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SUSPENDED SEDIMENT AND NUTRIENT FLUX DYNAMICS IN FOURLEAGUE BAY, LOUISIANA: THE ROLE OF WINTER COLD FRONTS AND ATCHAFALAYA RIVER DISCHARGE

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements of the degree of Doctor of Philosophy in The Department of Oceanography and Coastal Sciences

by

Brian Christopher Perez B.S. University of Alabama, 1992 May 2000

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To my parents, Bob and Laura Perez, and my personal angel, Bonnie Perez.
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ABSTRACT

Material concentrations and fluxes in Oyster Bayou, a tidal channel connecting Fourleague Bay, Louisiana and the northern Gulf of Mexico, were sampled every three hours for 3-months to examine the importance of atmospheric cold fronts and riverine forcing on the functioning of this estuarine system. The Atchafalaya River was the primary source of nitrate+nitrite (NO$_2$+NO$_3$), total nitrogen (TN), and total phosphorus (TP) to the estuary with greater influence associated with northerly post-frontal winds. Riverine influence coupled with wind-forced resuspension events led to the greatest concentrations of total suspended sediment (TSS) and particulate organic carbon (POC). Ammonium (NH$_4$) concentrations were highly variable with decreased concentrations associated with riverine influence, suggesting the importance of biological processes, while phosphate (PO$_4$) concentrations remained relatively stable throughout the study suggesting riverine, Gulf, and biological sources. High concentrations of sediment and nutrients entering the northern bay from the Atchafalaya River coupled with wind-forced transport led to large net exports of water (138.4 m$^3$ s$^{-1}$), TSS (24.1 kg s$^{-1}$), POC (1.2 kg s$^{-1}$), NO$_2$+NO$_3$ (43.5 g s$^{-1}$), NH$_4$ (10.6 g s$^{-1}$), TN (98.5 g s$^{-1}$), PO$_4$ (3.1 g s$^{-1}$), and TP (13.6 g s$^{-1}$) to the Gulf of Mexico. Increased instances of material imports occurred in the latter part of April as a result of tidally-dominated hydrodynamics and lack of high-energy wind events. Ratios of DIN:DIP in Oyster Bayou averaged 37:1 suggesting a potential P-limitation for the majority of the study with brief periods of potential N-limitation during April. High rates of N retention/loss, approximately 50% of each NO$_2$+NO$_3$ and TN inputs, within the estuary and surrounding wetlands were calculated with retention rates inversely
related to loading rates and estuarine flushing time. The results indicate that the high energy subsidy provided by natural pulsing events such as atmospheric cold fronts and seasonal river discharge are efficient mechanisms of sediment and nutrient delivery to adjacent wetlands and are important in maintaining coastal sustainability. If managed properly, the use of shallow estuarine and wetland systems in coastal restoration initiatives (for example, river diversions) may increase productivity and reduce excess water column nutrient concentrations prior to reaching offshore waters.
CHAPTER 1

PROCESSES REGULATING ESTUARINE-OCEAN EXCHANGE OF SEDIMENT AND NUTRIENTS BETWEEN FOURLEAGUE BAY AND THE GULF OF MEXICO
1.1 INTRODUCTION

The transport of materials between estuaries and coastal oceans has been an area of active research for over 30 years (Nixon, 1980; Childers et al., 2000). Not only are estuaries highly productive systems but they also represent an efficient means of trapping and transforming high loads of sediment and nutrients that would otherwise be delivered to offshore waters (Nixon, 1980; Boumans and Day, 1994; Nixon et al., 1996). In an effort to understand the overall functioning of estuarine systems and how they process materials from riverine sources, land drainage, and in situ production, we must understand the function of estuarine sub-systems and the interactions among them. Thus, a conceptual view of the interactions between the marsh and inundating water column, the marsh and estuarine basin, and the greater estuary and coastal ocean is warranted (Childers et al., 2000).

The export of net production from estuaries in the form of organic nutrients, known as the outwelling hypothesis, may potentially be utilized by offshore organisms and lead to increased productivity (Teal, 1962; Odum, 1969; Nixon, 1980; Odum, 1980). Quantification of outwelled materials, however, is difficult due to spatial and temporal variability in transport mechanisms (Boon, 1978; Kjerfve and Proehl, 1979; Dame et al., 1986). Much of the current knowledge of materials transport has been from studies conducted in tidally-driven estuaries along the east coast of the United States (Teal, 1962; Woodwell and Whitney, 1977; Odum, 1969; Nixon et al., 1980; Dame et al., 1986; Jordan et al., 1986). Many of these studies in macrotidal areas focused on tidal forcing as the main mechanism for driving material exchange with temporal sampling schemes chosen to examine the variability over several tidal cycles.
Previous studies in microtidal systems have indicated that material exchanges can be significantly altered by non-local forcing events such as winter cold fronts and tropical storms which occur on time scales of greater than the tidal cycle (Kjerfve et al., 1978; Childers and Day, 1990; Stern et al., 1991; Leonard et al., 1995). As such, generalizations about the magnitude and direction of exchange based on macrotidal systems may not apply to microtidal estuaries with high riverine influence such as those in the northern Gulf coast (Gardner and Kitchens, 1978).

Fourleague Bay, Louisiana, is a shallow, turbid, vertically well-mixed estuary with an area of approximately 95 km² and a mean tidal range of 0.30-0.35 m. The bay is located in south-central Louisiana approximately 11 km southeast of the Atchafalaya River mouth and is surrounded by extensive fresh, brackish, and saline wetlands. Oyster Bayou is located at the south end of Fourleague Bay and is the sole direct connection to the Gulf of Mexico. In late winter to early spring the Atchafalaya River is at peak flow and strongly impacts the bay with high inputs of fresh water, suspended sediment, and nutrients (Madden et al., 1988; Childers and Day, 1990; Stern et al., 1991). The frequency of cold front passages also peaks during this time occurring every 3-8 days on average (Wiseman et al., 1986; Roberts et al., 1989; Moeller et al., 1993). The coupled effects of peak Atchafalaya River discharge and cold front passage, two major estuarine forcing functions, dominate the hydrodynamics of Fourleague Bay and often overwhelm the local tidal regime (Denes and Caffrey, 1988; Madden et al., 1988). Enhanced exports of materials from the bay to the Gulf through Oyster Bayou result.
The purpose of this dissertation is to examine the processes controlling the magnitude of concentrations and fluxes of sediment and nutrients input to and exported from the Fourleague Bay estuary. The data presented are a part of a large collaborative effort to examine the physics, biology, and chemistry of Fourleague Bay during the late winter to early spring months. Principal Investigators included Dr. John Day, Dr. Rick Shaw, Dr. Larry Rouse, and Dr. Dubravko Justic from Louisiana State University. In this chapter, a summary of the major physical, biological, and ecological processes influencing the transformation of materials within and the exchange of materials from Fourleague Bay is presented. Next, the processes responsible for variations in water flux, suspended sediment concentrations, and suspended sediment flux are examined (Chapter 2). In Chapter 3, factors controlling the concentrations and exchange of nutrients are investigated. In Chapter 4, nutrient stoichiometry, the relationship between nutrient loading and uptake, and the effect of estuarine residence time on nutrient export are explored. Finally, Chapter 5 summarizes the conclusions and presents management implications of the study.

1.2 PROCESSES CONTROLLING THE EXCHANGE OF MATERIALS BETWEEN THE FOURLEAGUE BAY ESTUARY AND THE GULF OF MEXICO

Marsh-estuarine and estuarine-ocean exchange of materials is largely regulated by physical forcings. The operative components of these forcings vary in magnitude with individual estuarine systems and the most influential will depend on estuarine depth, area, drainage basin size, fetch, tide range, geographic location, geologic age of the marsh, geomorphic setting, and anthropogenic inputs to the estuary as well as the morphology of the connection to the coastal ocean. Pulsing events affecting coastal
systems occur on various time scales ranging from hours to millennia and include winds, waves, tides, cold fronts, river discharge, hurricanes, and delta lobe switching (Day et al., 1995; Hensel et al., 1998; Day et al., 2000). The annual discharge cycle of the Atchafalaya and Mississippi Rivers is such an impact by adding a pulse of sediment, nutrients, and fresh water to the delta and surrounding area. These pulsing events are major forcing functions and transport mechanisms for estuarine systems (Stevenson et al., 1985; Roberts, 1989; Stern et al., 1991; Murray et al., 1993; Leonard et al., 1995; Hensel et al., 1998; Day et al., 2000; Perez et al., 2000). The following are brief descriptions of physical, biological, and ecological processes that control the magnitude of material concentrations and flux between Fourleague Bay and the Gulf of Mexico.

1.2.1 Winds and Tides

In microtidal areas such as the northern Gulf of Mexico, wind influence on estuarine water levels and estuarine-ocean exchange is important. Along the central Louisiana coast, cross-shelf (north-south) wind forcing causes large variations in regional sea level due to shallow depths (Chuang and Wiseman, 1983). During storm events, the local tidal regime can be overwhelmed with water level variations often two to three times the normal tide range (Murray, 1976; Wax et al., 1978). In Corpus Christi Bay, Texas, for example, meteorologically-driven exchanges of water volume are nearly an order of magnitude more important than diurnal tidal exchanges (Smith, 1977). Instances of high water level variation in conjunction with high suspended sediment concentrations caused by wind-forced resuspension are efficient in
delivering sediment to adjacent marshes (Ward, 1981; Jordan et al., 1986) and are important to long-term wetland sustainability (Baumann et al., 1984).

1.2.2 Riverine Input and Mean Sea Level

Rivers are often the major source of fresh water, sediment, and nutrients supplied to estuarine environments (Day et al., 1989). The seasonal discharge cycle of the Atchafalaya River has a strong impact on the hydrology, nutrient chemistry, and productivity of the Fourleague Bay ecosystem. This is evidenced by seasonal fluctuations in flushing times calculated for the bay, 7 d during the spring peak discharge increasing to 65 d during low-flow in summer-fall (Madden et al., 1988). Seasonal variations in nutrient concentrations can also be dramatic in response to riverine influence ranging from 120 µM of nitrite plus nitrate (NO₂+NO₃) in the Upper Bay during spring to 30 µM during the summer and fall (Madden et al., 1988). Variations in water level in coastal areas are also influenced by riverine input and mean sea level variation. For instance, Stern et al. (1991) reported that marshes in Upper Fourleague Bay were flooded over 40% of the time during periods of high mean sea level and high river discharge and less than 6% of the time when sea level was low.

1.2.3 Loading Rates and Residence Time

The effectiveness of nutrient retention within a wetland system is dependent upon the rate at which it is delivered. As loading rates increase, the uptake efficiency decreases substantially (Mitsch and Gosselink, 1993; Kadlec and Knight, 1996). For instance, removal efficiencies ranged from 88-97% of NO₂+NO₃ entering the Breton Sound estuary in Louisiana with higher uptake rates associated with lower loading.
rates (Lane et al., 1999). Similarly, with longer estuarine residence times biological and geochemical removal processes are more efficient resulting in a potentially lower amount of nutrients exported from the system (Kadlec and Knight, 1996; Nixon et al., 1996).

1.2.4 Denitrification

Nitrification and denitrification are important processes in regulating the estuarine nitrogen cycle. Nitrification is the oxidation of ammonium (NH₄) to NO₃ and occurs only under aerobic conditions. In the denitrification process, NO₃ is used as an electron acceptor to oxidize organic matter under anaerobic conditions releasing N₂ gas as a result (Day et al., 1989). Thus, denitrification is a permanent loss pathway for nitrogen from the estuary/wetland to the atmosphere. This is an important process in Fourleague Bay with approximately 50% of the annual NO₃ entering the estuary undergoing denitrification (Smith et al., 1985). Estimates of nitrogen loss via denitrification in other estuaries include 19% in the Ems estuary, Germany (van Beusekom and de Jonge, 1998), 26% in Chesapeake Bay (Nixon et al., 1996), and 13-27% in Narragansett Bay (Nixon et al., 1996).

1.2.5 Sedimentation/Burial

The burial of nutrients within the estuary or adjacent wetlands via settling and deposition can be an important process in regulating nutrient concentration and flux. This is especially true in subsiding deltaic environments where rapid burial of deposited sediment in Barataria Bay marshes accounted for a net accumulation of 21 g Nm⁻²y⁻¹ and 2.3 gPm⁻²y⁻¹ (DeLaune and Patrick, 1980). Burial and sedimentation provide a net long-term storage of phosphorus which may be permanently removed if
the deposited particles contain insoluble minerals or refractory organophosphorus complexes (Kadlec and Knight, 1996).

1.2.6 Biological Assimilation and Regeneration

Dissolved inorganic nutrients are incorporated into particulate organic matter mainly by autotrophic photosynthetic organisms and macrophytes (Day et al., 1989). Organic matter resulting from excretion, defecation, and senescence of living organisms undergoes decomposition by microorganisms. This process releases the elements composing the organic matter in dissolved inorganic form if the process is complete (Day et al, 1989). In estuarine environments microbial decomposition occurs in the water column but due to short residence times the majority of nutrient regeneration probably takes place on or in the sediment (Day et al., 1989). Benthic communities contribute to elevated rates of primary productivity in estuarine systems by removing nutrients during periods of high loading and releasing the nutrients during periods of low ambient concentrations (Childers and Day, 1990; Twilley at al., 1999). This 'luxury consumption' is an important buffering mechanism in estuarine nutrient dynamics.

1.3 DISSERTATION AND CHAPTER OBJECTIVES

The purpose of this dissertation is to examine the processes controlling the magnitude of concentrations and fluxes of sediment and nutrients input to and exported from the Fourleague Bay estuary, namely the role of Atchafalaya River discharge and winter cold fronts. The main objectives are to:

1. Quantify tidal and cold front driven exchanges of dissolved and particulate material between Fourleague Bay and the Gulf of Mexico;
2. Determine the factors leading to increased concentrations of dissolved and particulate materials;

3. Determine how tidal phase-cold front phase interactions alter the transport regime;

4. Determine how Atchafalaya River discharge affects the volume of water refilling the bay;

5. Determine how variations in loading rates and estuarine residence time influences material concentrations and fluxes.

Specific objectives of each chapter are given below. Each chapter has been prepared in manuscript form for publication submittal. Chapter 2 has been published in the February 2000 issue of *Estuarine, Coastal, and Shelf Science*.

Chapter 2: Influence of Atchafalaya River Discharge and Winter Frontal Passage on Suspended Sediment Concentration and Flux in Fourleague Bay, Louisiana. The objectives of this chapter are to: (1) quantify the flux of total suspended sediment (TSS) between Fourleague Bay, a riverine-dominated, shallow, well-mixed estuary, and the Gulf of Mexico over a 3-month period; (2) ascertain factors which affect net fluxes and lead to increased sediment concentrations, especially the effect of atmospheric cold front passage on water and TSS flux; (3) determine how tidal phase-cold front phase interactions alter the transport regime; and (4) develop an index to categorize objectively the strength and intensity of individual cold fronts. I hypothesize that: (1) the Fourleague Bay estuary is a net exporter of water and sediment; (2) the highest TSS concentrations and fluxes occur during the post-frontal period of a cold front; (3) ebb-directed net fluxes are enhanced by the combination of
peak riverine forcing and winter frontal passage; and (4) marsh deposition occurs during the pre-frontal stage of cold fronts when winds are blowing onshore.

Chapter 3: Nitrogen and Phosphorus Transport Between Fourleague Bay, Louisiana and the Gulf of Mexico: The Role of Winter Cold Fronts and Atchafalaya River Discharge. The objectives of this chapter are to: (1) quantify the concentrations and instantaneous and net exchange of nutrients (nitrogen and phosphorus) and water between Fourleague Bay and the Gulf of Mexico over a three-month period; (2) determine how the passage of cold fronts and high Atchafalaya River discharge influence the concentrations and fluxes of nutrients between the Bay and the Gulf; and (3) determine the differences in concentrations and fluxes during both tidally driven and wind/riverine driven conditions. I hypothesize that: (1) the Fourleague Bay estuary is a net exporter of nutrients throughout the study period; (2) the concentration of nutrients, in particular nitrate+nitrite and total nitrogen, are higher when influenced by the Atchafalaya rather than the Gulf; (3) cold fronts enhance the magnitude of export of nutrients to the Gulf as a result of high velocity northerly winds; and (4) the concentrations of total nitrogen, total phosphorus, and nitrate+nitrite are lower during times of tidal influence due to longer residence times in the bay.

