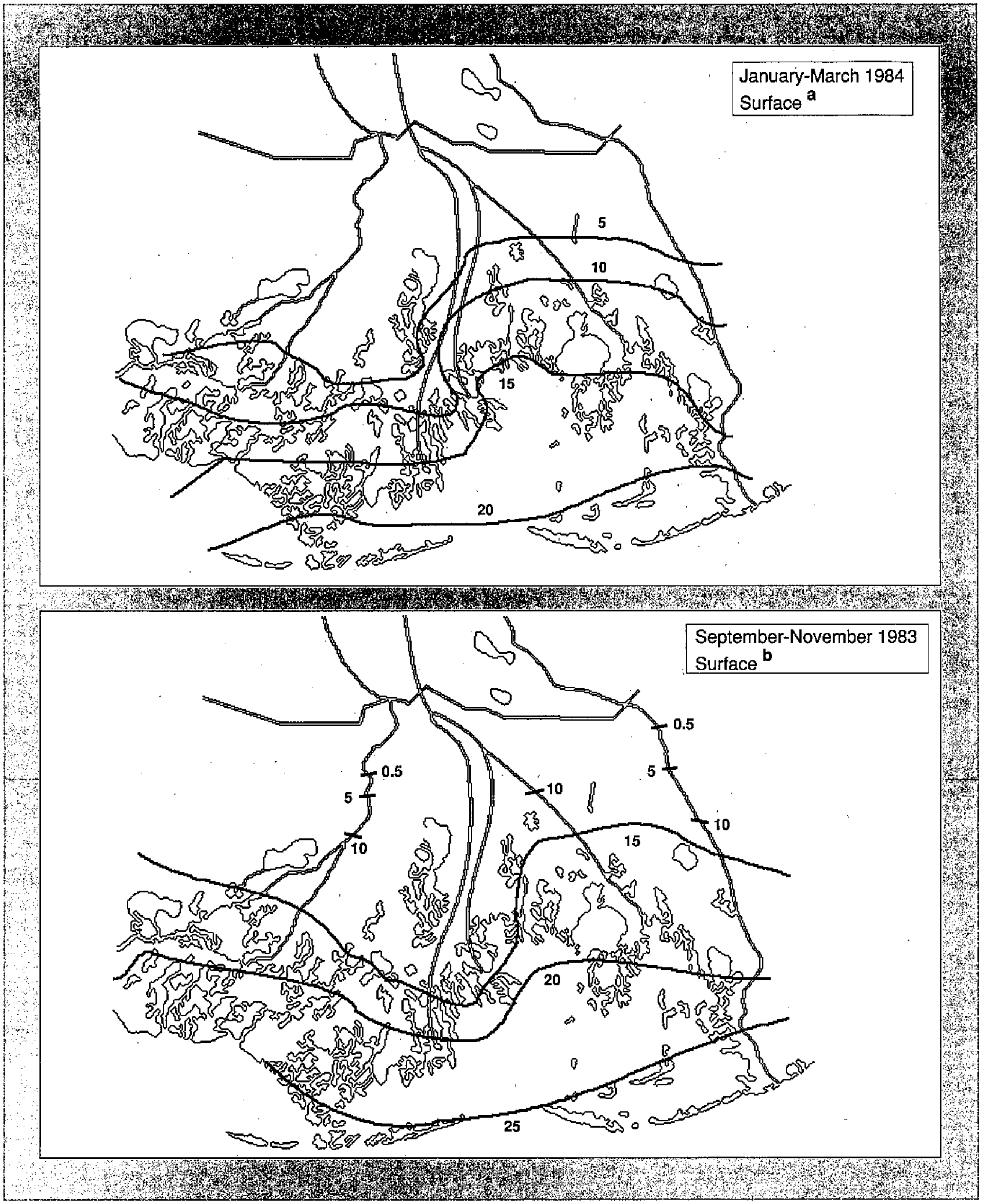
Abbreviation: ppt - parts per thousand
a. Subsystem(s) with high sampling density
b. Includes December 1983
c. Includes August 1983

Figure 100. *Comparison of gaged freshwater volume for the Mississippi River at Tarbert Landing, LA and estimated basin runoff during periods of salinity depiction to period-of-record averages*



Abbreviation: m3/s - cubic meters per second

Figure 101. *Surface salinities during low- and high-salinity periods*

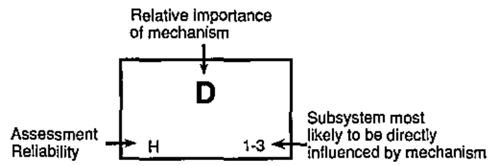


a. Data Sources: LDEQ, 1991; LDHHR, 1991; LDWF, 1991
b. Data Sources: LDEQ, 1991; LDHHR, 1991; LDWF, 1991

Figure 102. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		S (M 1)	S (H 1)	S (M 1)	
Tides		M (LIT 2-4)			
Wind		S (LIT 1-4)	M (LIT 2-4)		
Density Currents			M (LIT 1-2)		
Shelf Processes		M (LIT 2-4)	D (LIT 2-4)	S (LIT 2-4)	
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 101 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, short-term modification of salinity variability mainly at the interface between the open embayments and marshes of the upper estuary.

Months-Seasons: Secondary influence on the salinity structure, mainly at the interface between the open embayments and marshes of the upper estuary.

Year-Year: Secondary influence on the estuary-wide salinity structure, but most important in the upper basin.

Tides

Days-Weeks: Minor short-term alteration of salinity structure in the lower estuary.

Wind

Days-Weeks: Secondary short-term alteration of the salinity structure throughout the estuary. Cold fronts occur 15-20 times each winter (Leipper, 1954; USACE, 1984b). Winds inhibit stratification under most conditions.

Months-Seasons: Minor influence on the salinity structure. Prevailing southerly and easterly winds induce entrainment of Gulf waters from spring to fall.

Density Currents

Months-Seasons: Minor influence on the salinity structure, mainly at the interface between the open embayments and marshes near the HNC.

Shelf Processes

Days-Weeks: Minor influence on the salinity structure.

Months-Seasons: Dominant influence on the salinity structure. Mississippi and Atchafalaya River plumes decrease salinity of entrained shelf water usually from spring to summer. The effect is more apparent in open embayments than in the upper basin.

Year-Year: Secondary influence on the salinity structure (Wiseman et al., 1990b).

* Data Sources: See data sources listed in Appendix II for Louisiana.

Geographic Setting

The Atchafalaya/Vermilion Bays estuary is located between the Mermentau and Terrebonne/Timbalier systems and straddles the western boundary of the Mississippi River Deltaic Plain and the eastern edge of the Chenier Plain (Bahr et al., 1983). This estuary occupies 2,020 km^2 (NOAA, 1990a) and includes four major waterbodies, several bayous, locks, canals, and the Nation's third largest river system (Figure 103). Its boundaries consist of the head of tide on the Vermilion River at Abbeville, on the Atchafalaya River at its juncture with the GIWW, and on Wax Lake Outlet approximately 4 km south of the GIWW (Byrne, 1977). It is bordered by the Freshwater Bayou Canal to the west and the Bayou du Large basin to the east.

The Atchafalaya River is the primary freshwater source to the system, although the Vermilion River and Bayou Teche are important to Vermilion Bay and West Cote Blanche Bay, respectively. The Atchafalaya River conveys the entire flow of the Red River and 30% of diverted Mississippi River flow. Approximately 70% of this volume is discharged directly to Atchafalaya Bay, while 30% is diverted through the Wax Lake Outlet. Exchanges with Gulf waters occur through the Southwest Pass, along the southern boundaries of the East Cote Blanche and Atchafalaya Bays, and through several bayous east of Point au Fer Island. Gulf waters are frequently and severely diluted by the Atchafalaya River; the most saline Gulf waters enter the estuary through Southwest Pass (Juneau and Barrett, 1975). This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 103).

Bathymetry

The average depth of the estuary is 2 m at mid-tide level, although depths of the major bays differ (NOAA, 1990a). Active and nonliving oyster reefs create numerous shallow areas which affect circulation and salinity. Reefs located in Southwest Pass, south of Marsh Island, and at the entrances to Atchafalaya and East Cote Blanche Bays impede exchanges with the Gulf. Terrapin Reef constrains circulation between Vermilion and West Cote Blanche Bays (Dugas, 1970; Hoese, 1976). The deepest areas are found in the Atchafalaya River (15 m), Wax Lake Outlet (14 m), and at Southwest Pass (15 m), which contains a scour hole 46 m deep (Juneau and Barrett, 1975). Because sedimentation rates are high, the average depth of Atchafalaya Bay continues to decrease.

Other important bathymetric features having a dramatic effect on the estuary's hydrology include the GIWW, the Mississippi River levees, the tributaries flood-control project, and several locks and dams. Freshwater Bayou Canal locks restrict saltwater intrusion to the upper estuary (Figure 104). The Schooner Bayou Canal lock and dam, and the Vermilion lock limit exchanges with the Mermentau River estuary. A dam located near the mouth of Wax Lake Outlet diverts discharge through the Atchafalaya River. This outlet, however, carries flood waters (including those from Bayou Teche) during peak events (Wax et al., 1977).

Salinity Patterns

The Data. September-November 1975 and March-May 1985 were selected to represent high- and low-salinity periods, respectively. These periods should

Figure 103. *Location map and subsystem identification*

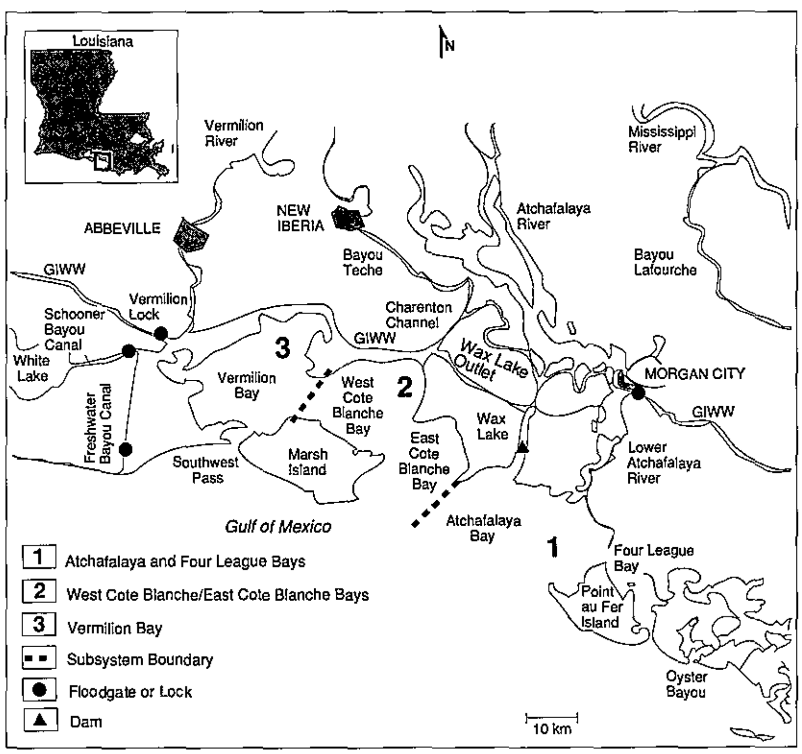
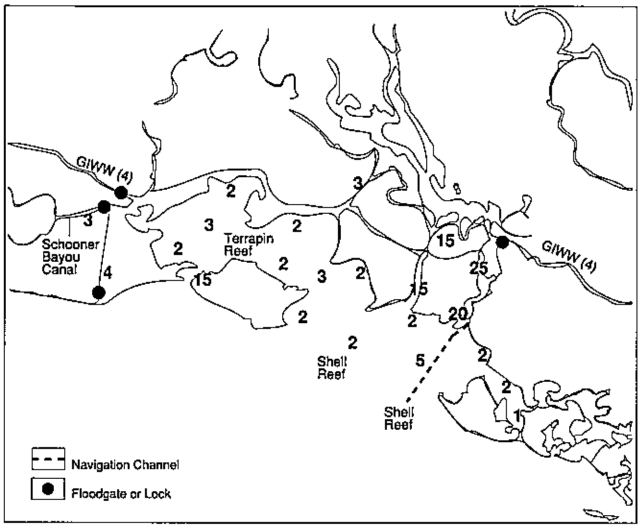


Figure 104. *Bathymetry (meters)*



reflect present-day conditions since no major modifications have occurred to the estuary or its watershed since the depth of Freshwater Bayou Canal was increased in 1968. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 105. Figure 106 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that September-November 1975 experienced relatively typical inflow conditions, while inflow during March-May 1985 was above average. Figure 107 presents salinity distributions for the selected periods, illustrating only subtle differences of the salinity structure between these two seasons. This structure experiences variability as indicated in Figure 108.

High-Inflow/Low-Salinity Period (March-May 1985). During this selected period and including February 1985, total inflow from the Atchafalaya River was approximately 10% higher than the long-term averages (Figures 105 and 106). Within this period, daily inflows were above 9,000 m^3/s during most of the period, but were lower during early February and late May. Peak flows occurred in mid-March (14,000 m^3/s) and mid-April (12,000 m^3/s). Vermilion River flows were much lower and more flashy than those in the Atchafalaya River. Peak flows (>55 m^3/s) occurred in mid-February, early and late March, and mid-May.

Freshwater dominated salinities throughout this estuary during this period. Salinities generally remained below 5 ppt, exhibited no vertical stratification, and were stable (Figure 107). Atchafalaya and Four League Bays typically remained below 0.5 ppt and were extremely stable. The highest and most variable salinities were recorded in Southwest Pass and in near-shore Gulf waters between Freshwater Bayou Canal and Shell Keys.

Low-Inflow/High-Salinity Period (September-November 1975). During this selected period and including August 1975, total inflow from the Atchafalaya River was approximately 5% above long-term averages (Figures 105 and 106). Within this period, daily inflows generally were above 2,800 m^3/s. Highest flows occurred in early August (5,000 m^3/s) and late October (5,100 m^3/s). Vermilion River flows generally remained below 14 m^3/s, except for minor peaks in early August (57 m^3/s) and late November (28 m^3/s).

Salinities throughout the system were dominated by river inflows. The salinity structure and stability were very similar to those observed during the low salinity period, but were approximately 5 ppt higher in Vermilion Bay. The lowest (near-fresh) and most stable salinities prevailed throughout Atchafalaya Bay. The greatest variability was noted within Southwest Pass, in near-shore Gulf waters near by Freshwater Bayou Canal, and, to a lesser degree, in Oyster Bayou. Salinities in the remainder of the estuary were relatively stable.

Factors Affecting Variability

The salinity structure is determined by the seasonal freshwater discharge from the Atchafalaya River; discharges from the Vermilion River are only locally important. Prevailing seasonal winds and entrainment of diluted Gulf waters are secondary modifiers of the salinity structure.

The important time scales of variability and responsible mechanisms are given in Figure 108. The Atchafalaya/Vermilion Bays estuary is, however, among the most stable of any estuarine system in the Gulf. On average, typical high- and low-inflow periods change estuary-wide salinities by approximately 3 ppt as river discharge reduces the influence of other mechanisms. Wind, typically associated with frontal passages, is an important modifier of the salinity structure. Freshwater pulses may cause localized freshening and induce weak stratification, especially in Vermilion Bay.

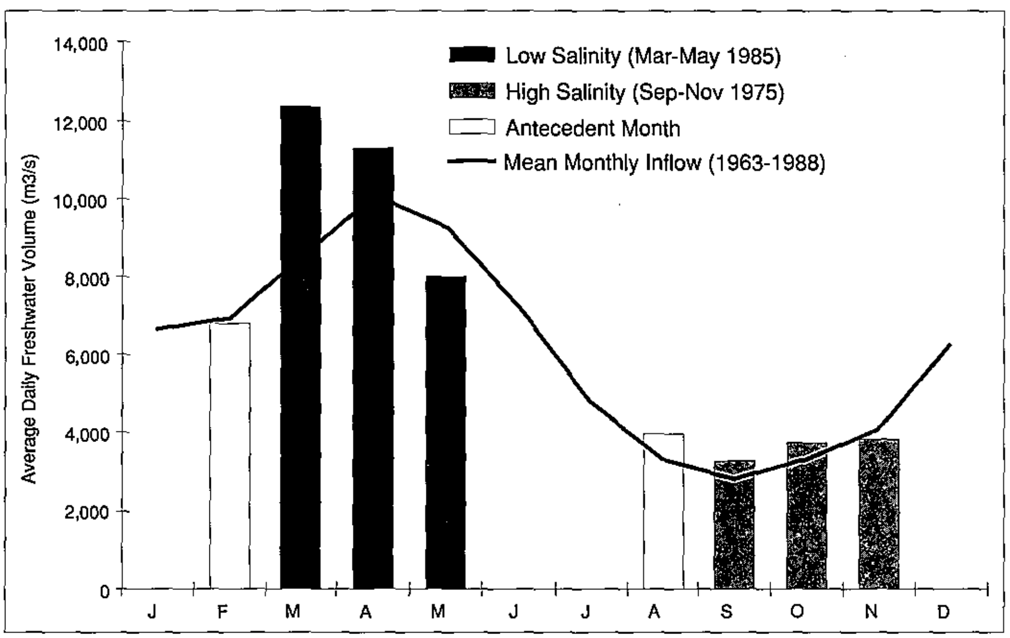
Figure 105. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	March-May 1985 (High Inflow/Low Salinity)	September-November 1975 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	139	174
Sampling Distribution [a]	2-3	2-3
Sampling Frequency	weekly-monthly	weekly-monthly
Average Salinity (ppt)	2.0	3.6
Bottom Salinity		
# of Observations	113	108
Sampling Distribution [a]	2-3	2-3
Sampling Frequency	weekly-monthly	weekly-monthly
Average Salinity (ppt)	2.1	5.1
Freshwater Inflow		
Volume	10% above average [b]	5% above average [c]
Return Frequency of Peak Events		
1-day duration	4.0-year	1.8-year
7-day duration	3.5-year	2.0-year
30-day duration	3.5-year	1.9-year

Abbreviations: ppt - parts per thousand

a. Subsystem(s) with high sampling density
b. Includes February 1985
c. Includes August 1975

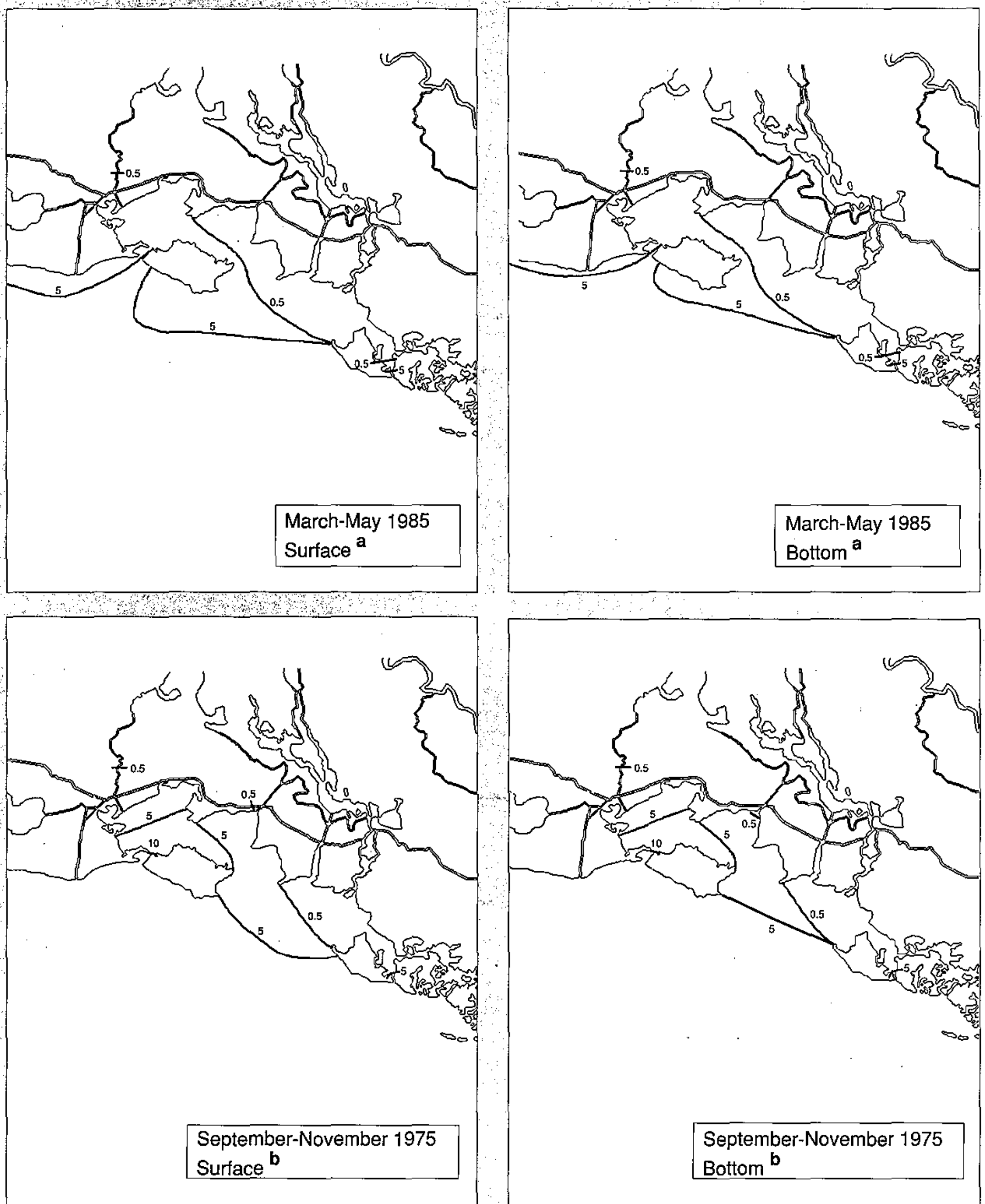
Figure 106. *Comparison of gaged freshwater volume for the Atchafalaya River at Simmesport, LA during periods of salinity depiction to period-of-record averages* *



Abbreviation: m3/s - cubic meters per second

* USGS gages reflect inflow from 87% of the estuary's total watershed (261,645 km2) (USGS, 1990)

Figure 107. *Surface and bottom salinities during low- and high-salinity periods*

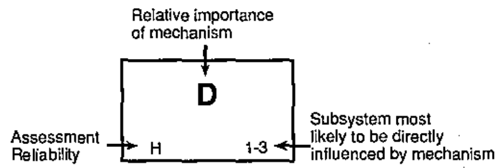


a. Data Sources: LDHHR, 1991; LDWF, 1991
b. Data Sources: Hoese, 1976; LDEQ, 1991; LDHHR, 1991; LDWF, 1991

Figure 108. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S (M 2-3)	D (H 1-3)	D (H 1-3)	
Tides					
Wind		S (LIT 1-3)	M (LIT 1-3)		
Shelf Processes			S (LIT 1-3)	M (LIT 1-3)	
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 107 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, short-term influence on the salinity structure and temporary increase of weak vertical stratification mainly in Vermilion Bay.

Months-Seasons. Dominant influence on estuary-wide salinity structure. Inflows during February-March were two to three times higher than during August-November and usually produced stable, near-fresh, and vertically homogeneous salinities. Weakened August-November inflows allowed increased variability in Vermilion Bay.

Year-Year. Dominant, but low influence on estuary-wide salinity structure. During 1970-1986, mean annual estuary-wide surface salinities ranged from 0.1 to 6.4 ppt. Year-to-year variability during September-November is higher than during March-May due to the decreased freshwater volume.

Wind

Days-Weeks. Secondary, short-term influence on the salinity structure throughout the estuary. Cold fronts occur 15 to 20 times each winter (Leipper, 1954; Wiseman et al., 1982). Winds inhibit stratification under most conditions.

Months-Seasons. Minor influence on the salinity structure. Prevailing southerly and easterly winds induce entrainment of Gulf waters from spring to fall (Denes and Caffrey, 1988).

Shelf Processes

Months-Seasons. Secondary influence on the salinity structure. Mississippi and Atchafalaya River plumes decrease salinity of entrained shelf waters usually between spring and summer.

Year-Year. Minor influence on the salinity structure.

* Data Sources: See data sources listed in Appendix II for Louisiana.

Geographic Setting

The Mermentau River estuary is located on the eastern edge of the Louisiana Chenier Plain between Calcasieu Lake and Vermilion Bay. The estuary extends from the head of tide on the Mermentau River at the Catfish Point Control Structure near Grand Lake to its terminus at the Mermentau River/Gulf of Mexico Navigation Channel (MR/GMNC) (Figure 109). Its watershed includes the coastal wetlands south of the Grand Cheniere-Pecan Island ridge (between the Mermentau River and Freshwater Bayou Canal), which is the approximate route of Louisiana Highway 82. Inland waterbodies associated with the lower Mermentau River account for less than 3% of the total area (Gosselink et al., 1979). Before the early 1950s, Grand Lake and White Lake were a functional part of the estuary. At present, impoundments effectively control salinity intrusion and other interactions with the Gulf.

The major freshwater source to this estuary is controlled discharge from the upper Mermentau River basin. Surpluses of freshwater generally occur in the basin from late fall to early spring. To alleviate flooding, water is released into the estuary from the water control structures at Catfish Point and on the Schooner Bayou Canal (Gagliano et al., 1973). Most freshwater enters the estuary from the west through lower Mermentau River. It can also flow between the Mermentau River estuary and the Calcasieu River estuary through Calcasieu Lock; the direction of flow depends on the hydraulic head induced by water level differences in the two estuaries (Gosselink et al., 1979). Tidal exchange occurs through the Mermentau River/Gulf of Mexico Navigation Channel (MR/GMNC), a 7.4 km channel dredged through Lower Mud Lake south to the Gulf and through numerous small bayous and canals that connect the estuary with the Gulf. This estuary has been divided into two subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 109).

Bathymetry

Most areas within the estuary are less than 1 m deep at mid-tide level (Figure 110) (NOAA, 1990a). The deepest areas (4 m) are in the GIWW and Freshwater Bayou Canal.

This estuary contains numerous control structures which have severely altered its hydrology. Historically, Grand Lake, White Lake, and their drainage basins were a functional part of the estuary. When the Mermentau River Basin Project was completed in the early 1950s, the upper Mermentau Basin was transformed into a large impoundment. Water control structures are currently located at Catfish Point, Schooner Bayou Canal, Leland Bowman Lock, Calcasieu Lock, and the Freshwater Bayou Canal. Thus, saltwater entering the upper basin is very limited, and this area no longer functions as an estuary (Gunter and Shell, 1958; Morton, 1973). A large portion of the estuary east of the Mermentau River is encompassed by Rockefeller Wildlife Refuge and Game Preserve (Figure 109). Large areas of the refuge are under active water management. In addition, water control structures on Little Constance and Big Constance Lakes are opened to allow surplus

Figure 109. *Location map and subsystem identification.*

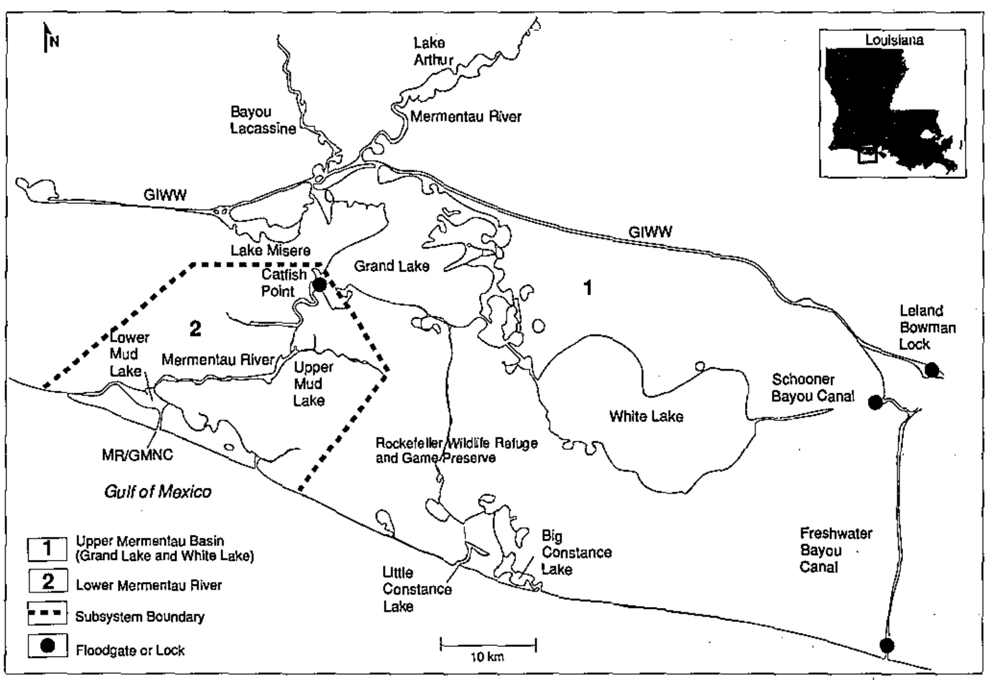
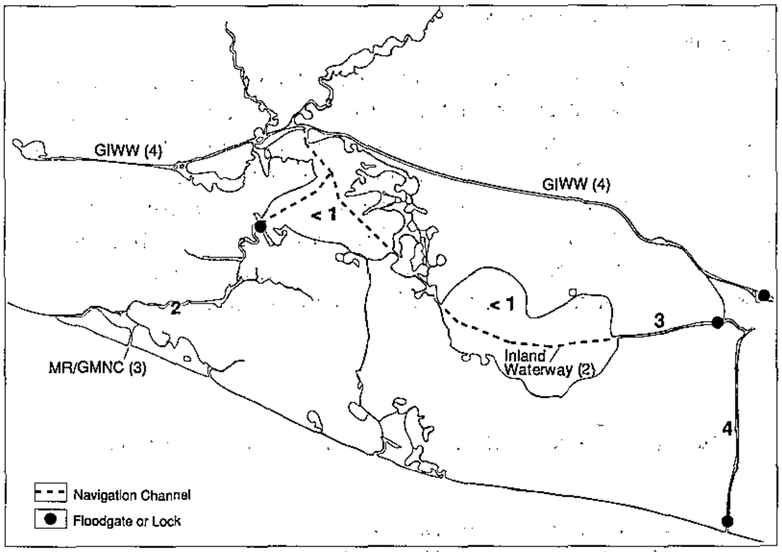


Figure 110. *Bathymetry (meters)*



freshwater to exit the Rockefeller Wildlife Refuge and Game Preserve during times of flooding and are closed to prevent saltwater intrusion when a freshwater deficit exists. Dredged material levees near navigation canals, oil and gas access canals, and the lower Mermentau River further inhibit exchanges across the estuary (Gosselink et al., 1979).

Salinity Patterns

The Data. June-August 1988 and January-March 1989 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions as no major modifications to the estuary or its watershed have occurred since the completion of the Leland Bowman Locks in 1985. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 111; salinity data was only available for the surface layer. Figure 112 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that both periods were wetter than normal. Figure 113 presents salinity distributions for the selected periods, illustrating the influence of seasonal freshwater discharge on the salinity structure in the lower Mermentau River. This structure, however, experiences variability as indicated in Figure 114.

High-Inflow/Low-Salinity Period (January-March 1989). During this selected period and including December 1988, total inflow from the Mermentau River was approximately 30% higher than the long-term averages (Figures 111 and 112). Within this period, daily inflow increased throughout December 1988 and reached 280 m^3/s in early January 1989 before falling below 100 m^3/s in mid-January. Inflow peaked at 340 m^3/s in late January, then remained below 120 m^3/s through March.

Stable, near-fresh (0.5 ppt) conditions prevailed within the Upper Mermentau Basin due to control structures and ample freshwater discharge. In contrast, salinities within the lower Mermentau River were not dominated by freshwater and were unstable. Salinities were highest in early January and lowest in February. Average salinities in the Mermentau River gradually increased from the Catfish Point Control Structure (0.5 ppt) to the MR/GMNC (15 ppt) (Figure 113).

Low-Inflow/High-Salinity Period (June-August 1988). During this selected period, total inflow from the Mermentau River was approximately 20% above long-term averages (Figures 111 and 112). Freshwater information was not available for May 1988. Daily inflow generally remained below 50 m^3/s, but experienced several pulses. Inflow reached 120 m^3/s in May, 90 and 65 m^3/s in early June, 225 m^3/s in late July, and 90 m^3/s in early August.

Stable, freshwater conditions (<1 ppt) again prevailed within the upper Mermentau Basin. However, saline waters (11 ppt) briefly penetrated the control structure just inside Grand Lake on June 29. In the lower Mermentau River, salinities were 5-10 ppt higher than during the low-salinity period and were unstable. The lowest salinities were in mid-July, coinciding with peak flows on the Mermentau River; salinities decreased by 5-10 ppt from June levels. The highest salinities were in August when base flows had returned on the river.

Factors Affecting Variability

The salinity structure is determined by the seasonal freshwater discharge and depends, primarily, on the magnitude and duration of inflow from the Mermentau River. A seasonal response is apparent in the unregulated, lower Mermentau River. Salinity in the estuary is lowest between January-March when the influence of upper basin releases is greatest (Wicker et al., 1983). Salinity peaks between June-

August when freshwater releases are low or nonexistent, evaporation is high, and Gulf water-levels are high due to summer heating, on-shore currents, and winds (Wicker et al., 1983). Control structures inhibit salinity intrusion in the upper basin.

Although vertical stratification could not be examined due to the lack of bottom salinity data, it is considered very unlikely to occur within the upper basin because of the control structures. Shallow depths, wind, and tidal action probably prevent vertical stratification in the lower Mermentau River under most conditions (Morton, 1973). Stratification is most likely to occur when freshwater is released from the Catfish Point Control Structure following a high-salinity period.

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 114. Salinities in the upper basin remain extremely stable, except for a rare intrusion of saline waters upstream of the control structures. In contrast, salinity in the lower Mermentau River is highly variable. This estuary is most influenced by periodic control structure releases and frontal passages.