Chapter 4: Nutrient Stoichiometry and Uptake Dynamics in Fourleague Bay, Louisiana. The objectives of this chapter are to: (1) examine the spatial and temporal pattern of nutrient concentrations in Fourleague Bay; (2) examine the effect of salinity on nutrient concentrations; (3) evaluate the stoichiometric balance of nitrogen and phosphorus (dissolved inorganic and total) in Fourleague Bay and the Atchafalaya River during the spring discharge months; (4) examine the relationship between
loading and uptake rates of nitrogen and phosphorus; and (5) determine the effects of
residence time as regulated by riverine influence and tidal influence on the magnitude
of nutrient flux to the coastal ocean. I hypothesize that: (1) concentrations of
NO₂+NO₃, TN, and TP are greater in association with increased Atchafalaya River
influence; (2) ratios of nitrogen to phosphorus are greater with increased Atchafalaya
River influence, especially dissolved inorganic ratios; (3) nutrient uptake rates and
efficiencies are greater during periods of low nutrient loading to the bay; and (4) net
export of nutrients is less during periods of increased estuarine residence time.

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CHAPTER 2

INFLUENCE OF ATCHAFALAYA RIVER DISCHARGE AND WINTER FRONTAL PASSAGE ON SUSPENDED SEDIMENT CONCENTRATION AND FLUX IN FOURLEAGUE BAY, LOUISIANA *

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16
2.1 INTRODUCTION

The mobilization, deposition and transport of sediment in coastal systems are very dynamic. Riverine input is a major sediment source to estuaries, but the input varies with discharge and the size and nature of the drainage basin. The resuspension and transport of sediment within estuaries is also largely related to high energy events (Baumann et al., 1984; Hsu, 1993; Cahoon et al., 1995; Day et al., 1995; Hensel et al., 1998). For example, Nichols (1991) reported that 73% of the sediment supply of the James River estuary, a tributary of Chesapeake Bay, is from fluvial input, and that 90% of the mean annual suspended sediment load for the James and Rappahannock River estuaries is transported in less than 11% of the year. Sediment can also be transported into estuarine systems from the near-shore ocean during storm events (Roberts 1997). Sediment transport within estuaries is also influenced by tidal dynamics. Stevenson et al. (1988) reviewed sediment fluxes in marsh systems along the Gulf and Atlantic coasts and suggested that southeastern estuaries of the United States are net exporters of water and sediment as a result of a tidal-velocity asymmetry which favors ebb-directed flows. Similarly, Leonard et al. (1995) concluded that sediment transport in Cedar Creek, Florida was influenced by time-velocity asymmetry of tidal currents, spring-neap tidal aberrations, and extra-tropical storm activity.

Marsh accretionary processes are related to sediment imported into estuarine systems and sediment dynamics within estuaries. Vertical accretion, whether from mineral sediment input or organic soil formation, is necessary to offset eustatic sea level if marshes are to remain healthy and survive (Mitsch and Gosselink, 1993; Cahoon et al., 1995). This is especially important for deltas where high rates of
subsidence lead to relative sea level rise rates which are much greater than eustatic sea level rise (Baumann et al., 1984; Stanley and Warne, 1993; Cahoon et al., 1995). Sediment suspended in the water column is deposited on the marsh surface during periods of inundation, whether by tidal action, storm related events, or other means. In microtidal areas such as the northern Gulf of Mexico, infrequent forcings such as atmospheric cold front passages and tropical storms which resuspend large amounts of sediment supply most of the sediment deposited on marsh surfaces (Baumann, 1980; Rejmanek et al., 1988; Conner et al., 1989; Reed, 1989; Cahoon et al., 1995). For example, Baumann et al. (1984) reported sedimentation rates in salt marshes of Barataria Bay, Louisiana were consistently higher in the winter months as a result of frontal passages. Similarly, Stumpf (1983) reported that strong storms led to most of the deposition in a Delaware salt marsh.

The coastal area of the north-central Gulf of Mexico is dominated by the Mississippi delta and its high river discharge. The Mississippi is ranked third, seventh, and seventh, respectively, in terms of length, sediment yield, and discharge (Meade, 1996). The mean flow of the lower Mississippi River is about 20,000 m$^3$s$^{-1}$, one third of which is discharged via the Atchafalaya river (Figure 2.1). Since this is an area of low tidal range (average about 0.35 m), wind forcing during storm events can cause much greater water level changes than tides (Wax et al., 1978; Murray, 1976). For example, Kemp et al. (1980) recorded meteorologically-induced water level ranges of 1.2 m during the winter months associated with frequent frontal passages, nearly double the maximum astronomical tide range along the northern gulf coast. In Caminada Bay, Louisiana, Kjerfve (1973) reported that water levels and circulation were
Figure 2.1. Location of Oyster Bayou (the study site), Fourleague Bay, and the Atchafalaya River in south-central Louisiana. The "p" north and south of Oyster Bayou indicates the location of pressure gauges for water level measurements. The shaded areas surrounding the Bay are marsh.
controlled by winds on a scale of a few days and diurnal tides on a daily scale. In addition to wind and tides, the study area, Fourleague Bay, is also highly impacted by Atchafalaya River discharge. For example, Madden et al. (1988) reported that flushing time of the bay was 7 days during peak river discharge compared to approximately 65 days during low discharge periods.

Tidal exchange studies are often used to estimate sediment budgets for estuarine systems. There have been several studies of water and materials transport in the Fourleague Bay system. Stern et al. (1986; 1991) investigated total suspended sediment (TSS) and nutrient transport in a tidal freshwater bayou near the mouth of the Atchafalaya River. TSS transport was ebb- or seaward-directed for all seasons, but transport was two orders of magnitude greater during high river discharge than during tidally-driven conditions. In lower Fourleague Bay, Childers and Day (1990) examined marsh-water column sediment exchanges utilizing throughflow flumes and reported that lower bay marshes were generally a sink for sediment during the high river flow months. Sediment was exported from the marsh, however, during a winter storm which occurred during low tide. All of these studies were carried out over short time periods, generally two tidal cycles, but show that riverine forcing and atmospheric frontal passages can greatly alter net fluxes. In order to determine the long-term quantitative impacts of these forcing functions, longer term studies with sampling designs at the appropriate time scales are needed. To examine patterns in concentrations and fluxes of dissolved and particulate materials on a more detailed scale, an intensive 89-day flux study was carried out in Oyster Bayou, a tidal channel which connects Fourleague Bay to the Gulf of Mexico (Figure 2.1). The time period (February - April) is concurrent
with peak river discharge of the Atchafalaya and peak cold front activity, two major estuarine forcings in coastal Louisiana.

The objectives of this study were: 1) to quantify the flux of TSS between Fourleague Bay, a riverine-dominated, shallow, well-mixed estuary, and the Gulf of Mexico over a three month period; 2) to ascertain factors which affect net fluxes and lead to increased sediment concentrations, especially the effect of atmospheric cold front passages on water and TSS flux; 3) to determine how tidal phase - cold front phase interactions alter the transport regime; and 4) to develop an index to objectively categorize the strength and intensity of individual cold fronts. We hypothesized that: 1) the Fourleague Bay estuary is a net exporter of sediment and water; 2) the highest TSS concentrations and fluxes occur during the post-frontal period; 3) ebb-directed net fluxes are enhanced by the combination of peak riverine forcing and winter frontal passages; and 4) marsh deposition occurs during the pre-frontal stage of cold fronts when the winds are blowing onshore.

2.2 SITE DESCRIPTION

Fourleague Bay is a shallow (mean depth 1.0 m), highly turbid, vertically well-mixed estuary with an area of approximately 95 km² (Figure 2.1). The bay is located in south central Louisiana approximately 11 km southeast of the Atchafalaya River mouth and is surrounded by extensive fresh, brackish, and saline wetlands. River discharge strongly impacts the bay due to high inputs of fresh water, suspended sediments, and nutrients. The Upper Bay has a northwest–southeast orientation and the Lower Bay has a north–south orientation. Salinity ranges from 0-8 ppt in the Upper Bay and 0-26 ppt in the Lower Bay (Caffrey and Day, 1986; Madden et al., 21)
During high discharge, bay hydrodynamics are driven by fresh water input and winds generated by winter storms, whereas the circulation during low discharge periods is dominated by diurnal tides. The bay is connected to the Gulf via Oyster Bayou, a 4 km long tidal channel with an average and maximum depth of about 5.5 m and 10 m, respectively, and a mean width of 180 m. The bayou is the only direct outlet to the Gulf and peak current velocities can exceed 2.0 m s\(^{-1}\). Extensive intertidal and subtidal oyster reefs line the bayou which is bordered by \textit{Spartina alterniflora} marshes.

During the winter months, cold fronts pass through southern Louisiana on average every 3-8 days (Wiseman et al., 1986; Roberts et al., 1989; Moeller et al., 1993). Prior to a frontal passage, southerly winds cause an onshore movement of Gulf water along the Louisiana coast. This very often induces a net influx of water through Oyster Bayou and into the bay and surrounding wetlands which can be inundated with 30-40 cm of water during this pre-frontal phase (Denes and Caffrey, 1988). As the front passes, winds shift to westerly and then northerly and water rapidly drains from the shallow wetlands and bay. This frequent and energetic inundation and draining is a major transport mechanism for sediment, nutrients, and organic matter among Fourleague Bay and adjacent wetlands and the Gulf of Mexico (Madden et al., 1988; Stern et al., 1991).

2.3 MATERIALS AND METHODS

In order to assess the effects of winter frontal passages on suspended sediment exchange between Fourleague Bay and the Gulf, an intensive study of the transport of water and materials through Oyster Bayou was carried out from 1 February to 1 May
1994. During this time period, current velocity and direction, and weather conditions were measured quasi-continuously and water samples were taken each three hours for measurement of various physical, chemical, and biological parameters. This high frequency sampling regime allowed net fluxes to be evaluated on various time scales ranging from hours to months. A temporary field research station was established on the eastern bank of Oyster Bayou about 1.5 km south of Fourleague Bay. A sampling platform extended about 15 meters into Oyster Bayou to a depth of approximately 5 m, or about the average depth of the bayou. A weather station consisting of a Campbell datalogger, R. M. Young wind sensors, and single bead temperature thermistors was installed on site 10 m above marsh level. Wind speed and direction, barometric pressure, humidity, and air and sea temperature were recorded once a minute. The data were down-loaded every 2-3 weeks and hourly averages were computed.

Currents were measured in mid-channel where the depth was approximately 10 m using two ENDECO 174 SSM current meters, one 2 meters below the surface and another 1.5 meters above the bottom. Time, current velocity and direction, temperature, and conductivity were recorded every 15 minutes. The current meters were cleaned and data down-loaded each two weeks. Two water level recorders were deployed on navigation platforms at each end of Oyster Bayou, one in Fourleague Bay about one km north of the bayou and another about one km offshore in the Gulf. Water flux (m$^3$s$^{-1}$) was calculated as the product of the average of surface and bottom current velocity and the cross-sectional area of the bayou. The cross-sectional area was measured when the bayou was bank full using a continuously recording fathometer and
water flux data were corrected for changes in cross-section area due to changing water level.

In order to statistically test the effect of frontal passage on concentration and flux parameters, an index of frontal occurrence and strength was developed. The passage of a cold front was defined by a shift in the wind from southerly to northerly. Depending upon the strength of the high pressure cell following the front, the shift in wind direction can be very abrupt (almost immediate) or can occur over several minutes. Numerous short-lived, weak, dry fronts passed throughout the course of the study. To focus on the more powerful fronts, an index comprised of a combination of barometric pressure, air temperature, and wind stress was used. The rate of change in pressure and temperature was calculated hourly over a 24-hour period (dP/dt and dT/dt; dt=24 hrs) to reduce diel effects. Additionally, hourly wind stress (τ), expressed in Nm⁻², was calculated to obtain the energy imparted on the water surface following Hsu (1993):

\[ \tau = \rho C_d U_{10}^2 \]

where \( \rho \) is the density of air, \( C_d = (U^*/U_{10})^2 \) is the drag coefficient, \( U^* \) is the shear (or friction) velocity, and \( U_{10} \) is the wind speed at 10 m above the sea surface. The more robust frontal events were defined as those time periods when all three factors exceeded a specific threshold concurrently (dP/dt > 0.3 mbar / 24h, dT/dt < -0.2 °C / 24h, and \( \tau > 0.10 \) Nm⁻²). Each calculated rate of change of pressure and temperature are hourly rates over a 24 h period (see example below). These thresholds were subjectively chosen based on first hand (on-site) observations of when significant cold
fronts passed. Thus, the index indicates the occurrence of a cold front, as well as its relative strength. A total of 23 frontal passages as defined by wind shifts were observed (Table 2.1). Of these, 7 satisfied the frontal index criteria of significant frontal events.

Table 2.1. Net total suspended sediment (TSS) flux (kg s⁻¹; kg) and Particulate Organic Carbon (POC) flux (kg s⁻¹; kg) per winter frontal passage from Feb. 1 to Apr. 30, 1994. The seven major cold fronts identified by the frontal index are indicated in bold type.

<table>
<thead>
<tr>
<th>Front</th>
<th>Dates</th>
<th>Duration (h)</th>
<th>Net TSS Flux (kg s⁻¹)</th>
<th>Net TSS Flux (kg)</th>
<th>Net POC Flux (kg s⁻¹)</th>
<th>Net POC Flux (kg)</th>
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<tr>
<td>1</td>
<td>2/2 2100 - 2/4 1400</td>
<td>41</td>
<td>-2.84</td>
<td>-5.5E+05</td>
<td>0.01</td>
<td>1.9E+03</td>
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<tr>
<td>2</td>
<td>2/4 1500 - 2/6 2100</td>
<td>54</td>
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<td>-0.38</td>
<td>-8.2E+03</td>
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<tr>
<td>3</td>
<td>2/6 2200 - 2/7 0400</td>
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<td>-19.01</td>
<td>-2.1E+06</td>
<td>-0.75</td>
<td>-8.1E+04</td>
</tr>
<tr>
<td>4</td>
<td>2/7 0500 - 2/11 2300</td>
<td>114</td>
<td>-46.01</td>
<td>-1.9E+07</td>
<td>-1.75</td>
<td>-7.2E+05</td>
</tr>
<tr>
<td>5</td>
<td>2/12 0000 - 2/13 0600</td>
<td>30</td>
<td>-19.01</td>
<td>-2.1E+06</td>
<td>-0.75</td>
<td>-8.1E+04</td>
</tr>
<tr>
<td>6</td>
<td>2/13 0700 - 2/22 0700</td>
<td>216</td>
<td>-28.85</td>
<td>-2.2E+07</td>
<td>-0.89</td>
<td>-6.9E+05</td>
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<tr>
<td>7</td>
<td>2/22 0800 - 2/25 1600</td>
<td>80</td>
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<td>-1.8E+07</td>
<td>-4.61</td>
<td>-1.3E+06</td>
</tr>
<tr>
<td>8</td>
<td>2/25 1700 - 3/1 0900</td>
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<td>-1.0E+07</td>
<td>-1.62</td>
<td>-5.1E+05</td>
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<tr>
<td>9</td>
<td>3/1 1000 - 3/3 1900</td>
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<td>-1.5E+06</td>
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<td>-2.1E+05</td>
</tr>
<tr>
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<td>-25.08</td>
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<td>-1.55</td>
<td>-1.5E+05</td>
</tr>
<tr>
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<td>-36.27</td>
<td>-5.7E+06</td>
<td>-2.03</td>
<td>-3.2E+05</td>
</tr>
<tr>
<td>19</td>
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<td>68</td>
<td>-22.35</td>
<td>-5.5E+06</td>
<td>-1.17</td>
<td>-2.9E+05</td>
</tr>
<tr>
<td>20</td>
<td>4/4 1800 - 4/9 1300</td>
<td>115</td>
<td>-19.96</td>
<td>-8.3E+06</td>
<td>-0.89</td>
<td>-3.7E+05</td>
</tr>
<tr>
<td>21</td>
<td>4/9 1400 - 4/13 2300</td>
<td>105</td>
<td>21.89</td>
<td>8.3E+06</td>
<td>1.04</td>
<td>3.9E+05</td>
</tr>
<tr>
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<td>4/14 0000 - 4/21 1900</td>
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<td>-1.0E+05</td>
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<td>4/21 2000 - 4/23 2000</td>
<td>48</td>
<td>-2.87</td>
<td>-5.0E+05</td>
<td>-0.19</td>
<td>-3.3E+04</td>
</tr>
</tbody>
</table>

The following example illustrates the mechanics of the cold front index using the threshold values for the three index factors given in the previous paragraph. The pressure and temperature thresholds were calculated as follows: 2 discreet time periods 24 hours apart were identified, for example, 0800 on day 1 and 0800 on day 2. The difference in value (either temperature or pressure) of each 24 hour time period was
calculated and entered as the mid-point value, 2000 hours in the above example, to reflect a +/- 12 hour calculation. Therefore, the temperature threshold represents a 4.8°C decrease in temperature between 0800 on day 1 and 0800 on day 2 (i.e., 0800 day 1 temperature is 15°C and 0800 day 2 is 10.2°C). Similarly, a 7.2 mbar increase in barometric pressure must occur over the same period. The fact that 2 discreet time periods evaluated 24 hours apart can change -4.8°C and 7.2 mbar simultaneously intuitively tells us that some meteorological aberration has occurred, in this case a cold front. The wind stress is calculated from the formula stated above from hourly weather data gathered on site. These thresholds are calculated every hour for the duration of the study.

An integrated water sample was taken from the sampling platform every 3 hours from the top 2-3 m of the water column with a one liter capacity LaMotte 1077 water sampler. We assumed that this integrated sample was representative of the entire bayou based on the high current velocities, the relative straightness of the bayou, and the shallow, well mixed nature of the bay. In addition, previous work in the area by Madden et al. (1988) and Day et al. (1995) have shown the bayou to be a well-mixed, homogenous water body. Once each day, a replicate sample was taken during a randomly chosen interval for calibration and statistical purposes. Water samples were placed in polyethylene bottles pre-washed with a 10% HCl solution and immediately put on ice and placed in the dark. Filtering was done within 12 hours of collection. From each sample, a known volume of water was filtered through a pre-combusted, pre-weighed Whatman 2.5 cm GF/F glass fiber filter and frozen until analyzed for TSS as described by Banse et al. (1963). Particulate organic carbon (POC) analysis was
performed on a Fisons NA 1500 Series 2 CNS instrument using the TSS filters already analyzed.

Instantaneous fluxes of suspended sediments (kg s\(^{-1}\)) were calculated for each three hour interval based on the concentration of TSS multiplied by the associated water flux value. Since water flux was measured more frequently, every 15 minutes, the average water flux for the previous 3 hours was used to calculate TSS fluxes. Net fluxes are reported as time weighted averages and were calculated as the algebraic sums of the instantaneous fluxes divided by the number of samples taken within the respective time period. Positive fluxes (+) indicate flood-directed flows moving north from the Gulf into Fourleague Bay. Negative fluxes (-) represent ebb-directed flows moving from the bay to the Gulf. Note that net fluxes are representative of what is moving in and out of Oyster Bayou only, we do not have any discreet information on what is entering or exiting the northern bay or adjacent bayous.

To determine which physical forcing functions were to be included in a statistical model, a stepwise regression was performed using SAS statistical software (SAS Institute, 1989). Correlations between log-transformed TSS concentrations and the physical forcing functions were determined by a least squares multiple regression. The parameters included in the model were a TSS variable lagged 3 hours, water velocity, wind stress, air temperature, tide direction, and chlorophyll \(a\) concentration. The lag of the TSS variable was included to remove the effect of serial correlation with prior TSS measurements and was tested using the Durbin-Watson statistic. As a result, Durbin-Watson was near 2 suggesting no autocorrelation among TSS was evident in the
data. An ANOVA was used to determine significant differences in TSS over various
time scales.

2.4 RESULTS

2.4.1 Wind

The high variability of wind speed and direction associated with winter frontal
passages was a major force affecting TSS concentrations and fluxes. With the
propagation of cold fronts, the wind rotates in a clockwise direction (Figure 2.2c).
During the pre-frontal period, winds were from the south changing abruptly to
northerly at high velocities as the front passes and during the post-frontal period.
Winds during the inter-frontal period were generally near calm and out of the northeast
to east quadrant. The velocity and duration of winds associated with a cold front are
dependent upon the strength of the high pressure cell following the front. Pre-, post-, and
inter-frontal periods are defined here as winds having a direction of 113° to 292°,
293° to 45°, and 46° to 112°, respectively.

Northerly winds had the greatest velocities throughout the study period (Figure
2.2c). Wind velocities reached a maximum of 14 ms⁻¹ (approximately 26 kts) from the
north during the April 6 (Julian Day 96, henceforth JD) front. Easterly and southerly
winds were not as intense but lasted for extended periods of time during inter-frontal
and pre-frontal periods. Wind direction played a very important role in the transport
of water and materials through Oyster Bayou. Winds from the southwest, west,
northwest, and north, which force river water into the bay through the northern
entrance, occurred 32% of the time (Figure 2.3). South winds, which occurred 16% of
the time, force gulf water into Fourleague Bay via Oyster Bayou.
Figure 2.2. Factors used in the frontal index determination. (a) Graph of the rate of change of barometric pressure (dP) and air temperature (dT) calculated over a 24 h period used in the frontal index equation. (b) Wind stress calculated hourly for the frontal index. (c) Wind vector diagram indicating hourly wind velocity and direction. Length of the vector indicates speed. Direction is read from the terminus of the vector into the origin of the graph, i.e., any vector originating above the zero axis has a northerly component and any vector originating below the zero axis has a southerly component. Diamonds and shaded areas indicate when all three factors exceeded thresholds defined for strong fronts by the frontal index. dP/dT; dT/dt.
Figure 2.3. Wind direction distribution depicting the percent frequency of occurrence for each month and for the total study. Site map shows the orientation of Fourleague Bay in relation to the Atchafalaya River. Wind directions marked with an asterisk force river water into the northern entrance of Fourleague Bay, those without asterisks divert river water away from the bay.
South winds also retard Atchafalaya River outflow to the Gulf which induces the flow of river water into the upper entrance of Fourleague Bay, thereby leading to increased water levels in the bay. The remaining wind directions (NE, E, SE), which largely tend to push river water away from the bay, had a frequency of 52%. Based on a calculation of the conservation of water volume, approximately 1.7% of the Atchafalaya River discharge entered Fourleague Bay at the northern entrance during February and March and less than 0.5% in April, similar to that calculated by Denes (1983).

A least squares regression of log-transformed TSS concentrations against a TSS variable lagged 3 hours, water velocity, wind stress, air temperature, tide direction, and chlorophyll a. derived from the stepwise regression was highly significant (p<0.0001, \( r^2 = 0.56 \)). The Durbin-Watson test statistic for autocorrelation associated with the model was 1.96 indicating no significant serial correlation. The relatively low \( r^2 \) (0.56) indicates the complex dynamics of the Bay.

2.4.2 Frontal Index

The frontal index was used to identify winter storms which would likely have a greater influence on the estuary in comparison to weaker fronts in terms of strength and duration. Seven major fronts were identified by the index (Figure 2.2a), and were verified by comparison to the weather data (figs. 2.2a-c). With the present thresholds, the index is sensitive only to the onset of a frontal passage due to the rate dynamics of the index parameters. Hence, the weather data must also be examined to determine the duration and specific characteristics of the front (i.e., figs. 2.2 and 2.4). Figure 2.2a is shaded at the points where the frontal index thresholds were exceeded, indicating that a
Figure 2.4. (a) Relative water levels in Lower Fourleague Bay. Horizontal dashed line at 1.38 m indicates the marsh elevation, i.e., water levels above this mark are indicative of marsh flooding. Solid horizontal line indicates the study mean water level. Shaded areas are the 7 major fronts identified by the frontal index. (b) Current velocity in Oyster Bayou. (c) Instantaneous water flux. Positive values indicate flood-directed flux into Fourleague Bay from the Gulf of Mexico. Negative values indicate ebb-directed flux from Fourleague Bay into the Gulf. All subsequent flux graphs follow the same convention.
strong front has occurred. These instances are, again, associated with the most intense rate changes of the front, usually when the winds rotate from southerly to northerly. The entire frontal period, as defined by a complete rotation in wind direction from south to south is much longer (Figure 2.4). Thus, the index identifies the more influential storms, those similar in strength in terms of physical forcing functions, and has the potential for categorizing fronts for future inferences. Figure 2.2c shows the major fronts as defined by the frontal index and the associated north winds. Periods with north winds not identified by the index are representative of weaker storms. Seven major frontal passages evaluated in this paper occurred on February 11, 13 and 23, March 1, 9, and 28, and April 6, 1994 (JD 42, 44, 54, 60, 68, 87, and 96, respectively).

2.4.3 Atchafalaya River Discharge

On average, Atchafalaya River discharge peaks in April followed by the seasonal low in September (Figure 2.5). Spring discharge in 1994 had a bi-modal peak considerably higher than the 40 year mean. During our study, mean monthly Atchafalaya River discharge was greatest in March followed by April and February with corresponding mean TSS concentrations of 321, 166, and 401 mg/l, respectively (Garrison et al. 1995).

2.4.4 Water Level

During the study, bay water levels varied by 0.9 m, nearly triple the astronomical tide range of 0.30-0.35 m (Figure 2.4a), and fluctuations were higher during frontal passages. During the pre-frontal period, long-fetch, southerly wind cause coastal set-up of Gulf water along the Louisiana coast and net inflow through
Figure 2.5. Atchafalaya River discharge at Simmesport, Louisiana. Study dates are indicated by vertical dashed lines.
Oyster Bayou into the southern bay, resulting in increased water levels and a greater potential for marsh inundation. The highest water levels in lower Fourleague Bay were associated with the onset of frontal passage due to a bottle-neck effect in the lower bay. After passage of a front, the bay and adjacent marshes rapidly drained as a result of northerly winds. For example, during the frontal passage of March 9 (JD 68, Figure 2.6), inshore water levels were near their highest level for the study period (1.48 m on March 7, JD 66) just prior to frontal passage. This high water was a result of the inflow of both river water from the north and wind-forced, gulf water from the south. Levels reached 1.48 m, an increase of 0.71 m from the lowest water levels which occurred during the onset of south winds. Bay water elevations exceeded the marsh surface level (1.38 m) inundating the marsh for a total of 12.75 hours. As the front passed, water levels rapidly decreased by 0.51 m. As winds relaxed, the influence of the diurnal tidal regime resumed and a rebound of gulf water into Fourleague Bay resulted in an increase in water levels above mean level. Although cold front induced water level fluctuations were high, the marsh was flooded for a relatively small portion of the total 89 day period (3% of the time in February, 3% in March, and 13% in April).

2.4.5 Water Velocity

As the only direct outlet to the Gulf, Oyster Bayou transports large volumes of water and current velocities reach high levels. The bayou must carry not only the volume of the tidal prism but also water draining from the wetlands surrounding the bay and water flowing in from the Atchafalaya River. The highest current velocities observed were ebb-directed (negative) and occurred after the passage of cold fronts as a
Figure 2.6. Detailed view of the March 9 (Julian Day 68) frontal passage. (a) Relative water level in Lower Fourleague Bay. Marsh elevation, average study water level, and average water level for the front duration are indicated. (b) Water flux (solid line) and total suspended sediments (TSS, columns). (c) Vector diagram of wind speed and direction (same as fig.2). Frontal passage occurrence on day 68 is indicated by a wind shift to the northerly quadrant.
result of strong northerly winds, high water levels inside the bay, and a favorable
gravity gradient as the water levels in the Gulf receded (Figure 2.4b). The maximum
flood-directed (positive) velocities occurred prior to frontal passage and were
associated with southerly winds during the pre-frontal phase. The maximum current
velocity during the study was ebb-directed with a speed of 1.55 m s\(^{-1}\) (February 11, JD
42), while the maximum flood-directed current velocity reached 1.06 m s\(^{-1}\), during the
March 9 (JD 68) front.

2.4.6 Water Flux

Instantaneous water fluxes were ebb-dominated reaching a maximum of 1420
m\(^3\) s\(^{-1}\) on February 11 (JD 42). The highest flood-directed flux was 935 m\(^3\) s\(^{-1}\) on April
6 (JD 96; Figure 2.4c). As with current velocities, large positive (flood-directed) water
fluxes were associated with pre-frontal, southerly winds and high negative (ebb-
directed) fluxes occurred with post-frontal, northerly winds. Daily net water fluxes
were ebb-dominated with only 16% of days having a flood dominated flux. The largest
net daily flux was over 620 m\(^3\) s\(^{-1}\) (5.36 \times 10\(^7\) m\(^3\) d\(^{-1}\)) and was associated with the March
1 (JD 60) post-frontal phase. This total volume is equivalent to 56% of the bay’s
volume exported to the Gulf in one day. The largest positive net daily flux measured
229 m\(^3\) s\(^{-1}\) (1.98 \times 10\(^7\) m\(^3\) d\(^{-1}\)) on April 11 (JD 101) and was associated with an extended
period of southeast winds.

2.4.7 Total Suspended Solids Concentrations and Fluxes

Concentrations of TSS over the 3-month period ranged from 11 to 1527 mg l\(^{-1}\)
(Figure 2.7). Highest values were associated with strong winds during the passage of
cold fronts. The frontal passage of March 1 (JD 60) generated the greatest

37
Figure 2.7. Total suspended sediment (TSS) concentration. Shaded areas are the 7 major fronts identified by the frontal index.
concentration of the study, 1527 mg/l (Figure 2.8); a result of: 1) northwest winds pushing the turbid Atchafalaya River plume directly into upper Fourleague Bay, 2) wind velocities which reached 13 ms⁻¹ and led to resuspension of shallow benthic sediments, and 3) sustained northerly winds of 8-10 ms⁻¹ which lasted for a 22-h duration. High TSS concentrations were not uncommon, as 8 samples exceeded 600 mg/l, all in association with frontal events. Background concentrations during tidally-driven, fair-weather conditions, were typically between 50-100 mg/l. Total suspended sediment concentrations in the latter half of April averaged approximately 90 mg/l and were indicative of fair-weather, tidally-driven conditions which consisted of prolonged periods of light to moderate southerly winds. No frontal events occurred during this period. Concentrations of TSS were significantly higher during the major cold fronts identified by the frontal index (mean concentration 366 mg/l) than during non-frontal forcing (mean concentration 98 mg/l; ANOVA, p<0.0001). Mean monthly TSS concentrations for the Atchafalaya River are normally 401 mg/l in February, 321 mg/l in March, and 166 mg/l in April (USGS 1985-1994).

Instantaneous TSS fluxes were large and predominantly ebb-directed, and ranged from an export of 1088 kgs⁻¹ to an import of 416 kgs⁻¹ (Figure 2.9a). Strong influxes of sediment occurred prior to cold front passage in association with southerly winds, while high exports of sediment to the Gulf occurred during northerly post-frontal winds. Inter-frontal periods and the latter half of April were characterized by low sediment transport and predominantly tidally-driven hydrodynamics resulting in nearly balanced net fluxes. Even during the high winds associated with the pre- and post-front periods, the tidal signature is often evident in TSS concentration and flux.

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Figure 2.8. Detailed view of the March 1 (Julian Day 60) frontal passage. (a) Relative water level in Lower Fourleague Bay. Marsh elevation, average study water level, and average water level for the front duration are indicated. (b) Water flux calculated (solid line) and total suspended sediments (TSS, columns). (c) Vector diagram of wind speed and direction (same as fig.2.2). Frontal passage occurrence on day 60 is indicated by a shift in wind to the northerly quadrant.
Figure 2.9. (a) Instantaneous total suspended sediment (TSS) flux calculated every 3 h. (b) Net TSS flux calculated daily.
The TSS flux was significantly more ebb-directed during fronts than during normal tidal influence (one-way ANOVA, $p<0.0000$).

The largest instantaneous import of suspended sediment into Fourleague Bay, 416 kilograms per hour (kg h$^{-1}$), occurred on February 10 (JD 41) during a pre-frontal period (Figure 2.9a). Sustained moderate south to southeast winds lasted for 101 hours, increasing in velocity to 7 meters per second (m s$^{-1}$) as the front approached. On February 11 the second highest instantaneous export of the study, 742 kg h$^{-1}$, was generated as winds shifted to the northwest at velocities reaching 8.5 m s$^{-1}$. Although the largest instantaneous import of sediment occurred during the pre-frontal period of the February 11 front, the net pre-frontal flux (0500 February 7 to 0900 February 11) was an export of 4 kg h$^{-1}$. This suggests that the moderate pre-frontal south winds were not strong enough to overcome the tidal and riverine influences forcing water and sediment through Oyster Bayou and into the Gulf. During the post-frontal period (1000 February 11 to 2300 February 11) the net export of sediment increased to 324 kg h$^{-1}$.