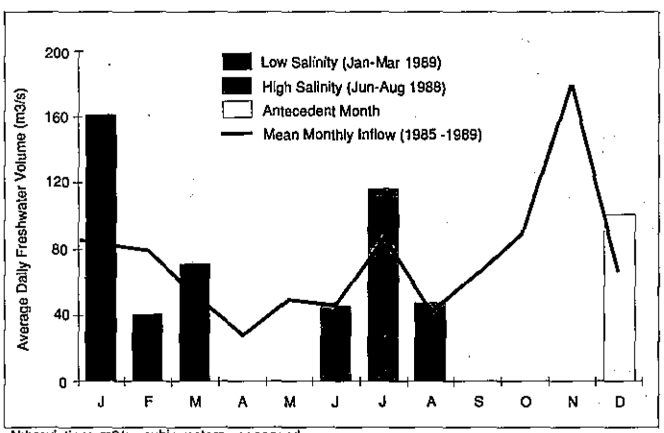
Figure 111. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	January-March 1989 (High Inflow/Low Salinity)	June-August 1988 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	42	40
Sampling Distribution [a]	1-2	1-2
Sampling Frequency	monthly	monthly
Average Salinity (ppt)	5.7	9.5
Bottom Salinity		
# of Observations	0	0
Sampling Distribution [a]	NA	NA
Sampling Frequency	NA	NA
Average Salinity (ppt)	NA	NA
Freshwater Inflow		
Volume	30% above average [b]	20% above average [c]
Return Frequency of Peak Events		
1-day duration	2.7-year	4-year
7-day duration	2.4-year	4-year
30-day duration	3.0-year	4-year

Abbreviations: ppt - parts per thousand; NA - not available

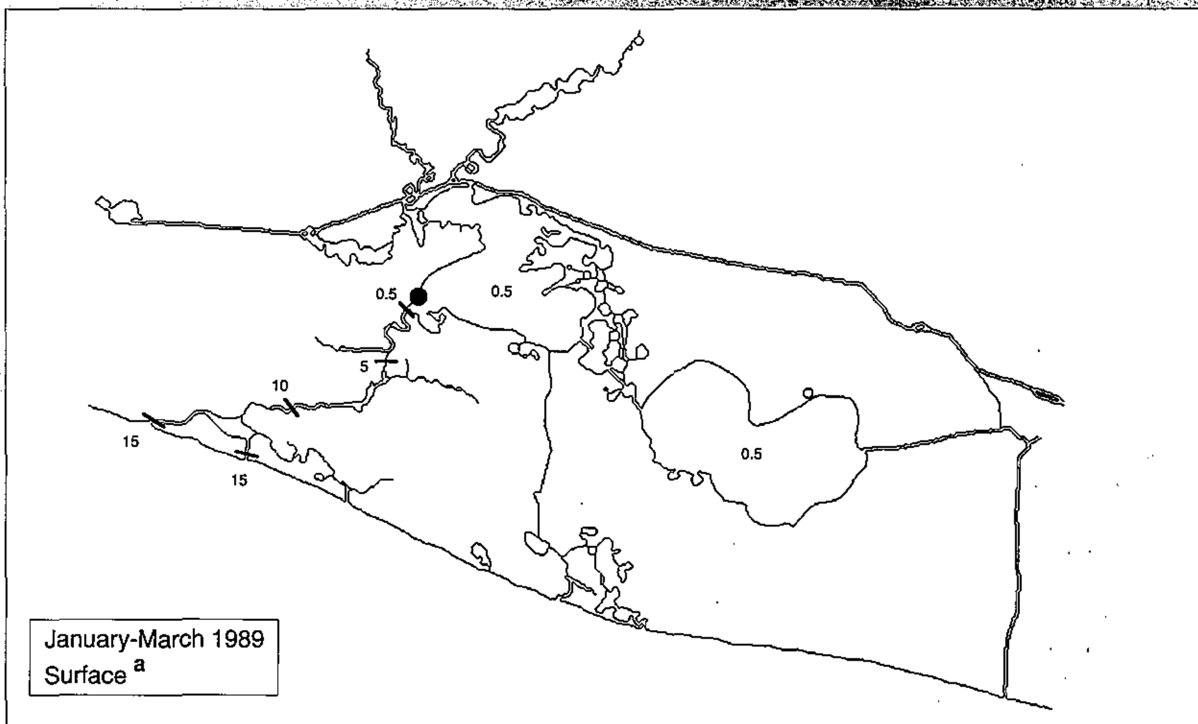
a. Subsystem(s) with high sampling density
b. Includes December 1988
c. Does not include May 1988

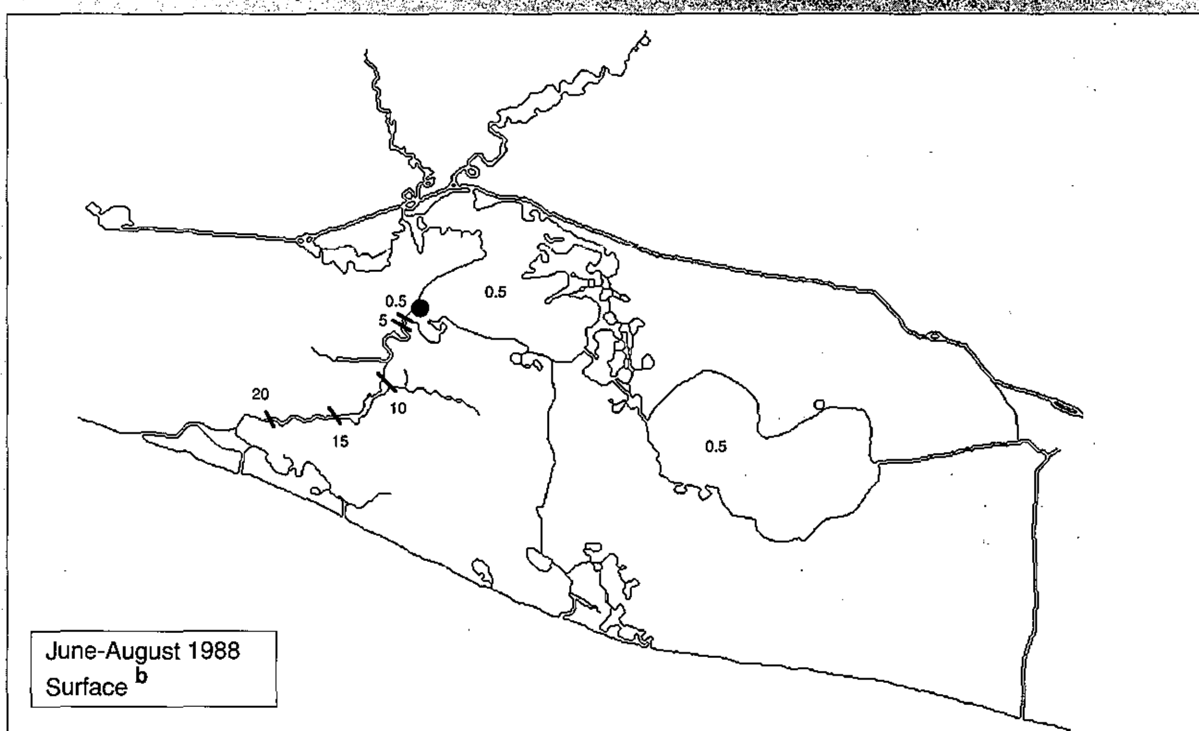
Figure 112. *Comparison of gaged freshwater volume for the Mermentau River at Mermentau, LA during periods of salinity depiction to period-of-record averages* *



Abbreviation: m3/s - cubic meters per second
*Percentage of watershed reflected by USGS gages is unknown

Figure 113. *Surface salinities during low- and high-salinity periods*



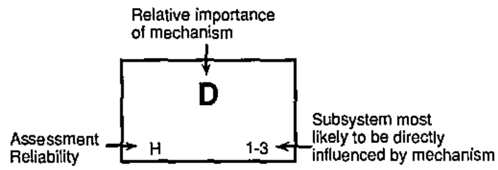


a. Data Sources: LDEQ, 1991; LDHHR, 1991
b. Data Sources: LDEQ, 1991; LDHHR, 1991; USACE, 1991

Figure 114. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		**S** LIT 2	**D** H 2	**S** M 2	
Tides					
Wind		**S** LIT 2			
Shelf Processes			**M** LIT 2	**S** LIT 2	
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 113 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 (Lock and Dam Releases). Secondary influence on the salinity structure below Catfish Point Control Structure (CPCS). Most frequent releases occur during the winter and spring, resulting in short-term displacement of isohalines and increased vertical stratification.

Months-Seasons. Dominant influence on the salinity structure below the CPCS. December-March inflows are two to three times greater than between May-August and alter the salinity structure by 10 ppt below the CPCS. Salinities above the CPCS are most often less than 0.5 ppt.

Year-Year. Secondary influence on the salinity structure below the CPCS.

Wind

Days-Weeks. Secondary influence on the salinity structure below the CPCS, usually associated with frontal passages. Winds inhibit stratification under most conditions.

Shelf Processes

Months-Seasons. Minor influence on the salinity structure. Mississippi and Atchafalaya River plumes decrease salinity of entrained shelf waters usually during the spring and summer.

Year-Year. Secondary influence on the salinity structure.

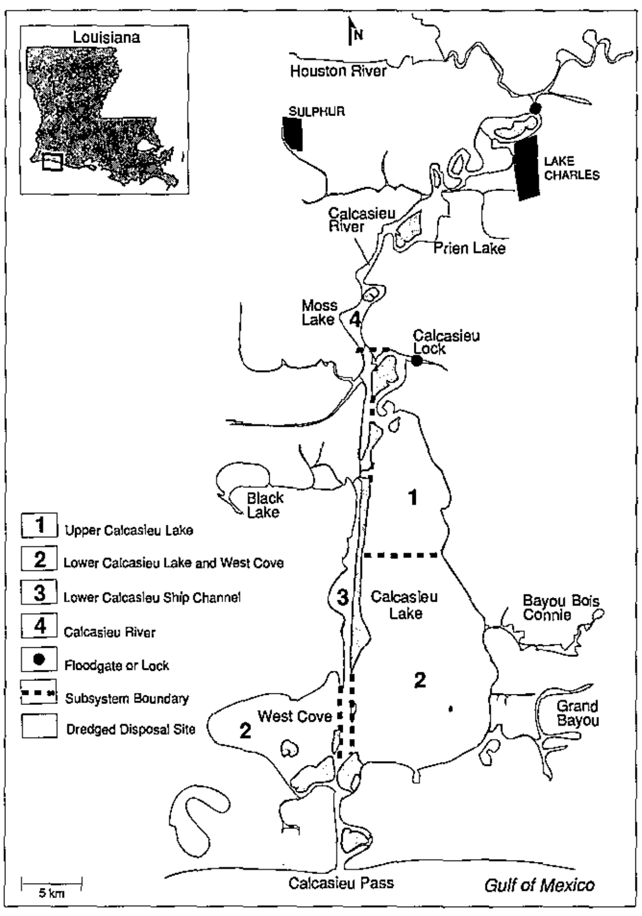
* Data Sources: See data sources listed in Appendix II for Louisiana.

Geographic Setting

The Calcasieu Lake estuary is located between the Mermentau and Sabine systems within the Chenier Plain. It consists of Calcasieu Lake, the largest of the estuary's waterbodies, and several secondary embayments (Figure 115). This estuary occupies 255 km² (NOAA, 1990a) and extends approximately 60 km from a saltwater barrier on the Calcasieu River, near Lake Charles, to the Gulf of Mexico.

The Calcasieu River is the major freshwater source, although Beckwith Creek, Bear Head Creek, and the Houston River may be locally significant. Freshwater can also flow between the Mermentau River and the Calcasieu River by way of the Calcasieu Lock; the direction of flow depends on the hydraulic head induced by water-level differences (Gosselink et al., 1979). Tidal exchange occurs through Calcasieu Pass. The estuary has been divided into four subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 115).

Figure 115. *Location map and subsystem identification*



Bathymetry

The average depth of the estuary is less than 2 m at mid-tide level (NOAA, 1990a). Major bathymetric features include the Calcasieu Ship Channel (CSC), the GIWW, and a large dredged material disposal island near the CSC (Figure 116).

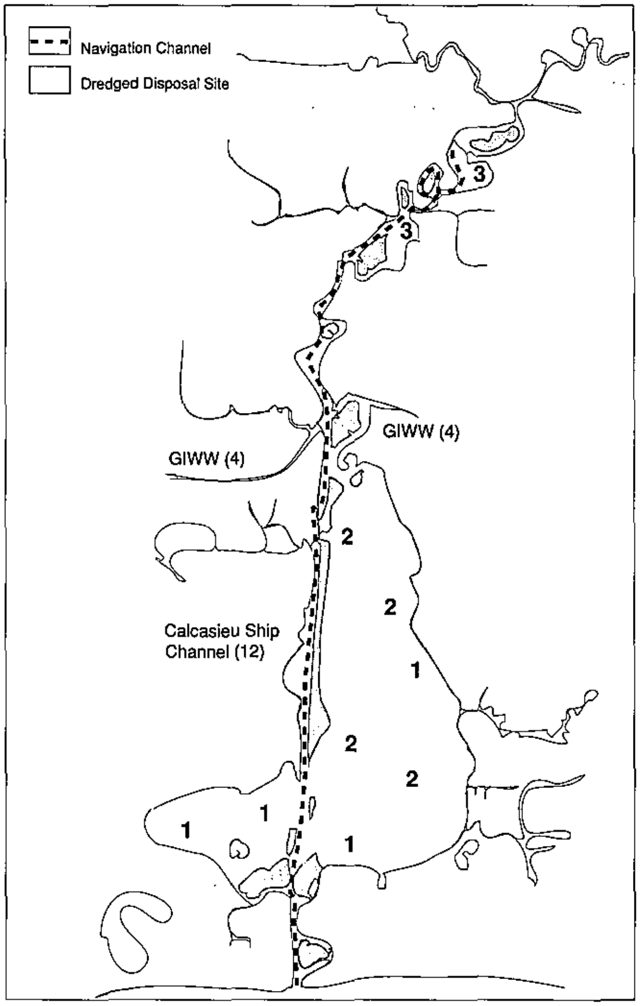
The CSC is an important conveyance for salinity intrusion. Saline bottom waters are essentially confined to the CSC by the extensive dredged disposal island to the east and may extend upstream of Lake Charles during low-flow periods when the saltwater barrier is open to ship traffic. Much of the Calcasieu River volume is directed west of the dredged disposal island, enhancing density currents in the CSC (Kjerfve and Sneed, 1987) and significantly reducing the circulation of freshwater through Calcasieu Lake (Alexander, 1985; Turner, 1988). Several small navigation canals and oil and gas access canals exist throughout the Calcasieu River basin. These canals have interrupted much of the natural runoff that had historically reached Calcasieu Lake (Gosselink et al., 1979).

Salinity Patterns

The Data. August-October 1984 and January-March 1984 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions since no major modifications to the estuary or its watershed have occurred since construction of the Calcasieu River saltwater barrier and the deepening of the CSC in 1968 (USACE, 1987). A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 117. Figure 118 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that neither period experienced typical inflow conditions. Freshwater inflow during January-March 1984 was above normal but was selected because of the limited salinity data available for other years. August-October 1984 is biased by an irregular freshwater peak that occurred in late October during an otherwise below average period. Figure 119 presents salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 120.

High-Inflow/Low-Salinity Period (January-March 1984). During this selected period and including December 1983, total inflow from Calcasieu River was

Figure 116. *Bathymetry (meters)*



approximately 45% above long-term averages (Figures 117 and 118). Within this period, base inflow remained near 125 m³/s but was interrupted by freshets which peaked at 425 m³/s during mid-December and 1300 m³/s during mid-February. This estuary is strongly influenced, but not dominated, by freshwater during this period. Salinities were relatively unstable throughout the system, especially within lower Calcasieu Lake and the CSC.

From January through early February, estuarine salinities slowly rebounded from a mid-December freshet; salinities in the upper estuary peaked and Calcasieu River bottom waters reached 29 ppt near the Lake Charles saltwater barrier. A major freshwater pulse in mid-February dropped surface salinities by 10 ppt throughout the estuary and pushed the saline bottom waters within the Calcasieu River to below Prien Lake. Salinities in upper Calcasieu Lake remained depressed through March, while the lower Lake and CSC surpassed pre-freshet salinities by late March. Vertical stratification was uncommon in upper Calcasieu Lake and West Cove. Moderate-to-high stratification occurred frequently within the lower Lake and very high stratification persisted within the Calcasieu River and CSC.

Low-Inflow/High-Salinity Period (August-October 1984). During this selected period and including July 1984, total inflow from Calcasieu Lake was approximately 110% higher than long-term averages (Figures 117 and 118). Within this period, however, inflow was below average from July to mid-October; baseline flow was approximately 30 m³/s, except during a modest freshet (125 m³/s) during late September. Inflow peaked (1,375 m³/s) during late October. Thus, salinity distributions presented in Figure 119 were influenced more by the below average inflow from July to mid-October than by the freshwater surge during late October.

Salinities were approximately 10 ppt higher than during the low-salinity period. Salinities throughout the estuary increased through August and peaked in mid-September. Bottom salinities within the Calcasieu River and CSC were especially high and unstable, reaching 24 ppt in September and averaging 15 ppt at the Lake Charles saltwater barrier. Salinities in upper Calcasieu Lake and the Calcasieu River demonstrated a modest response to the late September freshet, but dropped 15 ppt following the late October freshet. Salinities within the lake and lower CSC remained relatively stable until late October. Vertical stratification was generally absent in the lake and lower CSC, but the upper CSC and Calcasieu River were moderately-to-highly stratified.

Factors Affecting Variability

The salinity structure is determined, primarily, by the magnitude and duration of seasonal inflow from the Calcasieu River. Because typical inflows do not completely dominate the system, the influence of seasonal inflows is most apparent in the upper lake and Calcasieu River. Prevailing seasonal winds, density currents, and shelf processes are minor contributors to salinity structure.

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 120. Freshets are responsible for frequent short-term displacement of isohalines, especially in lower Calcasieu River and upper Calcasieu Lake. Wind, especially when associated with frontal passages, is an important modifier of the seasonal salinity structure and may induce short-term water-column mixing throughout the estuary.

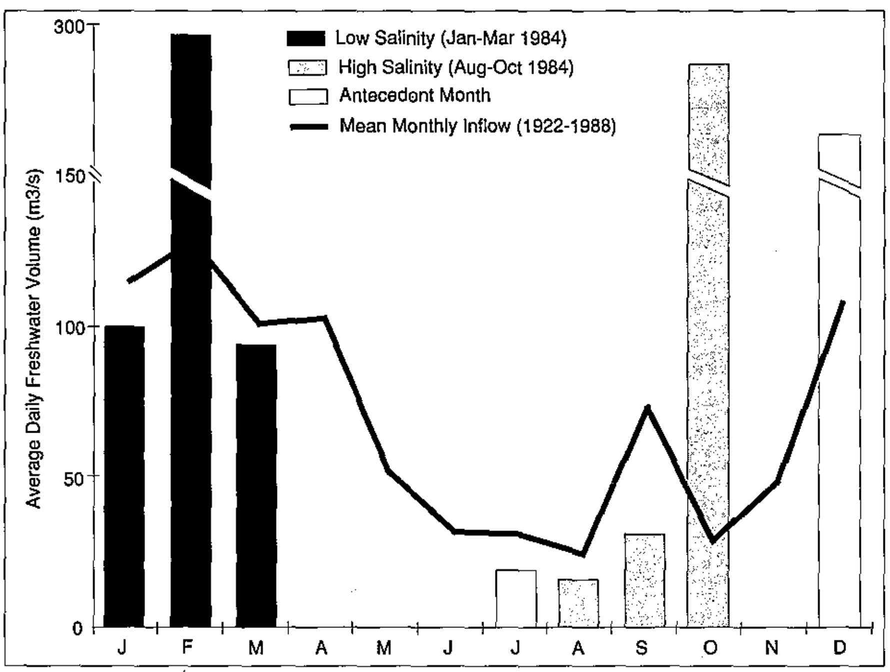
Figure 117. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	January-March 1984 (High Inflow/Low Salinity)	August-October 1984 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	210	173
Sampling Distribution [a]	1-4	1-4
Sampling Frequency	daily - monthly	daily - monthly
Average Salinity (ppt)	4.8	8.8
Bottom Salinity		
# of Observations	211	174
Sampling Distribution [a]	1-4	1-4
Sampling Frequency	daily - monthly	daily - monthly
Average Salinity (ppt)	12.1	14.7
Freshwater Inflow		
Volume	45% above average [b]	110% above average [c]
Return Frequency of Peak Events		
1-day duration	20-year	35-year
7-day duration	15-year	35-year
30-day duration	9-year	35-year

Abbreviation: ppt - parts per thousand

a. Subsystem(s) with high sampling density
b. Includes December 1983
c. Includes July 1984

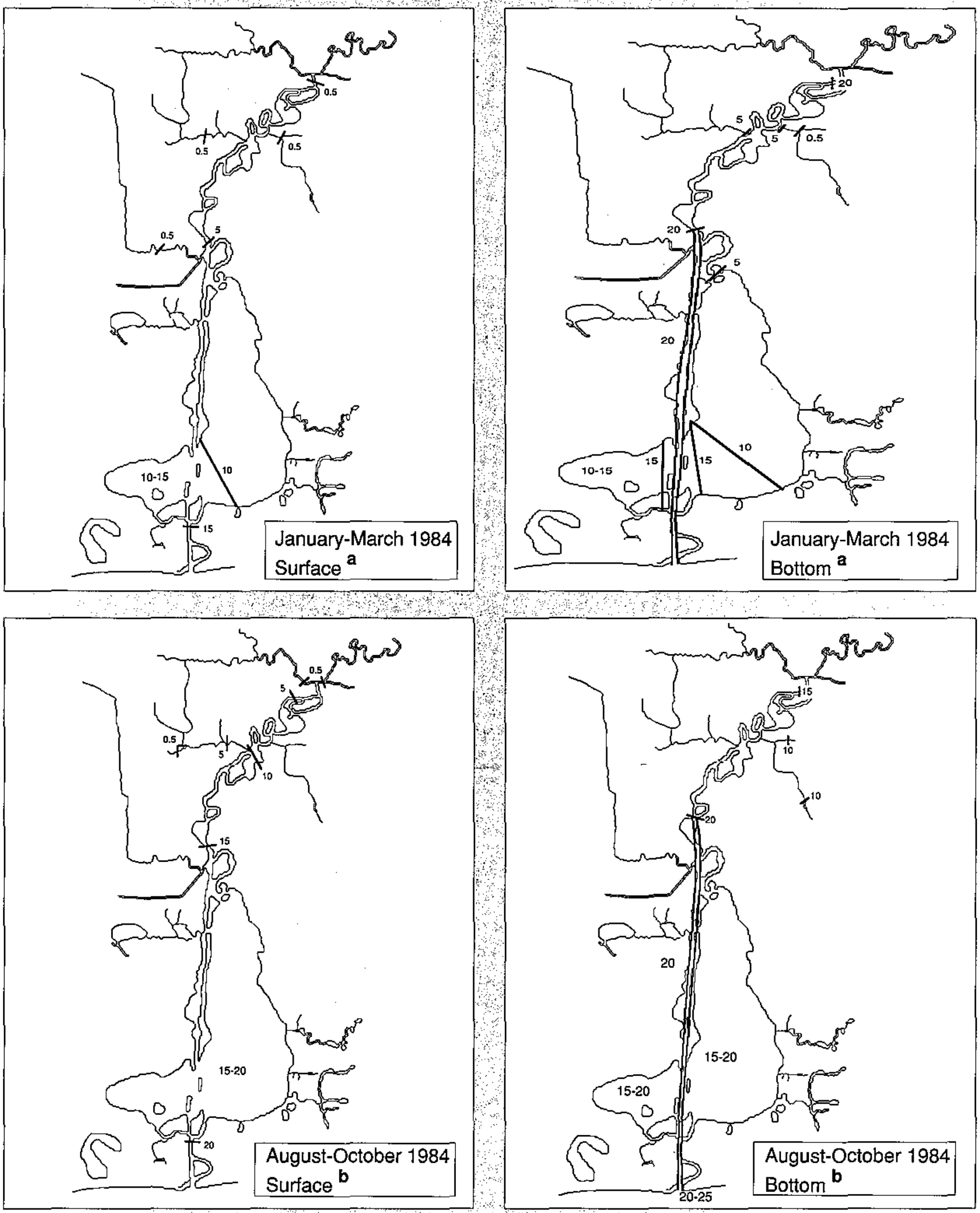
Figure 118. *Comparison of gaged freshwater volume for the Calcasieu River at Kinder, LA, during periods of salinity depiction to period-of-record averages* *



Abbreviation: m3/s - cubic meters per second

* USGS gages reflect inflow from 52% of the estuary's total watershed (11,100 km2) (USGS, 1990)

Figure 119. *Surface and bottom salinities during low- and high-salinity periods (NOTE: Isohalines for Jan.-Mar. depict a hydrological state that differs significantly from that most characteristic of the normal inflow due to salinity data limitations for this estuary)*

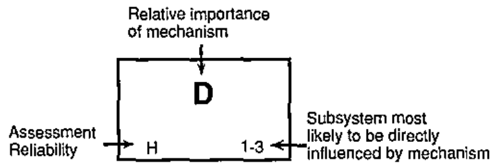


a. Data Sources: De Rouen et al., 1987; LDEQ, 1991; LDHHR, 1990; LDWF, 1991; USGS, 1991
b. Data Sources: De Rouen et al., 1987; LDEQ, 1991; LDHHR, 1990; LDWF, 1991; USGS, 1991

Figure 120. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		S (M 1,4)	D (H 1-4)	D (H 1-4)	
Tides					
Wind		S (LIT 1-4)	S (LIT 1-4)		
Density Currents		M (LIT 3-4)	S (LIT 3-4)		
Shelf Processes			M (LIT 2)	M (LIT 2)	
Effect on Salinity Variability	VERY LOW	LOW	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 119 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 the salinity structure and a temporary increase in vertical stratification, primarily in the Calcasieu River and upper Calcasieu lake. Short-term retarding of CSC bottom waters occurs during a significant Calcasieu River inflow.

Months-Seasons. Dominant influence on estuary-wide salinity structure. January-March inflows are four times greater than during August-October. January-March inflows produce relatively unstable conditions throughout the estuary, but the duration of these conditions is greatest in the Calcasieu River and upper Lake. Moderate-to-high stratification occurs in the lower Lake, Calcasieu River, and CSC. Weakened August-October inflows allow increased variability in the upper Lake, increased stability in the lower Lake, and persistent vertical stratification in Calcasieu River and upper portion of CSC.

Year-Year. A dominant impact on estuary-wide salinity structure. During 1970-1987, mean annual estuary-wide surface salinities ranged 5-18 ppt, but most often remained between 11-14 ppt. Year-to-year variability during the low- and high-salinity periods was relatively low.

Wind

Days-Weeks. Secondary influence on the salinity structure throughout the estuary. Cold fronts may override astronomical tides, induce mixing, and may cause a moderately important short-term alteration of salinity structure throughout the estuary.

Months-Seasons. Secondary influence on the salinity structure. Prevailing seasonal winds contribute moderately to the salinity structure throughout the estuary.

Density Currents

Days-Weeks. A minor, short-term landward displacement of saline bottom waters is apparent in the CSC during modest freshwater increases.

Months-Seasons. Secondary influence on the salinity structure. Sufficient freshwater sustains density currents in CSC during high- and low-inflow periods and may influence the salinities near the channel. Peak seasonal inflows temporarily displace saline bottom waters.

Shelf Processes

Months-Seasons. A minor, temporary decrease of entrained shelf water salinity is apparent in the lower lake, usually during late spring and summer (Wiseman et al., 1990b).

Year-Year. A minor, perhaps more prolonged decrease of entrained shelf water salinity is apparent in the lower lake, usually during late spring and summer.

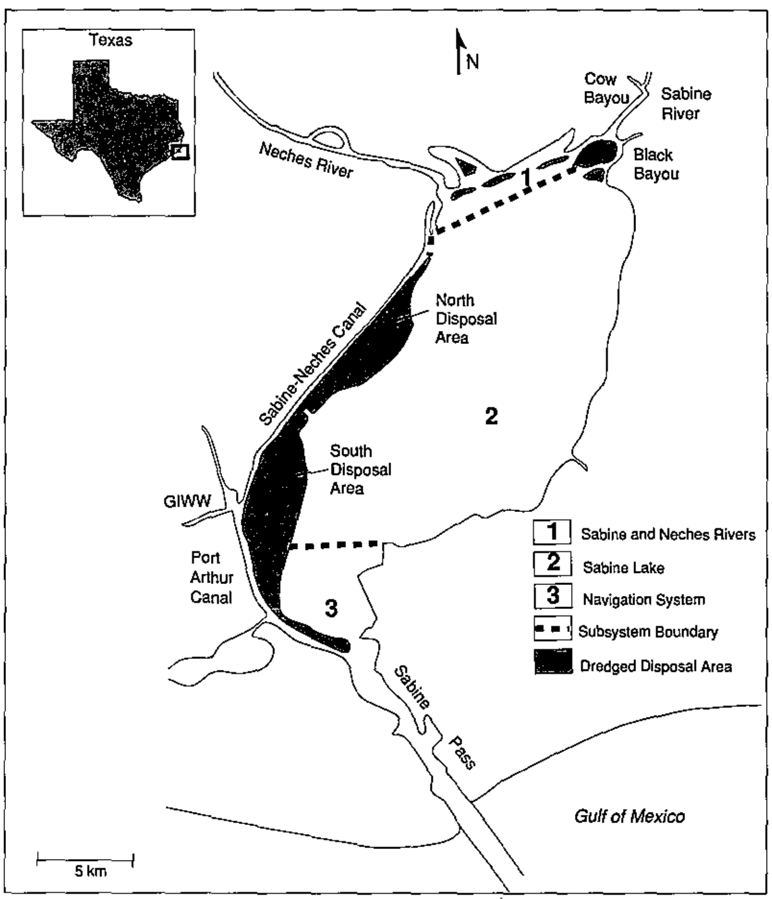
* Data Sources: See data sources listed in Appendix II for Louisiana.

Geographic Setting

The Sabine Lake estuary occupies 243 km^2 along the Texas-Louisiana border (NOAA, 1990a). It consists of a relatively broad and shallow open bay, and a narrow but deep channel system along its western boundary (Figure 121). Its boundaries are defined from the salt barriers on the Sabine River (approximately 32 km upstream of the turning basin at Orange, Texas) and on the Neches River (at its confluence with Village Creek) to its terminus with the Gulf at Sabine Pass. Tidal exchange occurs exclusively through Sabine Pass.

Of all the Texas estuaries, this estuary has the greatest freshwater inflow-to-bay volume ratio (Ward, 1980). The estuary receives most of its freshwater from the Sabine River (about 50% of gaged inflow) and Neches River (about 43% of gaged inflow) (USGS, 1990). This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 121).

Figure 121. *Location map and subsystem identification*

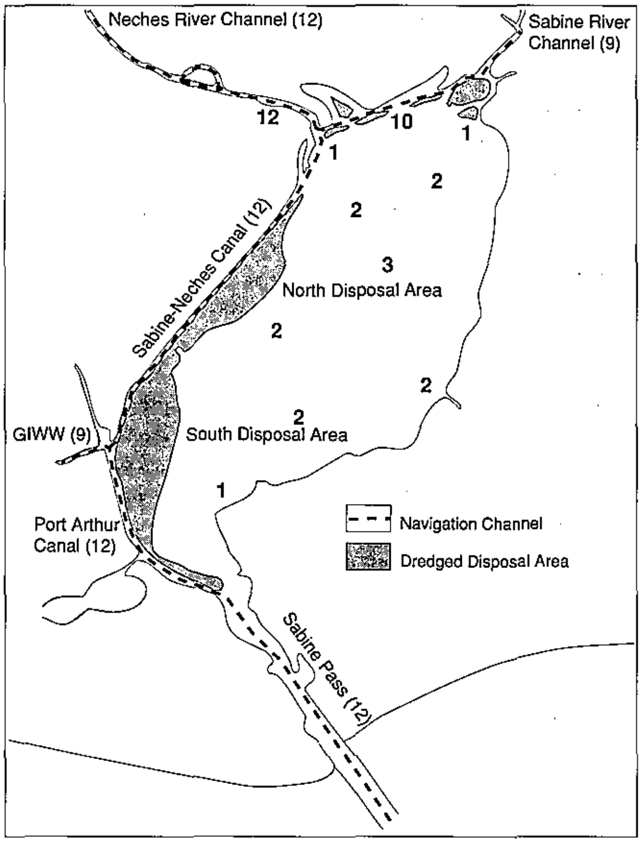


Bathymetry

The average depth of the open bay is approximately 2 m at mid-tide level, although some natural depths may exceed 7 m (Figure 122) (NOAA, 1990a). To facilitate shipping, a 12-m channel is maintained from the lower reaches of the Sabine and Neches Rivers, through Sabine Pass, including the Port Arthur Canal and Sabine-Neches Canal. Dredging of the channels along the bay's periphery and spoil disposal around the bayward side of the channel essentially separated the open bay from the channel system, except in the lower bay at Sabine Pass and in the upper bay at the mouth of the Neches River. This navigation system, which constitutes the deepest part of the estuary, greatly enhances saltwater intrusion into the upper estuary (Ward, 1973; Ward, 1980). Its channel system facilitates the development of density currents, which dramatically intensify with increasing water depth, and result in a net flow landward along the bottom even during high salinity periods (Ward, 1980). Density currents were responsible for a sharp increase in salinity intrusion, following the extension and deepening of the channel system to 10 m from 1924-1934 (Von Deesten, 1924; Ward, 1973). Because saltwater intrudes much more rapidly up the channel system than through Sabine Lake, salinities may sometimes be higher at the mouths of the Neches and Sabine Rivers than in Sabine Lake, resulting in a reverse salinity gradient in the upper estuary (Ward, 1980). The north and south disposal areas near Port Arthur Canal and the Sabine-Neches Canal were diked off between 1967-1969, reducing the water surface area of Sabine Lake by about 10%. Further, this may have substantially changed circulation patterns in the estuary (Ward, 1973).

Since 1948, about 20 reservoirs have been constructed within the watershed. The Toledo Bend and Sam Rayburn reservoir systems are the most significant and regulate flow in the Sabine and Neches Rivers, respectively. Their operation does not affect the annual mean river flow, but does affect the timing and fluctuations of river flows (Ward, 1980). The Toledo Bend reservoir has decreased winter and early spring inflows, and increased late spring and summer inflows, reducing summer salinities in the estuary (Ward, 1973; White and Perret, 1973). Although

Figure 122. *Bathymetry (meters)*



summer salinities are not below those of the spring high-flow period, they are significantly lower than before the reservoir's operation (White and Perret, 1973). During extreme low-flow years, the inflow to the estuary from the Neches River becomes essentially negligible and the longitudinal salt gradient in the Neches River vanishes, although a vertical stratification may exist. In this regime, the Neches River behaves more like a stagnant lake than a classical estuary (Ward, 1981).

Salinity Patterns

The Data. August-October 1974 and March-May 1985 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions as no major modifications to the estuary or its watershed have occurred since improvements to the navigation system in 1972 (USACE, 1988). A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 123. Figure 124 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that the low-salinity period was drier than normal, while the high-salinity period was wetter than normal. Figure 125 presents salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 126.

High-Inflow/Low-Salinity Period (March-May 1985). During this selected period and including February 1985, total inflow from the Sabine and Neches Rivers was approximately 15% below long-term averages (Figures 123 and 124). The combined average daily discharge from the Sabine and Neches Rivers was 600-900 m^3/s during most of February and March. Discharge decreased to 400-600 m^3/s during April and remained near 400 m^3/s during May. Peak discharges occurred in late February (1150 m^3/s) and mid-March (900 m^3/s).

Salinities throughout the estuary were lowest in March and gradually increased as river discharges diminished. The lowest salinities were observed in upper Sabine Lake where oligohaline (0.5-5.0 ppt) conditions persisted (Figure 125). The highest salinities were recorded within Sabine Pass and the channel system. By May, high-salinity bottom waters (10-15 ppt) had reached inland as far as the mouths of the Sabine and Neches Rivers. Limited data suggest that freshwater inflow was sufficient to maintain low surface salinities with little variability in most of the open bay throughout the period. The lower region of the open bay experienced less stable bottom salinities presumably because of its proximity to the Sabine Pass Channel where the influences of tides and density currents are more important. Surface salinities within the navigation channels appeared to be much more variable in time and space than those in the open bay, with a faster rate of salinity intrusion once inflows declined. Stratification was not apparent in Sabine Lake except in the upper and lower portions of the bay near navigation channels. Moderate-to-high stratification occurred in the navigation channels.

Low-Inflow/High-Salinity Period (August-October 1974). During this selected period and including July 1974, total inflow from the Sabine/Neches Rivers was approximately 55% above long-term averages (Figures 123 and 124). Frequent dam releases along the Sabine River produced somewhat higher-than-normal inflows that consistently peaked near 200 m^3/s from July through September. Consistent low flows (about 100 m^3/s) were observed in the Neches River.

Under typical low-inflow conditions, salinities within the open bay are most affected by flows from the

Sabine River, whereas salinities in the channel system are most influenced by Neches River discharges. Thus, relatively high flows from the Sabine River, with persistently low flows from the Neches River during this period, resulted in a reversal of the longitudinal salinity gradient (i.e., salinities in the upper bay exceeded those in the middle bay).

Salinities were approximately 5 ppt higher than during the low-salinity period, although above-normal discharges from the Sabine River may have prevented additional salinity intrusion. Also, surface and bottom salinities were less stable than during March-May 1985 and exhibited a weaker relationship to freshwater inflow. Moderate stratification was apparent in the Neches River and Sabine Pass, with weak stratification occurring in the lower Sabine River. Little, if any, stratification existed within the open bay.

Factors Affecting Variability

The salinity structure is primarily determined by seasonal freshwater discharge. During a low-salinity period, the estuary is completely dominated by freshwater (i.e., salinities are generally fresh-to-brackish, stable, and vertically homogeneous), except within navigation channels. Low salinities are further enhanced by river processes from estuaries east of Sabine Lake that depress shelf salinities and prevailing northerly winds that suppress salinity intrusion. In contrast, the influence of freshwater is less pronounced during a high-salinity period. Hence, density currents, pressure systems, and freshets become more important to the determination and modification of the salinity structure.