The largest instantaneous export of sediment into the Gulf, 1088 kg h$^{-1}$, occurred during the event associated with the March 1 (JD 60) frontal passage (Figure 2.8). Pre-frontal southerly winds lasted for a duration of 12 hours. During this pre-frontal period, a time normally associated with a net import of material, a net outflux of 5 kg h$^{-1}$ (49 metric tonnes) of sediment was exported into the Gulf via Oyster Bayou. Again, suggesting that the relatively short duration and moderate strength (2-5 m s$^{-1}$) of pre-frontal winds was not of ample magnitude to overcome the tidal and riverine forcings. A net export of 230 kg h$^{-1}$, nearly 40,000 metric tonnes, of sediment was transported into the Gulf during the 45 hours of high velocity (11 m s$^{-1}$; Figure

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2.8c) northerly winds following the frontal passage of March 1. The difference in the net fluxes of the February 11 front and the March 1 front results from the duration and timing of the winds. The high winds on February 7-11 induced the second largest instantaneous export of sediment of the study, but due to the limited duration of post-frontal winds (14 h compared to 45 h) the net export over the frontal period was only 25% of the export incurred by the high velocity, long duration northwest winds of the March 1-4 front.

Net fluxes of TSS on longer time scales were also ebb-directed (Figure 2.9). The largest net daily ebb flux was 352 kg/s day and the largest flood-directed net daily flux was 132 kg/s day (Figure 2.9b). Net daily TSS fluxes toward the Gulf occurred 62 out of 85 days (73%). A total of 23 fronts passed through south Louisiana during the study period. Net fluxes calculated for each front are given in Table 2.1 with the 7 major fronts identified. The largest export attributed to a frontal passage was 195 kg/s day in association with the March 1 front. There was a net export for all 3 months. March had the highest net flux with an export of $9.67 \times 10^7$ kg of sediment (36.1 kg/s day) followed by February ($7.16 \times 10^7$ kg, 34.5 kg/s day) and April ($8.34 \times 10^6$ kg, 3.2 kg/s day). The estimated net TSS flux over the entire 89 day study was an export of $1.77 \times 10^8$ kg (24.0 kg/s day).

2.4.8 Particulate Organic Carbon Concentrations and Fluxes

The mean particulate organic carbon (POC) concentration was 6 mg/l (range 0-53 mg/l; Figure 2.10a) and averaged 5% of TSS (range 0-22%). The POC data failed to meet the assumptions of normality and homogeneity of variances, therefore the Mann-Whitney non-parametric test statistic was used to determine differences under various
Figure 2.10. (a) Particulate organic carbon (POC) concentration and (b) POC flux.
circumstances. Concentrations of POC were highest during post-frontal conditions due to the higher TSS concentrations, however, concentrations were not significantly different on flood and ebb-directed flows. The organic percentage of TSS (%POC) was significantly higher during pre-frontal than post-frontal, but not significantly different from inter-frontal periods (p<0.028).

Particulate organic carbon fluxes ranged from an export of 55.70 kgs\(^{-1}\) to an import of 11.59 kgs\(^{-1}\) (Figure 2.10b), both associated with the passage of a major cold front. Fluxes of POC followed water and TSS flux patterns with a strong ebb-directed net flux over the study period. The greatest POC export of 55.7 kgs\(^{-1}\) occurred during the post-frontal period on February 24 (JD 55) and was concurrent with the highest POC concentration of the study. During the pre-frontal phase of front 6 (March 27, JD 86) the highest import of POC, 11.59 kgs\(^{-1}\), occurred. Net POC fluxes were ebb-directed with monthly exports to the Gulf of 3.37 x 10\(^6\), 4.55 x 10\(^6\), and 6.10 x 10\(^5\) kg. Over the 89 day study, a total of 8.53 x 10\(^6\) kg of POC was exported from Fourleague Bay to the Gulf.

2.5 DISCUSSION

2.5.1 Wind and Water Level

In microtidal areas such as the northern Gulf of Mexico, wind influence on estuarine water levels and bay-shelf exchange is important. Water level fluctuations during cold fronts can be dramatic, often more than doubling the normal tide range of the northern Gulf Coast. For example, we found that Fourleague Bay water levels varied by as much as 0.80 m over the course of a frontal passage (i.e., March 9, Figure 2.6a). Along the central Louisiana coast, cross-shelf (north-south) wind forcing is
responsible for causing high variability in regional sea level due to the shallow depths (Chuang and Wiseman, 1983). High cross-shelf winds are associated with the propagation of winter storm fronts in the northern Gulf. For instance, following the frontal passage on March 1 we calculated that 56% of Fourleague Bay’s volume was exported to the Gulf in one day. Similarly, Smith (1977) found that in Corpus Christi Bay, Texas, cold fronts were the most efficient means of displacing bay water with Gulf water and calculated that in 56 hours following a front, 10% of the bay’s volume was exported to the Gulf. Smith concluded that meteorologically driven exchanges of water volume are nearly an order of magnitude more important than diurnal tidal exchanges in Corpus Christi Bay.

2.5.2 Atchafalaya River Discharge

Riverine influence and mean sea level variation also lead to water level change in coastal areas. For example, in a tidal channel near Upper Fourleague Bay, Stern et al. (1991) reported that the marsh flooded for greater than 40% of the time during periods of high mean sea level and high river discharge and less than 6% of the time when sea level was low. Similarly, Kjerfve et al. (1978) reported that seasonal sea level change led to marsh flooding 42% of the time in October and 27% in January in North Inlet, SC.

Over the study period, mean bay water level gradually increased due to increases in both river discharge and mean sea level. Riverine sediment carried into Fourleague Bay is composed primarily of fine silts and clays. These fine sediments are easily resuspended and kept in suspension by physical forcings. Thus, as water levels and the associated sediment loads increase, the adjacent marshes have greater potential
for inundation and thus sediment deposition (Reed, 1989; Cahoon et al., 1995; Day et al., 1995; Hensel et al., 1998). In other areas of the world such as the Rhone River, sediment concentrations in excess of 4000 mg/l have been documented during flood stage which is essential to surrounding marshes in order to keep pace with relative sea level rise (Hensel et al., 1998).

2.5.3 Current Velocity

We measured strongly ebb-directed current velocities throughout the study period. Current velocities are highly variable in response to wind driven events. In Chesapeake Bay, Stevenson et al. (1985) recorded the highest water velocities (12-14 cm·s⁻¹) on an ebb-tide following a cold front. Time-velocity asymmetries of tidal currents have been invoked by various authors to explain tidal dominance in either flood or ebb directions (Ward, 1981; Stevenson et al., 1988; Leonard et al., 1995) and this strongly affects whether a particular estuary is a net exporter or importer of materials over a given time period. For our study, 59% of the currents were ebb-directed, 39% were flood-directed, and 2% were slack water (Table 2.2). This ebb dominance supports Stevenson et al.’s hypothesis that southeastern U.S. estuaries are ebb-directed and thus net exporters of water and materials. In Fourleague Bay the magnitude of transport and velocities in Oyster Bayou were ebb dominated (Table 2.2) due to the coupling of riverine input with high velocity north winds associated with cold fronts. Some tidal channels which have a higher frequency of ebb currents make up for the imbalance by having a more dominant flood tide, or visa versa. For example, Leonard et al. (1995) reported that in Cedar Creek, Florida, peak flooding currents were 10-20% stronger than ebb currents, but peak ebb velocities were longer in
duration. In Fourleague Bay, however, the addition of substantial volumes of Atchafalaya River water during high discharge periods creates a favorable hydraulic head which promotes net export to the Gulf.

Table 2.2. The frequency of occurrence of flood, ebb, and slack currents and mean velocity and flux values during the study.

<table>
<thead>
<tr>
<th>Current Direction</th>
<th>Number of Observations (Δt=15 min)</th>
<th>% Occurrence</th>
<th>Mean Velocity (cms⁻¹)</th>
<th>Mean Flux (m³s⁻¹)</th>
</tr>
</thead>
<tbody>
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<td>Flood</td>
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<td>26</td>
<td>256</td>
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<td>Ebb</td>
<td>4824</td>
<td>59</td>
<td>47</td>
<td>415</td>
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<tr>
<td>Slack</td>
<td>128</td>
<td>2</td>
<td>0</td>
<td>0</td>
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</table>

Storms have also been shown to radically change the hydrologic conditions in estuaries. In Oyster Bayou, maximum ebb and flood currents (Figure 2.4b) were both associated with winter fronts. In the Rappahannock estuary, net surface current velocities measured under normal conditions are approximately -5.4 cms⁻¹ at the head of the estuary and -4.0 cms⁻¹ near the estuary mouth, negative values indicating a seaward transport (Nichols, 1977). Under flood conditions in response to Tropical Storm Agnes maximum velocities increased to -67 and -24 cms⁻¹ at the estuary head and mouth, respectively (Nichols, 1977). This constitutes an order of magnitude change in current velocities in response to storm conditions.

2.5.4 Water Flux

Water flux over the 89-day study was strongly ebb-dominated (Table 2.2), especially during north winds of the post-frontal phase (Figure 2.4c). This ebb-dominance resulted in periodic rapid flushing of the bay. For example, during the front
of March 1, approximately 56% of the bay volume was flushed in one day and 100% over the 3 days following the frontal passage. Previously, Madden (1988) calculated turnover rates in Fourleague Bay to be as little as 7 days in spring during peak river discharge. Flushing times of such short duration are consequences of copious volumes of river water entering the northern bay coupled with wind induced exports through Oyster Bayou (Figure 2.11). Kjerfve and Proehl (1979) reported that net water transport varied dramatically over three successive tidal cycles in North Inlet, South Carolina as a result of differences in tidal range due to astronomical forcing or regional wind events. Net discharges of 92, -118, and 340 m$^3$s$^{-1}$ were calculated for the three tidal cycles (Kjerfve and Proehl, 1979). Our data also show similar high variability water fluxes during the study as a result of abrupt, intense changes in meteorological forcings.

2.5.5 TSS Concentration

TSS concentrations vary widely among estuaries based on such factors as riverine input, wind forcing, drainage basin size, depth, area, structure of surrounding marsh, sediment composition, extent of erosional processes, and tide range. Fourleague Bay is characterized by a low tidal range and high riverine input with more dynamic concentrations which can increase by an order of magnitude or more when associated with strong currents and resuspension due to cold front activity and the introduction of river water. Concentrations in Oyster Bayou ranged from 11-1527 mg$l^{-1}$ (Figure 2.7) with mean TSS concentrations of pre-, post-, and inter-frontal periods calculated at 94, 158, and 88 mg$l^{-1}$, respectively. Suspended sediment peaks were each connected with a winter frontal event, the largest values corresponding with post-frontal winds (Figure
Figure 2.11. Flushing time of Fourleague Bay in days. Solid black columns indicate dates during post-frontal winds for the 7 major fronts identified by the frontal index.
2.7, Table 2.3). In comparison, Settlemyer and Gardner (1977) measured TSS concentrations of 1-103 mg/l on flood tides and 2-133 mg/l on ebb tides in Dill Creek, SC, an area characterized by low riverine influence and high tidal range (1.5-2 m).

Very high TSS concentrations are often associated with meteorologically driven events. Stumpf (1988) recorded maximum TSS values of 2000 mg/l in the Potomac estuary during Tropical Storm Juan, while Stevenson et al. (1985) measured 1100-1400 mg/l concentrations in Blackwater National Wildlife Refuge during a winter storm. Leonard et al. (1995) found maximum TSS concentrations in excess of 1100 mg/l in Cedar Creek, Florida were two orders of magnitude higher during fronts than during fair weather. Even areas that normally do not have high riverine sediment inputs can have extremely high concentrations in association with meteorologically driven events. For example, Bayou Chitigue, Louisiana, does not receive riverine sediment, yet, Murray et al. (1993) recorded sediment concentrations over 2000 mg/l during a severe winter storm and attributed the high levels to channel scour and resuspension of bay sediment.

Sediment concentrations associated with tidal forcing alone are lower. For instance, in Fourleague Bay during the latter half of April, astronomical tidal flows dominated and TSS concentrations were generally below 100 mg/l (Figure 2.7). Strong winds were not apparent during this time period and the natural flood and ebb conditions prevailed. Thus, sediment dynamics in Fourleague Bay during the spring are controlled by non-tidal forcings, namely cold fronts and river input. This suggests that the erratic water level fluctuations associated with winter storms have a greater
Table 2.3. Statistics of individual frontal passages. The “strong” fronts (1-7) are those identified by the frontal index.

<table>
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<th>Duration (hrs)</th>
<th>Max. South Wind (m s⁻¹)</th>
<th>Max. North Wind (m s⁻¹)</th>
<th>Min. Inshore Water Level (m)</th>
<th>Mean Inshore Water Level (m)</th>
<th>Max. Inshore Water Level (m)</th>
<th>Current Velocity (cm s⁻¹) Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Net</th>
<th>Water Flux (m² s⁻¹) Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Net</th>
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potential for dispersing higher concentrations of sediment to the marsh surface than
during tidally driven periods.

2.5.6 TSS Flux

Total suspended sediment flux was large and ebb-directed throughout the 89-
day study with a net export of $1.77 \times 10^8$ kg of sediment through the tidal pass. Water
flux was a major determinant in TSS flux response and sediment fluxes were highly
variable and strongly influenced by changes in meteorological forcings with the largest
fluxes occurring after frontal passage (Table 2.3). Important factors leading to such
large exports through Oyster Bayou include a large, continuous source of sediment
derived from the Atchafalaya River and high intensity, long duration winds which kept
sediments resuspended. Although an ample supply of riverine sediment is available at
present, Kesel (1988) calculated that the average annual sediment content carried by
the Mississippi River has declined by 70% since 1850. Thus, lower sediment
availability in the future may compromise the ability of the adjacent marshes to keep
pace with relative sea level rise.

Erosional influences of the marsh surface are likely negligible to the overall TSS
transport through Oyster Bayou in comparison to sediment resuspension and riverine
input. Elsewhere, however, precipitation-driven erosion can be important. Jordan et al.
(1986) found that high magnitude discharges of sediment in the Rhode River estuary
are episodic and generated via precipitation events. Childers and Day (1990a) similarly
found that a rain event during low tide in another Louisiana bayou caused a net export
of sediment from the marsh as a result of erosion.
2.5.7 Particulate Organic Carbon Concentrations and Fluxes

POC concentrations in Oyster Bayou were highest during post-frontal periods corresponding to high concentrations of TSS, but the % POC content in suspended material was higher during pre-frontal times. Atchafalaya River influence in Fourleague Bay is a major factor leading to lower % POC because the river carries mostly inorganic suspended sediments (Garrison et al., 1994). Post-frontal conditions are indicative of increased riverine influence in Oyster Bayou suggesting that although the organic content percentage may be lower with the addition of Atchafalaya River water and resuspension of bottom sediments, the overall magnitude of POC exported is greater due to the increased suspended sediment load input via the river. Others have shown this inverse relationship between %POC and TSS (e.g., Cifuentes, 1991).

POC concentrations and export are influenced by a number of factors including riverine input, marsh flooding and drainage, and sea level. Higher POC export occurred during post-frontal periods associated with high water export. Marsh flooding characteristics changed over the study period. Early in the study, the marsh was flooded for shorter periods but water level changes were much more dramatic associated with frontal passages. During April, the marsh was flooded for longer periods due to increasing mean Gulf level (see Blaha and Sturges, 1981) but water level variability was less. Thus there was likely POC export from the marsh throughout the study period, but this resulted from different forcings. For instance, the largest POC export was associated with an ebb flow following a cold front which flooded the surrounding marsh for approximately 2 hours. Similarly, higher POC concentrations and size fractionations were observed by Roman and Daiber (1989) during ebb flows.
following storm events and attributed this increase to marsh flushing coupled with storm induced erosional processes. The higher %POC on flood tides in Oyster Bayou can also be the result of offshore particulate matter which has a higher % organic matter (Cifuentes, 1991). Ebb-dominated POC fluxes throughout the time period support the “Outwelling“ hypothesis and may potentially allow for the utilization of this organic material in the water column of Fourleague Bay and the nearshore Gulf of Mexico. The mechanism causing this net outwelling is the interaction of river discharge and frontal passage and the sources of the organic carbon are likely both riverine and marsh/estuarine.

2.6 REFERENCES


CHAPTER 3

NITROGEN AND PHOSPHORUS TRANSPORT BETWEEN FOURLEAGUE BAY, LOUISIANA AND THE GULF OF MEXICO: THE ROLE OF WINTER COLD FRONTS AND ATCHAFALAYA RIVER DISCHARGE
3.1 INTRODUCTION

Estuaries have long been recognized as highly productive and dynamic systems. Material from land drainage and *in situ* production is either utilized within the system or may be exported and utilized offshore. Export of net production in the form of organic nutrients is known as the outwelling hypothesis which has been a subject of active research for over 30 years (Teal, 1962; Odum, 1969; Nixon, 1980; Childers et al., 2000). To address the outwelling concept of nutrient and organic matter export, many researchers have conducted flux studies to measure the transformation, processing, and net export of materials within the estuary, in addition to the potential estimation errors of such measurements (Boon, 1978; Kjerfve and Proehl, 1979; Nixon, 1980; Stevenson et al., 1985; Jordan et al., 1986; Hensel et al., 1998; Sutula, 1999; Perez et al., 2000). An examination of marsh and estuarine flux literature over the past 20 years (Childers et al., 2000) shows that few studies have been designed to directly address the outwelling hypothesis as originally stated due to the extraordinary technological, physical, and financial requirements necessary (Boon, 1978; Kjerfve and Proehl, 1979; Nixon, 1980). In fact, much of the flux literature to date involves the flux of materials between marsh and the inundating water column and also between marsh and the surrounding estuary rather than quantifying the materials transported between the greater estuary and the coastal ocean (Nixon, 1980; Childers et al., 2000). These data provide us with a better understanding of the processes that control the functioning of estuarine sub-systems. We need to understand how these sub-systems
contribute to the overall system and how the connections between estuarine sub-systems lend to the larger picture of estuarine-ocean exchanges. Thus, the idea of having a conceptual view of the outwelling hypothesis as suggested by Childers et al. (1999) implies that estuarine flux studies be viewed in a hierarchical framework of marsh-inundating water column, marsh-estuarine-water column, and estuary-coastal ocean.

Marsh-estuarine and estuarine-ocean exchange of materials is largely regulated by physical forcings. These forcings vary in importance with individual estuarine systems and the most influential will depend on the depth, area, drainage basin size, fetch, tide range, geographic location, geologic age of the marsh, geomorphic setting, and anthropogenic inputs to the estuary as well as the connection to the coastal ocean. Pulsing events affecting coastal systems occur on various time scales ranging from hours to millennia and include winds, waves, tides, cold fronts, river discharge, hurricanes, and delta lobe switching (Day et al., 1995; Hensel et al., 1998; Day et al., 2000). The annual discharge cycle of the Atchafalaya and Mississippi Rivers is such an impact by adding a pulse of sediment, nutrients, and fresh water to the delta and surrounding area. These seasonal pulses are major forcing functions and transport mechanisms for estuarine systems (Stevenson et al., 1985; Roberts, 1989; Stern et al., 1991; Murray et al., 1993; Leonard et al., 1995; Hensel et al., 1998; Day et al., 2000; Perez et al., 2000). In order to understand how these pulsing events interact with coastal systems and the potential benefits that they may provide, flux measurements
taken on both short-term (hourly to daily) and long-term (seasonally to annually) intervals are necessary (Nixon, 1980; Sutula, 1999; Perez et al., 2000). Previous flux studies with a duration of 1-2 tidal cycles provide a snapshot of marsh-estuarine and estuarine-ocean exchange dynamics, but are not of sufficient duration to capture the variation associated with non-local forcings (Kjerfve and Wolaver, 1988). For instance, Perez et al. (2000) calculated differences in total suspended sediment flux estimates of greater than an order of magnitude within one month as a result of sampling during a cold front passage as opposed to a fair-weather, tidally dominated period. Four-fold differences were found even in fluxes calculated on consecutive tidal cycles (Perez et al., 2000), thus illustrating the importance of intensive temporal sampling strategies.

Sources of nutrients to estuarine systems include riverine, atmospheric, groundwater seepage, and the coastal ocean (Day et al., 1989; Nixon et al., 1996). Inputs from within the estuary via biogeochemical transformation and microbial recycling are often just as important (Teague et al., 1988; Twilley et al., 1999). The most important nutrient input to estuarine systems in south Louisiana is from the Mississippi and Atchafalaya Rivers. Concentrations, species, and forms (dissolved and particulate) of nutrient inputs vary with different drainage basins and with the geology and geomorphology associated with the basin. In estuaries with larger riversheds, nutrient concentrations and the extent of riverine influence are dependent on the seasonal pattern of river flow, mean sea level variations, and short-term variations of winds and tides (Kjerfve and Proehl, 1979; Madden et al., 1988; Stern et
variations of winds and tides (Kjerfve and Proehl, 1979; Madden et al., 1988; Stern et al., 1991). In the Atchafalaya River region of Louisiana, peak river discharge occurs during the winter and spring months with low flows during summer and fall. Mean sea level in the northern Gulf of Mexico is highest in October and lowest in January (Blaha and Sturges, 1981).

The coastal area of the north-central Gulf of Mexico is dominated by the discharge of the Mississippi and Atchafalaya Rivers. The mean flow of the lower Mississippi River is about 20,000 m$^3$s$^{-1}$, one third of which is discharged via the Atchafalaya River (Figure 3.1). The northern coast of the Gulf of Mexico is characterized by a low tidal amplitude (approx. 0.30-0.35 m) which makes Louisiana coastal marshes and estuaries highly susceptible to non-local physical forcings (Kjerfve, 1973). During storm events and high river discharge periods, the local tidal regime can be overwhelmed, with water level variations often two to three times the normal tidal range (Murray, 1976; Wax et al., 1978; Perez et al., 2000). In addition to wind and tides, the study area, Fourleague Bay, is also highly impacted by Atchafalaya River discharge. For example, Madden et al. (1988) reported that flushing time of the bay was 7 days during peak river discharge compared to approximately 65 days during low discharge periods. Similarly, Perez et al. (1999) calculated that approximately 56% of Fourleague Bay’s volume was exported to the Gulf in one day as a result of high northwest winds associated with the passage of a cold front and the influx of Atchafalaya River water during spring peak discharge. Short residence times
Figure 3.1. Location of Oyster Bayou (the study site), Fourleague Bay, and the Atchafalaya River in south-central Louisiana. The "p" north and south of Oyster Bayou indicates the location of pressure gauges for water level measurements. The shaded areas surrounding the Bay are marsh.
of 5-7 d have been calculated for most estuaries in the Atchafalaya delta complex due to the large inflow:estuary volume ratio while other estuaries in the Gulf of Mexico such as Corpus Christi and Aransas Bays have residence times of greater than 300 d (Solis and Powell, 1999) due to lower freshwater inflows. Not only do residence times among estuaries vary widely, but residence times may also vary temporally within the same estuary. For instance, in Celestun Lagoon in the Yucatan Peninsula calculated residence times varied by a factor of 2 within one year (Herrera-Silviera, 1995).

To estimate the flux of dissolved and total nitrogen and phosphorus between Fourleague Bay and the Gulf of Mexico and how pulsing events and flushing rates influence transport processes, an 89-day tidal-exchange study was conducted in Oyster Bayou, the sole direct connection between Fourleague Bay and the Gulf of Mexico (Figure 3.1). The study was conducted from February 1 to April 30, 1994 to coincide with peak Atchafalaya River discharge and peak cold front activity, the two major winter-spring physical forcings in south Louisiana estuaries.

The objectives of this study were to: 1) quantify the concentrations and instantaneous and net exchanges of nutrients (nitrogen and phosphorus) and water between Fourleague Bay and the Gulf of Mexico over a three-month period; 2) determine how the passage of atmospheric cold fronts and high Atchafalaya River discharge influence the concentrations and fluxes of nutrients between the bay and Gulf; and (3) determine the differences in concentrations and fluxes during both tidally-driven and wind/riverine-driven conditions. The study hypotheses were: 1) the
Fourleague Bay estuary is a net exporter of nutrients throughout the study period; 2) the concentration of nutrients, in particular nitrate and nitrite, are higher when influenced by the Atchafalaya rather than the Gulf; 3) cold fronts enhance the magnitude of export of nutrients to the Gulf as a result of high velocity northerly winds; and 4) the concentrations of total nitrogen, total phosphorus, and nitrate+nitrite are lower during times of tidal influence due to a longer residence time within the bay.

3.2 SITE DESCRIPTION

Fourleague Bay is a large (95 km²), shallow (mean depth 1.0 m), well-mixed estuary with a mean astronomical tide range of 0.30-0.35 m and lies 11 km southeast of the Atchafalaya River mouth (Figure 3.1). The bay is surrounded by extensive fresh, brackish, and saline marshes and essentially compartmentalized into two sections, the upper bay with a northwest-southeast orientation and the lower bay with a north-south orientation. Oyster Bayou, the study site, connects southern Fourleague Bay to the Gulf of Mexico. This bayou is approximately 4 km long, 180 m wide at the study site, with a mean depth of 5 m (maximum depth 10 m), and a cross-sectional area of approximately 1000-1100 m². For a more detailed description of the study area see Perez et al. 2000.

3.3 MATERIALS AND METHODS

To estimate the concentrations and fluxes of nutrients through Oyster Bayou, a 3-month intensive flux study was conducted from February 1 to April 30, 1994 (see
Perez et al. 2000). Throughout the study period current velocity and direction, conductivity, and sea temperature were recorded every 15 minutes in mid-channel (approximately 10 m depth) by two current meters, one 2 m below the surface and one 1.5 m above the bottom. Water flux (m$^3$s$^{-1}$) was calculated as the product of the average of surface and bottom current velocity and the cross-sectional area of the bayou. The cross-sectional area was measured when the bayou was bank full using a continuously recording fathometer and water flux data were corrected for changes in cross-section area due to changing water level. Integrated water column samples were taken from a sampling platform every 3 hours from the upper 2-3 m of the channel with a one-liter capacity LaMotte 1077 water sampler. This integrated sample was assumed to be representative of the entire bayou due to the high current velocities in the bayou, and the shallow, well-mixed nature of the bay (Perez et al., 2000). Samples were placed in acid-washed polyethylene bottles, immediately placed on ice in the dark, and were usually filtered within 12 h of collection. One sample period per day was randomly selected to obtain a duplicate sample to be used for statistical purposes. An on-site weather station 10 m above marsh level recorded wind speed and direction, air and sea temperature, barometric pressure, and humidity once a minute and hourly averages were computed. Two pressure gauges were deployed, one approximately 1 km north of Oyster Bayou in lower Fourleague Bay and another about 1 km south of the bayou in the nearshore Gulf. Relative water level readings were taken every 15 minutes.
For each water sample, a known volume was filtered through a Whatman GF-F glass-fiber filter. The filtrate was placed in acid-washed, pre-labeled 5 ml autoanalyser vials (AAV), immediately frozen, and used to determine concentrations of nitrate+nitrite (NO$_3$+NO$_2$), ammonium (NH$_4$), and phosphate (PO$_4$). An unfiltered sample was placed in a 125 ml Nalgene bottle pre-washed with a 10% HCl solution for determination of total nitrogen (TN) and total phosphorus (TP) and immediately frozen.

Dissolved inorganic constituents were analyzed on a Technicron Autoanalyser II using EPA method 350.1 for NH$_4$, method 353.2 for nitrate+nitrite, and method 365.2 for PO$_4$ (USEPA 1979). A persulfate oxidation (method 207; Valderama, 1981) was used for analysis of TN and TP and performed on an Alpkem 500 series autoanalyser.

Instantaneous fluxes of nutrients (gs$^{-1}$) were calculated for each three hour interval based on the concentration of the individual constituent multiplied by the associated water flux values. Since water flux was measured more frequently, every 15 minutes, the average water flux for the previous 3 hours was used to calculate material fluxes. Net fluxes over different time periods are reported as time-weighted averages and were calculated as the algebraic sums of the instantaneous fluxes divided by the number of samples taken within the respective time period. Positive fluxes (+) indicate flood-directed flows moving north from the Gulf into Fourleague Bay. Negative fluxes (-) represent ebb-directed flows moving from the bay to the Gulf. Note that net fluxes
are representative of what is moving in and out of Oyster Bayou only, we do not have any specific information during this study on what was entering or exiting the northern bay or adjacent bayous.

To examine the effects of cold fronts on the concentrations and fluxes of nutrients an index of frontal occurrence and strength was developed. The Cold Front Index was designed to focus on the more powerful fronts as they are the more physically dynamic events. A combination of the following parameters was used in the index: the rate of change of barometric pressure and temperature calculated hourly over a 24-hour period (dP/dt and dT/dt; dt=24 hrs) to reduce diel effects; and the hourly wind stress (τ), expressed in Newtons m⁻² calculated to obtain the energy imparted on the water surface following Hsu and Blanchard (1993). The more robust frontal events were defined as those time periods when all three factors exceeded a specific threshold concurrently (dP/dt > 0.3 mbar / 24h, dT/dt < -0.2 °C / 24h, and τ > 0.10 Nm⁻²). Seven fronts during the study surpassed the given thresholds of the cold front index to be classified as significant fronts (for a more detailed description of the Cold Front Index see Perez et al., 2000).

Factor analysis using a varimax rotation method was utilized to examine the covariability among the nutrient concentration variables (SAS, Proc Factor; SAS, 1989). High loading scores of a group of variables in one factor suggest a strong correlation among the variables. Included in the model were NO₂⁺NO₃, NH₄, PO₄, TN, TP, TSS, and POC. Relationships between the significant factors and physical
forcings were then examined to determine which forcings were most important in causing changes in the magnitude of nutrient concentrations. In addition, differences in nutrient concentrations over different time scales were determined by an ANOVA. Several transformations were used on the data to meet the assumption of normality. Data with non-normal distributions were examined by Wilcoxon non-parametric methods for all comparisons (Proc npar1way Wilcoxon; SAS, 1989). All statistics were run using SAS statistical software (SAS, 1989).

3.4 RESULTS

3.4.1 Physical Forcings

3.4.1.1 Atchafalaya River

The seasonal discharge cycle of the Atchafalaya River normally peaks in April-May and decreases to a seasonal low in September-October (Figure 3.2). Spring peak discharge during 1994 was considerably higher than the 40-year mean with the greatest mean monthly discharge in March followed by April and February.

3.4.1.2 Cold Fronts

Over the course of a cold front the wind rotates in a clockwise direction. During the pre-frontal stage winds are from the south and change abruptly to northerly at very high velocities as the front passes and during the post-frontal period (Moeller et al., 1993). Winds during the inter-frontal period are generally low in velocity and have a north-easterly to easterly direction. Pre-, post- and inter-frontal periods are defined here as winds having a direction of 113-292°, 293-45°, and 46-112°,
Figure 3.2. Atchafalaya River discharge at Simmesport, Louisiana. Study dates are indicated by vertical dashed lines.
respectively. Post-frontal, northerly winds had the greatest velocities throughout the
three month study reaching a maximum of 14 ms⁻¹ (Perez et al., 2000). Seven out of 23
cold fronts which passed through south Louisiana during the study period were the
most physically dynamic as defined by the Cold Front Index (Perez et al., 2000).
These seven frontal passages occurred on February 11, 13, and 23, March 1, 9, and 28,
and April 6; Julian Day (JD) 42, 44, 54, 60, 68, 87, and 96, respectively.

Due to the physical characteristics and geographical orientation of Fourleague
Bay high wind events, i.e. cold fronts, often dominate the hydrodynamics of the bay. High velocity north and northwest winds tend to force Atchafalaya River water into
the bay through the northern entrance and induce very large exports of water and
materials out of Oyster Bayou (Perez et al., 2000). Maximum ebb-directed current
velocities associated with post-frontal winds reached 1.55 ms⁻¹ on February 11 (JD 42) while the maximum flood-directed current velocity (1.06 ms⁻¹) occurred on March
9 (JD 68) associated with pre-frontal, southerly winds. For a more complete
description of cold front dynamics see Perez et al., 2000.