The important time scales of salinity variability and the responsible mechanisms are summarized in Figure 126. The most significant variation is attributable to winds, especially when associated with frontal passages; abrupt shifts in wind direction and changes in barometric pressure can dramatically affect water levels in the estuary, cancel any tidal effect, and ultimately lead to flushing of estuarine waters (Hauck, 1977; Ward, 1980; Wermund et al., 1989). Freshwater pulses reduce salinities in the open bay and retard bottom water intrusion within the rivers and navigation system. The influence of astronomical tides (enhanced mixing) is generally limited to Sabine Pass.

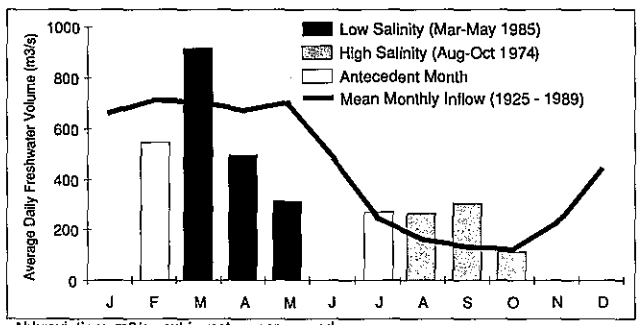
Figure 123. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	March-May 1985 (High Inflow/Low Salinity)	August-October 1974 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	30	167
Sampling Distribution [a]	2-3	1-2
Sampling Frequency	bi-weekly	monthly
Average Salinity (ppt)	4.1	10.7
Bottom Salinity		
# of Observations	20	74
Sampling Distribution [a]	2,3	1,2
Sampling Frequency	monthly	monthly
Average Salinity (ppt)	6.3	12.4
Freshwater Inflow		
Volume	15% below average [b]	55% above average [c]
Return Frequency of Peak Events		
1-day duration	<2.0-year	2-5-year
7-day duration	<2.0-year	2-5-year
30-day duration	2.0-year	5.0-year

Abbreviation: ppt - parts per thousand

a. Subsystem(s) with high sampling density
b. Includes February 1985
c. Includes July 1974

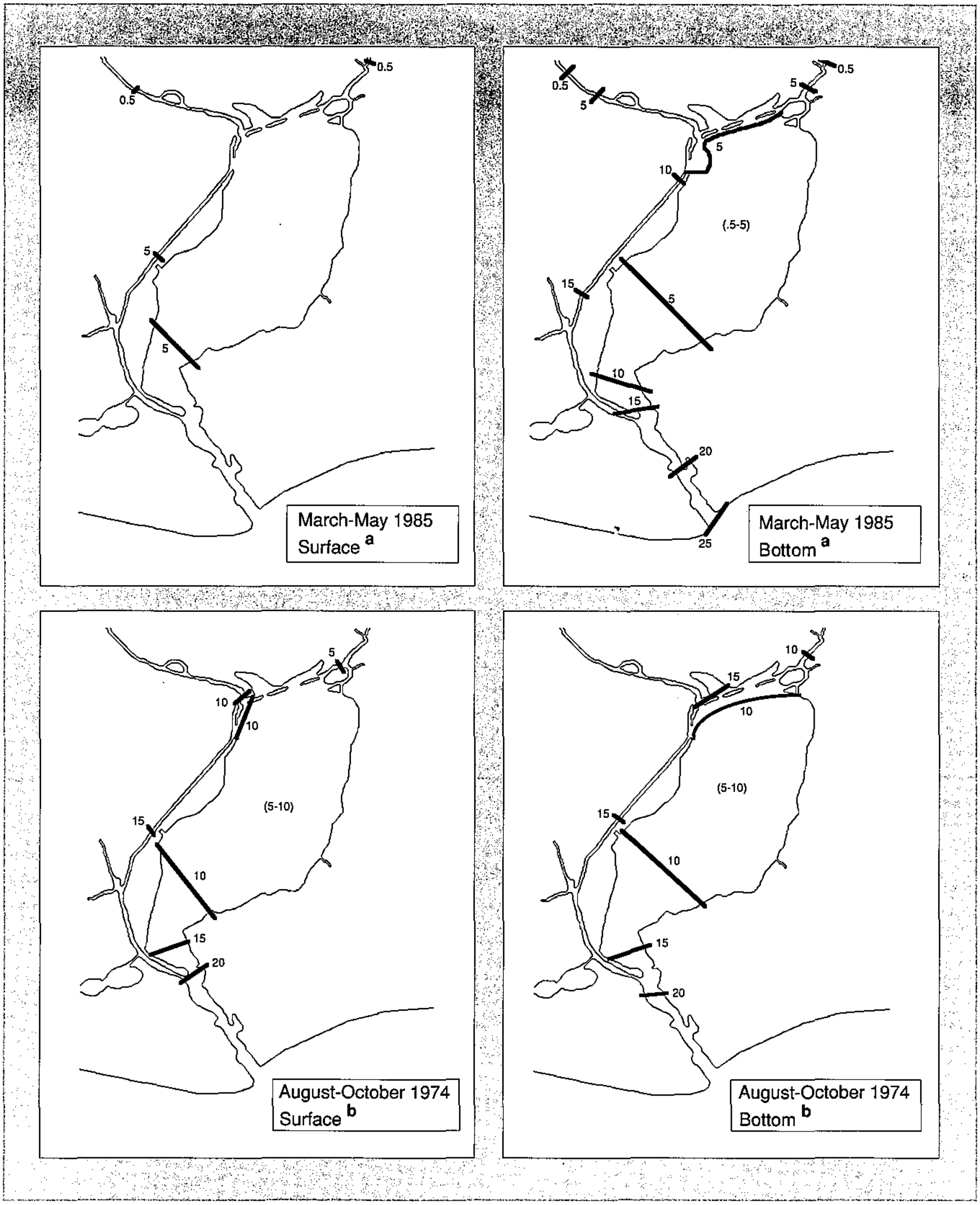
Figure 124. *Comparison of gaged freshwater volume for Sabine River near Ruliff, TX and Neches River at Evadale, TX during periods of salinity depiction and period-of-record averages**



Abbreviation: m3/s - cubic meters per second

* USGS gages reflect inflow from 83% of the estuary's total watershed (54,130 km2) (USGS, 1990)

Figure 125. *Surface and bottom salinities during low- and high-salinity periods*

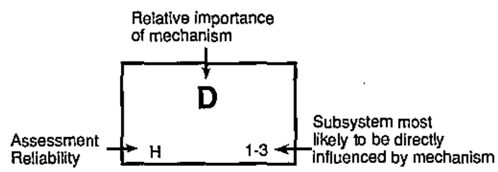


a. Data Sources: TSDH, 1991; TWC, 1991; TWDB, 1991a/b
b. Data Sources: TWC, 1991; TWDB, 1991a/b

Figure 126. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S (M 1-2)	D (H 1-3)	D (H 1-3)	
Tides	D (LIT 3)				
Wind		S (LIT 1-3)	M (LIT 1-3)		
Density Currents		S (LIT 1,3)			
Shelf Processes			S (LIT 3)	S (LIT 3)	
Effect on Salinity Variability	UNKNOWN	LOW	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 125 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, primarily in the open bay and upper portions of the navigation system.

Months-Seasons. Dominant influence on salinity structure throughout the estuary. March-May inflow is typically four times greater than during August-October; the difference in average salinities between the two periods is approximately 4 ppt.

Year-Year. Dominant influence on the salinity structure. Average annual salinities are relatively stable, though more variation is apparent in the surface layer during both periods. August-October salinities are relatively stable, reflecting the narrow range of inflow during this season. March-May salinities are more variable, reflecting the wider range of inflow.

Tides

Hours. Dominant influence on salinity variability, primarily in Sabine Pass, usually associated with enhanced water-column mixing. Astronomical tides are diurnal and exhibit a feeble range (0.3 m throughout the open bay and 0.5-1.0 m within Sabine Pass).

Wind

Days-Weeks. Secondary influence on salinity variability throughout the estuary. Cold fronts penetrate this area between September-April, but most frequently between December-February. These cold fronts may have considerable impact, but the salinity structure appears to rebound rapidly.

Months-Seasons. Minor, estuary-wide influence on salinity structure. Prevailing north winds depress water levels and encourage a Gulfward shift of isohalines; Von Deesten (1924) estimated that mean salinity near the mouth of the Neches River in 1922 was reduced 60% (6 ppt) when northerly winds prevailed. Construction of the north and south dredged disposal areas, however, may have significantly modified the circulation patterns that Von Deesten (1924) observed.

Density Currents

Days-Weeks. Secondary influence on salinity structure, primarily in the navigation system. Density currents within the navigation system may be controlled by Neches River inflow; under low-flow conditions, bottom water intrusion may produce a reverse salinity gradient in the upper portions of the open bay.

Shelf Processes

Months-Seasons. Secondary influence on salinity structure, primarily within Sabine Pass.

Year-Year. Secondary influence on salinity structure, primarily within Sabine Pass. Year-to-year variability of discharges, especially those of the Mississippi and Atchafalaya Rivers, may significantly lower shelf salinities entrained within Sabine Lake (Cochrane and Kelly, 1986).

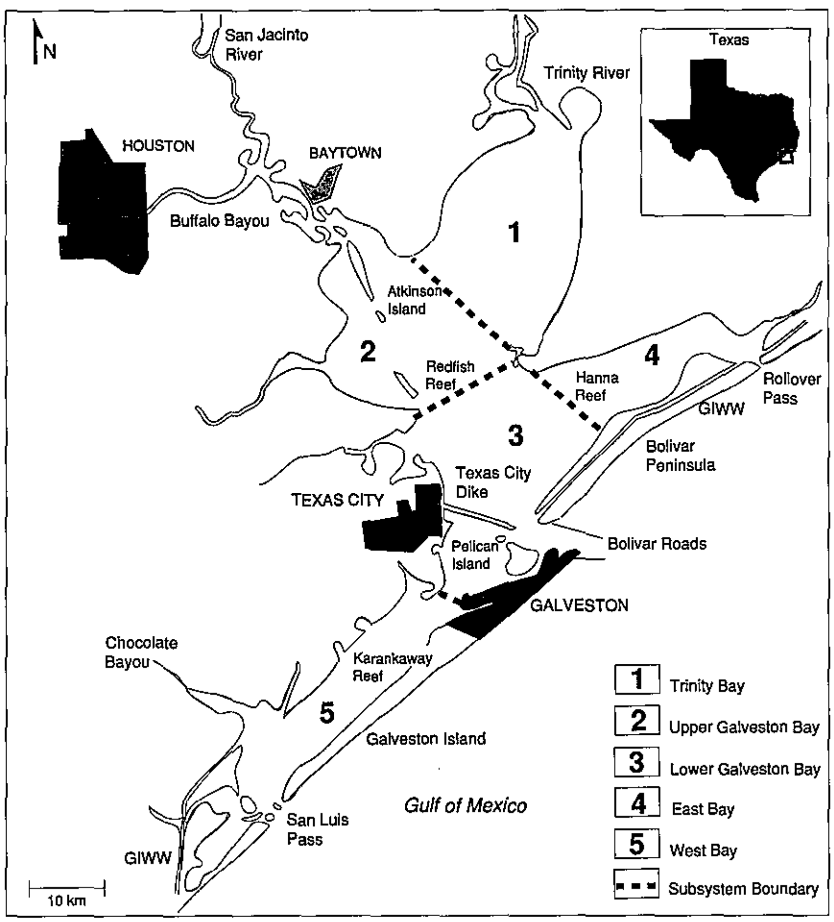
* Data Sources: See data sources listed in Appendix II for Texas.

Geographic Setting

The Galveston Bay estuary encompasses 1,360 km^2 and is the second largest estuary on the Texas coast (NOAA, 1990a). It includes several major embayments: Trinity Bay, Galveston Bay, East Bay, and West Bay, as well as several secondary bays around its periphery (Figure 127). Its boundaries are defined from the head of tide at Liberty on the Trinity River and at the Lake Houston Dam on the San Jacinto River to its terminus with the Gulf of Mexico.

This estuary receives most of its freshwater from the Trinity River, but contributions from the San Jacinto River, Buffalo Bayou complex, and other peripheral inflows may be locally significant. On average, the Trinity River contributes approximately 83% of the estuary's gaged inflow, the San Jacinto River (measured as spillover from the Lake Houston Reservoir which is most common during the winter and spring months) 8%, the Houston Ship Channel (HSC) drainage (Buffalo Bayou and tributaries) 6%, and Chocolate Bayou <1% (USGS, 1990). The ungaged portion is estimated to contribute an additional 3% of the total freshwater to the estuary (TDWR, 1981b). Most tidal exchange (80%) occurs through Bolivar Roads, although San Luis Pass admits the tidal prism for much of West Bay. Minimal exchange occurs through Rollover Pass. This estuary has been divided into five subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 127).

Figure 127. Location map and subsystem identification



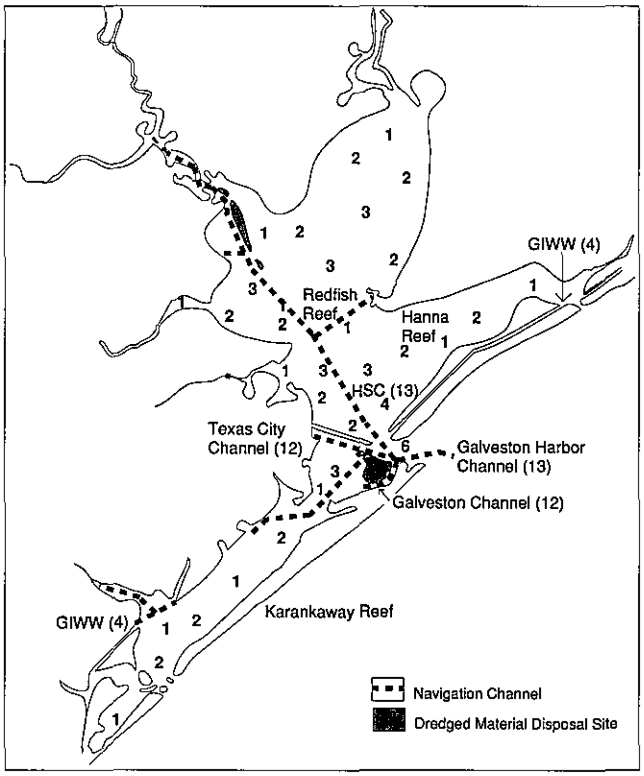
Bathymetry

The average depth of this estuary is 2 m at mid-tide level, although depths of the major and secondary bays differ (NOAA, 1990a). Oyster reefs create numerous shallow areas that may significantly affect currents and water circulation in the estuary (Figure 128). Redfish Reef forms a mid-bay constriction, impeding water exchange between upper and lower Galveston Bay. Hanna Reef retards circulation between East Bay and lower Galveston Bay. Karankaway Reef restricts circulation between the western arm of West Bay and the rest of the estuary. In addition, dredged material disposal sites near the HSC may hinder east-west exchanges across the channel.

The HSC (13 m) breaches Redfish Reef and enhances circulation between the upper and lower estuary. It also facilitates the development of density currents, an important mechanism for salinity intrusion. Density currents result in a net (tidal-mean) flow landward along the bottom, even during the high-salinity period as long as a salinity gradient exists (Ward, 1980). This is especially important in the lower 40 km of the channel, where a tongue of higher-salinity water is frequently aligned with the channel.

The Texas City Dike is a 8.6 km barrier that represents a major physical modification to this estuary. Most low-salinity water flowing from the upper estuary during high-salinity periods is shunted directly to the Gulf by the dike, bypassing West Bay. Because of the location of the dike and the presence of

Figure 128. *Bathymetry (meters)*



Karankaway Reef, salinities in West Bay can remain elevated even when discharges from the Trinity and San Jacinto Rivers are high.

Salinity Patterns

The Data. August-October 1986 and April-June 1985 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions, since the only recent modification to the estuary or its watershed was the completion of the Dallas-Ft. Worth reservoirs in 1986. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 129. Figure 130 compares the average daily freshwater inflow volume on the Trinity River during each month of the selected periods to long-term averages and suggests that the high-salinity period experienced typical inflow conditions (except for an unusually wet July), while freshwater during the low-salinity period was below normal. Figure 131 presents salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 132.

High-Inflow/Low-Salinity Period (April-June 1985). During this selected period and including March 1985, total inflow from Trinity River was approximately 15% below long-term averages (Figures 129 and 130). Daily inflow for the Trinity River generally remained near 200 m^3/s, but peaked in early March (850 m^3/s), early April (600 m^3/s), early May (500 m^3/s), and late May (350 m^3/s). The San Jacinto River was dry during this period, except for short-duration discharges during early March (180 m^3/s) and late March (210 m^3/s).

Salinities throughout the estuary were generally lowest in April following the March freshet, increased until mid-May when the freshet retarded further salinity intrusion, and then increased from late May through June. Salinities in Trinity Bay were most sensitive to fluctuations in the Trinity and San Jacinto River discharges, while West Bay salinities appeared to be independent of these inflows.

The lowest salinities (both surface and bottom) were found near the Trinity River delta and along the eastern shore of Trinity Bay (Figure 131). Salinities increased along a north-south gradient through Galveston Bay. The influence of the HSC was most apparent above Redfish Reef where bottom salinities were 5-10 ppt higher within the channel than in adjacent shallow areas. This difference was less than 5 ppt below Redfish Reef. East Bay salinities were lowest along the northern shore and increased toward Bolivar Roads. The intrusion of saline bottom waters from Bolivar Roads, however, appeared to be inhibited by Hanna Reef. Salinities in West Bay were highly variable and salinities west of Karankaway Reef were often slightly higher than those to the east. Moderate stratification existed within central and western Trinity Bay and within the HSC, while the remainder of the estuary was vertically homogeneous. Salinities were most stable above Redfish Reef and within the HSC, but were more variable near Bolivar Roads and West Bay.

Low-Inflow/High-Salinity Period (August-October 1986). During this selected period and including July 1986, total inflow from Trinity River was about 25% above long-term averages (Figures 129 and 130). Daily inflow for Trinity River remained below 70 m^3/s, except for peak inflows during early July (550 m^3/s) and mid-October (200 m^3/s). As a result, Trinity River discharges did not dominate estuarine salinities during this period as during the low-salinity period. No inflow occurred in the San Jacinto River during this period.

Salinities were higher and more variable during this period than during the low-salinity period (April-June 1985). Salinities in Trinity Bay were lowest along its eastern shore, while higher salinities penetrated the central and western bay. In Galveston Bay, salinities were 5-10 ppt higher than during the low-salinity period and were less stable. Although Gulf waters appeared to exert more control on salinity in lower Galveston Bay, a significant response to freshwater events was still apparent. Surface salinities below Redfish Reef were particularly unstable and bottom waters within the HSC showed a large range of variability. Salinity data for East Bay and West Bay were limited, but indicated a relatively stable structure in East Bay and highly variable conditions in West Bay. Moderate-to-high stratification occurred in the HSC, Galveston Channel, and in some locations near Bolivar Roads. Vertical stratification was generally absent in the remainder of the estuary.

Factors Affecting Variability

The salinity structure is determined by the seasonal freshwater discharge which depends primarily on the magnitude and duration of inflow from the Trinity River. It is most responsive to the seasonal discharge, but demonstrates important variability at other time scales. Prevailing seasonal winds, density currents, and shelf processes contribute less to salinity structure than the freshwater inflow (Figure 132). West Bay, however, is often isolated from seasonal discharges, and salinities are determined by local runoff and winds.

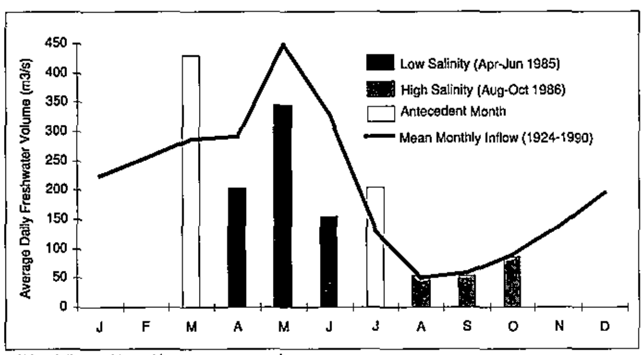
The important time scales of salinity variability and responsible mechanisms are summarized in Figure 132. Stability is strongly related to Trinity River discharge. Low frequency flood events (i.e., 10- to 20-year events) dominate the entire estuary and erase the vertical gradient in all but the HSC. They permit little variability and hinder recovery for extended periods. Typical seasonal discharges maintain relative stability within Trinity Bay and, to a lesser extent, in upper Galveston Bay. Vertical stratification is most widespread during seasonal high-salinity periods. Wind, especially when associated with frontal passages, is an important modifier of the seasonal structure and may induce short-term water-column mixing throughout the estuary. Tides may further enhance mixing in lower Galveston Bay. Low-salinity periods on the Trinity River allow amplification of diurnal winds, frontal passages, freshets, and tides on salinity variability. Inflows from the San Jacinto River and Buffalo Bayou are responsible for short-term displacement of high-salinity bottom waters in the HSC. Density currents have probably contributed to an increase in salinities over time, although the high-salinity variability due to other factors makes it difficult to separate the channel effect.

Figure 129. Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods

	April - June 1985 (High Inflow/Low Salinity)	August - October 1986 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	313	182
Sampling Distribution [a]	1-5	1-5
Sampling Frequency	weekly - monthly	weekly - monthly
Average Salinity (ppt)	12.3	15.6
Bottom Salinity		
# of Observations	524	49
Sampling Distribution [a]	1-5	1-5
Sampling Frequency	weekly - monthly	monthly
Average Salinity (ppt)	15.1	21.7
Freshwater Inflow		
Trinity River Volume	15% below average [b]	25% above average [c]
Return Frequency of Peak Events		
1-day duration	1.2-year	2.2-year
7-day duration	1.3-year	2.1-year
30-day duration	1.5-year	2.2-year

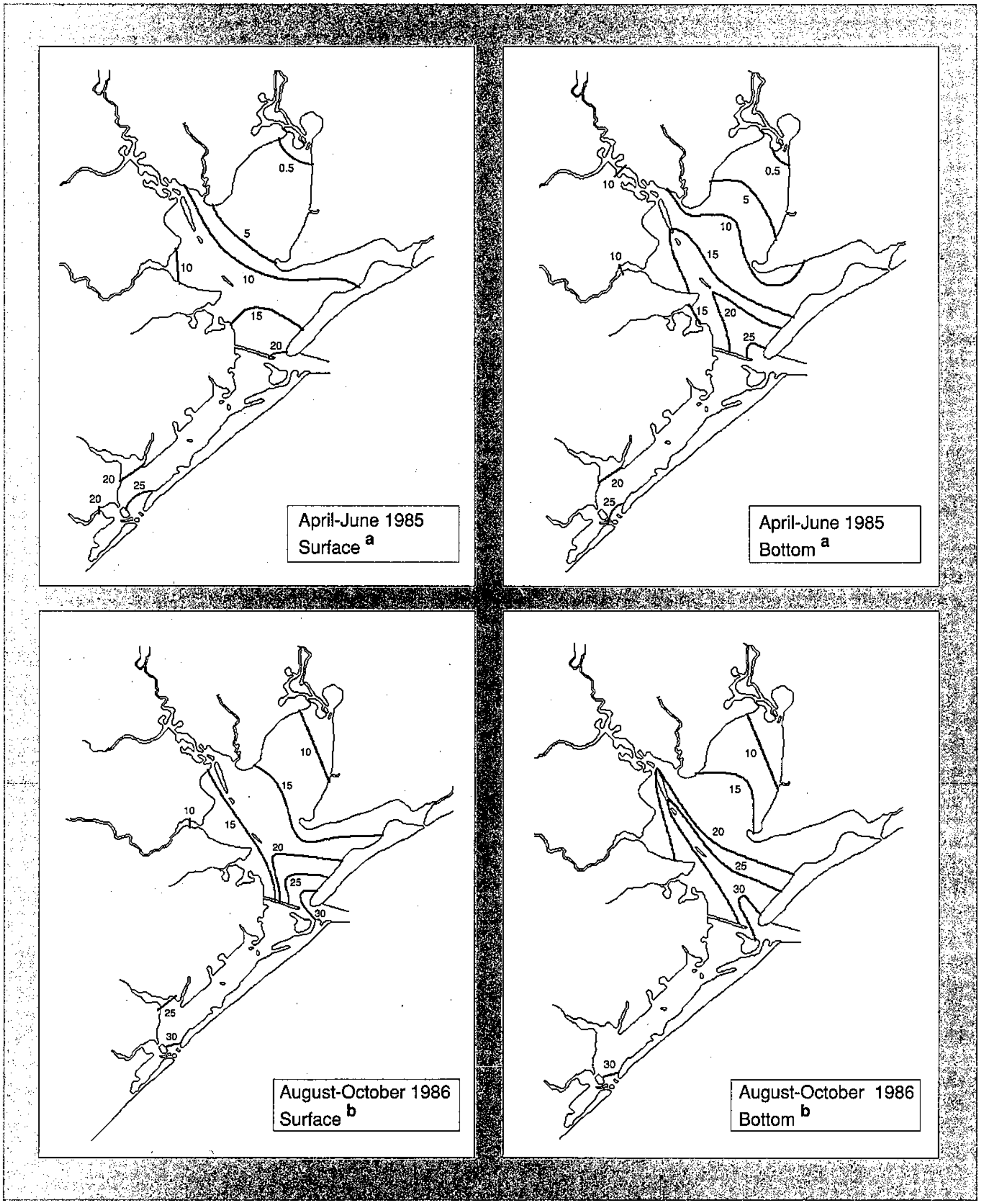
Abbreviation: ppt - parts per thousand
a. Subsystem(s) with high sampling density
b. Includes March 1985
c. Includes July 1986

*Figure 130. Comparison of gaged freshwater volume for the Trinity River at Romayor, TX, during periods of salinity depiction and period-of-record averages **



Abbreviation: m3/s - cubic meters per second
* USGS gages reflect inflow from 70% of the estuary's total watershed (63,455 km2) (USGS, 1990)

Figure 131. *Surface and bottom salinities during low- and high-salinity periods*

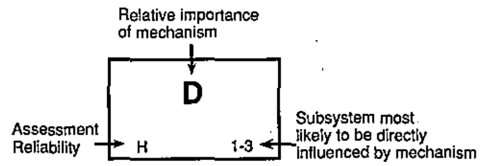


a. Data Sources: TSDH, 1991; TWC, 1991; TWDB, 1991a; TPWD, 1991
b. Data Sources: TSDH, 1991; TWC, 1991; TWDB, 1991a

Figure 132. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S (L 1-5)	D (H 1-5)	D (H 1-5)	
Tides		M (LIT 3)			
Wind		S (LIT 1-5)			
Density Currents		M (LIT 2-3)	S (LIT 2-3)		
Shelf Processes			S (LIT 3.5)	M (LIT 3.5)	
Effect on Salinity Variability	UNKNOWN	LOW	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 131 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 the salinity structure and temporary increase of vertical stratification near freshwater sources. Short-term retarding of HSC bottom waters for significant San Jacinto/Buffalo Bayou inflow.

Months-Seasons. Dominant influence on the salinity structure, except in West Bay. March-June inflow is four times greater than the July-October inflow. Also, April-June inflows usually produce stable, moderately stratified salinities above Redfish Reef, but less stable, moderately stratified salinities below the reef. Weakened July-October inflows allow increased variability in the upper bays, and a reduction in vertical stratification throughout the estuary.

Year-Year. Dominant influence on the salinity structure. Flood-drought sequence may produce near-fresh to near-Gulf salinities throughout the estuary. During 1970-1988, mean annual estuary-wide salinities ranged from 10-28 ppt. Year-to-year variability between April-June is higher than between August-October, due to the increased range of year-to-year freshwater volumes.

Tides

Days-Weeks. Minor influence on the salinity structure; less significant tropic-equatorial cycle in lower Galveston Bay induces mixing and decreases stability.

Winds

Days-Weeks. Secondary influence on the salinity structure. Cold fronts occur between October-March, but are most frequent between December-February. Winds induce mixing and may cause a moderately important short-term alteration of salinity structure throughout the estuary.

Density Currents

Days-Weeks. Minor influence on the salinity structure. Moderately important, short-term landward displacement of saline bottom waters exists in the HSC during modest freshwater increases.

Months-Seasons. Secondary influence on the salinity structure. Sufficient freshwater will sustain density currents in the HSC during high- and low-inflow periods, and may have an influence on salinities near this channel.

Shelf Processes

Months-Seasons. Secondary influence on the salinity structure. Temporary decrease of entrained shelf-water salinity to lower Galveston Bay usually during May and October (Cochrane and Kelly, 1986).

Year-Year. Minor, perhaps a more prolonged decrease of entrained shelf water salinity to lower Galveston Bay usually during May and October. Gulf salinities off Galveston range from 27-35 ppt.

* Data Sources: See data sources listed in Appendix II for Texas.

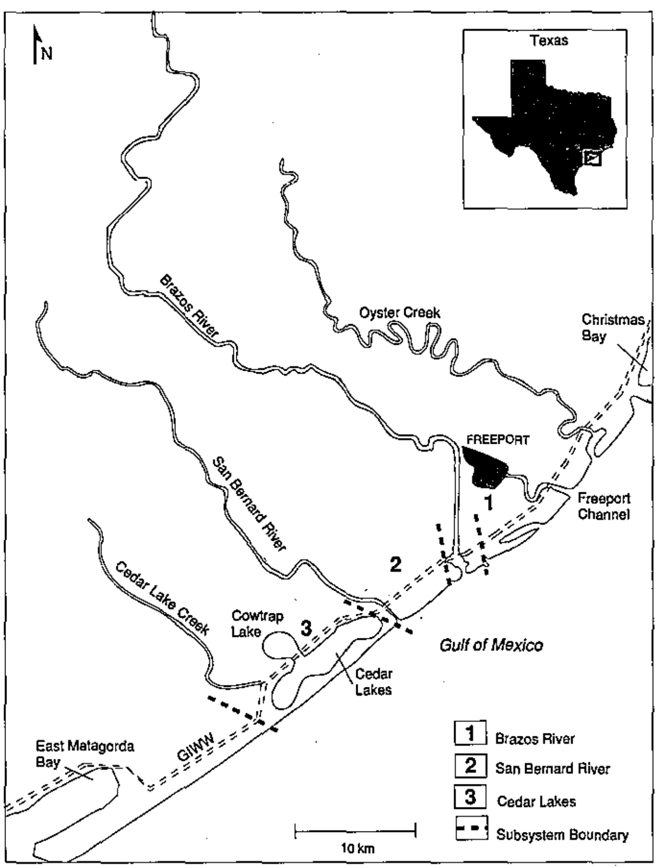
21 Brazos River & San Bernard River/Cedar Lakes, TX

Geographic Setting

The Brazos River and San Bernard River/Cedar Lakes estuaries occupy just 34 km^2 (NOAA, 1990a). Unlike most Texas estuaries, they do not include a large bay behind a barrier island system (Figure 133). Although close in geographical proximity, these estuaries are hydrologically separate systems except for the tenuous connection of the GIWW, connecting Christmas Bay on the east and East Matagorda Bay on the west. Freshwater inflow to these estuaries is derived almost exclusively from the Brazos and San Bernard Rivers.

The Brazos River estuary extends from the head of tide, approximately 5 km upstream of the Missouri Pacific Railroad (USFWS, 1982b), to the Gulf of Mexico. It includes the main stem of the Brazos River, the GIWW east of the river, and adjacent wetlands. In 1929, the lower Brazos River was re-routed west of the natural channel. Today, this channelized portion of the river is this estuary's primary inlet. The former lower reach of the river was blocked and now serves as Freeport Harbor.

Figure 133. Location map and subsystem identification.



Like Sabine Lake estuary, this estuary has a relatively high freshwater discharge to estuary volume ratio.

The San Bernard River/Cedar Lakes estuary extends from the head of tide at the salt barrier, approximately 2 km upstream of State Highway 35 (USFWS, 1982b), to its terminus with the Gulf. It encompasses the area west of the Brazos River, including the associated marshes interspersed with tidal creeks. Cedar Lakes and Cowtrap Lake, located west of the San Bernard River, are the two largest areas of open water within this estuary. Most exchange with the Gulf occurs through the mouth of the San Bernard River, although minimal exchange occurs through ephemeral washover inlets (e.g., Cedar Cut). The shoreline from Freeport to the Colorado River mouth is the most erosive on the Texas coast. Along Cedar Lakes, the sand has been lost and the clay foundation exposed. There is imminent danger that Cedar Lakes will be breached and opened to the Gulf. San Bernard River inflows are derived from a very localized portion of a watershed between the Brazos and Colorado Rivers and exhibit a strong response to rainfall (Bales, 1986). Cedar Lakes receives minor discharges from Cedar Lake Creek.

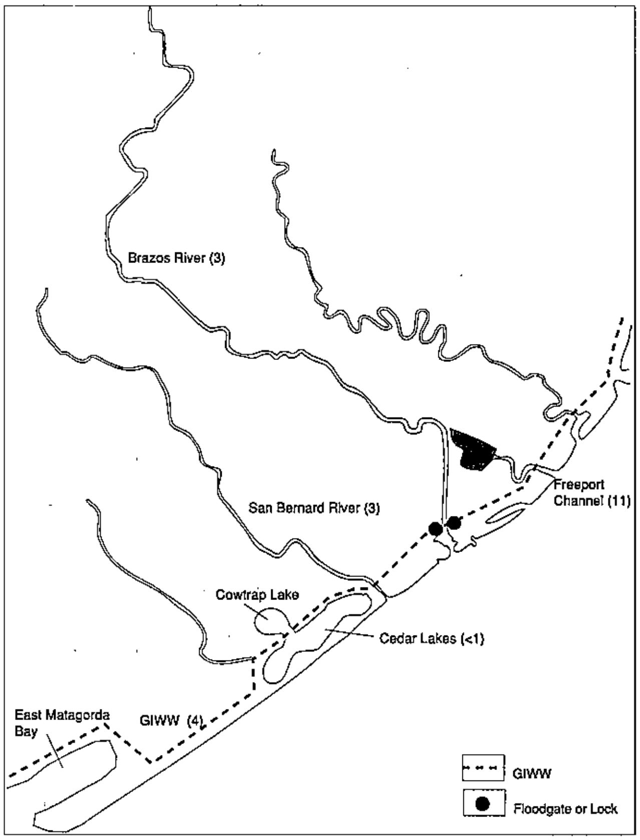
These estuaries have been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 133).

Bathymetry

Most areas within these estuaries are very shallow and water depths average less than 1 m at mid-tide level (NOAA, 1990a). The deepest parts are in the channels of the San Bernard and Brazos Rivers (3 m) and the GIWW (4 m) (Figure 134). Cedar Lakes has an average depth of <1 m at mid-tide level (Diener, 1975).

Although the GIWW intersects the Brazos and San Bernard Rivers, floodgates impede circulation between the Brazos River and GIWW (Johnson, 1977) (Figure 134). Exchanges occur only when the locks are open during periods of heavy ship traffic (Kirkpatrick, 1972). Free exchange occurs between the GIWW and the San Bernard River, and tidal scouring at their intersection maintains depths in excess of 12 m (Johnson, 1977). Kirkpatrick (1972) reported that flow in the GIWW was from southwest to northeast during low-inflow periods. During high-inflow periods, waters from the Brazos River flow out into the GIWW (when the locks are open to ship traffic), as well as into the Gulf (Kirkpatrick,

Figure 134. *Bathymetry (meters)*



1972). Exchange occurs between Cedar Lakes and the GIWW through several shallow channels, while flow between Cowtrap Lake and the GIWW is restricted to a single channel (Johnson, 1977).

Dredged material disposal areas affect water movement in Cedar Lakes. At present, the GIWW is partially separated from Cedar Lakes by a discontinuous ridge of dredge disposal material (McGowen et al., 1976a). Before 1925, the GIWW went through the center of Cedar Lakes. The submerged dredged material mounds near the old channel may still affect circulation within Cedar Lakes (Johnson, 1977).