3.4.1.3 Water Flux and Flushing Time

Water fluxes in Oyster Bayou were ebb-dominated throughout the study period. Largest transports were in response to high volumes of Atchafalaya River
water being pulsed into the bay through the northern entrance coupled with high
velocity, northerly winds associated with the passage of cold fronts. The peak ebb-
directed water flux measured was 1420 m³s⁻¹ on February 11 (JD 42) in association
with passage of a cold front. The largest flood-directed flux of 935 m$^3$s$^{-1}$ was measured on April 6 (JD 96) following pre-frontal southerly winds (Figure 3.3a). A net export of approximately 138 m$^3$s$^{-1}$ of water was transported to the Gulf over the 89-day study.

Large net exports of water led to short flushing times of the bay, averaging 7.9 d for the study period (Figure 3.3b). Flushing times as little as 3 d were calculated as a result of high velocity, long duration, northwest winds associated with the passage of the March 1 cold front during which approximately 56% of the bay volume was exported to the Gulf in 1 day. Flushing times increased in April as a result of tidally-driven hydrodynamics and decreased riverine influence.

3.4.2 Nitrogen Concentrations and Fluxes

Nitrogen concentrations varied widely over the course of the study with the highest concentrations associated with Atchafalaya River water which entered the bay through the northern entrance. Nitrite+nitrate ($\text{NO}_2^+\text{NO}_3^-$) was the dominant dissolved inorganic form of nitrogen in Fourleague Bay ranging from 0-45 $\mu$M and averaging 11.1 $\mu$M throughout the study (Figure 3.4a). Mean monthly concentrations increased from 13.2 $\mu$M in February to 16.6 $\mu$M in March, then decreased markedly in April to 4.1 $\mu$M, each significantly different from the others (ANOVA, $p<0.001$).

The large fluctuations in concentrations are due to the sampling of different water masses, namely Atchafalaya River and coastal ocean waters. Salinities measured in Oyster Bayou ranged from 0-23 ppt (Figure 3.5) with lower salinities indicative of
Figure 3.3. (a) Instantaneous water flux in Oyster Bayou. Positive values indicate flood-directed flux into Fourleague Bay from the Gulf of Mexico. Negative values indicate ebb-directed flux from Fourleague Bay into the Gulf. All subsequent flux graphs follow the same convention. (b) Flushing time of Fourleague Bay in days.
Figure 3.4. (a) Nitrate + nitrite concentration and (b) Nitrate + nitrite flux.
Figure 3.5. Salinity measured in Oyster Bayou.
river water dominance with higher concentrations of NO$_2$+NO$_3$, and higher salinities indicative of coastal ocean dominance with lower NO$_2$+NO$_3$ content. During periods with salinities less than 2 ppt the mean NO$_2$+NO$_3$ concentration was 21.3 µM. In contrast, when salinities were greater than 15 ppt, mean NO$_2$+NO$_3$ concentrations were 5.5 µM.

Atchafalaya River concentrations of NO$_2$+NO$_3$ during this the study were 48, 52, and 48 µM for February, March, and April, respectively (Garrison et al., 1995) which are higher than the mean concentrations measured in Oyster Bayou suggesting loss of NO$_2$+NO$_3$ in the bay and surrounding wetlands. NO$_2$+NO$_3$ concentrations in Oyster Bayou were significantly higher during frontal events than during non-frontal forcing periods (ANOVA, p<0.018), during high velocity northerly post-frontal winds than during pre- and inter-frontal winds (ANOVA, p<0.0001), and on ebb-directed (toward the Gulf of Mexico) tides rather than on flood and slack tides (ANOVA, p<0.0001).

As a result of frequent cold front passages and large volumes of river water entering the bay, water residence times averaged <8 days during the study and as low as 3 days (Figure 3.3b; Perez et al., 2000), depending upon the prevailing meteorological conditions. Higher frequency flushing of the bay did not allow for high rates of nutrient uptake/loss via biological and biogeochemical processes, thus a large portion of the nutrients were advected through the estuary and exported to the Gulf. Lower NO$_2$+NO$_3$ concentrations in April were the result of a change in bay
hydrodynamics from a riverine influenced, wind-driven system with short residence times in the first 10 days to a tidally-driven system with much longer residence times in the bay during the final 20 days of the study. Also during these final 20 days, no cold fronts passed through south Louisiana and the winds were generally calm and out of the southeast which tend to divert Atchafalaya water away from the bay. Salinity records during this period (JD 100-120), however, show a decreasing trend which would suggest that river water is being introduced to the bay and \( \text{NO}_2^+ + \text{NO}_3^- \) concentrations fall to nearly zero. Examination of sea surface temperature images of Fourleague Bay and the Atchafalaya River region in the latter part of April show the colder river plume diverted to the west and higher temperatures in the bay suggest that the decrease in salinities is not from a direct riverine influence, but rather from freshwater draining out of the surrounding shallow wetlands (images courtesy of LSU Earth Scan Laboratory). Thus, extremely low concentrations of \( \text{NO}_2^+ + \text{NO}_3^- \) in the end of April are the result of increased residence times in the bay which allow greater rates of biological uptake and denitrification and also from lower salinity river water introduced from adjacent marshes which have already been depleted in \( \text{NO}_2^+ + \text{NO}_3^- \).

Fluxes of \( \text{NO}_2^+ + \text{NO}_3^- \) were ebb-directed for all three months with net monthly exports of 59.7, 63.1, and 11.3 g s\(^{-1}\) for February, March, and April, respectively. The largest instantaneous export (ebb-directed flow) of \( \text{NO}_2^+ + \text{NO}_3^- \) was 442 g s\(^{-1}\) on March 2 (JD 61; Figure 3.4b) and was associated with the post-frontal phase of the most physically dynamic cold front of the study. During the post-frontal phase of the
March 1 front, approximately 56% of the bay volume was exported to the Gulf of Mexico in one day (Perez et al., 2000). The greatest instantaneous import (flood-directed flow) of NO$_2$+NO$_3$ was 194 g s$^{-1}$ on March 6 (JD 65) during a period of rebounding water levels in Fourleague Bay. A net flux of 43.5 g s$^{-1}$ of NO$_2$+NO$_3$ was exported to the Gulf over the 89-day study with the largest fluxes in response to cold front events and shifting riverine influences. Fluxes were nearly balanced in the latter part of April resulting from decreased NO$_2$+NO$_3$ concentrations and decreased water fluxes associated with hydrodynamics driven by tides alone.

Ammonium (NH$_4$) concentrations averaged 6.9 µM over the three months with a range of 0.3-35.7 µM (Figure 3.6a). Although mean monthly concentrations did not fluctuate very much with averages of 8.4, 7.0, and 5.4 µM in February, March, and April, respectively, significant differences between all months existed (Wilcoxon, p<0.001). Concentrations tended to decrease during post-frontal periods when lower concentration river water entered the bay suggesting that the bay is a source of NH$_4$. This is further indicated by the pattern of increasing NH$_4$ concentrations with decreasing NO$_2$+NO$_3$ concentrations (Figures 3.6a and 3.4a, respectively). NH$_4$ was also greater on flood-directed tides (7.7 µM) than ebb-directed tides (6.3 µM; Wilcoxon, p<0.0001). Atchafalaya River concentrations were 3.6, 3.2, and 5.0 µM for February, March, and April, respectively (Garrison et al., 1995). In contrast to NO$_2$+NO$_3$ concentrations, NH$_4$ did not decrease in the latter part of April. Rather, NH$_4$ concentrations remained similar to concentrations in February and March.
Figure 3.6. (a) Ammonium concentration and (b) Ammonium flux.
Warmer temperatures, increased biological activity, increased marsh flooding and subsequent marsh flushing are likely reasons for sustained NH$_4$ levels.

Instantaneous fluxes of NH$_4$ ranged from an import of 161 gs$^{-1}$ to an export of 359 gs$^{-1}$ on February 24 (JD 55) and February 26 (JD 57), respectively (Figure 3.6b). Net fluxes were ebb-directed in February (17.0 gs$^{-1}$), March (15.7 gs$^{-1}$), and April (0.6 gs$^{-1}$). Overall fluxes were lower than NO$_2$+NO$_3$ due to lower concentrations, but greater imports and wider ranges of fluxes of NH$_4$ were evident in the data. Over the course of the 89-day study, an average of 10.6 gs$^{-1}$ of NH$_4$ was exported from Fourleague Bay. This is less than $\frac{1}{4}$ of the net export of NO$_2$+NO$_3$.

Concentrations of Total Nitrogen (TN) ranged from 1.6 to 88.5 μM and averaged 36.6 μM for the study (Figure 3.7a). Mean values for February, March, and April were 35.0, 45.9, and 30.6 μM, respectively, with concentrations in March significantly higher than the other months (ANOVA, p<0.0001). Similar to NO$_2$+NO$_3$, TN concentrations were significantly higher during frontal events (p<0.0001), during post-frontal periods (p<0.0001), and on ebb tides (p<0.0001).

DIN (NO$_2$+NO$_3$+NH$_4$) comprises approximately 49% of the total nitrogen measured in Oyster Bayou over the 3-month period (Table 3.1). NO$_2$+NO$_3$ and NH$_4$ percentages are similar in February (28% and 36%, respectively) but NO$_2$+NO$_3$ is higher in March (42% to 17%) and NH$_4$ is higher in April (13% to 21%). Percent composition of TN calculated for the Atchafalaya River showed greater percentages of
Figure 3.7. (a) Total nitrogen concentration and (b) Total nitrogen flux. Gaps in data are missing values, not zero values.
NO₂+NO₃ and lesser percentages of NH₄ than found in Oyster Bayou during the study (Table 3.1).

Table 3.1. Percent composition of nitrogen and phosphorus in the Atchafalaya River and in Oyster Bayou. Residual N includes DON and PN. Residual P includes DOP and PP.

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<tr>
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<tr>
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<td>23.5</td>
<td>50.9</td>
<td>27.9</td>
</tr>
</tbody>
</table>

* Data source: Garrison et al. (1995)

Large fluxes of total nitrogen occurred throughout the study with the greatest transport occurring on February 24 (JD 55), an export of 1010 gs⁻¹ (Figure 3.7b). This export did not coincide with the largest exports of NO₂+NO₃ or NH₄ which suggests that much of the TN flux was particulates and organics. The maximum import of TN, 590 gs⁻¹, occurred on March 9 (JD 68) following 60 h of pre-frontal, southerly winds. Mean fluxes of 131, 167, and 34 gs⁻¹ of TN were exported from Fourleague Bay during February, March, and April, respectively. Again, the much lower flux in April was
due to more balanced water fluxes and lower concentrations during the tidally-driven conditions of the last 20 days. In fact, the net flux for April 1-9 (JD 90-99) was estimated at an export of 103 gs\(^{-1}\) while the net flux from April 10-30 (JD 100-120) was an import of 0.9 gs\(^{-1}\). Over the course of the 89-day study 98.5 gs\(^{-1}\) of TN was exported through Oyster Bayou to the Gulf. In table 3.2 net monthly and net study estimates of TN flux and are given with respective DIN flux components. For comparative purposes, due to blocks of missing TN and TP data, estimates of all dissolved inorganic fluxes in table 3.2 were computed only for the time periods where TN and TP data were available. Thus, net monthly fluxes of dissolved inorganic N and P calculated in other sections of this chapter may be different than reported in table 3.2 due to the incorporation of the full data set.

Table 3.2. Net monthly and study flux estimates for nitrogen and phosphorus from Oyster Bayou to the Gulf of Mexico. All estimates are exports in gs\(^{-1}\).

<table>
<thead>
<tr>
<th></th>
<th>NO(_2^+)NO(_3^-)</th>
<th>NH(_4^+)</th>
<th>TN</th>
<th>PO(_4^{3-})</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb.</td>
<td>51.3</td>
<td>18.7</td>
<td>130.7</td>
<td>2.5</td>
<td>23.4</td>
</tr>
<tr>
<td>Mar.</td>
<td>76.8</td>
<td>15.4</td>
<td>166.7</td>
<td>5.8</td>
<td>21.6</td>
</tr>
<tr>
<td>Apr.</td>
<td>13.2</td>
<td>0.1</td>
<td>33.5</td>
<td>1.0</td>
<td>2.5</td>
</tr>
<tr>
<td>89-day</td>
<td>42.2</td>
<td>9.2</td>
<td>98.5</td>
<td>3.0</td>
<td>13.6</td>
</tr>
</tbody>
</table>

3.4.3 Phosphorus Concentrations and Fluxes

Phosphate (PO\(_4^{3-}\)) concentrations were generally low in Fourleague Bay ranging from 0.0-3.0 µM with a study mean of 0.6 µM (Figure 3.8a). Mean concentrations in March were significantly higher than February and April (Wilcoxon, p<0.0001) with

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Figure 3.8. (a) Phosphate concentration and (b) Phosphate flux.
concentrations of 0.5, 0.7, and 0.5 µM for February, March, and April, respectively. No significant differences were found between PO₄ concentrations during pre-, post-, or inter-frontal periods or between frontal and non-frontal conditions. PO₄ concentrations were, however, significantly lower on flood tides than slack or ebb tides (Wilcoxon, p<0.0233). PO₄ concentrations measured in Oyster Bayou were similar to Atchafalaya River concentrations of 0.71, 1.13, and 1.29 µM for February-April (Garrison et al., 1995). PO₄ concentrations remained relatively stable over the course of the study and did not decrease in concentration in the latter part of April.

Regulated by low concentrations and water transport, the flux of PO₄ was also small with a range from an instantaneous export of 61 gs⁻¹ to an instantaneous import of 33 gs⁻¹ (Figure 3.8b) and a net export over the 89-day period of only 3 gs⁻¹. Mean ebb-directed fluxes of 3.1, 5.1, and 1.0 gs⁻¹ were calculated for February, March, and April, respectively. In the latter part of April (JD 100-120) PO₄ export was only 0.1 gs⁻¹ due to low net water flux.

Total phosphorus (TP) concentrations averaged 2.7 µM for the study with a range of 0.4-13.5 µM (Figure 3.9a). Only 24% of TP was PO₄ indicating that the majority of TP is bound in particulates and dissolved organics (Table 3.1). Mean monthly concentrations of 3.2, 3.3, and 2.0 µM for February-April, respectively, were estimated with February and March concentrations significantly higher than April (Wilcoxon, p<0.0001). TP was significantly higher during frontal events than during non-frontal events (p<0.0001) and during post-frontal conditions (p<0.0002) which is
Figure 3.9. (a) Total phosphorus concentration and (b) Total phosphorus flux. Gaps in data are missing values, not zero values.
consistent with total suspended sediment (TSS) data (Perez et al., 2000). This supports the idea that a large fraction of TP may be transported in suspension bound with sediment particles.

TP fluxes were ebb-dominated with net monthly exports of 23 g s\(^{-1}\) in February, 22 g s\(^{-1}\) in March, and 3 g s\(^{-1}\) in April. The largest instantaneous import of TP was 97 g s\(^{-1}\) on April 11 (JD 101) in response to greater than two days of moderate south-east winds while the greatest instantaneous export of 209 g s\(^{-1}\) was measured on February 24 (JD 55) in conjunction with northerly, post-frontal winds (Figure 3.9b).

3.4.4 Nitrogen and Phosphorus Net Daily Fluxes

Examination of the nutrient fluxes calculated on different time scales shows an even clearer seasonal pattern (Figures 3.10 a-e). Net daily fluxes of NO\(_2^+\)NO\(_3^-\) were completely ebb-dominated with a few negligible imports in late April as the result of tidally-driven, fair-weather conditions (i.e., southerly winds). The largest pulses out of the estuary were indicative of the dominance of Atchafalaya River water and were associated with strong, northerly, post-frontal winds. Net daily fluxes of NH\(_4^+\) were also ebb-directed throughout the study, but net influxes occurred more frequently during the latter part of April. Net daily PO\(_4^{3-}\) fluxes showed patterns similar to NH\(_4^+\)

Factor Analysis identified two significant factors. TN, NO\(_2^+\)NO\(_3^-\), and TP were grouped together in the first factor and explained 91% of the model variation. For each of these constituents, higher concentrations were associated with Atchafalaya River water, suggesting that the first factor reflects riverine influence in Fourleague
Figure 3.10. (a) Net nitrate + nitrite flux calculated daily. (b) Net ammonium flux calculated daily. (c) Net total nitrogen flux calculated daily. (d) Net phosphate flux calculated daily. (e) Net total phosphorus flux calculated daily.