Salinity Patterns

The Data. August-October 1975 and April-June 1975 were selected to represent high- and low-salinity periods, respectively, for the Brazos River (Figure 136). These periods should reflect present-day conditions as no major modifications to this estuary or its watershed have occurred since 1962. For the San Bernard River, August-October 1974 and April-June 1974 were selected to represent the high- and low-salinity periods, respectively. Data for both estuaries was extremely limited. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 135. Figure 136 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that neither period experienced typical inflow conditions. Figure 137 presents salinity distributions for the selected periods, illustrating the dominance of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 138.

High-Inflow/Low-Salinity Period

Brazos River Estuary (April-June 1975). During this selected period and including March 1975, total inflow from the Brazos River was approximately 45% above long-term averages (Figures 135 and 136). A significant freshening of the Brazos River is apparent during the high-inflow (low-salinity) period, but its magnitude may be exaggerated by the above-normal inflows during May or may be distorted by the relatively sparse data available for analysis (Figure 137); however, note the extent of bottom water intrusion within the Brazos River, even during high-inflow periods (Figure 137). For example, before the April freshet, bottom salinities exceeding 15 ppt reached 22.5 km above the river mouth, producing a highly stratified water column. Saline bottom water intrusion was abruptly interrupted between 22.5 and 29 km upstream of the river mouth. Following the April and May freshets, bottom waters were forced Gulfward and were suppressed below 1 ppt at sampling stations greater than 12 km upstream of the river mouth. Saline bottom waters within the lower river, however, returned quickly and re-established moderate-to-high vertical stratification.

San Bernard River/Cedar Lakes Estuary (April-June 1974). During this selected period and including March 1974, total inflow from the San Bernard River was approximately 45% below long-term averages (Figures 135 and 136). Flows from the San Bernard River were less than 10 m^3/s, except for two peaks in mid- and late-March (50 and 35 m^3/s, respectively) and one peak in mid-May (85 m^3/s). The lowest salinities occurred in May, coinciding with the peak inflow event. Surface salinities within the river were most responsive and remained depressed during the period. Bottom salinities within the river were also depressed during May, although high salinities were re-established in the lower river by June (Figure 137). Cedar Lakes salinities demonstrated little response to San Bernard River flows. Moderate stratification was observed in the lower

San Bernard River and high stratification occurred in the San Bernard River 42 km upstream of the GIWW near an industrial brine discharge point (Johnson, 1977). Stratification in the GIWW was not observed, except at one location in June.

Low-Inflow/High-Salinity Period

Brazos River Estuary (August-October 1975). During this selected period and including July 1975, total inflow from the Brazos River was approximately 5% above long-term averages (Figures 135 and 136). Salinity distributions and discussions of its stability are based on two measurements made during September 1975 (Figure 135). Salinity measurements were very similar from one date to the next since freshwater inflow was relatively unchanged for the two-week interval between sampling dates. Salinities were higher during this period than during the low-salinity period (Figure 135), and intrusion of high-salinity bottom waters was noted further upstream of the GIWW. Moderate-to-highly stratified conditions existed from the river mouth to more than 22.5 km upstream. Highly stratified conditions were again suddenly replaced by vertically homogeneous conditions at an unknown point between 22.5-29 km upstream of the river mouth.

San Bernard River/Cedar Lakes Estuary (August-October 1974). During this selected period and including July 1974, total inflow from the San Bernard River was approximately 30% above long-term averages (Figures 135 and 136). The major freshwater inflow peak from the San Bernard River occurred in mid-September (110 m^3/s). Minor peaks occurred in mid-July, mid-August, and early September (about 20 m^3/s each). Another minor peak (55 m^3/s) occurred in mid-October. Average salinities were very similar to those depicted for the low-salinity period, probably due to similar inflow volumes during the two periods and to the limited availability of salinity data. The response of salinity to the September freshet, however, was much weaker than the response to the May 1974 freshet. Irregular high-salinity values were recorded at the same sampling stations demonstrating this salinity response during June 1974.

Factors Affecting Variability

The salinity structure of these estuaries is determined by the seasonal freshwater discharge. Most freshwater from the Brazos River is shunted to the Gulf so that its effect on salinity is greatest in the channelized river and not in the interdistributary

Figure 135. Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods

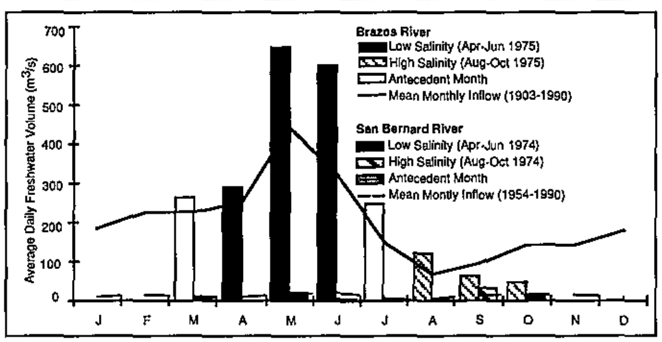
Brazos River	April-June 1975 (High Inflow/Low Salinity)	August-October 1975 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	48	28
Sampling Distribution [a]	1	1
Sampling Frequency	Biweekly (Sep only)	Monthly
Average Salinity (ppt)	1	4
Bottom Salinity		
# of Observations	50	28
Sampling Distribution [a]	1	1
Sampling Frequency	Biweekly (Sep only)	Monthly
Average Salinity (ppt)	7	18
Freshwater Inflow		
Volume	45% above average [b]	5% above average [c]
Return Frequency of Peak Events		
1-day duration	3.4-year	1.4-year
7-day duration	3.4-year	1.6-year
30-day duration	3.8-year	1.8-year

Abbreviation: ppt - parts per thousand
a. Subsystem(s) with high sampling density
b. Includes March 1975
c. Includes July 1975

San Bernard River	April-June 1974 (High Inflow/Low Salinity)	August-October 1974 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	33	33
Sampling Distribution [a]	2-3	2-3
Sampling Frequency	Monthly	Monthly
Average Salinity (ppt)	71	11
Bottom Salinity		
# of Observations	21	21
Sampling Distribution [a]	2-3	2-3
Sampling Frequency	Monthly	Monthly
Average Salinity (ppt)	13	14
Freshwater Inflow		
Volume	45% below average [b]	30% above average [c]
Return Frequency of Peak Events		
1-day duration	2.0-year	3.9-year
7-day duration	2.2-year	3.7-year
30-day duration	1.9-year	3.9-year

Abbreviation: ppt - parts per thousand
a. Subsystem(s) with high sampling density
b. Includes March 1974
c. Includes July 1974

*Figure 136. Comparison of gaged freshwater volume for the Brazos River at Richmond, TX and San Bernard River at Boling, TX during periods of salinity depiction and period-of-record averages**



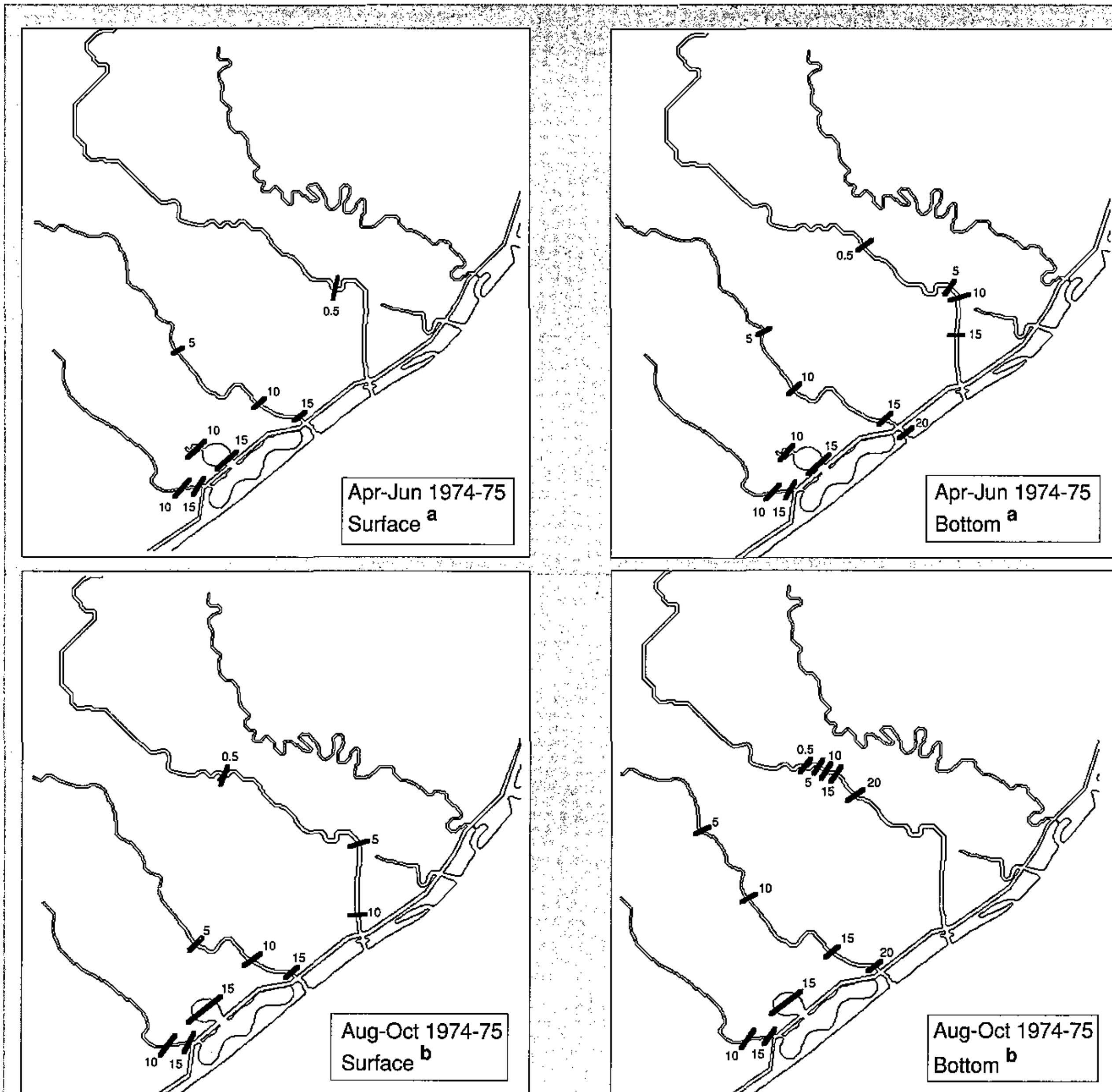
Abbreviation: m3/s - cubic meters per second

* USGS gages reflect inflow from 98% of the Brazos River/San Bernard River/Cedar Lakes' total watershed (121,207 km2) (USGS, 1990)

areas of the estuary. Flows from the San Bernard River, however, are not as confined to the river channel and may influence salinities over a large portion of its estuary. The salinity structure of Cedar Lakes is determined by wind-driven advection of waters from the San Bernard River or the Gulf through the GIWW. These mechanisms operate on time scales of weeks and result in an unstable salinity structure. Stratification is most common in the lower Brazos and San Bernard River channels (Johnson, 1977). Cedar Lakes and Cowtrap Lake, however, are very shallow and salinities are nearly vertically homogeneous (Johnson, 1977).

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 138. Variability in the Brazos and San Bernard River systems is primarily determined by short-term fluctuations of river discharges. Brine discharges also appear to locally influence salinity in the Brazos and San Bernard Rivers. Wind events are the most important modifier of the Cedar Lakes structure.

Figure 137. *Surface and bottom salinities during April-June 1975 and August-October 1975 for the Brazos River and April-June 1974 and August-October 1974 for San Bernard River*

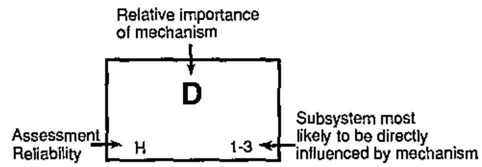


a. Data Sources: Armstrong and Goldstein, 1975; Johnson, 1977
b. Data Sources: Armstrong and Goldstein, 1975; Johnson, 1977

Figure 138. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		D L 1-3	D L 1-3	D L 1-3	
Tides	M LIT 1				
Wind		S LIT 3			
Density Currents		S LIT 1			
Shelf Processes			M LIT 1-3		
Brine Discharges		M LIT 1-2			
Effect on Salinity Variability	UNKNOWN	LOW	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 137 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, especially in the Brazos and San Bernard Rivers.

Months-Seasons. Dominant influence on salinity structure throughout the estuary. Freshwater inflow in the Brazos River is roughly three times greater during April-June 1975 than during August-October 1975. The result is a significant decrease in average surface salinities and retarding of saline bottom water intrusion during the high-inflow period. This process is less pronounced in the San Bernard River.

Year-Year. Dominant influence on salinity structure.

Tides

Hours. Minor influence on salinity variability, primarily near the Brazos River mouth. Astronomical tides are diurnal and typically range 0.6 m (NOAA, 1989b).

Wind

Days-Weeks. Secondary influence on salinity variability, particularly in Cedar Lakes. Cold fronts penetrate this area between October-March, but most frequently between December-February (on average 15-20 events). These events are associated with water-column mixing. Wind-driven exchanges with both the San Bernard River and Gulf determine salinity structure in Cedar Lakes.

Density Currents

Days-Weeks. Secondary influence on salinity structure, primarily in the Brazos River. High-salinity bottom waters may extend more than 25 km upstream of the river mouth, but are pushed Gulfward by freshets.

Shelf Processes

Months-Seasons. Minor influence on salinity structure, primarily at the river mouths.

Brine Discharges

Days-Weeks. Locally important, minor influence on salinity variability in the Brazos and San Bernard Rivers.

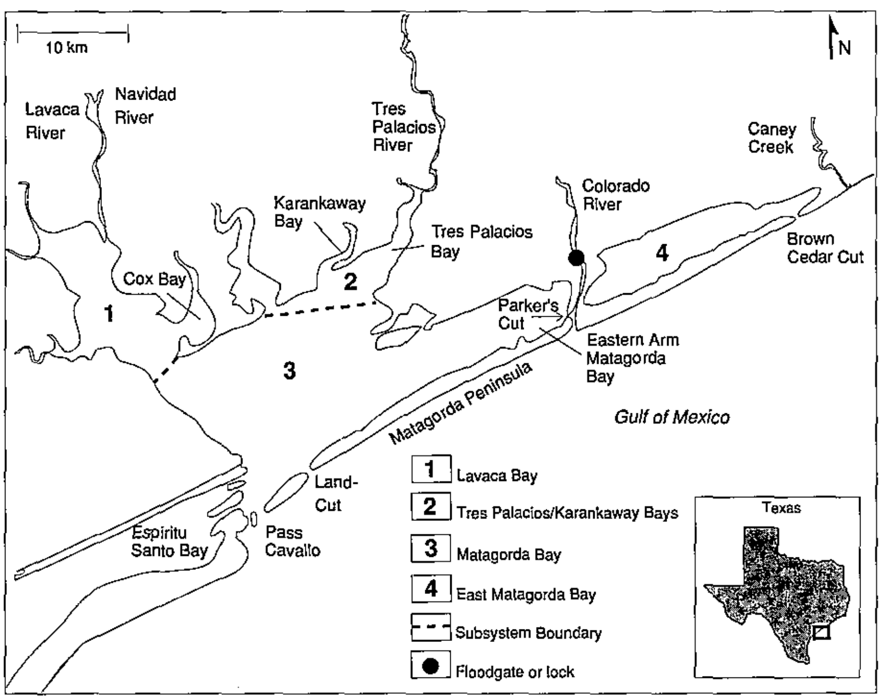
* Data Sources: See data sources listed in Appendix II for Texas.

Geographic Setting

The Matagorda Bay estuary is a broad, shallow lagoonal system which occupies 1200 km^2 (NOAA, 1990a) and is nearly isolated fromthe Gulf by Matagorda Peninsula. It encompasses the estuarine reach of the Colorado River, and the bar-built embayments of Matagorda Bay to the west and East Matagorda Bay to the east (Figure 139). Matagorda Bay, in turn, includes the secondary bays of Lavaca, Karankaway, and Tres Palacios. The inland boundaries of the estuarine system are defined from the head of tide on the Colorado River at the Missouri Pacific Railroad crossing (salt barrier); State Highway 35 on the Tres Palacios River; and Lake Texana on the Navidad River.

The Colorado River is estimated to deliver 25-80% of the total freshwater volume to the estuary (primarily through Parker's Cut), depending on river flow, river mouth conditions, and tides (Ward et al., 1980). The estuary also receives significant inflow from the Lavaca/Navidad and Tres Palacios basins. A lock system prevents Colorado River floodwaters from entering the GIWW; the locks are closed when Colorado River inflows exceed 140 m^3/s (Ward et al., 1980). Most tidal exchange occurs through Pass Cavallo and the Land Cut (Masch and Associates, 1971), although some exchange occurs through the Colorado River mouth complex through Parker's Cut. The estuary also has a minor connection to Espiritu Santo (the eastern arm of the San Antonio Bay estuary) through two narrow channels on the west shore of Pass Cavallo. Although the exchange between the two estuaries is unknown, it may be equivalent to 10% of the estuary's tidal prism volume (Ward et al., 1980). This estuary has been divided into four subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 139).

Figure 139. *Location map and subsystem identification*



Bathymetry

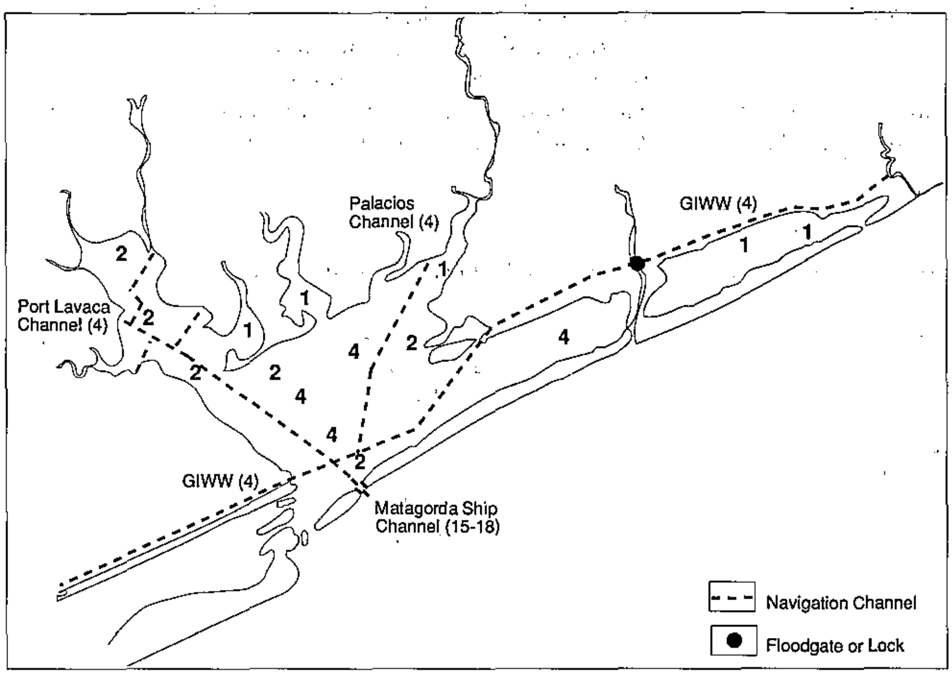
The average depth of this estuary is only 2 m at mid-tide level (Figure 140) (NOAA, 1990a). Numerous shoals exist throughout the estuary and are most commonly associated with oyster reefs. These shoals may significantly affect currents and water circulation.

Creation of the Matagorda Ship Channel (MSC) in 1963 represents one of the few instances in which a deep-draft channel (11 m) was instituted *from scratch* and alterations to the patterns of tidal exchange and salinity intrusion within the system could potentially be documented. The MSC allowed the development of density currents, an important mechanism for salinity intrusion into this estuary. These density currents likely result in a net flow landward along the bottom even during the high-salinity period. In the open bay, tidal mean flow can probably be directed upstream throughout the water column (Ward et al., 1980). This density-current mechanism was believed to have been responsible for a 2-5 ppt increase in the average salinities of Lavaca Bay and western Matagorda Bay, following the deepening of the channel (Ward et al., 1980).

Salinity Patterns

The Data. August-October 1975 and April-June 1985 were selected to represent high- and low-salinity periods, respectively. August-October 1975 does not reflect the construction of the Palmetto Bend (Lake Texana)

Figure 140. *Bathymetry (meters)*



Salinities increased from the secondary bays toward the inlets of the Land Cut and Pass Cavallo, and from the eastern arm of Matagorda Bay towards the inlets. High-salinity waters associated with the MSC dominated the western portion of this estuary and extended deep within Lavaca Bay. Salinities within the secondary bays were most responsive to the freshwater discharge and exhibited a steep horizontal salinity gradient. Freshwater appeared to have a more limited influence on salinities within the central and lower bay.

Reservoir in 1980 (USACE, 1988). A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 141. Figure 142 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that neither period experienced typical inflow conditions. Figure 143 presents salinity distributions for these periods, illustrating the influence of seasonal freshwater discharge on the salinity structure. This structure, however, experiences variability as indicated in Figure 144.

High-Inflow/Low-Salinity Period (April-June 1985). During this selected period and including March 1985, total inflow for the Colorado River was approximately 30% below long-term averages, while the Lavaca/Navidad Rivers were approximately 20% above long-term averages (Figures 141 and 142). Discharges from the Colorado River were below average in April but near normal during May and June. The Lavaca/Navidad discharge was above normal in April, but below normal in May and June. In general, the lowest salinities occurred in late April, following a short-term freshwater pulse, while the highest salinities occurred in late May when freshwater inflow was hardly detectable. Where available, data indicated nearly vertically homogeneous conditions, except within the MSC (Figure 143). Salinity data for East Matagorda Bay were extremely limited.

Low-Inflow/High-Salinity Period (August-October 1975). During this selected period and including July 1975, total inflow for the Colorado River was approximately 15% above long-term averages, while the Lavaca/Navidad Rivers were approximately 35% below long-term averages (Figures 141 and 142). Colorado and Lavaca/Navidad inflows generally declined from July through October, with peak discharges occurring in early July and early August.

Salinity data were only available for August and October, but indicated certain differences when compared to the low-salinity period. Average salinities were less than 5 ppt higher, indicating a modest influence of seasonal freshwater on salinity. High-salinity bottom waters within the MSC appeared to intrude further into this estuary, resulting in moderate-to-high stratification in Lavaca Bay (Figure 143). The remainder of this estuary was generally vertically homogeneous.

Factors Affecting Variability

The most significant changes in bay-wide salinity distributions are arguably attributable to seasonal fluctuations of freshwater inflow. The response of salinity is most direct in bays near the freshwater source; however, the indirect influence of freshwater is important, even at low inflows, in establishing salinity variations across the open bay. Vertically homogeneous conditions commonly exist in the open bay, although a vertical gradient may be present in western Matagorda Bay and the secondary embayments.

The important time scales of salinity variability and responsible mechanisms are given in Figure 144.

Most variability occurs within the secondary embayments and is associated with variation in the freshwater discharge. Density currents within the MSC are responsible for intrusion of high-salinity bottom waters and increased variability in western Matagorda Bay and Lavaca Bay. Eastern and central Matagorda Bay are relatively stable.

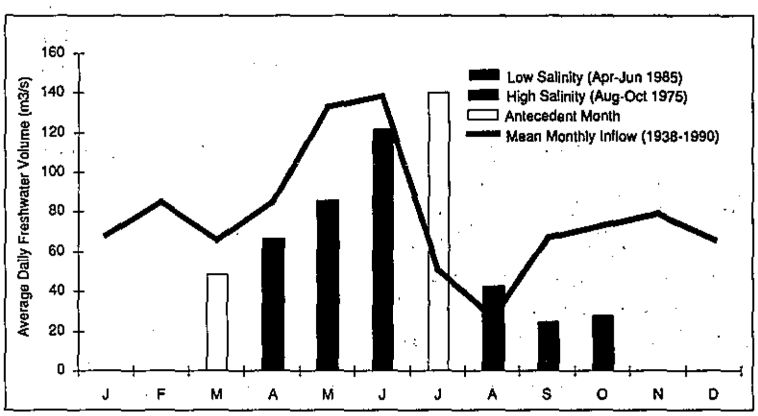
Figure 141. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	April-June 1985 (High Inflow/Low Salinity)	August-October 1975 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	154	50
Sampling Distribution [a]	1-4	1-4
Sampling Frequency	monthly	monthly
Average Salinity (ppt)	12.7	16.5
Bottom Salinity		
# of Observations	113	32
Sampling Distribution [a]	1-4	1-4
Sampling Frequency	weekly-monthly	monthly
Average Salinity (ppt)	22.0	22.2
Freshwater Inflow		
Volume		
Colorado River	30% below average [b]	15% above average [c]
Lavaca-Navidad Rivers	20% above average [b]	35% below average [c]
Return Frequency of Peak Events		
Colorado River		
1-day duration	1.3-year	1.5-year
7-day duration	1.3-year	1.6-year
30-day duration	1.6-year	1.5-year
Lavaca River		
1-day duration	9.0-year	1.2-year
7-day duration	5.1-year	1.3-year
30-day duration	5.0-year	1.5-year

Abbreviation: ppt - parts per thousand

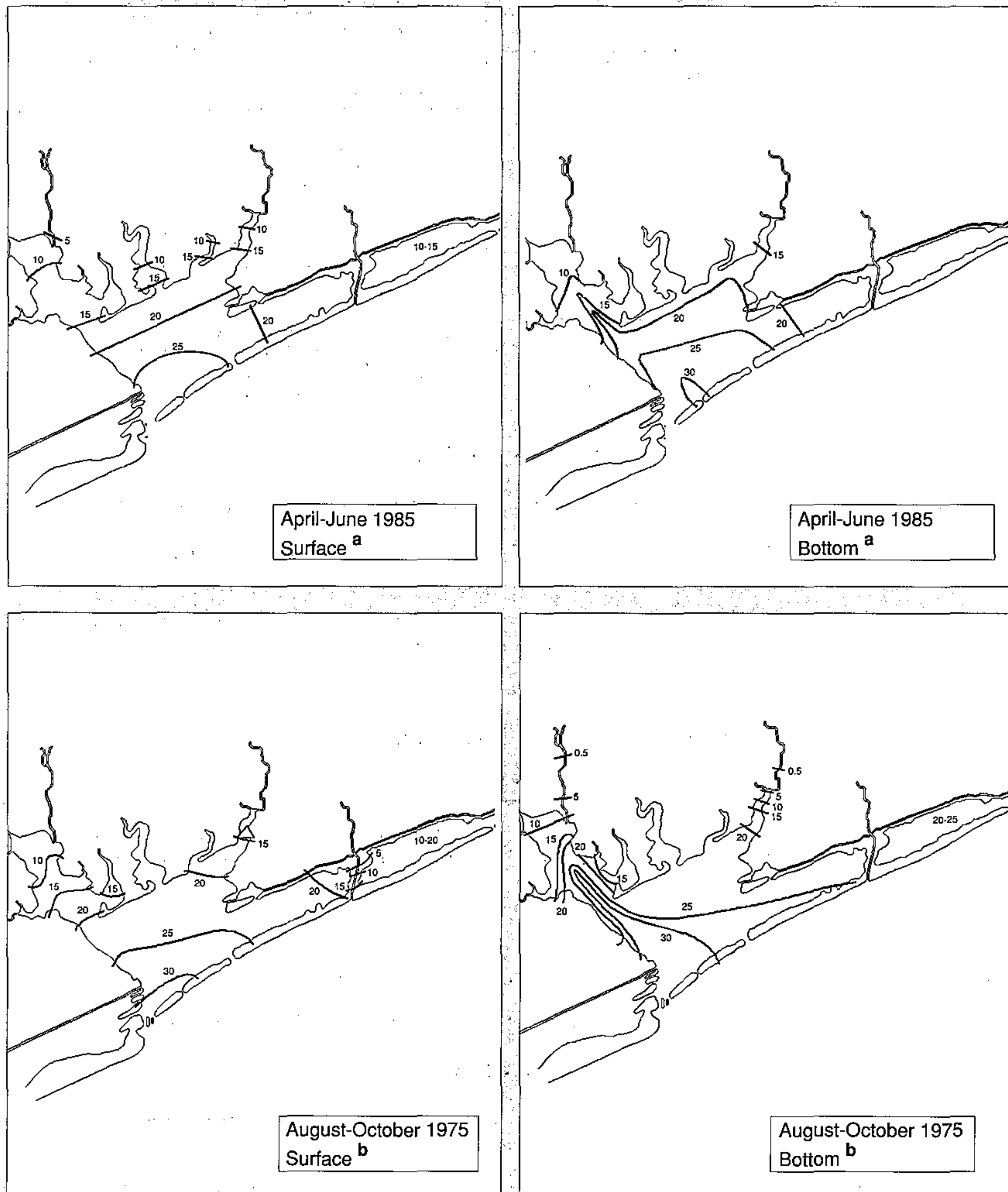
a. Subsystem(s) with high sampling density
b. Includes March 1985
c. Includes July 1975

Figure 142. *Comparison of gaged freshwater volume for the Colorado/Navidad/Lavaca Rivers during periods of salinity depiction to period-of-record averages**



Abbreviation: m3/s - cubic meters per second
* USGS gage reflects inflow from 86% of the estuary's total watershed (130,272 km2) (USGS, 1990)

Figure 143 *Surface and bottom salinities during low- and high-salinity periods*

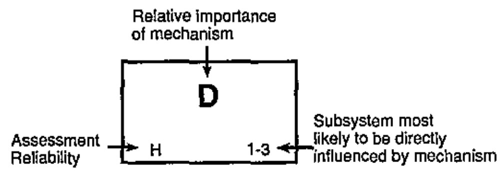


a. Data Sources: TPWD, 1991; TSDH, 1991; TWC, 1991; TWDB, 1991a/b
b. Data Sources: TWC, 1991; TWDB, 1991a

Figure 144. *Time scales and forcing mechanisms important to salinity structure and variability*

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		D (M 1-2)	D (H 1-4)	D (M 1-4)	
Tides		M (LIT 3)			
Wind		S (LIT 3-4)			
Density Currents		M (LIT 1,3)	S (LIT 1,3)		
Shelf Processes			M (LIT 3)	M (LIT 3)	
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 143 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, short-term influence on salinity structure, primarily in the secondary embayments.

Months-Seasons. Dominant estuary-wide influence on salinity structure. Inflows during April-June are two times higher than during July-October.

Year-Year. Dominant influence on estuary-wide salinity structure. During 1970-1988, average annual salinities indicate a trend toward decreasing freshwater inflow and increasing average salinity.

Tides

Days-Weeks. Minor influence on salinity variability in lower Matagorda Bay.

Wind

Days-Weeks. Secondary influence on salinity structure throughout the estuary. Cold fronts occur between October-March, but most frequently between December-February (15-20) (McGowen et al., 1976b). Winds inhibit vertical stratification under most conditions.

Density Currents

Days-Weeks. Minor influence on salinity variability and vertical stratification in western Matagorda Bay and Lavaca Bay.

Months-Seasons. Secondary influence on salinity structure in western Matagorda Bay and Lavaca Bay.

Shelf Processes

Months-Seasons. Minor influence on salinity structure. River plumes from Louisiana and north Texas estuaries may decrease salinity of entrained shelf waters usually during spring-summer.

Year-Year. Minor influence on salinity structure. River plumes from Louisiana and north Texas estuaries may decrease salinity of entrained shelf waters usually during spring-summer.

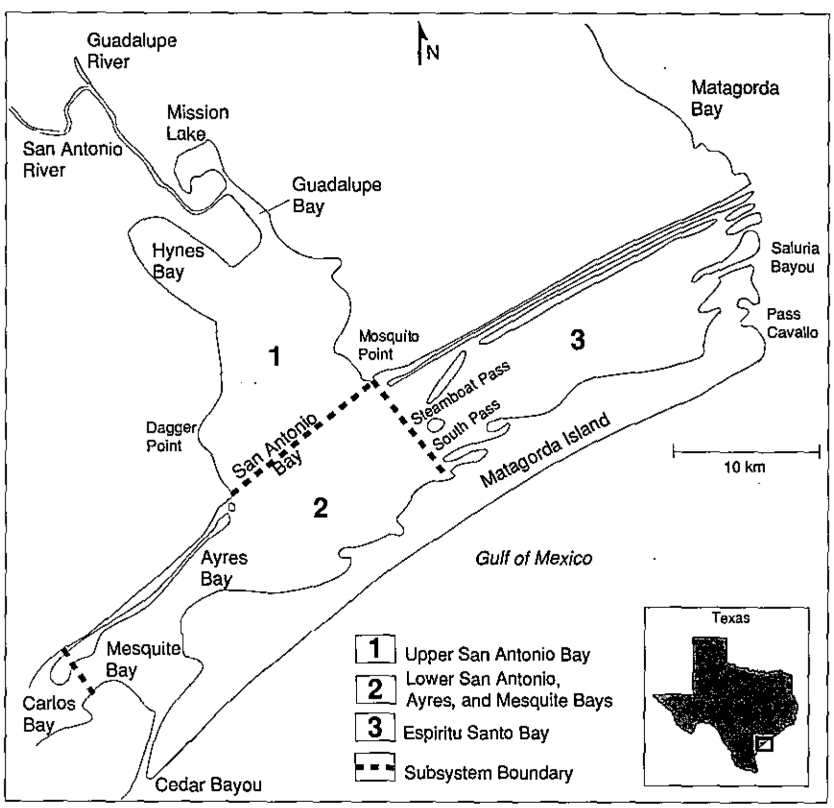
* Data Sources: See data sources listed in Appendix II for Texas.

Geographic Setting

The San Antonio Bay estuary occupies 530 km² (NOAA, 1990a) and is nearly isolated from the Gulf of Mexico by Matagorda Island. It consists of three major embayments: San Antonio, Espiritu Santo, and Mesquite Bays, as well as several secondary bays around its periphery (Figure 145). An inflatable saltwater barrier, defining the head of tide below the confluence of the Guadalupe and San Antonio Rivers, is in place during the irrigation season (roughly June-September). Pass Cavallo is *shared* with Matagorda Bay, but is the main tidal inlet for the San Antonio Bay estuary. This estuary also connects with the Aransas system through shallow and constricted channels. Minimal exchange with the Gulf occasionally occurs through Cedar Bayou, a small intermittent inlet, which was closed during the periods depicted in this report.

The estuary receives most of its freshwater from the Guadalupe River (70% of gaged inflow) and San Antonio River (26% of gaged inflow) (USGS, 1990). Their watersheds lie between the humid climate of the east and the arid climate of the south. River flows seem to fluctuate from one climate to the other, routinely experiencing extended droughts, but likely to encounter severe storms at any time during the year. This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 145).

Figure 145. *Location map and subsystem identification*



Bathymetry

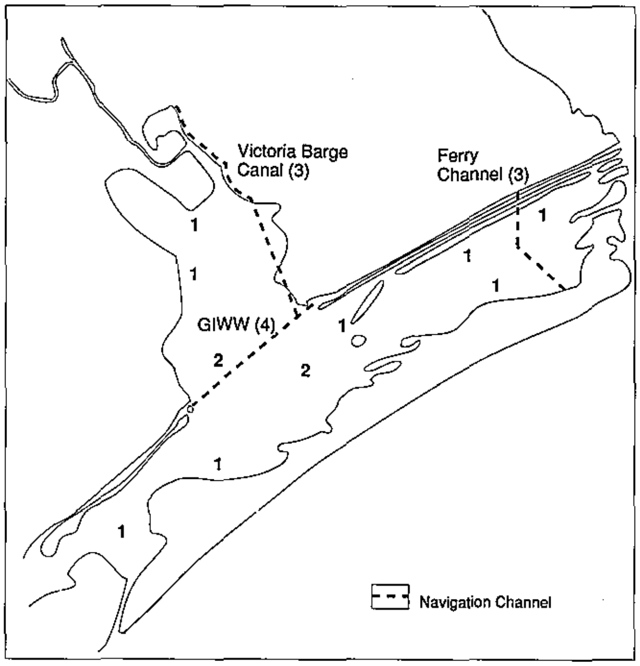
The average depth of this estuary is approximately 1 m at mid-tide level (NOAA, 1990a), but depths of the major bays differ (Figure 146). Oyster reefs form numerous shallow areas in the middle and lower estuary, and can significantly affect currents and water circulation (Hall et al., 1976). Shell-dredging operations may temporarily create approximately 5-12 m cuts in bay bottoms, but these cuts normally fill to less than 1 m deep within five years (Hall et al., 1976).