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Bay. POC and TSS were grouped together in the second factor. Both constituents are particulates and are suggestive of cold front induced resuspension and transport. The correlation coefficients of both constituents in factor 2 were positive indicating a similar response to physical forcings and high wind events.

3.5 DISCUSSION

High Atchafalaya River discharge coupled with the passage of atmospheric cold fronts lead to high amounts of freshwater input to Fourleague Bay which is a major factor in determining the magnitude of nutrient concentrations and fluxes. Riverine influence is greatest when coupled with northerly and northwesterly winds associated with winter cold fronts which act in concert to enhance ebb-directed fluxes and decrease flushing times of the bay. Northerly, post-frontal winds increase riverine input into the northern bay. Atchafalaya River water, however, is retarded from entering, or is diverted away from the northern bay during southerly and easterly winds of pre- and inter-frontal periods, respectively, leading to greater tidally-dominated hydrodynamics and Gulf water influence. High energy wind events and freshwater input are significant pumping mechanisms which lead to enhanced water movement and flushing of shallow bays in Louisiana. For example, Kemp et al. (1980) recorded meteorologically-induced water level ranges of 1.2 m during the winter months associated with frequent frontal passages, nearly double the maximum astronomical tide range along the northern gulf coast. In Caminada Bay, Louisiana,
Kjerfve (1973) reported that water levels and circulation were controlled by winds on a scale of a few days and diurnal tides on a daily scale.

3.5.1 Nitrogen Concentrations and Fluxes

The results indicate that concentrations and fluxes of NO$_2$+NO$_3$ increase when associated with pulses of Atchafalaya River water and decrease when associated with Gulf water inputs during periods of tidally-driven hydrodynamics. This is evidenced by increased concentrations on ebb tides rather than on flood or slack tides and in lower salinity waters indicative of Atchafalaya River water. Increased concentrations of NO$_2$+NO$_3$ in the bay in association with the seasonal discharge pattern of the Atchafalaya have been well documented by previous investigators (Caffrey and Day, 1986; Madden, 1986; Madden et al., 1988; Childers and Day, 1990; Stern et al., 1991; Madden, 1992; Day et al., 1995). For instance, Madden et al. (1988) reported that nutrient concentrations in Upper Fourleague Bay were similar to those in the river with concentrations decreasing in the Lower Bay and Oyster Bayou. They report average monthly concentrations of nitrate in the Upper Bay and Lower Bay of 120 µM and 15 µM, respectively, during spring, whereas mean concentrations during the summer and fall were 30 µM and <1 µM for the Upper and Lower Bay, respectively (Madden et al., 1988). The mean NO$_2$+NO$_3$ concentration calculated in our study of 11.1 µM is within the range of Madden’s findings and is consistent with river water diverted into the northern bay by northerly and northwesterly winds associated with the passage of cold fronts. Freshwater influence on DIN concentrations in the Ems
estuary are even more pronounced with upper estuary maximum values of 755 μM in the winter and 215 μM during summer and lower estuary values of approximately 25-40 μM in the winter decreasing to 0.4 μM in summer (van Beusekom and de Jonge, 1998). In the Carpenteria Salt Marsh in southern California, Page et al. (1995) reported NO₃ concentration ranges from 4.7-121 μM on ebb tides and from 0.7-17.1 on flood tides with highest concentrations in March-April associated with the greatest stream flow into the marsh.

NO₂⁺NO₃ concentrations in Fourleague Bay decreased to <5 μM with changes in estuarine hydrology from a riverine/wind-forced to a tidally-dominated system as a result of moderate southerly winds, limited freshwater input, and increased residence times in the bay. Denitrification is likely a significant pathway of NO₂⁺NO₃ loss during these times. Smith et al. (1985) measured rapid denitrification of NO₂⁺NO₃ in Fourleague Bay and estimated that approximately 50% of the annual NO₃ entering the estuary is lost to the atmosphere via denitrification. The authors also suggest potential losses of NO₂⁺NO₃ via dissimilatory reduction to NH₄ since denitrification rates in the sediment did not account for all of the nitrogen lost. Somewhat lower rates of total N loss via denitrification have been calculated for the Ems (19%; van Beusekom and de Jonge, 1998), the Chesapeake (26%; Nixon et al., 1996), Narragansett Bay (13-27%; Nixon et al. 1996), and the Potomac (16%; Nixon et al. 1996). Another potentially important N loss mechanism is via burial and uptake in the adjacent marshes.
Ebb-directed fluxes of $\text{NO}_2^+\text{NO}_3^-$ were also greatly enhanced by riverine input. Over the course of the 89-day study, $1.02 \times 10^8 \text{m}^3$ (138.4 m$^3$s$^{-1}$) of water was exported from Oyster Bayou to the Gulf of Mexico as a result of Atchafalaya River influence and high velocity wind events (Perez et al., 2000). During peak discharge months in the spring, Denes and Caffrey (1988) calculated 152 m$^3$s$^{-1}$ of Atchafalaya River water entered Fourleague Bay through the north entrance as opposed to low-flow periods during the summer-fall when only 15 m$^3$s$^{-1}$ entered the bay. High concentrations of $\text{NO}_2^+\text{NO}_3^-$ coupled with large volume exports of water resulted in an export of $3.34 \times 10^8$ kg of $\text{NO}_2^+\text{NO}_3^-$ out of Fourleague Bay. This value greatly exceeds the $3.3 \times 10^3$ kg of $\text{NO}_2^+\text{NO}_3^-$ exported to the coastal ocean during the spring in North Inlet, SC (Dame et al., 1986), although this is not surprising due to the differences in riverine influence. Similarly, nitrate transport in Willow Bayou, which lies near the northern entrance of Fourleague Bay, was consistently ebb-directed and increased from January to May primarily due to water transport originating from the Atchafalaya River (Stern et al., 1991). Nitrate fluxes decreased in magnitude from May through October as a result of lower concentrations of nitrate in the system compounded by nearly balanced water fluxes (Stern et al., 1991).

The results show that concentrations of $\text{NH}_4^+$ measured in Oyster Bayou were highly variable and, on average, greater than the concentrations entering the bay via the Atchafalaya River. This indicates that the bay and surrounding marshes are a source of $\text{NH}_4^+$ and indicates that the river is not controlling the lower bay concentrations.
Benthic fluxes have been indicated as an important NH$_4$ source with annual estimates in the bay averaging a release of 130-140 μmol m$^{-2}$h$^{-1}$ of NH$_4$ to the overlying water column with high variability (range=10-330 μmol m$^{-2}$h$^{-1}$; Twilley et al., 1999). In addition, NH$_4$ concentrations averaged 23.5% of TN throughout the 89-day study which is in contrast to previous work by Madden et al., (1988) and Stern et al., (1991) who calculated a lesser percent contribution to the total N pool in Fourleague Bay. Possible explanations for the increased concentrations of NH$_4$ may be due to: (1) benthic remineralization (Teague et al., 1988; Cowan et al., 1996; Rudnick et al., 1999; Twilley et al., 1999); (2) increased residence times in the bay (Nixon et al., 1996); (3) more frequent sampling near slack tides when increased NH$_4$ concentrations have been measured due to oyster production in lower Fourleague Bay and Oyster Bayou (Miller-Way, 1994); (4) dissimilatory reduction of NO$_3$ (Smith et al., 1985); (5) export from the flooding and flushing of surrounding marsh (Childers and Day, 1990; Page et al., 1995); (6) Gulf of Mexico influence (Sutula, 1999); and (7) reduced phytoplankton assimilation due to colder temperatures and light-limitation (Madden, 1992).

In the Barataria Bay, Louisiana marshes DeLaune et al. (1989) estimated that 10 g N m$^{-2}$y$^{-1}$ was fixed, however, no significant N-fixation was measured in the water column, only in the marsh (Casselman, 1979; Casselman et al., 1981). In addition, N-fixation has been found to be inhibited in the presence of high inorganic N concentrations, especially nitrate and ammonium (Buresh and Patrick, 1980; DeLaune et al., 1981) During our study in Fourleague Bay the marshes were only flooded
approximately 3% of the time in February and March and 13% in April (Perez et al., 2000). This relatively low flooding duration coupled with high DIN concentrations derived from the Atchafalaya River suggests that nitrogen fixation is likely not a major source of N to Fourleague Bay during the high river discharge months. However, N fixation may become a more important factor in late April as nitrate concentrations were low and the surrounding marshes were flooded more frequently.

Ammonium fluxes were on average ebb-directed with water transport a major determinant of net flux. Large pulses of river water forced through the bay caused net exports in February and March, but as the hydrology shifted to a tidally-dominated system in April, longer residence times and increasing instances of flood-directed fluxes were observed resulting in almost balanced fluxes. Similar patterns were reported in Chesapeake Bay where large quantities of dissolved nutrients were flushed through the system during periods of high flow, while under low-flow conditions significant retention of nitrogen, likely due to phytoplankton uptake, was observed (Magnien et al., 1992).

TN concentrations were mainly composed of DIN, although the significance of NO$_2$+NO$_3$ and NH$_4$ varied with changes in hydrologic flow patterns, riverine influence, and estuarine retention time. Riverine TN averaged >50% NO$_2$+NO$_3$ and approximately 5% NH$_4$ during the study (Garrison et al., 1995) which is dramatically different from that measured in Oyster Bayou where NO$_2$+NO$_3$ and NH$_4$ accounted for approximately 26% and 24% of TN, respectively. This is lower than reported in
the Ems estuary where DIN represented 98% of the total N load during winter, 86% of which was exported from the estuary (van Beusekom and de Jonge 1998). In the tidally influenced portion of the Hudson River, DIN accounted for approximately 75% of TN (Lampman et al. 1999), while in the mainstem Chesapeake, Potomac, and Patuxent estuaries DIN comprised between 61% and 79% of TN (Magnien et al., 1992).

TN fluxes were ebb-dominated due to the net water export from Fourleague Bay. The largest TN flux did not occur in conjunction with the greatest exports of DIN, however, suggesting that the bay was a source of particulate N. This is consistent with TSS data which showed elevated concentrations during the post-frontal phase of a cold front which increased resuspension of the shallow benthic sediments in the bay (Perez et al., 2000). Over the 89-day study 7.6 \times 10^8 \text{ kg} of TN were exported to the Gulf which is greater than spring exports of 2.2 \times 10^5 \text{ kg} and 2.03 \times 10^6 \text{ kg TN from the North Inlet (Dame et al. 1986) and the Patuxent marshes (Heinle and Flemer, 1976), respectively.}"

3.5.2 Phosphorus Concentrations and Fluxes

PO$_4$ concentrations were low and remained relatively constant throughout the study which is consistent with previous work in the bay (Madden et al., 1988; Stern et al., 1991) and in other Louisiana estuaries (Lane et al., 1999). PO$_4$ concentrations were somewhat higher during periods of riverine influence, but elevated concentrations at other times suggest benthic remineralization (Twilley et al., 1999), marsh export

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(Heinle and Flemmer, 1976; Nixon, 1980; Dame et al., 1986; Childers and Day, 1990), and the Gulf (Madden, 1986; Sutula, 1999) as potential sources. \( \text{PO}_4 \) sorption to and desorption from clay and organic particles have been recognized as buffering mechanisms in estuarine environments (Jitts, 1959; Sharp et al., 1982; Madden, 1988) and are likely processes regulating the temporal stability of \( \text{PO}_4 \) concentrations in Fourleague Bay. \( \text{PO}_4 \) Fluxes were driven by both the magnitude of concentrations and water fluxes with stronger ebb fluxes in response to Atchafalaya River influence. \( \text{PO}_4 \) import occurred more often during the latter part of April which may be due to increased metabolic activity and regeneration in the bay and surrounding marshes as well as offshore sources. Nearly balanced fluxes, however, suggest that significant P-recycling is taking place in the estuary. Nixon (1980) reported that \( \text{PO}_4 \) was consistently exported from marshes to the coastal ocean with highly variable and inconsistent seasonal patterns, similar to our findings.

The majority of TP transported between the bay and Gulf consisted of particulate and dissolved organic P, with \( \text{PO}_4 \) only representing approximately 24% of the total phosphorus pool. This contrasts with nitrogen which consisted of a higher proportion of dissolved inorganic fractions. The river was the ultimate source of TP with resuspension events caused by high velocity post-frontal winds leading to greater TP concentrations. Magnien et al. (1992) reported that particulates dominated TP in the mainstem Chesapeake (62-71%) and Potomac (50-74%) estuaries and that sedimentation is probably a large sink for phosphorus which could result in TN:TP
ratios in the estuary being higher than those of inputs. We estimate that 13.3 gs\(^{-1}\) of TP was exported from Fourleague Bay during the study which is similar to that reported for the mid-Hudson which averaged approximately 30 gs\(^{-1}\) (ranged from 4-75 gs\(^{-1}\)) between 1992 and 1996 (Lampman et al., 1999).

3.5.3 Additional External Nutrient Sources

Precipitation and groundwater nutrient inputs are likely negligible to the overall magnitude of concentrations and fluxes measured in Fourleague Bay during this study due to the overwhelming influence of the Atchafalaya River. However, in estuarine systems without such a pronounced riverine signature, large percentages of the annual nutrient budget may be delivered from groundwater seepage and precipitation events (Valiela et al., 1978; Boynton et al., 1995; Sutula, 1999). For instance, in Great Sippewissett Marsh, Valiela et al., (1978) calculated that nitrogen inputs via groundwater and precipitation were more than sufficient to sustain annual plant growth, with groundwater supplying over 20 times the amount carried by precipitation. On the other hand, atmospheric deposition (wet-fall) directly to the surface waters in Chesapeake Bay was found to be small, ranging from 5.1-12.7% of TN and 2.5-6.6% of TP inputs (Boynton et al., 1995). Percentages were higher in the Choptank River, however, representing 33.1% and 17.1% of TN and TP inputs, respectively, and was attributed to small inputs from other sources and the large surface area of the estuary (Boynton et al., 1995).
In sub-tropical and tropical estuaries, freshwater and nutrient input often follow distinct wet- and dry-season patterns. Three tropical estuaries in North Queensland, Australia (Jardine, Annan, and Daintree) had greater variation between low and high flows than three temperate estuaries in Scotland, U.K. (Inverness, Cromarty, and Dornoch Firths) with 152-fold and 4-fold differences, respectively (Eyre and Balls, 1999). Freshwater concentrations of DIP, NO₃, and TSS in the Jardine, Annan, and Daintree estuaries increased 63-97% following flood events (Eyre and Balls, 1999) whereas the less variable input of freshwater to temperate estuaries showed a reduced proportion of total yearly transport. Similarly, rainy season forcing in Taylor River in the southeast Everglades, Florida showed an increase in TN of 20-40 μM in 1996 and 1997, while dry season concentrations remained constant (Sutula, 1999). Following the same pattern, total organic carbon (TOC) concentrations in Taylor and Trout creeks increased 200-300 μM during the rainy season (Sutula, 1999).

3.5.4 Tidal versus Far-Field Forcings

Far-field influences (river input and frontal passages) often overwhelmed tidal forcing on hydrodynamics, nutrient concentrations and fluxes. To illustrate this, we compare two 57-h time periods during the study period. From March 1-3 (JD 60-62) the most physically intense cold front of the study passed through south Louisiana. Over the course of the cold front, 8-10 m s⁻¹ sustained velocity north-northwest winds forced Atchafalaya River water into upper Fourleague Bay, spurred resuspension, and caused extreme ebb-directed fluxes of water and materials. The residence time
calculated for this time period was approximately 3.3 days. The second time period, April 28-30 (JD 118-120), was characterized by light south-southeasterly winds, little to no riverine influence in the bay, and tidally-dominated hydrodynamics. The mean nutrient concentrations and associated fluxes for these two periods are given in table 3.3. It is immediately evident that during the March 1-3 period riverine and wind-driven forcing dominated the hydrology forcing 335 m$^3$s$^{-1}$ of water out of the bay, whereas in April tidal forcing resulted in nearly balanced fluxes with an import of 29 m$^3$s$^{-1}$. NO$_2$+NO$_3$, TN, and TP concentrations were all considerably higher when associated with water derived from the Atchafalaya, while NH$_4$ concentrations were higher during the low-energy, low-riverine influenced period more indicative of a biologically dominated system. PO$_4$ concentrations were similar suggesting that both the river and biologically-mediated processes affect PO$_4$ concentrations.