Construction of the GIWW and Victoria Barge Canal has probably modified circulation patterns in the estuary due to the increased capacity of these navigation channels to carry a tidal current. However, the significance of these modified circulation patterns is unknown due to the limited predredging information available. Under normal conditions, tidal waters enter Espiritu Santo Bay through the GIWW and are conveyed to the upper estuary by the Victoria Barge Canal (Hall et al., 1976). Circulation in San Antonio Bay is normally in a counterclockwise direction, as waters flow along the western shore of the bay, and out the lower estuary through the GIWW (Hall et al., 1976).

Salinity Patterns

The Data. July-September 1986 and April-June 1985 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions as no major modifications have been made to this estuary or its watershed since 1969 (USACE, 1988). A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 147. Figure 148 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that

Figure 146. *Bathymetry (meters)*



both periods experienced typical inflow conditions. Figure 149 presents salinity distributions for the selected periods. This structure experiences variability as indicated in Figure 150.

High-Inflow/Low-Salinity Period (April-June 1985). During this selected period and including March 1985, total inflow for San Antonio River was approximately 10% below long-term averages, while inflow for Guadalupe River was consistent with long-term averages (Figures 147 and 148). The combined average daily discharge of the Guadalupe and San Antonio Rivers generally remained between 75-100 m^3/s, except for peaks during mid-March (225 m^3/s), mid-April (250 m^3/s), and mid-June (375 m^3/s). From Guadalupe Bay to Ayers Bay, salinities often varied in response to freshwater discharge, but sometimes were not responsive to defined freshwater pulses. Salinities in Espiritu Santo Bay were usually unaffected by freshwater discharge. Salinities were most stable in Guadalupe Bay, Hynes Bay, and near Pass Cavallo (Figure 149), but were unstable within the eastern portions of San Antonio Bay.

The data appeared to support previously described salinity patterns within the bay, including: 1) the freshwater influence along the western shoreline of San Antonio Bay which produced consistently lower salinities compared to the eastern shore; 2) consistently lower salinities within Guadalupe Bay and Hynes Bay (<2 ppt and <3 ppt, respectively); 3) a horizontal gradient through Espiritu Santo Bay, increasing toward Pass Cavallo; and 4) a prolonged freshwater influence on salinities within San Antonio Bay (Figure 149). Stratification seldom occurred in this estuary, except along the eastern shore of San Antonio Bay within Victoria Barge Canal.

Low-Inflow/High-Salinity Period (July-September 1986). During this selected period and including June 1986, total inflow for San Antonio River was approximately 40% above long-term averages, while inflow for Guadalupe River was 15% below long-term averages (Figures 147 and 148). The combined average daily discharge of the Guadalupe and San Antonio Rivers peaked in early June (450 m^3/s), but remained below 75 m^3/s between July-September.

Average salinities were approximately 5 ppt higher than during the low-salinity period. Salinities increased along a north-south gradient from Guadalupe Bay to Mesquite Bay (Figure 149). Lower salinities along the western shore of San Antonio Bay were not evident during this period. Stratification was absent in most of this estuary, except in the Victoria Barge Canal near Mesquite Point where moderate (2-5 ppt surface-to-bottom differences) stratification occurred. Salinities were relatively stable within upper San Antonio Bay and Mesquite Bay, but unstable within Espiritu Santo Bay (Figure 149).

Factors Affecting Variability

Except within the eastern portions of Espiritu Santo Bay, the salinity structure is determined by infrequent freshwater discharges that, once introduced, are retained within the system. Salinities remain low until meteorological events induce circulation that favors the saline water intrusion from adjacent estuaries or through restricted inlets. In a similar nature, prolonged high salinities may persist due to freshwater inflow reductions associated with droughts. The salinity structure within the eastern portions of Espiritu Santo Bay probably depends more on the conditions in lower Matagorda Bay. This estuary is most often vertically homogeneous.

The important time scales of salinity variability and responsible mechanisms are given in Figure 150. Variability, determined by short-term freshets and meteorological events, is most apparent in lower San Antonio Bay and in western portions of Espiritu Santo Bay. Exchanges with adjacent estuarine systems can be a significant variability source to Espiritu Santo, Mesquite, and Ayres Bays.

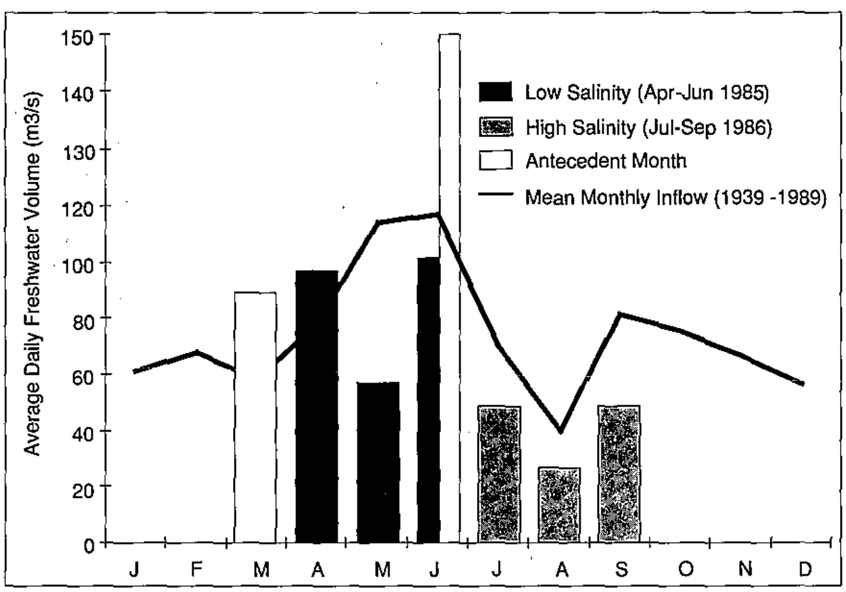
Figure 147. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	April-June 1985 (High Inflow/Low Salinity)	July-September 1986 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	95	41
Sampling Distribution [a]	1-3	1-3
Sampling Frequency	weekly-monthly	monthly
Average Salinity (ppt)	14.0	17.3
Bottom Salinity		
# of Observations	74	34
Sampling Distribution [a]	1-3	1-3
Sampling Frequency	weekly-monthly	monthly
Average Salinity (ppt)	13.0	18.6
Freshwater Inflow		
Volume		
Guadalupe River	average [b]	15% below average [c]
San Antonio River	10% below average [b]	40% above average [c]
Return Frequency of Peak Events (Guadalupe River)		
1-day duration	1.7-year	1.7-year
7-day duration	1.5-year	1.5-year
30-day duration	1.8-year	1.6-year

Abbreviation: ppt - parts per thousand

a. Subsystem(s) with high sampling density
b. Includes March 1985
c. Includes June 1986

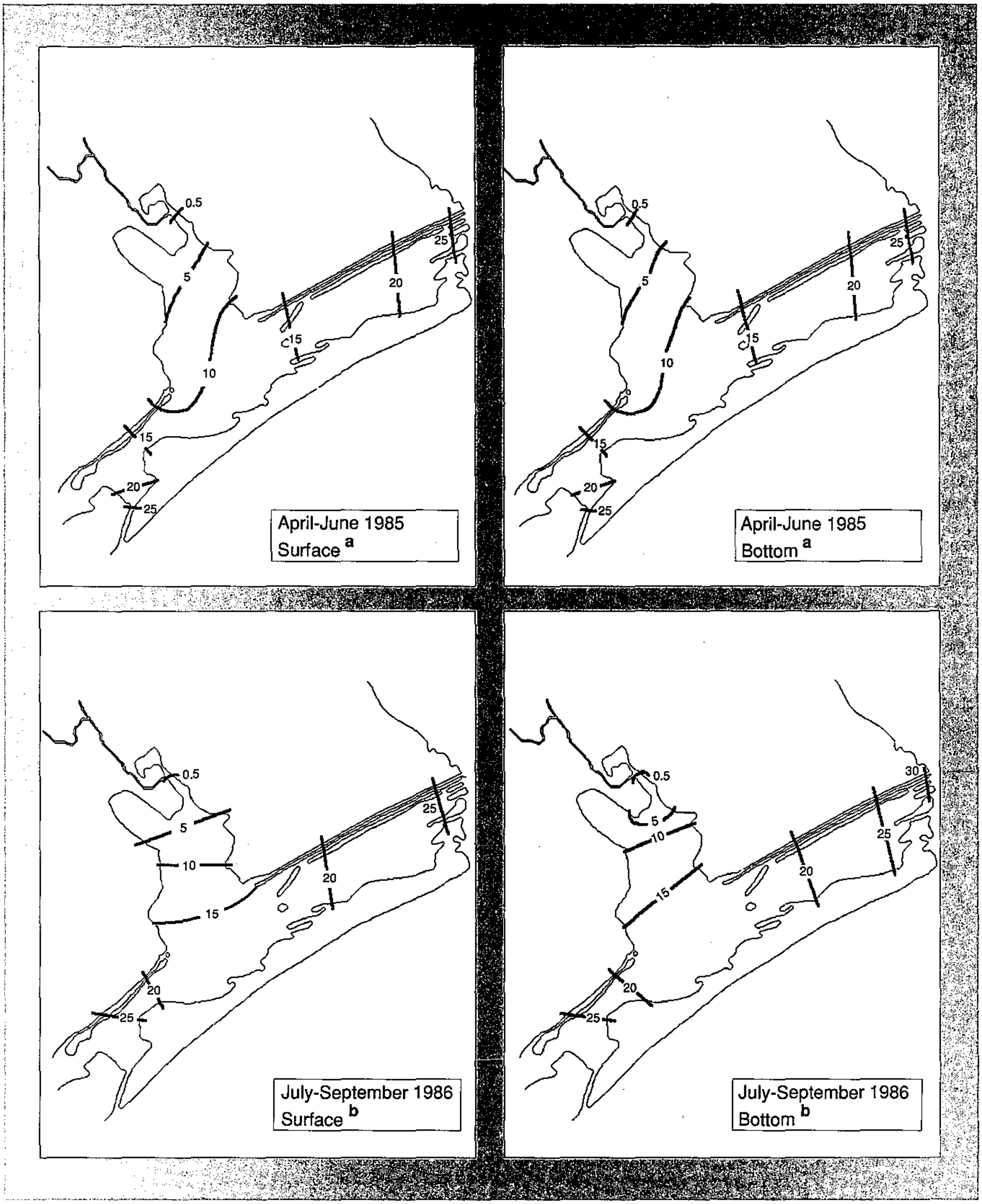
Figure 148. *Comparison of gaged freshwater volume for the Guadalupe River at Victoria, TX and San Antonio River at Goliad, TX during periods of salinity depiction to period-of-record averages* *



Abbreviation: m3/s - cubic meters per second

* USGS gages reflect inflow from 89% of the estuary's total watershed (28,200 km2) (USGS, 1990)

Figure 149. *Surface and bottom salinities during low- and high-salinity periods*

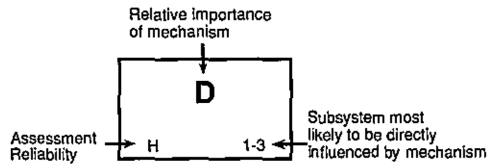


a. Data Sources: TPWD, 1991; TWC, 1991; TWDB, 1991a
b. Data Sources: TWC, 1991; TWDB, 1991a

Figure 150. *Time scales and forcing mechanisms important to salinity structure and variability**

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

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 149 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 structure and variability, except in Espiritu Santo Bay.

Months-Seasons. Secondary influence on salinity structure, except within Espiritu Santo Bay. Average salinities differ by only 2 ppt between typically high- and low-salinity periods.

Year-Year. Dominant influence on salinity structure throughout the bay. This estuary routinely experiences droughts which may extend for several months, producing hypersaline conditions in the lower estuary and seawater concentrations in the upper estuary (Phleger and Lankford, 1957; Harper and Hopkins, 1976). Estuary-wide salinity concentrations less than 5 ppt are associated with peak discharge events which typically occur every 5-20 years; these events are equally likely to occur any time during the year.

Episodic. Dominant influence on salinity structure and variability throughout the estuary. Hurricanes and tropical storms produce rainfall significantly greater than normal rainfall and, therefore, reduce salinities to nearly fresh values.

Wind

Days-Weeks. Secondary influence on the salinity variability. From December-February, north winds associated with cold fronts tend to mix and destratify shallow estuarine waters. On occasion, wind can enhance stratification when it induces a clockwise current in the estuary (Hall et al., 1976). Under these conditions, surface-to-bottom salinity differences may reach 15 ppt, especially in the Victoria Barge Canal. In addition, high-salinity waters can become trapped within Hynes Bay, producing a reverse salinity gradient in the upper estuary.

Months-Seasons. Secondary influence on salinity structure throughout the estuary. Winds primarily have southerly and easterly components during most of the year, thereby affecting water levels and circulation patterns.

Density Currents

Months-Seasons. Minor influence on salinity structure, primarily within the Victoria Barge Canal.

Inter-estuary Exchanges

Days-Weeks. Minor influence on salinity structure and variability within Espiritu Santo Bay.

Months-Seasons. Minor influence on salinity structure and variability within Espiritu Santo Bay.

Year-Year. Minor influence on salinity structure and variability within Espiritu Santo Bay.

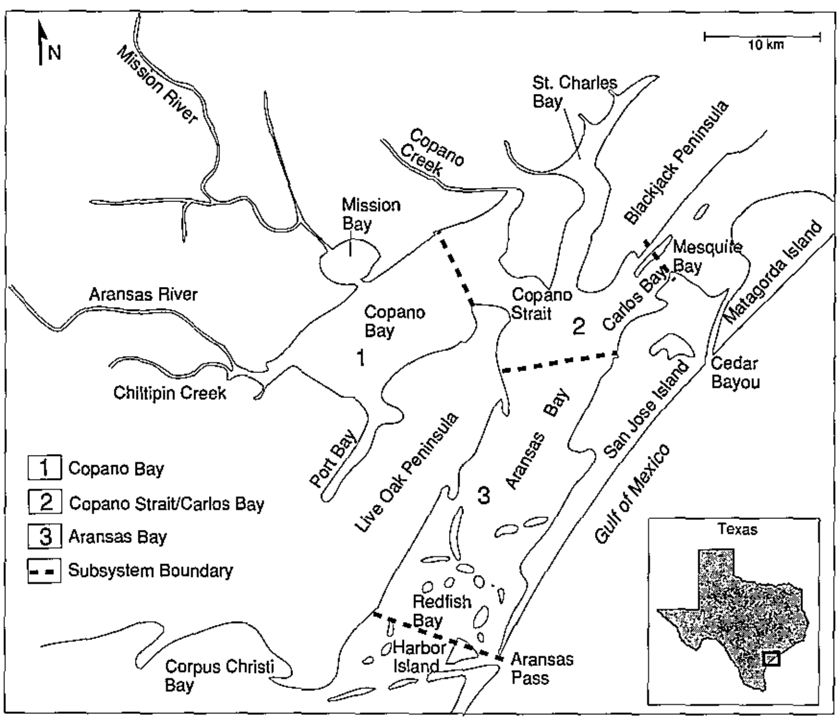
* Data Sources: See data sources listed in Appendix II for Texas.

Geographic Setting

The Aransas Bay estuary is a lagoonal system of approximately 540 km^2 (NOAA, 1990a), separated from the Gulf by San Jose Island (Figure 151). Copano and Aransas Bays (connected by Copano Strait) are the primary bays, with Mission, St. Charles, and Carlos Bays as the secondary bays. The inland boundaries are defined at the head of tide on Mission River at its confluence with Blanco Creek and on the Aransas River approximately 5 km upstream of its confluence with Chiltipin Creek. The estuary is connected to the San Antonio Bay system at Carlos Bay and to the Corpus Christi Bay system at Redfish Bay. Exchanges between the estuary and the Gulf are regulated through the inlets near San Jose Island after hurricanes. Essentially all exchange occurs through Aransas Pass, although intermittent exchanges occur through Cedar Bayou and through ephemeral washover inlets that sometimes breach San Jose Island after hurricanes. North Pass, located at the southern end of San Jose Island, is this estuary's most persistent washover inlet, although it has been shoaled closed for many years (Masch and Brandes, 1972).

The estuary receives only 15% of its annual freshwater volume as gaged inflow. On average, the Mission River contributes 49% of this gaged volume; the Aransas River, 15%; the Chiltipin River, 18%; and Copano Creek, 18% (USGS, 1990). Ungaged inflow accounts for an additional 39% and direct precipitation 46% of freshwater input to the estuary (TDWR, 1981c). Due to the arid, quasi-tropical climate of this area, freshwater inflow tends to be more widely spaced (in both time and space) and of isolated pulses, even during the high-inflow months. Most precipitation occurs in early fall due to tropical storms or in late spring due to frontal systems (TDWR, 1982b). On an annual basis, evaporation far exceeds precipitation. This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 151).

Figure 151. *Location map and subsystem identification*



Bathymetry

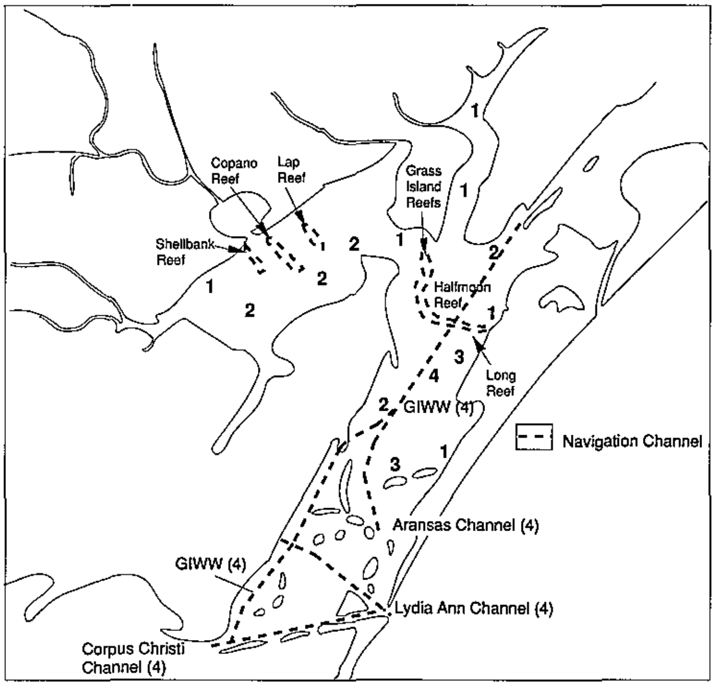
The average depth of the estuary is approximately 2 m at mid-tide level (NOAA, 1990a). Numerous oyster reefs extend transversely across Copano Bay (Diener, 1975; Gunter, 1945). Because they are perpendicular to the direction of flow, these reefs impede water circulation and affect salinity patterns in the upper estuary by retaining low-salinity water and dampening the tidal range (Collier and Hedgpeth, 1950; Shepard and Moore, 1960). Intra-estuarine circulation has also diminished due to spit accretion and shell berm formations which partially isolate Port Bay and Mission Bay from Copano Bay (Brown et al., 1976).

Navigation channels form the deepest parts of the estuary: Aransas Channel (>4 m); Lydia Ann Channel (4 m); Corpus Christi Channel (4 m); and GIWW (4 m) (Figure 152). Compared to the Sabine and Galveston systems, these channels are probably not as important for salinity intrusion because of their shallow depth and the lack of a horizontal salinity gradient sufficient to maintain density currents.

Salinity Patterns

The Data. June-August 1974 and September-November 1974 were selected as the high- and low-salinity periods, respectively. Although September-November

Figure 152. *Bathymetry (meters)*



1974 was biased by a freshwater event that occurs, on average, every 7.5 years, it was selected because data were so limited during other years. These periods precede the most recent dredging of the Corpus Christi and Aransas Channels, but are expected to otherwise reflect present-day conditions (USACE, 1988). A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 153. Figure 154 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages and suggests that the high-salinity period was drier than average, while the low-salinity period was wetter than average. Because a significant fraction of freshwater to the estuary is not reflected by USGS gages, precipitation records at Rockport (located north of Aransas Pass between Copano and lower Aransas Bays) and Beeville (located in the northwestern portion of the Aransas River drainage basin) were also examined. Figure 155 presents salinity distributions for the selected periods, illustrating the dominance of an *event-driven* freshwater discharge on the salinity structure. This structure experiences variability as indicated in Figure 156.

High-Inflow/Low-Salinity Period (September-November 1974). During this selected period and including August 1974, combined inflow from the Mission and Aransas Rivers was 85% above long-term averages (Figures 153 and 154). The combined average daily discharge of the Mission and Aransas Rivers remained less than 10 m^3/s, except for peaks in mid-September (625 m^3/s) and late November (30 m^3/s). In addition, several rainfall events, recorded at Rockport and Beeville, did not coincide with any observable peak at either the Mission or Aransas River gages. These events, occurring in August and from mid-October to mid-November, measured 1-3 cm each. The latter events may be partially responsible for maintaining the depressed salinities established by the mid-September freshet.

The lowest salinities in the estuary were observed in Mission Bay, while the highest were usually in Redfish Bay (Figure 155). The September freshet immediately overwhelmed Mission and Copano Bays and continued to dominate salinities throughout the period. Salinities in Aransas and Redfish Bays were also immediately impacted (but to a lesser degree) and continued to decline through November. The estuary was vertically homogeneous during the averaging period except near Copano Strait where surface-to-bottom differences were 5-10 ppt following the mid-September freshet. This scenario demonstrated the dispersion of the freshwater plume through this estuary and suggests that the residence time of freshwater was high.

Low-Inflow/High-Salinity Period (June-August 1974). During this selected period and including May 1974, combined inflow from the Mission and Aransas Rivers was about 40% below long-term averages (Figures 153 and 154). Combined average daily discharge from the Mission and Aransas Rivers remained less than 10 m^3/s, except for a peak discharge in mid-June (110 m^3/s) and minor freshets (20 m^3/s) in May and August.

The mid-June freshet depressed salinities throughout the estuary, although the residence time of this event was considerably longer within Copano and Mission Bays than in Aransas or Redfish Bays. Salinities were more stable within Copano and Mission Bays than in Aransas or Redfish Bays. The mid-June freshet produced moderate stratification (surface-to-bottom difference 3-6 ppt) near Copano Strait and weak stratification (<3 ppt surface-to-bottom differences) in Aransas Bay (Figure 155). This estuary was otherwise vertically homogeneous.

Factors Affecting Variability

The salinity structure is determined by isolated freshwater pulses that, once introduced, are retained within the system. Despite relatively small freshwater inflows, the salinity values were low compared to those found in adjacent estuaries (Shew et al., 1981; Wicker et al., 1989). This estuary has more *memory* of freshwater events than the bays along the upper portion of the Texas coast. Like the San Antonio estuary, freshwater pulses tend to depress salinities and maintain low salinities for a much longer period, especially in Copano Bay, due to the constricted inlet connection and the lack of any deep draft channels. Wicker et al. (1989) also attributed the lower salinities to the relatively efficient connection between the estuary and the San Antonio estuary that allowed a large input of estuarine waters from San Antonio Bay. Because this estuary is shallow and contains few deep channels, stratification was not widespread. Stratification was most common following freshets, and usually occurred near Copano Strait.

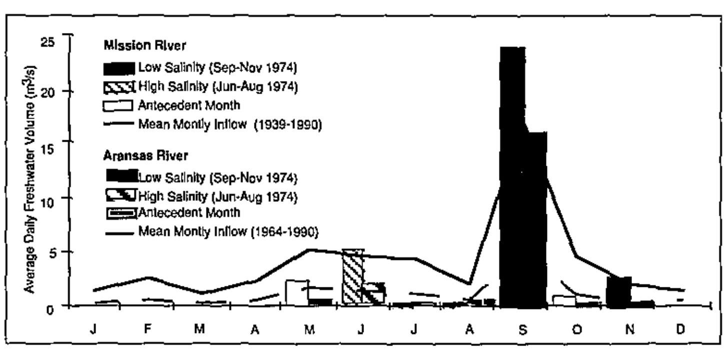
The important time scales of salinity variability and responsible mechanisms are summarized in Figure 156. Salinities are most variable in upper Aransas Bay (Figure 155) due to short-term freshets, wind, and exchanges within the San Antonio estuary. Salinity distributions depicted for the low-salinity period demonstrate the significant interannual variability that may exist.

Figure 153. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	September-November 1974 (High Inflow/Low Salinity)	June-August 1974 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	44	58
Sampling Distribution [a]	1-3	1-3
Sampling Frequency	monthly	monthly
Average Salinity (ppt)	11.2	17.0
Bottom Salinity		
# of Observations	39	36
Sampling Distribution [a]	1-3	1-3
Sampling Frequency	monthly	monthly
Average Salinity (ppt)	12.3	19.3
Freshwater Inflow		
Volume		
Mission River	60% above average [b]	45% below average [c]
Aransas River	150% above average [b]	30% below average [c]
Return Frequency of Peak Events (Mission River)		
1-day duration	7.5-year	3.5-year
7-day duration	8.5-year	2.9-year
30-day duration	7.5-year	2.9-year

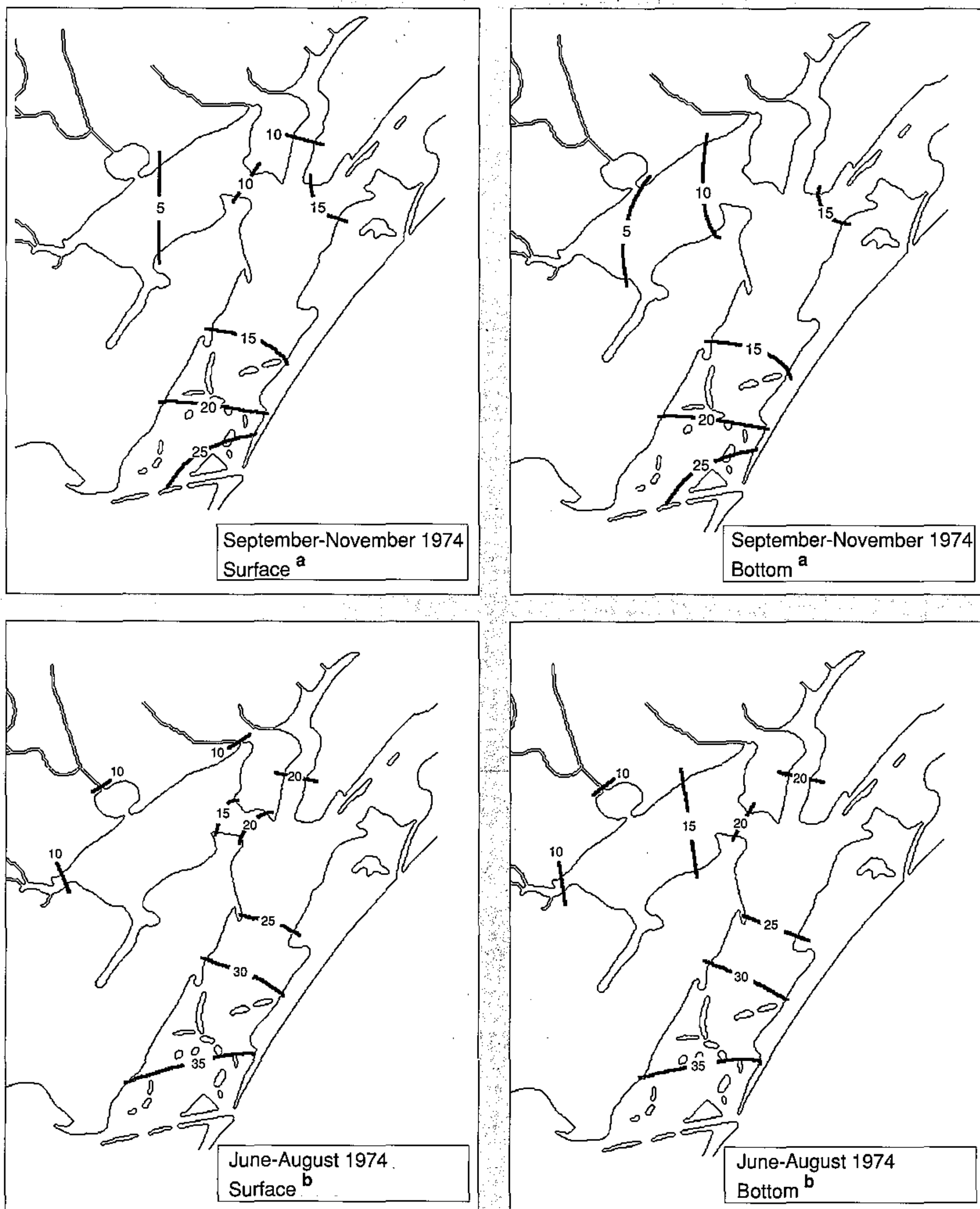
Abbreviation: ppt - parts per thousand
a. Subsystem(s) with high sampling density
b. Includes August 1974
c. Includes May 1974

Figure 154. *Comparison of gaged freshwater volume for the Aransas River near Skidmore, TX and Mission River at Refugio, TX during periods of salinity depiction and period-of-record averages* *



Abbreviation: m3/s - cubic meters per second
* USGS gages reflect inflow from 33% of the estuary's total watershed (7,250 km2) (USGS, 1990)

Figure 155. *Surface and bottom salinities during low- and high-salinity periods (NOTE: Isohalines for Sep.-Nov. 1974 depict a hydrological state that differs significantly from that most characteristic of the normal inflow due to salinity data limitations for this estuary)*

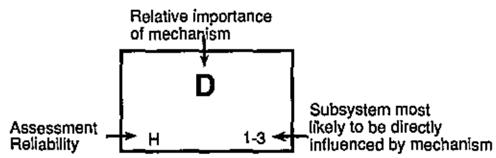


a. Data Sources: TWC, 1991; TWDB, 1991a/b
b. Data Sources: TWC, 1991; TWDB, 1991b

Figure 156. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		D M 1-2	S M 1-2	D M 1-3	D LIT 1-3
Tides					
Wind		M LIT 1-3			
Evaporation			S LIT 1-3		
Inter-estuary Exchanges		M LIT 2-3	S LIT 2-3	S LIT 2-3	
Effect on Salinity Variability	UNKNOWN	HIGH	LOW	MEDIUM	HIGH

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 155 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 structure and variability, primarily in Mission, Copano, and upper Aransas Bays.

Months-Seasons. Secondary influence on salinity structure, primarily in Mission, Copano, and upper Aransas Bays. The volume of inflow is insignificant during both high- and low-salinity periods; thus, seasonal estuary-wide salinity differences are small and probably attributable to lower evaporation rates and more frequent freshwater pulses during September-November.

Year-Year. Dominant influence on salinity structure throughout the estuary. Minimal freshwater inflows (and high evaporation) during the 1950-1957 drought produced hypersaline conditions throughout Aransas Bay (Parker, 1959). Annual variability in river discharges also occurs during the low-inflow period, although it is less variable than during the high-inflow period. The magnitude of the peak discharge, rather than the total volume, appears to determine variability.

Episodic. Dominant influence on salinity structure and variability throughout the estuary. Hurricanes and tropical storms produce significantly greater than normal rainfall and, therefore, reduce salinities to nearly fresh values.

Wind

Days-Weeks. Minor influence on salinity structure throughout the estuary. This estuary has the same enhanced sensitivity to meteorological systems as the San Antonio Bay estuary. Because it lies further south, this estuary is not subject to frontal passages as frequently as the upper bays. Wind destratifies the water column and may potentially control circulation and inter-estuarine exchanges.

Evaporation

Months-Seasons. Secondary influence on salinity structure throughout the estuary.

Inter-estuary Exchanges

Days-Weeks. Minor influence on salinity structure and variability, primarily in Aransas Bay.

Months-Seasons. Secondary influence on salinity structure and variability, primarily in Aransas Bay.

Year-Year. Secondary influence on salinity structure and variability, primarily in Aransas Bay.

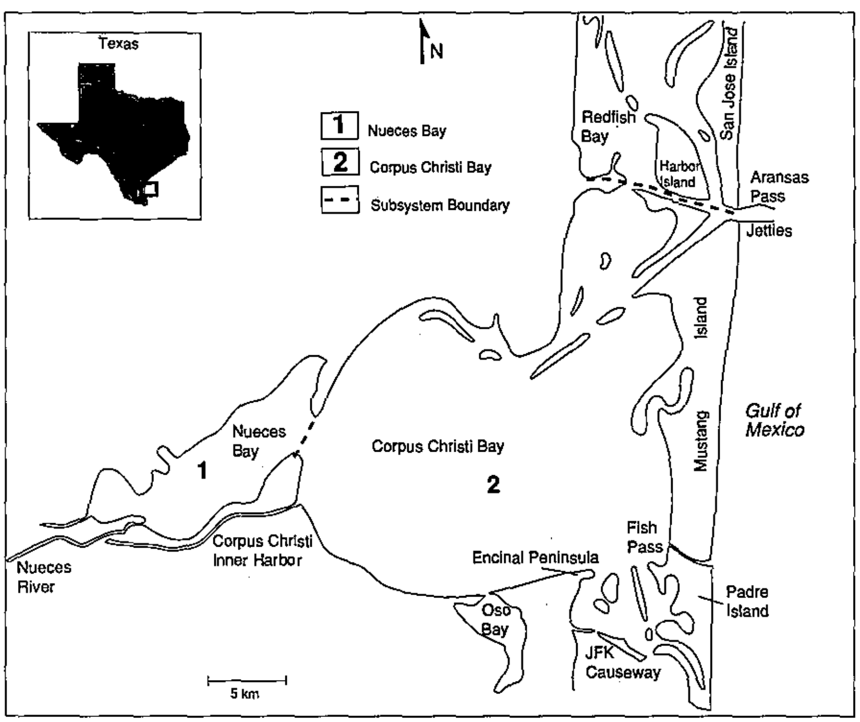
* Data Sources: See data sources listed in Appendix II for Texas.

Geographic Setting

Corpus Christi Bay estuary is a bar-built system occupying approximately 500 km^2 (NOAA, 1990a), separated from the Gulf of Mexico by Mustang Island (Figure 157). It consists of two major bays (Corpus Christi and Nueces) and two secondary bays (Oso and Redfish) (TDWR, 1982b). Its boundaries are from the head of tide on the Nueces River at Calallen Dam to its terminus with the Gulf at Aransas Pass (USFWS, 1982a). Most exchanges between this estuary and the Gulf occur through Aransas Pass (TDWR, 1982b), although limited exchange occurs through Fish Pass during rare high-water events (Behrens, 1981). This estuary connects with the Aransas Bay estuary through Redfish Bay and connects to upper Laguna Madre through the GIWW and Humble Channel cuts in the John F. Kennedy (JFK) Causeway.

This estuary receives most of its freshwater from the Nueces River (about 99% of gaged inflow) and Oso Creek (<1% of gaged inflow). Gaged inflow from Nueces Bay accounted for only 60% of the total freshwater to this estuary during the period 1941-1976 (TDWR, 1981c); ungaged inflow contributed 28% and direct precipitation, the remaining 8% during this same period. Due to the arid, quasi-tropical climate of this portion of the coast, freshwater inflow tends to be more widely spaced (in both time and space) and is characterized by isolated pulses, even during the high-inflow months. On an annual basis, evaporation far exceeds precipitation. This estuary has been divided into two subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 157).

Figure 157. *Location map and subsystem identification*



Bathymetry

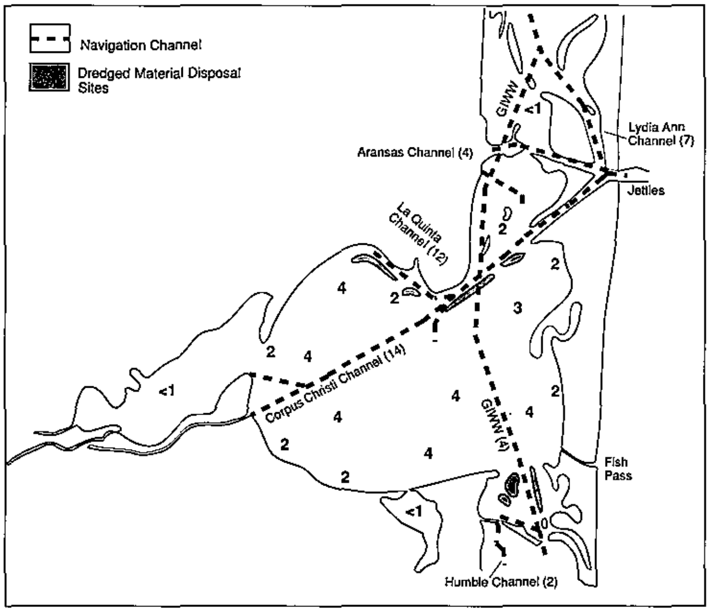
The average depth of the estuary is approximately 2 m at mid-tide level (Armstrong, 1982). Several navigation channels bisect the estuary, including the Corpus Christi Channel (14 m) which provides direct access to the Gulf through Aransas Pass (Figure 158). Occasionally, these navigation channels increase the exchange of estuarine and Gulf waters; density currents are generally not important since the necessary horizontal salinity gradient is usually present only after significant freshwater events.

Water exchanges in this estuary are impeded by both natural and man-made obstructions. Circulation between Redfish Bay and Corpus Christi Bay is partially obstructed by dredged material disposal areas along the Corpus Christi Ship Channel. Nueces Bay and Oso Bay have been partially isolated from the rest of this estuary by spit accretion and deposition of shell berms (Brown et al., 1976). Exchanges between this estuary and Upper Laguna Madre are severely restricted by the earthen JFK Causeway; exchanges occur only through the GIWW and Humble Channel cuts.

Salinity Patterns

The Data. June-August 1974 and September-November 1973 were selected to represent high- and low-salinity periods, respectively. These periods precede the Choke Canyon Reservoir construction (1982) and recent channel dredging. Also, September-November 1973 was biased by a freshwater event that occurs, on average, every 5-10 years. This period was intentionally selected to illustrate a significant decrease in system-wide salinity distributions and weakened variability due to

Figure 158. *Bathymetry (meters)*



freshwater forcing. *In the absence of these events, the salinity structure and variability are nearly identical during "typical" high- and low-salinity periods.* A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 159. Figure 160 compares the average daily freshwater inflow volume from the Nueces River during each month of the selected periods to long-term averages and suggests that neither period experienced typical inflow conditions. Because precipitation represents a significant fraction of freshwater to the estuary, rainfall records at Corpus Christi Airport and Chapman Ranch (both located in the Oso Creek drainage area) were also examined. Figure 161 presents salinity distributions for the selected periods, illustrating the influence of low-frequency storms on the salinity structure. This structure experiences variability as indicated in Figure 162.

High-Inflow/Low-Salinity Period (September-November 1973). During this selected period and including August 1973, total inflow from the Nueces River was approximately 150% above long-term averages (Figures 159 and 160). Discharge from the Nueces River was generally less than 30 m^3/s during August, September, and November. During October, three large discharges occurred: 325 m^3/s in early October, 600 m^3/s in mid-October, and 225 m^3/s in late October. Several rainfall events, measuring 2-5 cm at Corpus Christi Airport and Chapman Ranch during August and September, did not coincide with any observable peaks on the Nueces River or Oso Creek gages.

A freshening occurred throughout this estuary following the October freshets, but it was most significant in Nueces Bay. Salinities (15-20 ppt before the freshets) were reduced to less than 3 ppt after the October freshets. By late November, salinities near the Nueces River delta remained near 0.5 ppt, while the remainder of the bay had recovered to only 10 ppt. Surface salinities in Redfish Bay and southwest Corpus Christi Bay also exhibited a rapid response to the freshet, but rebounded quickly to pre-freshet salinities. Bottom salinities in central and southern Corpus Christi Bay were less responsive to the freshet and showed moderate stratification in these areas.

Low-Inflow/High-Salinity Period (June-August 1974). During this selected period and including May 1974, total inflow from the Nueces River was approximately 60% below long-term averages (Figures 159 and 160). Discharge from the Nueces River was below normal for this period. Inflow was less than 10 m^3/s throughout the period, except during a mid-August freshet (140 m^3/s). Precipitation recorded at Corpus Christi Airport and Chapman Ranch coincided with peaks on the Nueces River gage, suggesting that precipitation reinforced the response to inflow.

The effects of the mid-August freshet were limited to the western and central portions of Nueces Bay. Salinities in this estuary were reduced to brackish concentrations with weak vertical stratification. In Corpus Christi Bay, salinities were near Gulf values throughout the period and gradually approached hypersaline conditions in the eastern portion of the bay. The highest salinities occurred along the GIWW from Aransas Pass to Laguna Madre and the lowest were near Nueces Bay and in Redfish Bay. Salinities in Corpus Christi Bay were stable and vertically homogeneous. Redfish Bay salinities were less stable, possibly due to conditions in lower Aransas Bay.

Factors Affecting Variability

The salinity structure is determined by isolated freshwater pulses rather than seasonal freshwater discharges. Salinities remained near Gulf concentrations and occasionally reached hypersaline conditions, especially near Upper Laguna Madre. Vertical stratification is uncommon but may occasionally occur in Nueces Bay, following freshwater events, and infrequently at Aransas Pass and major ship channels.

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 162. In general, the Corpus Christi system is relatively stable. Variability, greatest in Nueces Bay and Oso Creek, is primarily attributable to freshets. Meteorology and exchanges with the Upper Laguna Madre and Aransas Bay systems may be important modifiers of the salinity structure in Redfish Bay and eastern Corpus Christi Bay. Salinity distributions depicted for September-November 1973 demonstrate the significance of low-frequency storms.

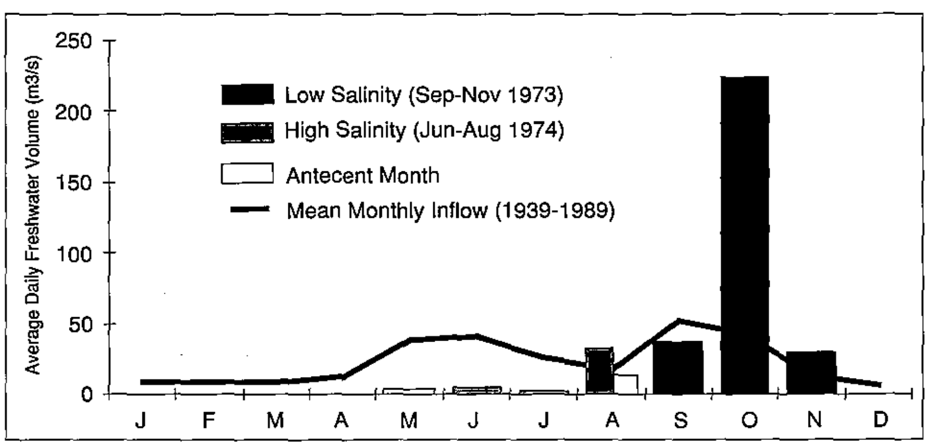
Figure 159. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

	September-November 1973 (High Inflow/Low Salinity)	June-August 1974 (Low Inflow/High Salinity)
Surface Salinity		
# of Observations	104	146
Sampling Distribution [a]	1, 2	1, 2
Sampling Frequency	monthly	monthly
Average Salinity (ppt)	14.8	31
Bottom Salinity		
# of Observations	78	83
Sampling Distribution [a]	1, 2	1, 2
Sampling Frequency	monthly	monthly
Average Salinity (ppt)	16.6	30.6
Freshwater Inflow		
Volume		
Nueces River	150% above average [b]	60% below average [c]
Return Frequency of Peak Events (Nueces River)		
1-day duration	9.1-year	2.5-year
7-day duration	7.3-year	2.7-year
30-day duration	10.1-year	2.2-year

Abbreviation: ppt - parts per thousand

a. Subsystem(s) with high sampling density
b. Includes August 1973
c. Includes May 1974

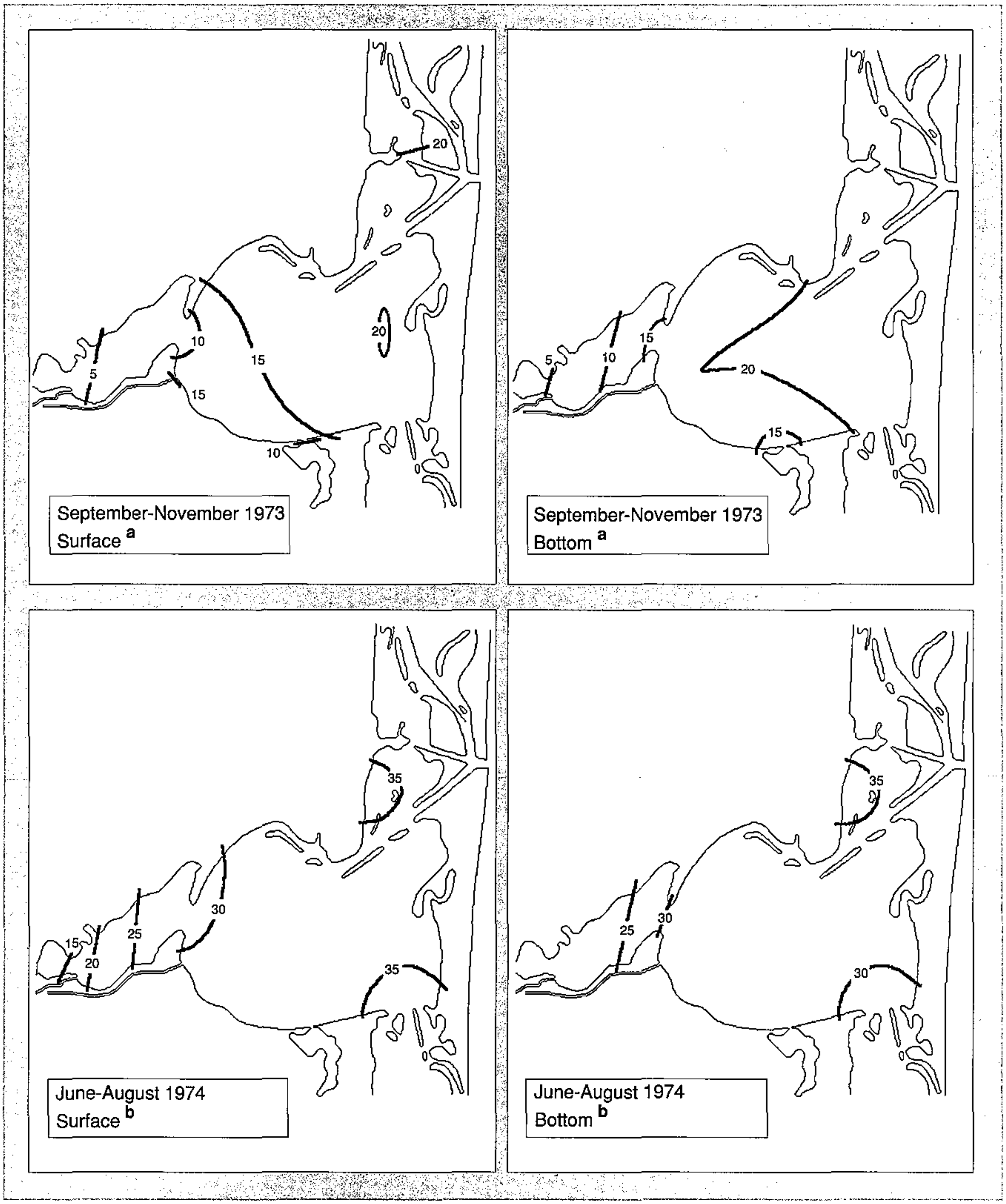
Figure 160. *Comparison of gaged freshwater volume for the Nueces River near Mathis, TX during periods of salinity depiction and period-of-record averages**



Abbreviation: m3/s = cubic meters per second

* USGS gages reflect inflow from 95% of the estuary's total watershed (45,580 km2) (USGS, 1990)

Figure 161. *Surface and bottom salinities during low- and high-salinity periods (NOTE: Isohalines for Sep.-Nov. 1973 depict a hydrological state that differs significantly from that most characteristic of the normal inflow due to the objective of better depicting potential salinity response)*

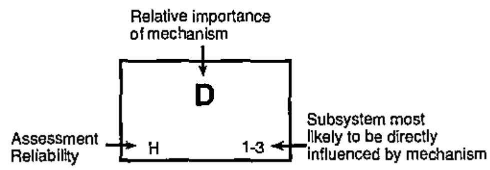


a. Data Sources: TWC, 1991; TWDB, 1991b
b. Data Sources: TWC, 1991; TWDB, 1991b

Figure 162. *Time scales and forcing mechanisms important to salinity structure and variability* *

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

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 161 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, primarily within Nueces Bay. This influence may induce short-term stratification in Nueces Bay.

Months-Seasons. Minor influence on salinity structure. Salinity profiles are nearly identical during the "typical" high- and low-salinity periods because the water volume entering the estuary during an "average" high-inflow (i.e., low-salinity) period is not of sufficient magnitude to significantly displace the isohalines.

Year-Year. Dominant influence on the salinity structure throughout the estuary. The most significant alterations of salinity structure are associated with low-frequency storms (i.e., 5-10 year return frequency).

Episodic. Dominant influence on salinity structure and variability throughout the estuary. Hurricanes and tropical storms produce significantly greater than normal rainfall and, therefore, reduce salinities to nearly fresh values.

Wind

Days-Weeks. Secondary influence on salinity variability throughout the estuary, especially when associated with cold fronts occurring infrequently between December-February. Winds may alter circulation and induce water-column mixing.

Months-Seasons. Minor influence on salinity structure throughout the estuary. Prevailing seasonal winds may be responsible for net flow from Upper Laguna Madre into Corpus Christi Bay through the ship channels including the GIWW, and continuing into Redfish and Aransas Bays (TDWR, 1982b).

Evaporation

Months-Seasons. Dominant influence on salinity structure throughout the estuary. June-August represents the period of low precipitation, high evaporation, and consequently, high salinity. Annually, precipitation averages only 74 cm/yr, while evaporation averages 151 cm/yr (Armstrong, 1987).

Density Currents

Days-Weeks. Occasional, minor influence on salinity structure in Corpus Christi and Redfish Bays; short-term stratification develops within deep navigation channels following significant freshwater events.

Inter-estuary Exchanges

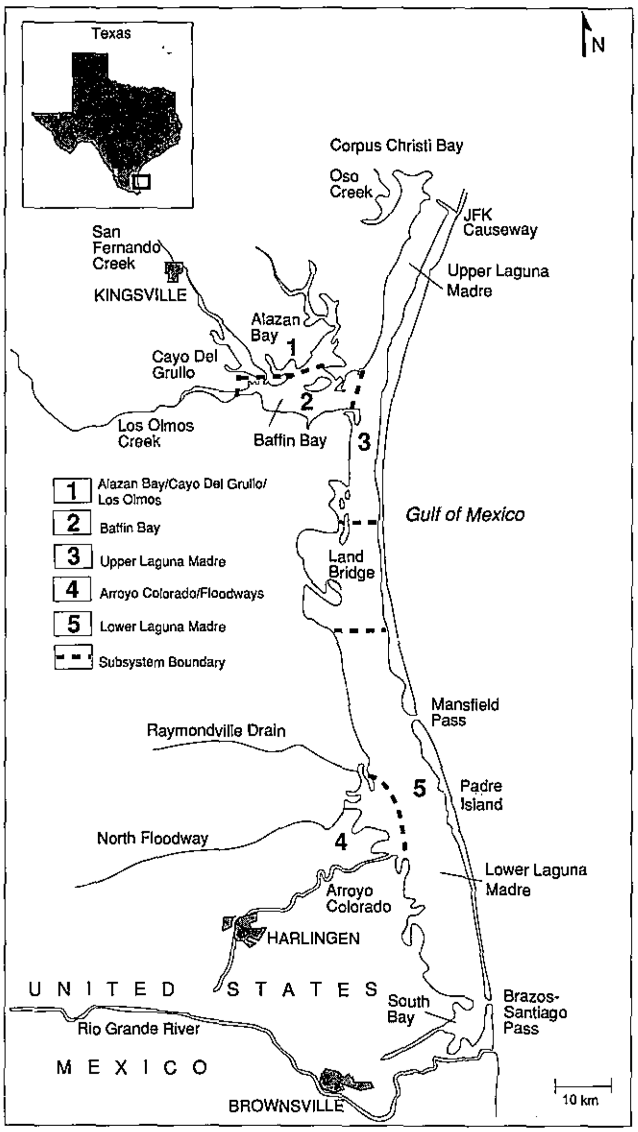
Year-Year. Minor influence on salinity structure, primarily in Redfish Bay, due to conditions in Aransas Bay.

* Data Sources: See data sources listed in Appendix II for Texas.

Geographic Setting

The Laguna Madre estuary is a bar-built coastal lagoon separated from the Gulf by Padre Island (Figure 163). It has the largest surface area (1500 km^2) and length (170 km) of any Texas estuary (Armstrong, 1987). Major bays are the Upper/ Lower Laguna Madres, Baffin Bay, and South Bay; secondary bays include Alazan and Cayo Del Grullo. This estuary consists mostly of mud-sand flats inundated intermittently by wind-driven flows. The most prominent of these flats is the *land bridge*, an extensive mud-sand platform with active dunes located about midway down the Laguna, that effectively separates the lagoon into upper and lower bays. Therefore, in this characterization, the Upper and Lower Laguna Madres are examined as quasi-autonomous systems.

Figure 163. Location map and subsystem identification



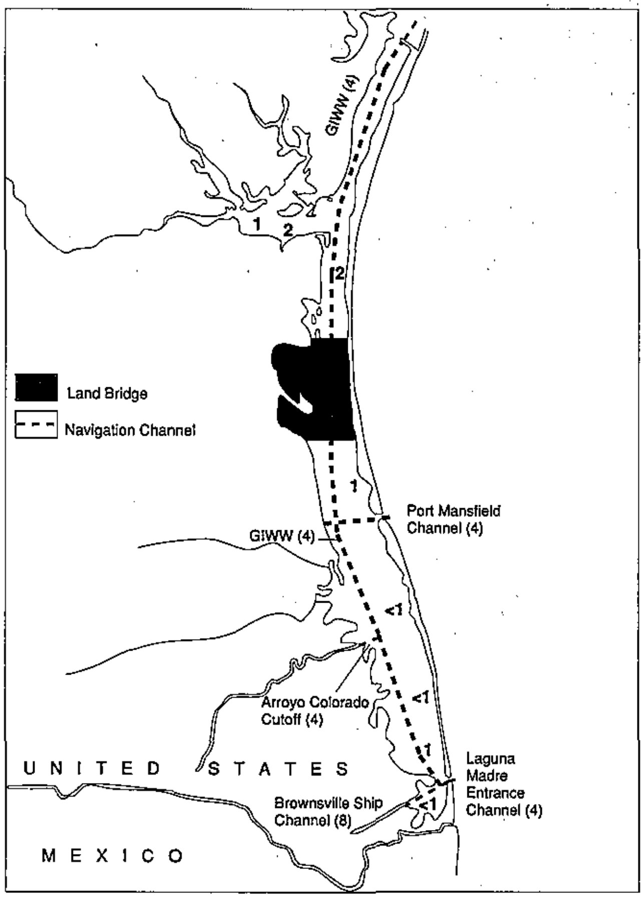
The Laguna Madre estuary is unique among Texas estuaries because no major streams discharge to this system. San Fernando Creek and Los Olmos Creek discharge to Upper Laguna Madre through Baffin Bay, although discharge volume averages only 1 m^3/s (Smith, 1988; USGS, 1990). Limited freshwater (approximately 10 m^3/s) is discharged to Lower Laguna Madre from the Arroyo Colorado, the North Floodway, and the Raymondville Drain. The freshwater plume from the Rio Grande is less of a hydrographic feature of Lower Laguna Madre than it was a couple of decades ago. Only runoff from the lowermost reach of the river currently contributes to the *plume* (i.e., that reach of the river below the Anzaldulas Dam at Brownsville). Under low-inflow conditions, the Rio Grande's flow is entirely impounded in Amistad and Falcon and diverted for municipal and irrigation use. When the rare Rio Grande floods occur, the North Floodway system in the U.S. and the South Floodway in Mexico are activated, diverting flood waters away from the river channel to the U.S. Laguna Madre and the Laguna Madre of the South (Mexico), respectively. Direct precipitation contributes approximately 65% of the total freshwater discharged to the estuary, while gaged inflow represents only 17% (Brown et al., 1977b; TDWR, 1983).

Exchange between Upper Laguna Madre and the Gulf occurs through Aransas Pass through Corpus Christi Bay, through limited openings in the JFK Causeway (Brown et al., 1977a; Simmons, 1952). Gulf waters enter lower Laguna Madre through Mansfield Pass (an artificial land cut through Padre Island) and the southern inlet of Brazos-Santiago Pass. The estuary has been divided into five subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 163).

Bathymetry

The average depth of the estuary is approximately 1 m at mid-tide level, although Upper Laguna Madre averages <2 m; lower Laguna Madre, 1 m; and Baffin Bay, 2 m (Figure 164) (NOAA, 1990a). The GIWW spans the length of this estuary and has become an important conduit for exchanges between Upper Laguna Madre and Corpus Christi Bay, as well as the upper and lower Laguna. Before completion of the GIWW, salinities over three times that of seawater were routinely recorded in Upper Laguna Madre (Diener, 1975).

Figure 164. Bathymetry (meters)



Shoals significantly affect water circulation and salinity in this estuary. Reefs at the mouth of Baffin Bay impede water exchange with Upper Laguna Madre and retain hypersaline waters within the bay. In a similar manner, freshwater is also retained in Baffin Bay for long periods, following large storms due to these reefs. Exchanges between South Bay and Lower Laguna Madre are essentially blocked by dredge material from the Brownsville Ship Channel. Along the main north-south axis of the Laguna, an extensive line of dredged material disposal sites lies near the eastern shore of the GIWW.

Salinity Patterns

The Data. June-August 1985 and September-November 1985 were selected to represent high- and low-salinity periods, respectively. These periods should reflect present-day conditions since no major modifications to the estuary or its watershed have occurred since the Brownsville Channel was expanded in 1980. The salinity structure (Gulf concentrations or higher) and variability were almost identical during these periods because of comparable and feeble freshwater discharges. Like the Corpus Christi estuary, significant system-wide salinity reductions occur only during low-frequency storms (i.e., 5-10 years). However, since the U.S. Geological Survey (USGS) gage on San Fernando Creek represents a very small fraction of the watershed, caution should be exercised when using its values to determine if representative conditions existed during the period of depiction and when comparing the salinity response to its hydrograph. Certainly, the negligible volumes recorded at the USGS gaging station are not impacting salinities in such a large estuary, but the hydrograph may be used to suggest the timing of significant precipitation or freshwater inflows. Also, freshwater conditions within the Nueces River and Oso Creek gages were considered a surrogate indicator of hydrographic conditions within the adjacent Nueces system. In addition, precipitation records at Falfurrias and Kingsville (Upper Laguna Madre) and Harlingen and Raymondville (Lower Laguna Madre) were examined to determine the extent to which freshwater input to the estuary was the result of significant rainfall not reflected by the USGS gages. A summary of freshwater inflow conditions and salinity data for these periods is given in Figure 165. Figure 166 compares the average daily freshwater inflow volume during each month of the selected periods to long-term averages. Figure 167 presents salinity distributions for these selected periods. This structure experiences variability as indicated in Figure 168.

High-Inflow/Low-Salinity Period (September-November 1985). During this selected period and including August 1985, total inflow from the San Fernando Creek was approximately 95% below long-term averages (Figures 165 and 166). Discharge from San Fernando Creek remained below 1 m^3/s throughout the period. However, isolated precipitation measuring 6 cm and 7 cm was recorded at Raymondville on August 16 and September 16, respectively, and a large storm on September 30 measured 7 cm at Kingsville and 11 cm at Raymondville.

In Upper Laguna Madre, freshwater inflow was apparently too weak to depress salinities much below seawater concentrations. Modestly lower salinities and weak stratification were short-lived and confined to Cayo Del Grullo and Alazan Bay following precipitation. In Upper Laguna Madre, salinities gradually decreased throughout the period, possibly due to hydrographic conditions within Corpus Christi Bay. Salinities in the *Hole* (i.e., a relatively deep and somewhat isolated area near the land bridge in Upper Laguna Madre) were less influenced by freshwater events.

Data were limited for Lower Laguna Madre, but indicated that salinity increased from Brazos-Santiago Pass to the land bridge, except for localized depressions near Arroyo Colorado and the North Floodway. By early October, salinities were reduced to 27 ppt near the Brazos-Santiago Pass, 22 ppt near Arroyo Colorado, and 32 ppt near the land bridge. By late November, however, salinities in the lower estuary had increased nearly 10 ppt. Salinities in Lower Laguna Madre were vertically homogeneous during this period, except for weak stratification (3 ppt surface-to-bottom difference) near Arroyo Colorado during October.

Low-Inflow/High-Salinity Period (June-August 1985). During this selected period and including May 1985, total inflow from the San Fernando Creek was approximately 50% above long-term averages (Figures 165 and 166). Discharge from San Fernando Creek was less than 1 m^3/s during this period, except in late May when a storm with a 5-year return frequency delivered 30 m^3/s on May 20. Most rainfall occurred from mid-June to early July. In addition, two significant rainfall events were observed at Raymondville in August.

In Upper Laguna Madre, salinities remained above seawater concentrations, except for short-lived depressions in the upper reaches of Cayo Del Grullo and Alazan Bay. By August, precipitation disappeared and bottom salinities increased, reaching more than 40 ppt in Upper Laguna Madre and 50 ppt in Baffin Bay near Alamazon Creek. Surface salinity data were very limited.

In Lower Laguna Madre, salinities generally exhibited little gradient in either the horizontal or vertical direction. Salinities were at Gulf values (about 35 ppt) near Brazos-Santiago Pass and the Brownsville Channel and were hypersaline (35-45 ppt) throughout the Laguna. Slightly lower salinities were again observed near Arroyo Colorado. Stratification occurred near Arroyo Colorado and in South Bay following precipitation.

Factors Affecting Variability

The salinity structure is determined by isolated freshwater pulses and intense evaporation rather than by seasonal freshwater discharge. Salinity distributions were nearly identical during the typical high- and low-salinity periods because the water volume entering this estuary during a typical high-inflow (i.e., low-salinity) period was not of sufficient magnitude to significantly displace the isohalines. Salinities in this estuary remained near Gulf concentrations and commonly reached hypersaline conditions, especially in Upper Laguna Madre. Vertical stratification is uncommon, but may occasionally occur in the upper reaches of Cayo Del Grullo and Alazan Bay, and near Arroyo Colorado following freshwater events.

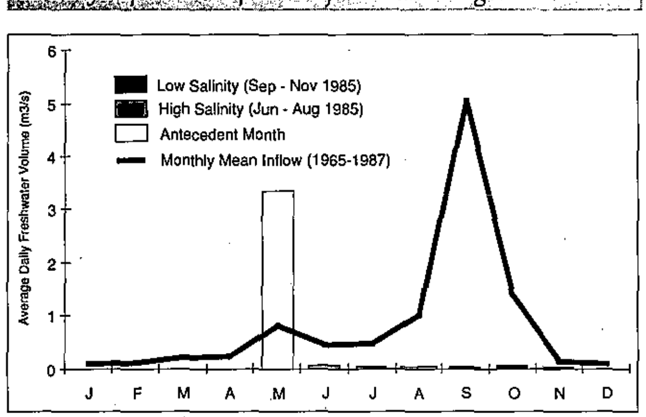
Figure 165. *Freshwater inflow, salinity sampling, and average salinity during low- and high-salinity periods*

		September-November 1985 (High Inflow/Low Salinity)	June-August 1985 (Low Inflow/High Salinity)
Surface Salinity			
# of Observations		116	67
Sampling Distribution [a]		1,2,3,5	1,2,3,5
Sampling Frequency		biweekly-monthly	monthly
Average Salinity (ppt)	ULM	38.4	38.0
	LLM	30.3	34.4
Bottom Salinity			
# of Observations		41	24
Sampling Distribution [a]		1,2,3,5	1,2,3,5
Sampling Frequency		biweekly-monthly	July only
Average Salinity (ppt)	ULM	38.6	37.7
	LLM	31.3	37.0
Freshwater Inflow			
Volume			
San Fernando River		95% below average [b]	50% above average [c]
Return Frequency of Peak Events (San Fernando River)			
1-day duration		1.4-year	1.1-year
7-day duration		1.3-year	1.1-year
30-day duration		1.3-year	1.2-year

Abbreviations: ppt - parts per thousand; ULM - Upper Laguna Madre; LLM - Lower Laguna Madre

a. Subsystem(s) with high sampling density
b. Includes August 1985
c. Includes May 1985

Figure 166. *Comparison of gaged freshwater volume for the San Fernando Creek at Alice, TX during periods of salinity depiction to period-of-record averages* *



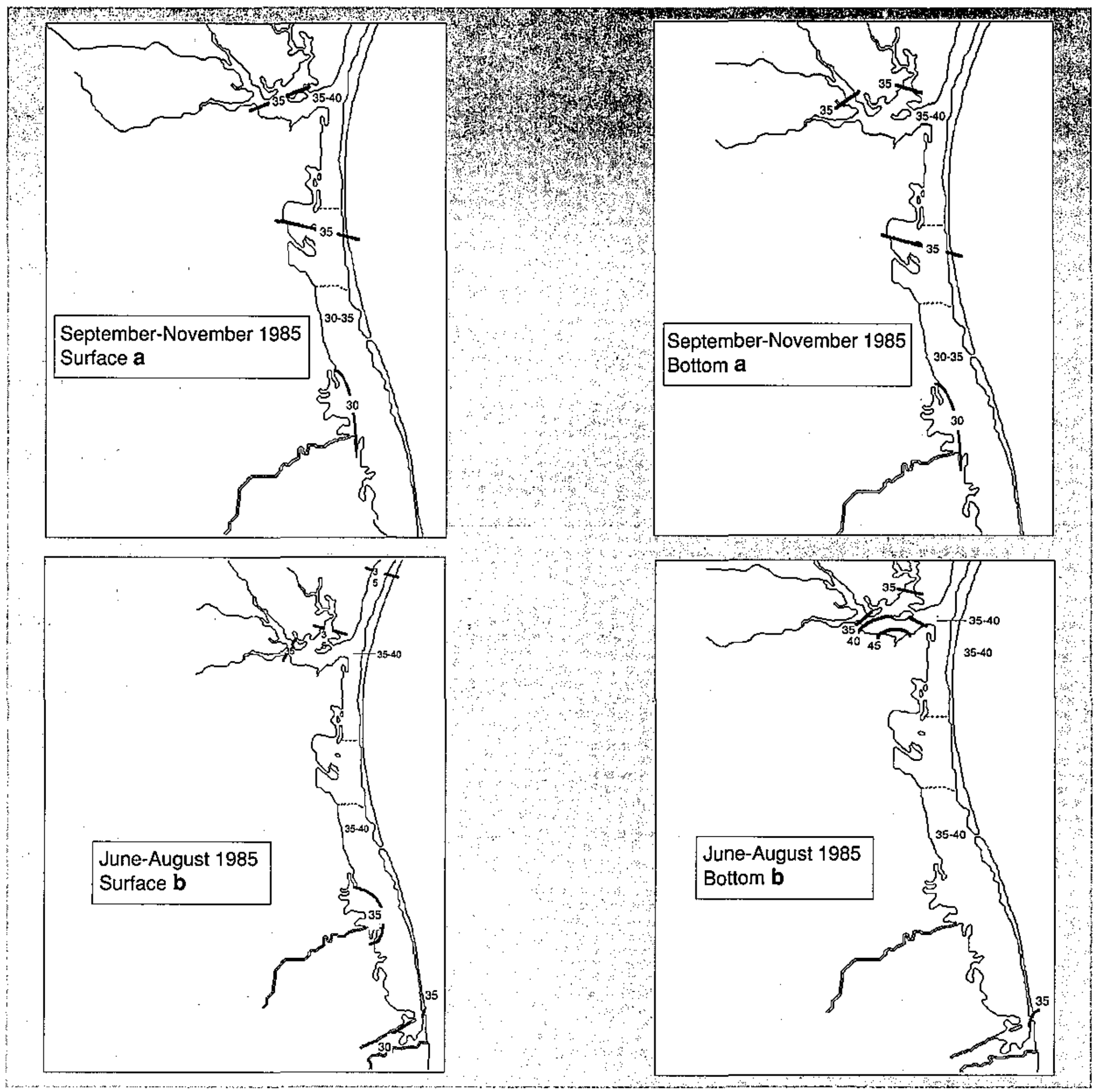
Abbreviation: m3/s - cubic meters per second

* The percentage of the watershed reflected by USGS gages is unknown, but it does not accurately reflect total freshwater to the estuary.

The Laguna Madre estuary is the best known of the Texas estuaries, because it is such an extensive lagoonal system and is notoriously hypersaline. It has become a textbook example of a hypersaline or *negative* estuary (Dyer, 1973). This hypersalinity is a result of two dominating factors of the Laguna hydrography: the large excess of evaporation over freshwater influx; and the shallow, enclosed morphology with limited exchange with the Gulf. Wind and especially alterations in wind velocity are most important in causing exchanges; wind drives water from one end of the Laguna to the other, and alters the exchange with the Gulf through this system's inlets. Vertical stratification is uncommon, but may occasionally occur in the upper reaches of Cayo Del Grullo and Alazan Bay, and near Arroyo Colorado following freshwater events.

The important time scales of salinity variability and responsible mechanisms are summarized in Figure 168. In general, salinity in this estuary is relatively stable, particularly in Lower Laguna Madre where winds continually promote Gulf-water circulation through the system. Variability is greatest in the upper reaches of Cayo Del Grullo and Alazan Bay and near Arroyo Colorado following freshwater events, but its effect is generally short-lived. Exchanges between Upper Laguna Madre and Corpus Christi Bay may also be an important modifier of the salinity structure.

Figure 167. *Surface and bottom salinities during low- and high-salinity periods*

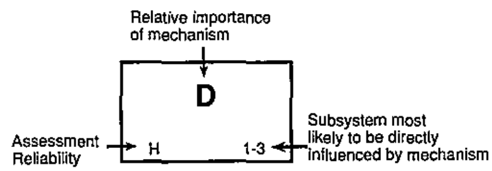


a. Data Sources: TPWD, 1991; TWC, 1991; TWDB, 1991a
b. Data Sources: TPWD, 1991; TWC, 1991; TWDB, 1991a

Figure 168. *Time scales and forcing mechanisms important to salinity structure and variability* *

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		**S** M 1,2,4	**M** M 1,2,4	**D** M 1,2,4	**D** LIT 1-5
Tides					
Wind		**S** LIT 1-5	**D** LIT 1-5		
Evaporation			**D** LIT 1-5		
Inter-estuary Exchanges				**M** LIT 3	
Effect on Salinity Variability	UNKNOWN	LOW	VERY LOW	LOW	HIGH

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 167 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, primarily within the upper reaches of Cayo Del Grullo and Alazan Bay, and near Arroyo Colorado. This influence may induce short-term stratification in these areas.

Months-Seasons. Minor influence on salinity structure. Salinity profiles are nearly identical during the "typical" high- and low-salinity periods because the water volume entering the estuary during an "average" high-inflow (i.e., low-salinity) period is not of sufficient magnitude to significantly displace the isohalines.

Year-Year. Dominant influence on the salinity structure throughout the estuary. The most significant alterations of the salinity structure are associated with low-frequency events (i.e., 10-20 year return frequency). Floodwater diversions from the Rio Grande basin were limited to September 1971, July 1973, August 1976, and October 1978.

Episodic. Dominant influence on salinity structure and variability throughout the estuary. Hurricanes and tropical storms produce copious rainfall significantly greater than normal rainfall and, therefore, reduce salinities to nearly fresh values.

Wind

Days-Weeks. Secondary influence on salinity variability throughout the estuary, especially when associated with cold fronts which occur infrequently (15-20 times) from December-February (Brown et al., 1977b). Winds may alter circulation and induce water-column mixing.

Months-Seasons. Dominant influence on salinity structure within Lower Laguna Madre. Prevailing seasonal winds may be responsible for net south-to-north circulation from Brazos-Santiago Pass to Mansfield Pass (Breuer, 1962).

Evaporation

Months-Seasons. Dominant influence on salinity structure throughout the estuary. June-August represents the period of low precipitation, high evaporation, and consequently, high salinity. Annually, precipitation over the estuary averages only 74 cm/yr, while evaporation averages 158 cm/yr (Armstrong, 1987).

Inter-estuary Exchanges

Year-Year. Minor influence on salinity structure, primarily between Upper Laguna Madre and Corpus Christi Bay.

* Data Sources: See data sources listed in Appendix II for Texas.

Concluding Comments

This report has examined the salinity structure and variability of 26 Gulf of Mexico estuaries. To the extent that data allowed, the 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.

Nearly all Gulf estuaries experience significant salinity variability over various temporal scales. This variability reflects the relative influence of the principal forcing mechanisms which differs both between estuaries and within any given estuary. In this section, temporal variability was used to differentiate functional differences between five estuary types having direct influence on resource distribution and water quality. This preliminary categorization suggests that management, monitoring, and research strategies for salinity-dependent estuarine attributes may be more effective in certain estuary types than in others.

Variability Across the Region

The geographical proximity of these estuaries suggests a certain degree of similarity in such features as morphology, hydroclimatology, and salinity structure. In general, five broad geographic groupings are recognizable. The extremes, represented by the shallow, arid, high-salinity systems of the Florida peninsula and south Texas, sharply contrast with the broad, water-rich, low-salinity embayments of the Mississippi and Atchafalaya River deltas. Intermediate conditions exist from the Florida panhandle to the Mississippi Sound and from western Louisiana to the Texas coastal bend; the former are relatively deep, receive moderate-to-high freshwater inflows, and have intermediate salinity concentrations, while the latter are typically shallow embayments that receive low-to-moderate freshwater volumes and have correspondingly higher salinities.

While these geographic groupings reflect a certain commonality among the Gulf estuaries, important *functional* differences exist among many *adjacent systems*, due to variation in other controlling factors such as Gulf exchange, wind, and bathymetric influences. The dynamic balance of these factors can be determined by characterizing estuarine salinity. The temporal behavior of salinity provides a framework for an improved categorization of estuarine types, from which may ultimately evolve management insights that recognize the variable dynamics on estuarine resources and water quality.

Improved Management Classification

Figure 169 arranges the Gulf systems by combinations of salinity variability, expressed at the days-weeks (referred to as weekly) and months-seasons (referred to as seasonal) time scales:

Type	Magnitude of Variability		Average Annual Salinity
	*Weekly**	*Seasonal**	
1	L	L	High (Seawater-dominated)
2	M	L	Intermediate
3	M	M	Intermediate
4	L	M	Intermediate
5	L	L	Low (Freshwater-dominated)

* L - low; M - medium

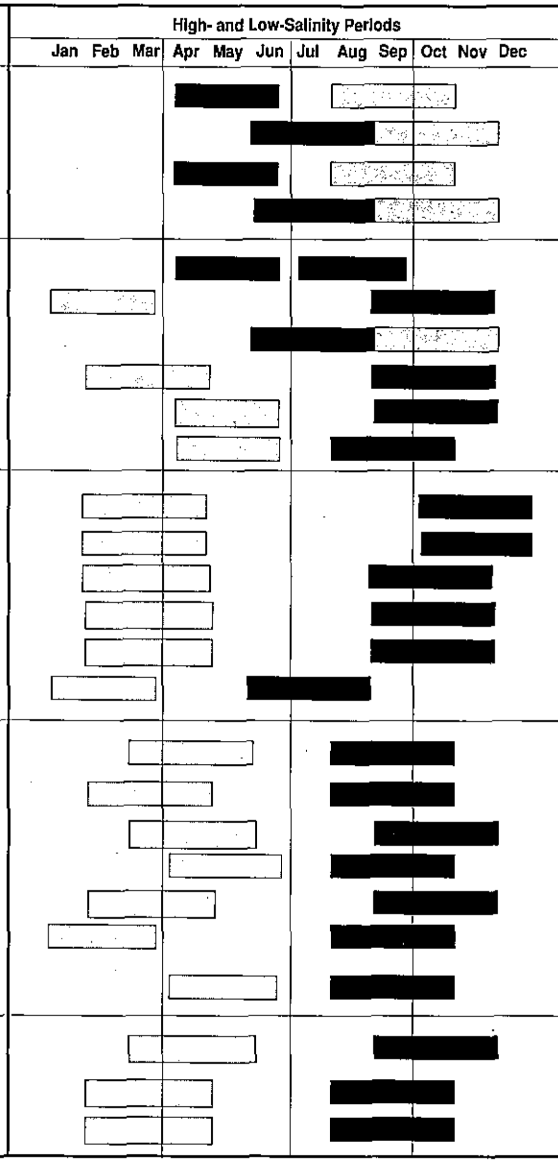
This categorization is based on average annual salinity and its intra-annual variability *under normal hydrologic conditions.* Some estuaries may be inappropriately typed due to the lack of data (e.g., Suwannee River, Mississippi Sound, and Mermentau River).

The resulting five estuarine types include a sampling of systems from around the Gulf with different morphological features. Despite this, estuaries within each type share a common relationship to salinity variability, mean estuarine salinities, and freshwater inflow. While seemingly discrete, the five estuary types actually lie along a continuum with considerable overlap between types 2 through 4.

Types 1 and 5. These types are *stable.* They represent the extreme range of freshwater inflow to Gulf estuaries and, correspondingly, the extreme range of salinity behavior. At these extremes, a single mechanism dictates the salinity (in this case, average annual salinities) and precludes any significant intra-annual variability. In type 1 estuaries, which lack a dominant and continuous freshwater source, salinity is predominantly near (or above) Gulf values and quite stable. In contrast, type 5 salinities are overwhelmed by a dominant and continuous freshwater inflow source. Even when variable, inflow is still so great that there is little salinity intrusion and, therefore, low variability. Consequently, low variability may be realized through either of two opposing scenarios: seawater dominance or freshwater dominance.

Figure 169. *Estuary types based on intra-annual salinity variability*

Type	Estuary	Magnitude of Salinity Variability: Days-Weeks	Months-Seasons	Year-Year	Average Annual Salinity (ppt): Surface	Bottom
1	Tampa Bay	L	L	L	25	26
	Corpus Christi Bay	L	VL	L	27	28
	Sarasota Bay	VL	VL	VL	32	33
	Laguna Madre	L	VL	L	NA	NA
2	San Antonio Bay	H	L	M	11	11
	Terrebonne/Timbalier Bays	M	L	L	12	12
	Aransas Bay	H	L	M	16	17
	Apalachee Bay Estuaries	M	L	M	16	18
	Barataria Bay	M	L	L	17	18
	Matagorda Bay	M	L	L	18	20
3	Suwannee River	M	H	M	3	NA
	Perdido Bay	M	H	M	8	14
	Apalachicola Bay	M	H	M	11	16
	Pensacola Bay	M	H	M	13	16
	St. Andrew Bay	M	M	L	16	21
	Mermentau River	M	M	L	NA	NA
4	Sabine Lake	L	M	M	5	7
	Mobile Bay	L	H	M	9	15
	Breton Sound	L	M	L	12	15
	Galveston Bay	L	M	M	12	16
	Choctawhatchee Bay	L	M	L	13	16
	Calcasieu Lake	L	M	L	13	14
	Brazos River & San Bernard River/ Cedar Lakes	L	M	M	NA	NA
5	Atchafalaya/Vermilion Bays	L	L	L	5	6
	Lakes Pontchartrain/Borgne and Chandeleur Sound	L	L	L	5	6
	Mississippi Sound	L	L	L	16	22



3-month low-salinity period

3-month high-salinity period

Abbreviations: NA, not available; H, high; M, medium; L, low; VL, very low

Types 2 through 4. These three estuary types are *variable*. They reflect intermediate freshwater inflow conditions, intermediate mean salinities, and a shift in both the magnitude and dominant time scale of salinity variability. In these systems, the salinity structure and variability are *not* determined solely by freshwater inflow, but also depend on the relative influence of other physical factors such as tidal exchange. Freshwater inflow generally increases and becomes more continuous from type 2 to type 4, progressively suppressing seawater intrusion and shifting the dominant time scale of salinity variability from weekly to seasonal. The magnitude of salinity variability, however, achieves a maximum at type 3 (i.e., these systems experience medium variability at both the weekly and seasonal time scales), as neither seawater nor freshwater sources predominate. Because the range of inflow defining each of these intermediate types is somewhat overlapping, a given estuary can transition between types.

Management Implications

The magnitude of salinity variability and the time scales over which it is expressed have direct implications for both water quality and resource management issues. This report highlighted the most important time-space relationships of salinity across the Gulf of Mexico region, defining first its structure (i.e., seasonal surface and bottom isohalines) at a scale recognized as important for many estuarine-dependent resources. In addtion, this structure provides an improved spatial framework for resource characterization and serves as a baseline for assessing variability at other time scales. This information suggests that different research, management, and monitoring approaches may be required for specific estuarine types.

Estuarine Water Quality. The distribution and concentration of many pollutants are affected by the same physical processes that determine estuarine salinity. The ability to flush, mix, and retain freshwater inflow is *an indicator* that pollutants affect resultant ambient concentrations. Thus, an estuary's susceptibility to either short-term and possibly acute pollution levels or longer-term changes in average pollutant concentrations is directly related to the same physical transport mechanisms affecting salinity behavior.

Type 5 systems, which receive steady high-volume inflows that rapidly and continually replace the estuary water column, are unlikely to retain incoming pollutants. In contrast, type 1 estuaries are highly stable and exhibit little-to-no system-wide response to freshwater inflow, except during extreme floods. These systems, therefore, tend to concentrate incoming pollutants for prolonged periods. The intermediate estuary types (i.e., types 2 through 4) have alternating high- and low-energy periods, as suggested by the dominant time scales of variability for each type. Type 4 systems, for example, are more likely to flush (or at least dilute) pollutants during the high-inflow (i.e., low-salinity) period than during the low-inflow period. Type 2 estuaries are generally susceptible to short-term pollution problems which are intermittently resolved by freshwater pulses. However, these pulses are often low in volume and may not affect system-wide concentrations.

Estuarine Living Marine Resources. The success and distribution of many estuarine biota depend on the interaction between habitats (e.g., surficial bottom sediments and wetlands) and dynamic parameters (i.e., salinity and temperature). Although many estuarine fish can tolerate various salinity and temperature regimes, others have restricted tolerances and must migrate within a preferred zone. Invertebrates, such as clams and oysters, grow within restricted (and generally stable) salinity zones. A management strategy being increasingly considered and actually operating in certain estuaries is to regulate salinity through flow diversions (especially during low-flow periods) to benefit shellfisheries. Such a strategy is likely to be most successful in type 2 estuaries in areas nearest the freshwater source, as suggested by their salinity-freshwater inflow relationship. In other estuary types, the relative influence of the flow augmentation is outweighed by the natural variability of the system.

Salinity and transport are also important to the reproductive success of certain estuarine fisheries. For instance, many fish depend on a seasonal salinity change to initiate spawning. In particular, the migration of diadromous species coincides with the development of a sustained tidal-fresh estuarine environment, characteristic of estuary types 3 and 4. Other species have larval and/or juvenile life stages that are estuarine-dependent but they require transport from Gulf waters to the estuary. These species depend on entrainment events, defined by the interaction of tides and winds that maximize transport into the estuary. These events typically occur at the days-weeks time scales, producing variability characteristics of types 2 and 3.

***

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 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

Alabama Department of Environmental Management (ADEM). 1991. *Hydographic Data Base for Perdido Bay.* Mobile, AL. Unpublished.

Alabama Department of Public Health (ADPH). 1991. *Salinity Data Base for Mobile, AL.* Mobile, AL. Unpublished.

Alexander, C.E. 1985. *An Examination of Habitat Changes in the Calcasieu Basin of Louisiana Using an Automated Geographic Information System.* Draft Report. Slidell, LA: U.S. Fish and Wildlife Service, National Coastal Ecosystems Team.

Armstrong, N.E. 1987. *The Ecology of Open-bay Bottoms of Texas: A Community Profile.* U.S. Fish and Wildlife Service, Biology Report 85(7.12). 104 pp.

Armstrong, N.E. 1982. "Responses of Texas Estuaries to Freshwater Inflows." In: *Estuarine Comparisons,* edited by V.S. Kennedy, 103-120. New York, NY: Academic Press.

Armstrong, N.E. and A. Goldstein. 1975. *Determination of Effects of Dow Chemical Discharge on Temperatures and Organisms of the Lower Brazos River.* Final Report. Austin, TX: Center for Research in Water Resources, University of Texas. 164 pp.

Austin, G.B. 1954. *On the Circulation and Tidal Flushing of Mobile Bay, Alabama.* Technical Report No. 24. College Station, TX: Texas A&M University. 28 pp.

Austin, H. and J. Jones. 1974. *Seasonal Variation of Physical Oceanographic Parameters on the Florida Middle Ground and their Relation to Zooplankton Biomass on the West Florida Shelf.* Florida Scientist 37(1):16-32.

Bahr, L.M., Jr., R. Costanza, J.W. Day, Jr., S.E. Bayley, C. Neill, S.G. Liebowitz, and J. Fruci. 1983. *Ecological Characterization of the Mississippi Deltaic Plain Region: A Narrative with Management Recommendations.* FWS/OBS-82/69. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services. 189 pp.

Bales, J.D. 1986. *Field and Numerical Studies of Tracer Gas Transport and Surface Gas Transfer in Laterally Uniform, Partially Stratified Estuaries.* PhD Dissertation. Austin, TX: University of Texas.

Barrett, B.B. 1971. *Cooperative Gulf of Mexico Estuarine Inventory and Study, Louisiana, Phase II, Hydrology and Phase III, Sedimentology.* New Orleans, LA: Louisiana Wildlife and Fisheries Commission. 191 pp.

Bass, D.G., Jr. and V.G. Hitt. 1978. *Sport Fishery Ecology of the Escambia River, Florida.* Holt, FL: Florida Game and Freshwater Fish Commission. 112 pp. + Appendices.

Bass, D.G., Jr., D. Yeager, and V.G. Hitt. 1979. *Ecology of the Yellow River System, Florida.* Holt, FL: Florida Game and Freshwater Fish Commission. 191 pp.

Bault, E.I. 1972. *Hydrology of Alabama Estuarine Areas - Cooperative Gulf of Mexico Estuarine Inventory.* Alabama Marine Resources Bulletin No. 7. Dauphin Island, AL: Alabama Marine Resources Laboratory.

Baumann, R.H. 1987. "Physical Variables." In: *The Ecology of Barataria Basin, Louisiana—An Estuarine Profile,* edited by W.H. Conner and J.W. Day, Jr., 8-17. U.S. Fish and Wildlife Service Biology Report 85(7.13).

Behrens, E.W. 1981. *A Large Scale Intracoastal Circulation Pattern Affecting Estuarine Continental Shelf Exchange.* Marine Geol. 40:15-25.

Behringer, D., R. Molinari, and J. Festa. 1977. *The Variability of Anticyclonic Current Patterns in the Gulf of Mexico.* Journal of Geophysical Research 82(34):5469-5476.

Blackford, C.M. 1977. *The Devil's Playmate.* Cruising World, February 1977, pp. 36-37.

Blaha, J. and W. Sturges. 1981. *Evidence for Wind-forced Circulation in the Gulf of Mexico.* Journal of Marine Resources 39(4):711-734.

Bomar, G.W. 1983. *Texas Weather.* Austin, TX: University of Texas Press.

Breuer, J.P. 1962. *An Ecological Survey of the Lower Laguna Madre of Texas, 1953-1959.* Austin, TX: University of Texas, Institute of Marine Science 8:153-185.

Brown, L.F., Jr., J.L. Brewton, T.J. Evans, J.H. McGowen, W.A. White, C.G. Groat, and W.L. Fisher. 1977a. *Environmental Geologic Atlas of the Texas Coastal Zone: Brownsville-Halingen Area.* Austin, TX: University of Texas, Bureau of Economic Geology. 131 pp.

Brown, L.F., Jr., J.H. McGowen, T.J. Evans, C.G. Groat, and W.L. Fisher. 1977b. *Environmental Geologic Atlas of the Texas Coastal Zone: Kingsville Area.* Austin, TX: University of Texas, Bureau of Economic Geology. 131 pp.

Brown, L.F., Jr., J.L. Brewton, J.H. McGowen, T.J. Evans, W.L. Fisher, and C.G. Groat. 1976. *Environmental Geologic Atlas of the Texas Coastal Zone: Corpus Christi Area.* Austin, TX: University of Texas, Bureau of Economic Geology. 123 pp.

Byrne, P.A. 1977. *Climatology, Hydrology, and Hydrography of the Vermilion Basin, Part II. Vermilion Basin: Hydrologic and Hydrographic Processes.* Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), Office of Coastal Zone Management. 110 pp.

Byrne, P.A., M. Borengasser, G. Drew, R.A. Muller, L. Smith, Jr., and C. Wax. 1976. *Barataria Basin: Hydrologic and Climatology Processes.* Baton Rouge, LA: Center for Wetland Resources, Louisiana State University, Sea Grant Publ. No. LSU-T-76-010. 176 pp.

Carothers, H.P. and H.C. Innis. 1960. *Design of Inlets for Texas Coastal Fisheries.* Journal of Waterways and Harbors ASCE 86(WW3):103-128.

Chew, F. 1964. *Sea-level Changes Along the Northern Coast of the Gulf of Mexico.* Transactions, American Geophysical Union 45(1):272-280.

Christmas, J.Y. 1973. *Cooperative Gulf of Mexico Estuarine Inventory and Study, Mississippi.* Ocean Springs, MS: Gulf Coast Research Laboratory. 434 pp.

Chuang, W., W. Schroeder, and W. Wiseman. 1982. *Summer Current Observations off the Alabama Coast.* Contributions in Marine Science 25:121-131.

Chuang, W.S. and E.M. Swenson. 1981. *Subtidal Water Level Variations in Lake Pontchartrain, Louisiana.* J. Geophysical Research 86:4198-4204.

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.

Cochrane, J.D. and F.J. Kelly. 1986. *Low-frequency Circulation on the Texas-Louisiana Continental Shelf.* Journal of Geophysical Research 91(C9):10,645-10,659.

Collier, A. and J.W. Hedgpeth. 1950. *An Introduction to the Hydrography of Tidal Waters of Texas.* Austin, TX: University of Texas, Institute of Marine Science 1:125-177.

Conner, C., A. Conway, and D.M. Windham. 1981. *Modelling of the Apalachicola System: A Hydrodynamic and Water Quality Model with a Hydrodynamic and Water Quality Atlas of Apalachicola Bay.* Gainesville, FL: Florida Sea Grant Project R/EM-13, Report 8107.

Conner, W.H. and J.W. Day, Jr. 1987. "Description of the Basin." In: *The Ecology of Barataria Basin, Louisiana: An Estuarine Profile*, edited by W.H. Conner and J.W. Day, 1-7. U.S. Fish and Wildlife Service, Biology Report 85(7.13).

Crance, J.H. 1971. "Description of Alabama Estuarine Areas." In: *Alabama Marine Resource Bulletin*, No. 6. Dauphin Island, AL: Alabama Marine Resources Laboratory. 85 pp.

Denes, T.A. and J.M. Caffrey. 1988. *Changes in Seasonal Water Transport in a Louisiana Estuary, Four League Bay, Louisiana.* Estuaries 11:184-191.

DeRouen, L.R., L.H. Stevenson, J.N. Beck, J.D. Felley, G.R. Gaston, B.J. Kjerfve, R.S. Maples, H.E. Murray, and M. Vecchione. 1987. *Ecosystem Analysis of the Calcasieu River/Lake Complex, Vols. I-IV.* Final Report to U.S. Department of Energy, Grant #DE-FG01-83EOP31111. Lake Charles, LA: McNeese State University.

Diener, R.A. 1975. *Cooperative Gulf of Mexico Estuarine Inventory and Study—Texas: Area Description.* NOAA Technical Report NMFS Circ. 393. Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service. 129 pp.

Dinnel, S.P. and W.J. Wiseman, Jr. 1986. *Freshwater on the Louisiana and Texas Shelf.* Continental Shelf Research 6:765-784.

Dugas, R.J. 1979. *Some Observations on the Post Construction Effects of the Mississippi River-Gulf Outlet on Louisiana Oyster Production.* Technical Bulletin No. 28. Grand Terre Island, LA: Louisiana Department of Wildlife and Fisheries, Marine Research Laboratory. 15 pp.

Dugas, R.J. 1970. *An Ecological Survey of Vermilion Bay, 1968-1969.* MS Thesis. Lafayette, LA: University of Southwestern Louisiana. 107 pp.

Dyer, K.R. 1973. *Estuaries: A Physical Introduction.* London: Wiley and Sons. 140 pp.

Eleuterius, C.K. 1978a. *Classification of Mississippi Sound as to Estuary Hydrographical Type.* Gulf Research Reports 6:185-187.

Eleuterius, C.K. 1978b. *Classification of Mississippi Sound as to Estuary Hydrographical Type by Vertical Salinity Structure.* J. Miss. Acad. Sci. XXIII:23-32.

Eleuterius, C.K. 1978c. *Location of the Mississippi Sound Oyster Reefs as Related to Salinity of Bottom Waters During 1973-1975.* Gulf Research Reports 6:17-23.

Environmental Planning and Associates (EP&A). 1991. *Cooperative Management Project Data Base for Perdido Bay.* U.S. Environmental Protection Agency Tallahassee, FL: Region 4. Unpublished.

Etter, P.C., W.F. Ulm, and J.D. Cochrane. 1985. *The Relationship of Wind Stress to Heat Flux Divergence of Texas-Louisiana Shelf Waters.* Continental Shelf Resources 4(5):547-552.

Fagerburg, T.L. 1990. *Mississippi River Gulf Outlet, Louisiana: Field Data Report.* Technical Report HL-90-7. U.S. Army Corps of Engineers Waterways Experiment Station. 22 pp.

Flannery, M.S. 1989. "Tampa and Sarasota Bays: Watersheds and Tributaries." In: *Tampa and Sarasota Bays: Issues, Resources, Status, and Management.* E.D. Estevez (Editor), 18-48. Washington, DC: U.S. Department of Commerce, NOAA Estuarine Program Office.

Florida Department of Environmental Regulation (FDER). 1991. *Surface and Bottom Salinity Data Base for Selected Florida Estuaries.* Tallahassee, FL: Unpublished.

Florida Department of Natural Resources (FDNR). 1991. *Salinity Data Base for Selected Florida Estuaries.* Tallahassee, FL: Unpublished.

Gael, B.T. 1980. "Computation of Drift Patterns in Lake Pontchartrain, Louisiana." In: *Environmental Analysis of Lake Pontchartrain, Louisiana, its Surrounding Wetlands, and Selected Land Uses,* edited by J.H. Stone, 39-56. New Orleans, LA: U.S. Army Corps of Engineers, Contract No. DACW-29-77-C-0253.

Gagliano, S.M., P. Light, R. Muller, and M. Al-Awady. 1973. *Water Balance in Louisiana Estuaries.* Hydrologic and Geologic Studies of Coastal Louisiana, Report No. 3. Baton Rouge, LA: Center for Wetland Resources, Louisiana State University. 177 pp.

Geraghty, J., D. Miller, M. Pinther, F. Van der Leeden, and F. Troise. 1973. *Water Atlas of the United States.* Port Washington, NY: Water Information Center.

Giovannelli, R.F. 1980. *Relation Between Freshwater Inflow and Salinity Distributions in the Alafia River, Bullfrog Creek, and Hillsborough Bay, Florida.* U.S. Geological Survey Water Resources Investigations 80-102. 68 pp.

Goodwin, C.R. 1987. *Tidal Flow, Circulation, and Flushing Changes Caused by Dredge and Fill in Tampa Bay, Florida.* USGS Water-Supply Paper 2282. 88 pp.

Gorsline, D.S. 1963. "Oceanography of Apalachicola Bay, Florida." In: *Essays in Marine Geology in Honor of K.O. Emery,* 145-176. Los Angeles, CA: University of Southern California Press.

Gosselink, J.G., C.L. Cordes, and J.W. Parsons. 1979. *An Ecological Characterization Study of the Chenier Plain Coastal System of Louisiana and Texas, Vols. 1-3.* U.S. Fish and Wildlife Service, FWS-OBS-78/9, 10 & 11.

Grace, S. 1932. *The Principal Diurnal Constituent of Tidal Motion in the Gulf of Mexico.* Monthly Notices of Royal Astronomical Society Geophysical Supplement 3(2):70-83.

Graham, D.S., J.P. Daniels, and B.A. Christensen. 1979. *Predicting Circulation Changes from Bathymetric Modification.* Proceedings of Special Conference: Civil Engineering in the Oceans IV. San Francisco, CA: American Society of Civil Engineers. pp. 531-549.

Gulf Coast Research Laboratory. 1991. *Mississippi Sound and North/Central Gulf of Mexico Salinity Data Base.* Ocean Springs, MS. Unpublished.

Gunter, G. 1945. *Studies on Marine Fishes of Texas.* University of Texas, Institute of Marine Science 1:1-190.

Gunter, G. and W.E. Shell, Jr. 1958. *A Study of an Estuarine Area with Water-Level Control in the Louisiana Marsh.* Proceedings of the Louisiana Academy of Sciences 21:5-34.

Hall, G.L., A.H. Bouma, and G.L. Huebner, Jr. 1976. "Overall Circulation and Tides in San Antonio Bay." In: *Shell Dredging and Its Influence on Gulf Coast Environments,* A.H. Bouma (Editor), 71-78. Houston, TX: Gulf Publishing Co.

Harper, D.E., Jr. 1977. "Distribution and Abundance of Macrobenthic and Meiobenthic Organisms." In: *Environmental Assessment of an Active Oil Field in the Northwestern Gulf of Mexico, 1976-77.* Project No. EPA-IAG-D6-E693-EO. Washington, DC: U.S. Environmental Protection Agency.

Harper, D.E., Jr. and S.H. Hopkins. 1976. "The Effects of Oyster Shell Dredging on Macrobenthic and Nektonic Organisms in San Antonio Bay." In: *Shell Dredging and Its Influence on Gulf Coast Environments,* edited by A.H. Bouma, 232-279. Houston, TX: Gulf Publishing Co.

Hart, W.E. 1976. *A Numerical Study of Currents, Circulation, and Surface Elevations in Chandeleur-Breton Sounds, Louisiana.* PhD Dissertation. Baton Rouge, LA: Louisiana State University. 221 pp.

Hauck, L.M. 1977. *Development and Application of Hydrodynamic and Mass Transfer Models of the Trinity Deltaic System. Part III: A Study of the Hydrological and Nutrient Transfer Exchange Processes in the Trinity River Delta, Texas.* Report to the Texas Department of Water Resources. Espey, Huston, and Associates, Inc., Doc No. 77-101.

Hawes, S.R. and H.M. Perry. 1978. *Effects of 1973 Floodwaters on Plankton Populations in Louisiana and Mississippi.* Gulf Research Reports 6:109-124.

Henry, W.K., D.M. Driscoll, and J.P. McCormack. 1975. *Hurricanes on the Texas Coast.* Texas Sea Grant Publication TAMU-SG-75-504. 48 pp.

Higgins, G.G. and C.K. Eleuterius. 1978. *Mississippi Sound: Volume, Surface Area, and Bathymetric Statistics.* J. Miss. Acad. Sci. XXIII:39-45.

Hillsborough County Environmental Protection Commission (HCEPC). 1991. *Surface and Bottom Salinity Data Base for Tampa Bay, 1974-1991.* Tampa, FL. Unpublished.

Hoese, H.D. 1976. *Study of Sport and Commercial Fishes of the Atchafalaya Bay Region.* Final Report to U.S. Fish and Wildlife Service. Lafayette, LA: University of Southwestern Louisiana. 50 pp.

Hopkins, T.S. and N.S. Schomer. Undated. *An Analysis of Selected Ecosystem Parameters in Escambia and East Bays in Response to Removal of Point Source Effluents.* A Report to the Florida Office of Sea Grant. Pensacola, FL: University of West Florida. Unpublished Report.

Hutchinson, C.B. 1983. *Assessment of the Interconnection between Tampa Bay and the Floridan Aquifer, Florida.* USGS Water-Resource Investigations Report 82-54.

Ichiye, T. and M.L. Jones. 1961. *On the Hydrography of the St. Andrew Bay System, Florida.* Limnology and Oceanography 6(3):302-311.

Ichiye, T., H.H. Kuo, and M. Carnes. 1973. *Assessment of Currents and Hydrography of the Eastern Gulf of Mexico.* Contr. 601, College Station, TX: Texas A&M University, Department of Oceanography.

Isphording, W., J. Stringfellow, and H. Helton. 1983. *Proceedings of the Northern Gulf of Mexico Estuaries and Barrier Islands Research Conference.* S. Shabica, N. Cofer, and E. Cake (Editors). Atlanta, GA: U.S. Department of Interior Park Service, Southeast Regional Office.

Johnson, R.B., Jr. 1977. *Fishery Survey of Cedar Lakes and the Brazos and San Bernard River Estuaries.* Texas Parks and Wildlife Department, Technical Series No. 23. 64 pp.

Juneau, C.L., Jr. and B.B. Barrett. 1975. *An Inventory and Study of the Vermilion Bay-Atchafalaya Bay Complex,* Technical Bulletin No. 13. Baton Rouge, LA: Louisiana Wildlife and Fisheries Commission. 153 pp.

Kirkpatrick, J.S. 1972. *Lower Brazos River Project: Final Report.* Austin, TX: Texas Water Quality Board. 203 pp.

Kjerfve, B. 1983. *Mississippi Sound and Adjacent Areas: Analysis and Synthesis of Oceanographic*

Conditions in Mississippi Sound, April-October 1980. Final Report to U.S. Army Corps of Engineers, Contract No. DACW01-82-Q-0022. 438 pp.

Kjerfve, B. and J.E. Sneed. 1987. "Hydrology of the Calcasieu River/Lake Complex." In: *Ecosystem Analysis of the Calcasieu River/Lake Complex,* edited by L.R. DeRouen and L.H. Stevenson, 7-1 to 7-32. Final Report to U.S. Department of Energy, Contract No. DE-FG01-83EP31111. Lake Charles, LA: McNeese State University.

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.

Lawing, R.J., R.A. Boland, and W.H. Bobb. 1975. *Mobile Bay Model Study, Report 1. Effects of Proposed Theodore Ship Channel and Disposal Areas on Tides, Currents, Salinities, and Dye Dispersion.* Technical Report H-75-13. Mobile, AL: U.S. Army Corps of Engineers. 58 pp.

Leadon, C.J. 1979. *Environmental Effects of River Flows and Levels in the Suwannee River Sub-Basin below Wilcox and the Suwannee River Estuary, Florida.* Suwannee River Water Management District. 150 pp.

Leipper, D.F. 1954. *Marine Meteorology of the Gulf of Mexico.* Fishery Bulletin 55:89-98.

Lewis, R.R. III and E.D. Estevez. 1988. *The Ecology of Tampa Bay, Florida: An Estuarine Profile.* U.S. Fish and Wildlife Service, Biological Report 85(7.18). 135 pp.

Livingston, R.J. 1990. *Salinity Data Base for Apalachicola Bay.* Tallahassee, FL: Florida State University. Unpublished Report.

Livingston, R.J. 1986. *The Choctawhatchee River-Bay System, Volume 1: Executive Summary.* Tallahassee, FL: Florida State University. 44 pp.

Livingston, R.J. 1984a. *Trophic Response of Fishes to Habitat Variability in Coastal Seagrass Systems.* Ecology 65:1258-1275.

Livingston, R.J. 1984b. *Long-term Effects of Dredging and Open Ocean Disposal on the Apalachicola Bay System.* Washington, DC: Office of Coastal Zone Management, National Oceanic and Atmospheric Administration. Unpublished Report.

Livingston, R.J. 1984c. *The Ecology of the Apalachicola Bay System: An Estuarine Profile.* Tallahassee, FL: U.S. Fish and Wildlife Service FWS/OBS 82/05. 148 pp.

Livingston, R.J. 1979. "Multiple Factor Interactions and Stress in Coastal Systems: A Review of Experimental Approaches and Field Implications." In: *Marine Pollution: Functional Responses,* F.J. Vernberg (Editor), 389-413. New York, NY: Academic Press, Inc.

Livingston, R.J. 1975. *Impact of Kraft Pulp-Mill Effluents on Estuarine and Coastal Fishes in Apalachee Bay, Florida, USA.* Marine Biology 32:19-48.

Louisiana Department of Environmental Quality (LDEQ). 1991. *Coastal Louisiana Water-Quality Data Base.* Baton Rouge, LA: Water Pollution Control Division. Unpublished.

Louisiana Department of Health and Human Resources (LDHHR). 1991. *Oyster Water Monitoring Program Salinity Data Base.* New Orleans, LA: Office of Public Health. Unpublished.

Louisiana Department of Wildlife and Fisheries (LDWF). 1991. *Fisheries Monitoring Program Salinity Data Base.* Baton Rouge, LA: Seafood Division. Unpublished.

Louisiana Office of State Climatology (LOSC). 1989. *Water Budget Components Calculated by the Thornwaite Water Budget Method.* Southwest Climate Division. Computer printout.

Louisiana Wildlife and Fisheries Commission (LWFC). 1971. *Cooperative Gulf of Mexico Estuarine Inventory and Study, Louisiana: Phase I, Area Description and Phase IV, Biology.* Baton Rouge, LA. 175 pp. + Maps.

Martin, J. 1977. "Hydrography of the Buccaneer Oil Field and Adjacent Water." In: *Environmental Assessment of an Active Oil Field in the Northwestern Gulf of Mexico, 1976-1977.* Proj. No. EPA-JAG-D6-E693-E0. College Station, TX: Texas A&M University. pp. 575-632.

Masch, F.D. and Associates. 1971. *Tidal Hydrodynamic and Salinity Models for San Antonio and*

Matagorda Bays, Texas. Austin, TX: Texas Water Development Board. 130 pp.

Masch, F.D. and R.J. Brandes. 1972. *Tidal Hydrodynamic and Salinity Models for Corpus Christi and Aransas Bays, Texas.* Austin, TX: Texas Water Development Board. 98 pp.

Mattson, R.A. and M.E. Rowan. 1989. "The Suwannee River Estuary: An Overview, and Research and Management Needs." In: *Water: Laws and Management*, edited by F.E. Davis, 14B17-14B31. Bethesda, MD: American Water Resources Association.

McFarlane, R.W, T.J. Bight, B.W. Cain, M. Hightower, J.J. Kendall, J.W. Kolb, A.J. Mueller, P.F. Sheridan, C.B. Smith, E.G. Wermund, and T.E. Whitledge. 1989. "Issues and Information Needs." In: *Issues, Resources, Status, and Management*, T.E. Whitledge and S.M. Ray (Co-organizers), 67-77. Washington, DC: NOAA Estuary-of-the-Month Seminar Service, No. 13.

McGowen, J.H., C.V. Proctor, Jr., L.F. Brown, Jr., T.J. Evans, W.L. Fisher, and C.G. Groat. 1976a. *Environmental Geologic Atlas of the Texas Coastal Zone: Port Lavaca Area.* Austin, TX: University of Texas, Bureau of Economic Geology. 98 pp.

McGowen, J.H., L.F. Brown, Jr., T.J. Evans, W.L. Fisher, and C.G. Groat. 1976b. *Environmental Geologic Atlas of the Texas Coastal Zone: Bay City-Freeport Area.* Austin, TX: University of Texas, Bureau of Economic Geology. 98 pp.

McNulty, J.K., W.N. Lindall, Jr., and J.E. Sykes. 1972. *Cooperative Gulf of Mexico Estuarine Inventory and Study, Florida: Phase 1, Area Description.* NOAA Technical Report NMFS Circ-368. Washington, DC: U.S. Department of Commerce. 127 pp.

Meeter, D.A., R.J. Livingston, and G. Woodsum. 1979. "Short- and Long-term Hydrologic Cycles of the Apalachicola Drainage System with Application to Gulf Coastal Populations." In: *Ecological Processes in Coastal and Marine Systems*, edited by R.J. Livingston. 315-338. New York, NY: Plenum Press.

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: National Oceanic and Atmospheric Administration (NOAA), Strategic Environmental Assessments Division. 107 pp.

Morang, A. 1992. *Inlet Migration and Hydraulic Processes at East Pass, Florida.* Journal of Coastal Research 8(2):457-481.

Morton, T. 1973. *The Ecological Effects of Water-Control Structures on an Estuarine Area, White Lake, Louisiana, 1972-1973.* MS Thesis. Lafayette, LA: University of Southwestern Louisiana. 43 pp.

Mote Marine Laboratory (MML). 1991. *National Estuary Program Water-Quality Data Base for Sarasota Bay, 1975-1991.* Sarasota, FL. Unpublished.

Murray, S. 1976. *Currents and Circulation in the Coastal Waters of Louisiana.* Sea Grant Publ. LSU-T-76-003. Baton Rouge, LA: Louisiana State University, Center for Wetland Resources. 33 pp.

Musgrove, R.J., J.B. Foster, and L.G. Toler. 1964. *Water Resources of the Econfina Creek Basin Area in North-western Florida.* Florida Geological Survey Report Investigation 41. 51 pp.

National Oceanic and Atmospheric Administration (NOAA). 1991. *United States Coast Pilot Atlantic Coast: Gulf of Mexico, Puerto Rico, and Virgin Islands.* 22d Ed. Rockville, MD. 339 pp. + Appendices.

National Oceanic and Atmospheric Administration (NOAA). 1990a. *Estuaries of the United States: Vital Statistics of a National Resource Base.* Rockville, MD: Strategic Environmental Assessments Division. 79 pp.

National Oceanic and Atmospheric Administration (NOAA). 1990b. *Tides Tables 1990: East Coast of North and South America including Greenland.* Washington, DC: Department of Commerce, National Ocean Service. 289 pp.

National Oceanic and Atmospheric Administration (NOAA). 1989a. *National Estuarine Inventory Supplement 3: Physical and Hydrologic Characteristics—The Mississippi Delta System Estuaries.* Rockville, MD: Strategic Assessment Branch. 17 pp.

National Oceanic and Atmospheric Administration (NOAA). 1989b. *Tide Tables: High and Low Water Predictions, East Coast of North and South America, Including Greenland.* Washington, DC: Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service.

National Oceanic and Atmospheric Administration (NOAA). 1985a. *Local Climatological Data: Annual Summaries for 1984, Part 1 - Eastern Region.* Asheville, NC: National Climatic Data Center.

National Oceanic and Atmospheric Administration (NOAA). 1985b. *National Estuarine Inventory Data Atlas, Volume 1: Physical and Hydrologic Characteristics.* Rockville, MD: Strategic Assessments Branch, Office of Oceanography and Marine Assessments. 103 pp.

Niiler, P. 1976. *Observations of Low-frequency Currents on the West Florida Continental Shelf.* Mem. R. Soc. Sci. Liege 6(10):331-358.

Nowlin, W.D. 1972. "Winter Circulation Patterns and Property Distributions." In: *Contributions on the Physical Oceanography of the Gulf of Mexico,* L. Capurro and J. Reid (Editors), 13-31. Houston, TX: Gulf Publications.

Nowlin, W.D. and J.M. Hubertz. 1972. "Contrasting Summer Circulation Patterns for the Eastern Gulf." In: *Contributions on the Physical Oceanography of the Gulf of Mexico,* L. Capurro and J. Reid (eds), 199-137. Houston, TX: Gulf Publications.

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.

Olinger, L.W., R.G. Rogers, P.L. Fore, R.L. Todd, B.L. Mullins, F.T. Bisterfeld, and L.A. Wise. 1975. *Environmental and Recovery Studies of Escambia Bay and the Pensacola Bay System, Florida.* Atlanta, GA: U.S. Environmental Protection Agency, Region IV. 356 pp. + Appendices.

Parker, R.H. 1959. *Macro-invertebrate Assemblages of Central Texas Coastal Bays and Laguna Madre.* Bulletin of American Association of Petroleum Geologists 43:2100-2166.

Phleger, F.B. and R.L. Lankford. 1957. *Seasonal Occurrences of Living Benthic "Foraminifer" in Some Texas Bays.* Cushman Foundation Foram. Res. 8:95-105.

Pilkey, O., R. Morton, J. Kelley, and S. Penland. 1989. *Coastal Land Loss.* Washington, DC: AGU short course presented at 28th International Geologic Congress.

Poirrier, M.A. 1978. *Studies of Salinity Stratification in Southern Lake Pontchartrain near the Inner Harbor Navigation Canal.* Proc. of the Louisiana Academy of Science 41:26-35.

Pritchard, D.W. 1952. *Estuarine Hydrography.* Advances in Geophysics 1:243-280.

Rezak, R., T. Bright, and D. McGrail. 1983. *Reefs and Banks of the Northwestern Gulf of Mexico: Their Geological, Biological, and Physical Dynamics.* New York, NY: Wiley Interscience. 530 pp.

Rodriguez, A.J. and T. Wu. 1990. *Initial Analysis of the Circulation and Flushing Characteristics of the St. Andrew Bay System.* Northwest Florida Water Management District, Water Resources Special Report 90-1. 105 pp.

Rounsefell, G.A. 1964. *Preconstruction Study of the Fisheries of the Estuarine Areas Traversed by the Mississippi River Gulf Outlet Project.* Mobile, AL: University of Alabama, Dauphin Island Marine Laboratory. Fisheries Bulletin 63:373-393.

Salsman, G.G. and A.J. Ciesluk. 1978. *Environmental Conditions in Coastal Waters Near Panama City, Florida.* Technical Report. Panama City, FL: Naval Coastal Systems Center. 83 pp.

Schroeder, W.W. 1979. *Dispersion and Impact of Mobile River System Waters in Mobile Bay, Alabama.* WPRI Bulletin 37. Mobile, AL: University of Alabama, Dauphin Island Marine Laboratory. 48 pp.

Schroeder, W.W., S.P. Dinnel, and W.J. Wiseman, Jr. 1988a. *Salinity Stratification in a River-Dominated Estuary.* Mobile, AL: University of Alabama, Dauphin Island Marine Laboratory. Unpublished Report.

Schroeder, W.W., W. J. Wiseman Jr., A. Williams Jr., D.C. Raney, and G.C. April. 1988b. *Climate and Oceanography.* Mobile, AL: University of Alabama, Dauphin Island Marine Laboratory. Unpublished Report.

Schroeder, W.W. and W.J. Wiseman, Jr. 1986. *Low-frequency Shelf-estuarine Exchange Processes in Mobile Bay and Other Estuarine Systems on the Northern Gulf of Mexico.* Estuarine Variability. New York, NY: Academic Press.

Schroeder, W.W., O.K. Huh, L.J. Rouse, Jr., and W.J. Wiseman. 1985. *Satellite Observations of the Circulation East of the Mississippi Delta: Cold-Air Outbreak Conditions.* Remote Sensing of the Environment 18:49-58.

Schroeder, W.W. and W.J. Wiseman, Jr. 1985. *An Analysis of the Winds (1974-1984) and Sea-Level Elevations (1973-1983) in Coastal Alabama.* Mississippi-Alabama Sea Grant Consortium Report MASGP-84-024. Ocean Springs, MS.

Schroeder, W.W. and W.R. Lysinger. 1979. "Hydrography and Circulation of Mobile Bay." In: *Symposium on the Natural Resources of the Mobile Estuary, Alabama,* H.A. Loyacano Jr. and J.P. Smith (Editors), 75-94. Mobile, AL: University of Alabama, Dauphin Island Marine Laboratory.

Sheng, Y.P. and S. Peene. 1992. "Circulation and Its Effect on Water Quality." In: *Sarasota Bay: 1992 Framework for Action, Sarasota Bay National Estuary Program.* Gainesville, FL: University of Florida. 47 pp.

Shepard, F.P. and D.G. Moore. 1960. "Bays of the Central Texas Coast." In: *Recent Sediments Northwest Gulf of Mexico, 1951-1958,* edited by F.P. Shepard, F.B. Phleger, and T.H. Van Andel, 117-152. Tulsa, OK: American Association of Petroleum Geologists.

Shew, D.M., R.H. Baumann, T.H. Fritts, L.S. Dunn, J.B. Johnston, M.W. Young, and R.M. Rogers. 1981. *Texas Barrier Islands Region Ecological Characterization: Environmental Synthesis Papers.* Washington, DC: U.S. Fish and Wildlife Service, FWS/OBS-81/32. 413 pp.

Sikora, W.B. and B. Kjerfve. 1985. *Factors Influencing the Salinity Regime of Lake Pontchartrain, Louisiana, A Shallow Coastal Lagoon: Analysis of Long-term Data Set.* Estuaries 8:170-180.

Simmons, E.G. 1952. *An Ecological Survey of the Upper Laguna Madre.* Austin, TX: University of Texas, Institute of Marine Science 4:156-200.

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.

Smith, M.F., Jr (Ed.). 1984. *Ecological Characterization Atlas of Coastal Alabama: Map Narrative.* U.S. Fish and Wildlife Service. FWS/OBS 82/46. MMS 84-0052. Washington, DC: Minerals Management Service. 189 pp. + 30 maps.

Smith, N.P. 1988. "The Laguna Madre of Texas: Hydrography of a Hypersaline Lagoon." In: *Hydrodynamics of Estuaries, Vol. II of Estuarine Case Studies,* B. Kjerfve (Editor), 31-39. Boca Raton, FL: CRC Press.

Smith, N.P. 1979. *Meteorological Forcing of Coastal Waters by the Inverse Barometer Effect.* East Coast Mar. Sci. 8:149-156.

Sturges, W. and J.P. Blaha. 1976. *A Western Boundary Current in the Gulf of Mexico.* Science 192:367-369.

Sturges, W. and J. Evans. 1983. *On the Variability of the Loop Current in the Gulf of Mexico.* Journal of Marine Resources 41(4):639-653.

Swenson, E.M. 1981. *Physical Effects of the 1979 Opening of the Bonnet Carre Spillway.* Proceedings of the Louisiana Academy of Sciences 44:121-131.

Swenson, E.M. 1980a. "General Hydrography of Lake Pontchartrain, Louisiana." In: *Environmental Analysis of Lake Pontchartrain, Louisiana, Its Surrounding Wetlands and Selected Land Uses,* J.H. Stone (Editor), 57-155. Contract No. DACW-29-77-C-0253. U.S. Army Corps of Engineers, New Orleans District.

Swenson, E.M. 1980b. "General Hydrography of the Tidal Passes of Lake Pontchartrain, Louisiana." In: *Environmental Analysis of Lake Pontchartrain, Louisiana, Its Surrounding Wetlands and Selected Land Uses,* J.H. Stone (Editor), 157-215. Contract No. DACW-29-77-C-0253. U.S. Army Corps of Engineers, New Orleans District.

Swenson, E.M. and W. S. Chuang. 1983. *Tidal and Subtidal Water Volume Exchange in an Estuarine System.* Estuarine Coastal Shelf Science 16:229-240.

Taylor Biological Company, Inc. 1991. *Surface and Bottom Salinity Data Base for St. Andrew Bay (Lake/Baywatch Program).* Panama City, FL. Unpublished.

Texas Department of Water Resources (TDWR). 1983. *Laguna Madre Estuary: A Study of the Influence of Freshwater Inflows* . Austin, TX: Texas Water Development Board and Texas Water Commission, LP-182. 266 pp.

Texas Department of Water Resources (TDWR). 1982a. *The Influence of Freshwater Inflows upon the Major Bays and Estuaries of the Texas Gulf Coast.* Austin, TX: Texas Water Development Board and Texas Water Commission, LP-115. 51 pp.

Texas Department of Water Resources (TDWR). 1982b. *Nueces and Mission-Aransas Estuaries: An Analysis of Bay Segment Boundaries, Physical Characteristics, and Nutrient Processes.* Austin, TX: Engineering and Environmental Systems Section of Planning and Development Division, LP-83. 73 pp.

Texas Department of Water Resources (TDWR). 1981a. *Sabine-Neches Estuary: A Study of the Influence of Freshwater Inflows.* Austin, TX: Texas Water Development Board and Texas Water Commission, LP-126. 284 pp.

Texas Department of Water Resources (TDWR). 1981b. *Trinity-San Jacinto Estuary: A Study of the Influence of Freshwater Inflows.* Austin, TX: Texas Water Development Board and Texas Water Commission, LP-113. 383 pp.

Texas Department of Water Resources (TDWR). 1981c. *Nueces and Mission-Aransas Estuaries: A Study of the Influence of Freshwater Inflows.* Austin, TX: Texas Water Development Board and Texas Water Commission, LP-108. 356 pp.

Texas Parks and Wildlife Department (TPWD). 1991. *Fishery Monitoring Program Data Base, 1970-1991.* Austin, TX. Unpublished.

Texas State Department of Health (TSDH). 1991. *Salinity Data Base from Shellfish Monitoring Program.* Austin, TX. Unpublished.

Texas Water Commission (TWC). 1991. *Statewide Monitoring Network (SMN) Data Base.* Austin, TX. Unpublished.

Texas Water Development Board (TWDB). 1991a. *Coastal Data System (CDS) Data Base.* Austin, TX. Unpublished.

Texas Water Development Board (TWDB). 1991b. *Special Study - Salinity Measurements for Corpus Christi Bay.* Austin, TX. Unpublished.

Turner, R.E. 1988. "Landscape Development and Change." In: *Causes of Wetland Loss in the Coastal Central Gulf of Mexico, Vol II: Technical Narrative,* R.E. Turner and D.R. Cahoon (Editors), 31-54. New Orleans, LA: Minerals Management Service, OCS Study/MMS 87-0120.

Turner, R. and J. Gosselink. 1975. *A Note on Standing Crop of "Spartina alterniflora" in Texas and Florida.* Contr. Mar. Sci. 19:13-18.

U.S. Army Corps of Engineers (USACE). 1991. *Hydrographic Data Base for Mermentau River.* New Orleans District. Unpublished.

U.S. Army Corps of Engineers (USACE). 1988. *Fiscal Year Annual Report of the Chief of Engineers on Civil Works Activities.* Report of the Galveston District. 39 pp.

U.S. Army Corps of Engineers (USACE). 1987. *Water Resources Development in Louisiana, 1987.* Lower Mississippi Valley Division. 130 pp.

U.S. Army Corps of Engineers (USACE). 1984a. *Analysis of Sikes Cut Monitoring Data Collected Before and After Maintenance Dredging, February 1-2, 1984 and March 8-9, 1984.* Mobile, AL: Mobile District. Unpublished Report.

U.S. Army Corps of Engineers (USACE). 1984b. *Louisiana Coastal Area, Louisiana. Freshwater Diversion to Barataria and Breton Sound Basins, Vol* 2. New Orleans, LA: New Orleans District. 575 pp.

U.S. Army Corps of Engineers (USACE). 1983a. *Detailed Project Report and Environmental Impact Statement on Breakwater at Eastpoint, Florida.* Unpublished Report.

U.S. Army Corps of Engineers (USACE). 1983b. *Mississippi Sound and Adjacent Areas Plan Formulation Report.* Mobile, AL: Mobile District. 275 pp. + Appendices.

U.S. Army Corps of Engineers (USACE). 1983c. *Mississippi and Louisiana Estuarine Areas, Freshwater Diversion to Lake Pontchartrain Basin and Mississippi Sound, Feasibility Study.* Volume 2 and Technical Appendices A-D. New Orleans, LA: New Orleans District.

U.S. Army Corps of Engineers (USACE). 1982. *Benthic Macrofauna Community Characterizations in Mississippi Sound and Adjacent Areas.* Final Report to USACE, Contr. No. DACW01-80-C-0427. Mobile, AL: Mobile District.

U.S. Environmental Protection Agency (USEPA). 1991. *Hydrographic Data Base for Perdido Bay.* Gulf Breeze, FL: Gulf Breeze Laboratory. Unpublished.

U.S. Fish and Wildlife Service (USFWS). 1982a. *Gulf Coast Ecological Inventory: Beeville, Texas Base Map.* Washington, DC: U.S. Department of the Interior.

U.S. Fish and Wildlife Service (USFWS). 1982b. *Gulf Coast Ecological Inventory: Houston, Texas Base Map.* Washington, DC: U.S. Department of the Interior.

U.S. Fish and Wildlife Service (USFWS). 1982c. *Gulf Coast Ecological Inventory: New Orleans, Louisiana Base Map.* Washington, DC: U.S. Department of the Interior.

U.S. Fish and Wildlife Service (USFWS). 1982d. *Gulf Coast Ecological Inventory: Valdosta, Georgia/ Florida Base Map.* Washington, DC: U.S. Department of the Interior.

U.S. Fish and Wildlife Service (USFWS). 1982e. *Gulf Coast Ecological Inventory: Pensacola, Florida Base Map.* Washington, DC: U.S. Department of the Interior.

U.S. Geological Survey (USGS). 1991. *Water Quality Data Base for Louisiana Estuaries.* Reston, VA. Unpublished Data.

U.S. Geological Survey (USGS). 1990. *Gaged Streamflow Data.* Reston, VA. Unpublished Data.

Vidal, F.V., V.M. Vidal, and J.M. Molero. 1990. *Atlas Oceanografico del Golfo de Mexico.* Cuernavaca, Morelos, Mexico: Inst. Investig. Electr.

Von Deesten, A.P. 1924. *Sabine-Neches Waterway (Saltwater Guard Lock) Salinity Survey.* Washington, DC: House of Representatives, Committee on Rivers and Harbors, 68th Congress, 2nd Session, Document No. 12.

Walton, R. and R.A. Gibney. 1988. "Meteorology and Hydrology of Sarasota Bay." In: *Proceedings of the Sarasota Bay Area Scientific Information Symposium.* Tampa, FL: Camp Dresser and McKee.

Wang, F.C. 1988. "Saltwater Intrusion Modeling: The Role of Man-made Features." In: *Causes of Wetland Loss in the Coastal Central Gulf of Mexico, Vol II: Technical Narrative,* R.E. Turner and D.R. Cahoon (Editors), 71-100. New Orleans, LA: Minerals Management Service, Contract No. 14-12-0001-30252, OCS Study/MMS 87-0120.

Ward, G.H., Jr. 1983. *The Effect of Deep-draft Ship Channels on Salinity Intrusion in Shallow Bays.* Ports '83, American Society of Civil Engineers. pp. 532-542.

Ward, G.H., Jr. 1981. *Modeling of Salinity and Dissolved Oxygen in the Neches River Estuary.* Doc. No. 81454. Austin, TX: Espey, Huston, and Associates.

Ward, G.H., Jr. 1980. "Hydrography and Circulation Processes of Gulf Estuaries." In: *Estuaries and Wetland Processes with Emphasis on Modeling,* P. Hamilton and K.B. MacDonald (Editors), 183-215. New York, NY: Plenum Press.

Ward, G.H., Jr. 1973. *Hydrodynamics and Temperature Structure of the Neches Estuary: Vol.1, Physical Hydrography.* Document No. T73-AU-9509. Austin, TX: Tracor, Inc.

Ward, G.H., Jr., N.E. Armstrong, and the Matagorda Bay Project Team. 1980. *Matagorda Bay, Texas: Its Hydrology, Ecology, and Fishery Resources,* FWS/OBS-81/52. Washington, DC: U.S. Fish and Wildlife Service. 230 pp.

Wax, C.L., R.A. Muller, and M.J. Borengasser. 1977. *Climatology, Hydrology, and Hydrography of the Vermilion Basin. Part I. Vermilion Basin: Synoptic Weather Types and Environmental Responses.* Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), Office of Coastal Zone Management. 48 pp.

Weisberg, R.H. 1989. *Sikes Cut - A Review of Data and Physical Model Studies by the COE on the Salinity Effects for Apalachicola Bay.* Final Report. Tallahassee, FL: Florida Department of Environmental Regulation.

Weisberg, R.H. 1976. *A Note on Estuarine Mean Flow Estimation.* Jour. Mar. Res. 34:387-394.

Wermund, E.G., R.A. Morton, and Gowell. 1989. "Geology, Climate, and Water Circulation of the Galveston Bay System." In: *Galveston Bay: Issues, Resources, Status, and Management,* T.E. Whitledge and S.M. Ray (co-organizers), 3-22. Washington, DC: National Oceanic and Atmospheric Administration (NOAA), Estuary-of-the-Month Seminar Service, No. 13.

White, C.J. and W.S. Perret. 1973. *Short-term Effects of the Toledo Bend Project on Sabine Lake, Louisiana.* Proceedings of the S.E. Association, Game & Fish Commission 27:710-721.

Wicker, K.M., D. Davis, and D. Roberts. 1983. *Rockefeller State Wildlife Refuge and Game Preserve:*

Evaluation of Wetland Management Techniques. Baton Rouge, LA: Louisiana Department of Natural Resources. 84 pp.

Wicker, K.M., R.E. Emmer, D. Roberts, and J. van Beek. 1989. *Pipelines, Navigation Channels, and Facilities in Sensitive Coastal Habitats, An Analysis of Outer Continental Shelf Impacts, Coastal Gulf of Mexico, Vol 1: Technical Narrative.* New Orleans, LA: U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, OCS Report/MMS 89-0051. 470 pp.

Wilson, A. and K. Iseri. 1969. *River Discharge to the Sea from the Shores of the Coterminous United States,* Hydrologic Investigation Atlas HA-282 (Revised). Washington, DC: U.S. Geological Survey.

Wiseman, W.J., Jr. 1986. "Estuarine-shelf Interactions." In: *Baroclinic Processes on Continental Shelves,* edited by C. Mooers. Coastal and Estuarine Science 3. Washington, DC: American Geophysical Union.

Wiseman, W.J., Jr., E.M. Swenson, and F.J. Kelly. 1990a. *Control of Estuarine Salinities by Coastal Ocean Salinity.* Coastal and Estuarine Studies 38:184-193.

Wiseman, W.J., Jr., E.M. Swenson, and J. Power. 1990b. *Salinity Trends in Louisiana Estuaries.* Estuaries 13:265-271.

Wiseman, W.J., Jr., S.P. Murray, J.M. Bane, and M.W. Tubman. 1982. *Temperature and Salinity Variability within the LA Bight.* Contributions in Marine Science 25:109-120.

Wolfe, S.H. (Ed). 1990. *An Ecological Characterization of the Florida Springs Coast: Pithlachascotee to Waccasassa Rivers.* USFWS Biological Report 90(21). 323 pp.

Wolfe, S.H., J.A. Reidenauer, and D.B. Means. 1988. *An Ecological Characterization of the Florida Panhandle.* U.S. Fish and Wildlife Service, Biology Rep. 88(12). OCS Study/MMS 88-0063. Washington, DC: Minerals Management Service. 277 pp.

Wolfe, S.H. and L.E. Wolfe. 1985. *The Ecology of the Suwannee River Estuary: An Analysis of Ecological Data from the Suwannee River Water Management District Study of the Suwannee River Estuary, 1982-1983.* Suwannee River Water Management District. 118 pp.

Yeager, D.M., V. Ogilive, and R. Krause. 1989. *Final Report for Investigations Project, North Florida Stream Research Project: Study IV, Evaluation of Sport Fish Introductions: 1983-1988.* Holt, FL: Florida Game and Freshwater Fish Commission. 59 pp.

Zetler, B.D. and D.V. Hansen. 1972. "Tides in the Gulf of Mexico." In: *Contributions on the Physical Oceanography of the Gulf of Mexico.* L. Capurro and J. Reid (Editors), 265-275. Houston, TX: Gulf Publications.

Personal Communications

Bartel, R., NW Florida Water District, Havannah, FL.

Dujardin, C., Hydroqual, Mahwah, NJ.

Hopkins, T.S., University of Alabama, Dauphin Island, AL.

Imsand, F.D., U.S. Army Corps of Engineers, Mobile, AL.

Livingston, R.J., Department of Biology, Florida State University, Tallahassee, FL.

Niedaroda, A., Environmental Sciences and Engineering, Inc., Gainesville, FL.

Appendix I. Data Availability

Salinity data were obtained primarily from long-term data programs and special studies. The data programs covered large ranges of spatial and temporal resolution. A single data set with sufficient spatial and temporal intensity to thoroughly investigate the salinity structure and its variability was rare, although several combined data sets were sufficient to characterize the structure and make certain observations regarding variability. Data unavailable for public use and "lost" data further complicated this synthesis effort. The salinity data available for this study and periods-of-record for which the data were available are given in Table I-1.

Table I-1. *Data Availability for the Gulf of Mexico Estuaries*

Estuary	Number of Major Data Sources	Number of Special Studies	Years Available	Periods of Depiction Low Salinity	Periods of Depiction High Salinity
Sarasota Bay	1	4	1975-1991	Feb-Apr 1988	Feb-Apr 1988
Tampa Bay	4	0	1970-1992	Feb-Apr 1988	Feb-Apr 1988
Suwannee River	2	0	1979-1988	Feb-Apr 1988	Oct-Dec 1984
Apalachee Bay	2	0	1971-1991	Feb-Apr 1990 Feb-Apr 1978	Sep-Nov 1989 Sep-Nov 1975
Apalachicola Bay	4	1	1979-1991	Feb-Apr 1984	Sep-Nov 1983
St. Andrews Bay	2	0	1980-1992	Feb-Apr 1988	Feb-Apr 1988
Choctawhatchee Bay	3	0	1972-1989	Feb-Apr 1987	Sep-Nov 1985
Pensacola Bay	4	1	1973, 1976-89	Feb-Apr 1988	Sep-Nov 1973
Perdido Bay	1	1	1987-1990	Feb-Apr 1988	Oct-Dec 1988
Mobile Bay	1	0	1968-1969	Feb-Apr 1969	Aug-Oct 1968
Mississippi Sound	0	4	1967-1991	Feb-Apr 1984	Aug-Oct 1980
Lakes Pontchartrain/Borgne & Chandeleur Sound	2	1	1970-1990	Feb-Apr 1984	Aug-Oct 1980
Breton Sound	3	0	1970-1989	Mar-May 1987	Sep-Nov 1982
Barataria Bay	1	2	1970-1988	Apr-Jun 1978	Sep-Nov 1978
Terrebonne/Timbalier Bays	3	0	1970-1990	Jan-Mar 1984	Sep-Nov 1983
Atchafalaya/Vermilion Bays	3	1	1970-1990	Mar-May 1985	Sep-Nov 1975
Mermentau River	3	1	1975-1990	Jan-Mar 1989	Jun-Aug 1988
Calcasieu Lake	4	1	1970-1990	Jan-Mar 1984	Aug-Oct 1984
Sabine Lake	3	1	1968-1989	Mar-May 1985	Aug-Oct 1974
Galveston Bay	4	0	1968-1989	Apr-Jun 1975	Aug-Oct 1986
Brazos River	2	2	1969-1989	Apr-Jun 1975 Apr-Jun 1974	Aug-Oct 1975 Aug-Oct 1974
Matagorda Bay	4	1	1968-1989	Apr-Jun 1985	Aug-Oct 1975
San Antonio Bay	4	1	1967-1989	Apr-Jun 1985	Jul-Sep 1986
Aransas Bay	4	1	1968-1989	Sep-Nov 1974	Jun-Aug 1974
Corpus Christi Bay	4	1	1968-1989	Sep-Nov 1973	Jun-Aug 1974
Laguna Madre	4	1	1968-1989	Sep-Nov 1985	Jun-Aug 1985

Appendix II. Primary Data Sources

FLORIDA

- *Florida Department of Natural Resources (FDNR).* FDNR reclaimed the responsibility for the state shellfish monitoring program from Florida counties in 1980, and now maintains a water-quality record for Florida estuaries. Salinity measurements are usually collected monthly, although more intense sampling is sometimes performed. Prior to 1984, only surface salinities were collected; however, bottom salinities are now included in recent FDNR data sets.

- *Florida Department of Environmental Regulation (FDER).* FDER collects salinity data in conjunction with their water-quality monitoring program. Sampling frequency is sometimes monthly, although it usually occurs one to six times per year. Surface and bottom salinities are collected at a few fixed stations.

- *Center for Aquatic Research and Resource Management, Florida State University (FSU).* A long-term record of physical, chemical, and biological processes has been maintained by R.J. Livingston for most of north Florida's Gulf coast estuaries. Long-term physical measurements, supplemented by documented changes in biota, provide an opportunity to examine historical changes within these estuaries. Surface and bottom salinities were collected once per month.

- *Suwannee River Water Management District (SRWMD).* As part of ambient water-quality assessments, SRWMD collected four years of monthly surface salinity measurements at 40 stations in the Suwannee River estuary.

- *United States Fish and Wildlife Service (USFWS).* Data from this agency's Striped Bass Survey provided four years of salinity measurements at sites in Eastern Choctawhatchee Bay. The sampling frequency of surface and bottom data was generally monthly to bi-monthly.

- *Environmental Protection Agency (EPA), Gulf Breeze Laboratory.* Unpublished hydrographic data for Perdido Bay are part of an ecological assessment initiated by the Environmental Research Laboratory-Gulf Breeze in 1987. In 1988, the hydrographic study was incorporated into the U.S. EPA Region 4 cooperative management project for Perdido Bay. Surface and bottom data in Perdido Bay cover four years, with monthly or bi-monthly sampling at 15 stations.

- *University of West Florida (Thomas S. Hopkins).* Escambia Bay/East Bay ecosystem parameters were provided, including extensive surface and bottom data for this estuary (excluding Santa Rosa Sound) during January-March, May-July, and September-November 1973.

- *Taylor Biological Company, Inc.* This company provided three years of surface and bottom salinity data as part of the Lake/Baywatch Program for St. Andrew Bay. It is currently developing a long-term water-quality data base for Bay County to assist planners and resource managers in making county-level decisions.

- *Hillsborough County Environmental Protection Commission.* This commission monitors air and water quality in Hillsborough County, produces periodic reports, and recommends improvements for these parameters. From 1974-1991, surface and bottom salinity data were collected monthly at approximately 90 stations throughout Tampa Bay and its tributaries.

- *United States Geological Survey (USGS).* This agency provided 20 years of surface and bottom salinity samples taken from Tampa Bay per week, month, or bi-monthly. A large portion of the data collected during the 1970s was part of a comprehensive environmental assessment of a harbor deepening project.

- *Southwest Florida Water Management District (SWFWMD).* This regional agency regulates water resource activities, including consumptive water use and stormwater permitting. Their primary management objective has been to protect adequate freshwater inflows to estuaries. Salinity, water quality, and biological data have been collected in Florida's West Coast estuaries to support research activities. Salinity data was collected in the Alafia and Little Manatee Rivers of Tampa Bay. From 1985-1990, surface and bottom salinities were collected at approximately 2-mile intervals from 15 stations.

- *Mote Marine Laboratory (MML).* Among various other functions, this lab is the primary water-quality data collection and collation organization for the National Estuary Program in Sarasota Bay.

Their salinity data base spans from 1975 to 1991, with the most consistent sampling beginning in 1978, and includes sampling from FDNR, Sarasota High School, and MML.

ALABAMA

- *Alabama Marine Resources Laboratory (Edward I. Bault).* From January 1968 to March 1969, surface and bottom salinities were measured monthly at 21 stations in Mobile Bay for the Cooperative Gulf of Mexico Estuarine Inventory Study.

- *Alabama Department of Environmental Management (ADEM).* This agency's Coastal Zone Program provided salinity and temperature data for Mobile Bay, the GIWW, and Wolf Bay (Perdido). About nine stations in lower Perdido Bay were sampled monthly at the surface and bottom from 1988 to the present, as part of the agency's trend monitoring program. ADEM also used this data as the basis for state water-use classifications and planning, for the agency's annual Report to Congress on Alabama's coastal waters, and to assess wastewater permits.

- *Alabama Department of Public Health.* This agency provided salinity data at approximately 48 to 55 stations in Mobile Bay from 1978-1991 as part of the Shellfish Sanitation Monitoring Program. Surface salinities were measured at monthly to bi-monthly intervals.

MISSISSIPPI

- *Gulf Coast Research Laboratory.* This lab collected salinity data as part of fishery assessments in the Mississippi Sound and North/Central Gulf of Mexico. Nearly 120 stations throughout the sound were sampled bi-monthly or monthly from 1967 to the present. Depending on the study, either surface only or both surface and bottom samples were collected.

LOUISIANA

- *McNeese State University (DeRouen et al., 1987).* A special study of the Calcasieu Estuary was conducted by numerous investigators under contract to the U.S. Department of Energy. From October 1983 through August 1986, monthly water-quality samples and salinity data were collected from within 1 m of the surface, mid-depth, and within 1 m from the bottom.

- *Louisiana Department of Environmental Quality (LDEQ).* Since 1958, the Water Pollution Control Division of the Office of Water Resources (and the organizations that preceded it in the water quality mission) collected monthly water-quality data, including dissolved chloride concentrations, at fixed stations in coastal Louisiana. Water-quality samples from streams were collected from mid-channel at a depth of about 1 m. Lake samples were also collected one meter below the surface.

- *United States Geological Survey (USGS).* The Water Resources Division collected water-quality data, including dissolved chloride concentrations and specific conductances from which salinity could be calculated. Specific conductances were measured in the field and lab using a meter. Since the 1940s, water-quality surface samples have been collected generally every month at several fixed stations within coastal Louisiana.

- *Louisiana Department of Wildlife and Fisheries (LDWF).* As part of the Seafood Division's Fisheries Monitoring Program initiated in 1966, salinity data was collected to examine trends in the relative abundance of selected fishery species and to manage the estuarine fishery resources of Louisiana. Sampling was conducted weekly from March-October and biweekly from November-February at fixed stations. Surface samples were collected at approximately 30 cm below the water surface and bottom samples were taken about 30 cm above the bottom.

- *Louisiana Department of Health and Human Resources (LDHHR).* Salinity data, collected by the Office of Public Health for the Oyster Water Monitoring Program, were used to classify oyster growing areas, ensuring that oysters are only harvested in areas with acceptable water quality. Frequency of sampling was generally monthly, and samples were collected at about 60-90 cm below the surface at fixed stations.

TEXAS

- *Texas Water Development Board (TWDB).* As part of a long-term Water-quality Monitoring Program, this board provided the Coastal Data System (CDS), which consists of salinity measurements collected to better understand the relationship between freshwater inflow, salinity, and estuarine water quality. Surface and bottom samples are collected four to six times per year at fixed locations; surface and bottom salinities were collected monthly at fixed CDS stations. Special studies were conducted in the Sabine, Matagorda, San Antonio, Aransas, and Corpus Christi estuaries by the TWDB in the mid-1970s for one to three years. TWDB also conducted an intensive-inflow study in the summer of 1980.

- *Texas Water Commission (TWC).* The Statewide Monitoring Network (SMN) includes salinity measurements collected as part of a long-term Water-quality Monitoring Program to regulate pollutant discharges into Texas waters. Surface and bottom salinities are collected at fixed stations. Sampling frequency is generally one to four times per year, although monthly sampling occurred at a few stations.

- *Texas State Department of Health (TDH).* The Division of Shellfish Sanitation Control collects salinity data at fixed stations as part of their Shellfish Monitoring Program. Sampling usually occurs one to six times per year, or on a monthly basis at fixed stations.

- *Texas Parks and Wildlife Department (TPWD).* As part of the Fishery Monitoring Program, this agency collected salinity data to examine trends in the relative abundance of selected fishery species, and to regulate and manage the fishery resources of Texas. This data base was initiated in the mid-1970s. Sampling is generally conducted weekly at randomly selected sites and at depths depending on the sampling technique used. Salinity is measured at the surface for seines and purse nets and at the bottom for trawls and oyster dredges. TPWD provided only 1985 data for the Texas estuaries, except for Laguna Madre where 6 years of data were provided. No data were available for the Sabine or Brazos-San Bernard estuaries.

- *University of Texas at Austin, Center for Research in Water Resources (Armstrong and Goldstein, 1975).* From 1974 to 1975, surface and bottom salinities were collected monthly at 12 stations in the Brazos River estuary to determine the effects of Dow Chemical Plant discharges into the lower Brazos River.

- *Texas Parks and Wildlife Department (Johnson, 1977).* Surface, middle, and bottom salinity data were collected monthly at 19 stations in the Brazos River and San Bernard River/Cedar Lakes estuaries during 1973-1974, as part of a fishery survey.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1993—3 0 0 - 5 6 6 / 8 3 0 9 4