Table 3.3. Far-Field Forcing (March) vs. Tidal Forcing (April) concentration and flux comparison. Units: nutrient concentrations, µM, nutrient fluxes, g s$^{-1}$, water flux, m$^3$s$^{-1}$. Negative fluxes are ebb-directed (to the Gulf). Positive fluxes are flood-directed (to the bay).

<table>
<thead>
<tr>
<th>Concentrations</th>
<th>March 1-3 (JD 60-62)</th>
<th>April 28-30 (JD 118-120)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_4$</td>
<td>4.6</td>
<td>8.0</td>
</tr>
<tr>
<td>NO$_2$+NO$_3$</td>
<td>22.3</td>
<td>2.4</td>
</tr>
<tr>
<td>TN</td>
<td>49.8</td>
<td>28.9</td>
</tr>
<tr>
<td>PO$_4$</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>TP</td>
<td>3.3</td>
<td>2.0</td>
</tr>
<tr>
<td>Fluxes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH$_4$</td>
<td>-19.8</td>
<td>4.9</td>
</tr>
<tr>
<td>NO$_2$+NO$_3$</td>
<td>-136.9</td>
<td>0.6</td>
</tr>
<tr>
<td>TN</td>
<td>-264.8</td>
<td>12.3</td>
</tr>
<tr>
<td>PO$_4$</td>
<td>-7.9</td>
<td>0.2</td>
</tr>
<tr>
<td>TP</td>
<td>-31.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Water Flux</td>
<td>-334.9</td>
<td>29.4</td>
</tr>
</tbody>
</table>
3.6 REFERENCES


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CHAPTER 4

NUTRIENT STOICHIOMETRY AND UPTAKE DYNAMICS IN FOURLEAGUE BAY, LOUISIANA
4.1 INTRODUCTION

Nutrient dynamics in estuaries is a function of river and marine inputs, and processes of uptake, transformation, and remineralization of organic matter in the estuary. The origin of nutrient inputs and the processes most important in regulating their fate are specific to each estuarine system. The efficiency of estuaries in retaining and transforming nutrients are largely influenced by the geology and geomorphology of the estuary, extent of surrounding wetlands, benthic communities, freshwater inflow, estuarine residence time, and physical forcings (Nixon et al., 1996; Twilley et al., 1999; Day et al., 2000). In order to manage coastal areas correctly and sustain an ecological balance within the estuary and offshore, we must first understand how nutrients are processed in estuarine and coastal systems (Magnien et al., 1992).

Phytoplankton preferentially assimilate dissolved inorganic nitrogen (DIN), silicon (Si), and dissolved inorganic phosphorus (DIP) in an atomic ratio of 16:16:1, better known as the Redfield ratio, when nutrient levels are sufficient (Redfield et al., 1958). Deviations from this stoichiometric balance indicate potential growth limitation to phytoplankton (Dortch and Whitledge, 1992). Ratios of N:P below the Redfield ratio are indicative of N limitation, whereas ratios above 16:1 are indicative of P limitation. The Redfield ratio is commonly used in coastal waters as an indicator of the health and balance of the system, but even if nutrient balance is sustained, an excess of nutrients can still cause plankton blooms and low oxygen conditions (Justic et al., 1995; Rabalais et al., 1996). For instance, in the Mississippi River, loadings of nitrogen and phosphorus have increased while silicon concentrations have decreased resulting in nutrients approaching Redfield ratios which may lead to phytoplankton...
species shifts and increased primary production which, in turn, may influence the size and severity of the offshore hypoxic zone (Rabalais et al., 1996). Thus, measures to reduce excess nutrient concentrations prior to reaching offshore waters are necessary.

Wetland environments are natural sinks for nutrients with several pathways of permanent loss and have been documented to dampen the effects of high nutrient loads in coastal systems and for municipal wastewater effluent (Smith et al., 1985; Day et al., 1989; Mitsch and Gosselink, 1993; Breaux and Day, 1994; Kadlec and Knight, 1996; Nixon et al., 1996; Lane et al., 1999). For instance, nitrogen is permanently lost to the atmosphere via denitrification and phosphorus may be removed by settling and subsequent burial of particulate matter. Reduction estimates of 30-65% of the total N and 10-55% of the total P that would otherwise be transferred to the coastal North Atlantic Ocean have been attributed to estuarine processes, however, the removal efficiency is directly related to estuarine residence time (Nixon et al., 1996). Estuaries with shorter residence times do not allow for efficient biological assimilation and chemical transformation of nutrients in the water column and sediment thus exporting the majority of the nutrients input to the system. As residence time increases, so do loss and uptake rates resulting in reduced offshore nutrient loading.

Issues of eutrophication in coastal Louisiana are of major concern due to high nutrient loading rates from the Mississippi and Atchafalaya Rivers. Large hypoxic zones as great as 9500 km$^2$ during the summer have been documented by Rabalais et al. (1991; 1994) in the north central Gulf of Mexico. As such, questions regarding the impact of present and future planned diversions of Mississippi River water into coastal marshes and bays as part of coastal restoration initiatives have surfaced. In a recent
study by Lane et al. (1999) on the water quality of the Breton Sound estuary in Louisiana in response to the Caernarvon freshwater diversion, removal efficiencies of 88-97% for NO$_2$+NO$_3$, 32-57% for TN, and 0-46% for TP were observed with no apparent detrimental effects to the addition of river water. The authors also noted that removal rates decreased rapidly in response to increasing nutrient loads (Lane et al., 1999) indicating that management strategies should include the utilization of wetlands and shallow waters to assimilate nutrients at a rate which would increase estuarine and wetland productivity while reducing the eutrophication of coastal systems (Day et al., 1997).

The Fourleague Bay estuary in south Louisiana receives large volumes of fresh water from the Atchafalaya River which carries high concentrations of nutrients (see chapter 2). During the spring peak discharge period, riverine influence and high winds associated with atmospheric cold front passages dominate bay hydrodynamics causing large exports of water and materials to the Gulf of Mexico and rapid flushing of the bay (Perez et al., 2000). The objectives of this paper are to: (1) examine the temporal pattern of nutrient concentrations in Fourleague Bay; (2) examine the effect of salinity on nutrient concentrations; (3) evaluate the stoichiometric balance of nitrogen and phosphorus (dissolved inorganic and total) in Fourleague Bay and the Atchafalaya River during the spring discharge months; (4) examine the relationship between loading and uptake rates of nitrogen and phosphorus; and (5) determine the effects of estuarine residence time as regulated by riverine and tidal influence on the magnitude of nutrient flux to the coastal ocean. I hypothesized that: (1) concentrations of NO$_2$+NO$_3$, TN, and TP would be greater in association with increased Atchafalaya
River influence; (2) ratios of nitrogen to phosphorus would be greater with increased
Atchafalaya River influence, especially dissolved inorganic ratios; (3) nutrient uptake
rates and efficiencies would be greater during periods of low nutrient loading to the
bay; and (4) net export of nutrients would be less during periods of increased estuarine
residence time.

4.2 SITE DESCRIPTION

Fourleague Bay is a shallow (1 m mean depth), highly turbid, vertically well-
mixed estuary approximately 95 km\(^2\) in size (Figure 4.1). Surrounding the bay are
extensive fresh, brackish, and saline wetlands. The bay is located in south-central
Louisiana and is strongly impacted by Atchafalaya River discharge and associated
nutrient concentrations. During spring peak discharge months, February-May,
flushing times of the bay average approximately 8 days and are as low as 3 d (see
Perez et al., 2000). Fourleague Bay is connected directly to the Gulf of Mexico by
Oyster Bayou, the sole outlet at the southern terminus. Oyster Bayou is approximately
180 m wide at the study site, 4 km long, 5-10 m deep, with a cross-section of
approximately 1000-1100 m\(^2\). Extensive intertidal and subtidal oyster reefs line the
bayou which is bordered by *Spartina alterniflora* marshes.

4.3 MATERIALS AND METHODS

4.3.1 Oyster Bayou Data

Water samples were taken in Oyster Bayou every three hours from February 1
to April 30, 1994 for the analysis of nitrite+nitrate (NO\(_2^+\)NO\(_3^-\)), ammonium (NH\(_4^+\)),
phosphate (PO\(_4^{3-}\)), total nitrogen (TN), and total phosphorus (TP). Throughout the study
period current velocity and direction, conductivity, and sea temperature were recorded
Figure 4.1. Location of Oyster Bayou (the study site), Fourleague Bay, and the Atchafalaya River in south-central Louisiana. The "p" north and south of Oyster Bayou indicates the location of pressure gauges for water level measurements. The shaded areas surrounding the Bay are marsh.
every 15 minutes in mid-channel by two current meters, one 2 m below the surface and one 1.5 m above the bottom. Water flux \( (m^3 \cdot s^{-1}) \) was calculated as the product of the average of surface and bottom current velocity and the cross-sectional area of the bayou. The cross-sectional area was measured when the bayou was bank full using a continuously recording fathometer and water flux data were corrected for changes in cross-section area due to changing water level.

For each water sample, a known volume was filtered through a Whatman GF-F glass-fiber filter. The filtrate was placed in acid-washed, pre-labeled 5 ml autoanalyser vials (AAV), immediately frozen, and used to determine concentrations of nitrate+nitrite \((NO_2+NO_3)\), ammonium \((NH_4)\), and phosphate \((PO_4)\). The filter was frozen and used for chlorophyll \(a\) (Chl) determination. An unfiltered sample was placed in a 125 ml Nalgene bottle pre-washed with a 10% HCl solution and immediately frozen for determination of total nitrogen \((TN)\) and total phosphorus \((TP)\).

Dissolved inorganic constituents were analyzed on a Technicron Autoanalyser II using EPA method 350.1 for \(NH_4\), method 353.2 for \(NO_2+NO_3\), and method 365.2 for \(PO_4\) (USEPA 1979). A persulfate oxidation (method 207; Valderama, 1981) was used for analysis of TN and TP and performed on an Alpkem 500 series autoanalyser. Chlorophyll \(a\) was analysed using a modified dimethylsulfoxide:acetone extraction technique (Strickland and Parsons, 1972; Burnison, 1980) and measured fluorometrically with a Turner Designs 10-AU analog fluorometer.

Instantaneous fluxes of nutrients \((gs^{-1})\) were calculated for each three hour interval based on the concentration of the individual constituent multiplied by the
associated water flux values. Since water flux was measured more frequently, every 15 minutes, the average water flux for the previous 3 hours was used to calculate material fluxes. Net fluxes over different time periods are reported as time-weighted averages and were calculated as the algebraic sums of the instantaneous fluxes divided by the number of samples taken within the respective time period. Positive fluxes (+) indicate flood-directed flows moving north from the Gulf into Fourleague Bay. Negative fluxes (-) represent ebb-directed flows moving from the bay to the Gulf. For a more detailed description of sampling and data analysis see Perez et al. (2000) 4.3.2 Statistical Analysis

To determine which physical forcing functions were to be included in a statistical model for the various N:P ratios, a linear stepwise regression was performed using SAS statistical software (SAS, 1989). Various transformations were used to meet the assumption of normality. For non normal data non parametric statistics were used. Cross correlations were run to determine covariability between nutrient ratios and multiple regressions were run to determine correlations with physical forcings. ANOVAs were used to determine significant differences in ratios over various time scales. In addition, regressions were used for determining the relationships between nutrient loading versus uptake and residence time versus nutrient export. 4.3.3 Atchafalaya River Data

Concentrations of all nutrient constituents in the Atchafalaya River were taken from the 1994 USGS Water Resources Data at Morgan City, Louisiana. No samples were taken in February 1994, therefore, a 5-year mean from 1987-1991 was used to
estimate the February loading rate from the river. TN concentrations were calculated by summing TKN and NO$_2$+NO$_3$ values.

4.3.4 Definitions and Calculations

Several different definitions for estuarine residence time, or flushing time (used interchangeably throughout the text), have been used in the literature (Solis and Powell, 1999). In this paper we define flushing time as the amount of time required to replace the entire volume of the estuary with freshwater inputs. Using the principle of conservation of water mass, the known volume of water exported from Fourleague Bay to the Gulf of Mexico measured in Oyster Bayou is assumed to have entered the bay through the north entrance. The replacement water source is primarily derived from the Atchafalaya River which is supported by previous studies conducted during high discharge periods (Denes and Caffrey, 1988; Madden et al., 1988) which have shown that freshwater inputs from surrounding bayous are negligible during the winter-spring months. Atchafalaya Bay may also be a source of water to upper Fourleague Bay with maximum inflows during prevailing southwesterly and westerly wind forcing. However, due to the high volumes of Atchafalaya River water and low percent frequency of southwesterly and westerly winds during this study (see chapter 2, Figure 2.3), the water entering northern Fourleague Bay via Atchafalaya Bay is likely minimal. In addition, the developing Atchafalaya delta and the extended Atchafalaya River channel essentially serves to hinder large transports of water from the western Atchafalaya Bay into Fourleague Bay. As the sole direct outlet to the Gulf, Oyster Bayou is the primary conduit of export.

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With this assumption of water replacement by the Atchafalaya River, calculations of nutrient loading rates to the bay were made by multiplying the water flux values from Oyster Bayou by the nutrient concentration values taken from the lower Atchafalaya River at Morgan City. This value represents the nutrient inputs to the estuary. In a previous study, concentrations of nitrate measured at the northern entrance of Fourleague Bay were approximately 95% of the concentrations in the lower Atchafalaya River during high flow conditions and northerly winds (Madden, 1986; Garrison et al., 1995). Concentrations in April during southerly wind conditions were approximately 85% of those in the lower Atchafalaya River (Madden, 1986; Garrison et al., 1995). These physical forcing conditions are similar to those during our study, therefore, the lower Atchafalaya River concentrations were assumed to be representative of the concentrations at the upper Fourleague Bay entrance. Differences in nutrient flux data between estimated input values and those measured in Oyster Bayou were used to determine uptake rates. To assure a net export of water and nutrients to the Gulf, 7-day net values were used for all loading/uptake relationships.

4.4 RESULTS

4.4.1 Nitrogen and Phosphorus Concentrations

The variation in magnitude of nitrogen and phosphorus concentrations measured in Oyster Bayou were large and highly dependent upon the origin of the water mass sampled. \( \text{NO}_2 + \text{NO}_3 \), TN, and TP were consistently higher in association with Atchafalaya River influence while \( \text{NH}_4 \) concentrations increased during tidally-driven periods associated with increased residence times in the bay and Gulf water.
influence. PO₄ concentrations remained relatively stable with both riverine and Gulf sources. Concentrations of NO₂+NO₃ ranged from <1 to 45 μM during the study with a relatively low mean concentration of 11 μM due to large variations resulting from different hydrological patterns and physical forcings. For instance, during tidally-driven, fair-weather conditions (i.e., moderate south or southeast winds) there was clear evidence of marine influence as seen during February 19-21 (JD 50-52) when salinities ranged from 15-18 ppt and NO₂+NO₃ concentrations averaged <2 μM (Figures 4.2 and 4.3). On the other hand, during the post-frontal phase of a cold front on March 1 (JD61) salinities were <1 ppt and concentrations increased to 40 μM as a result of the high velocity northwesterly winds which directed large volumes of Atchafalaya River water into the bay. Although on a smaller scale, similar fluctuations were evident in the other nutrient constituents as well (Figure 4.2).

Concentrations of NO₂+NO₃ and TN were greater when associated with lower salinity river water and decrease with increasing salinity indicating a riverine source. At any given salinity range, NO₂+NO₃ and TN also decrease by month indicating higher uptake in the warmer months. TP is also greater at lower salinities and also decreases by month but shows a less distinct pattern compared to NO₂+NO₃ and TN. In contrast, NH₄ concentrations increase with salinity suggesting sources from the Gulf and from within the bay and surrounding marshes, while PO₄ is fairly stable at all salinities reflecting the strong buffering of PO₄ in this estuarine system.

4.4.2 N:P Stoichiometry

DIN:DIP atomic ratios calculated in Oyster Bayou over the three month study averaged 37:1 which is more than double the Redfield ratio of 16:1. Ratios ranged
Figure 4.2. Nutrient concentrations in Oyster Bayou. Units for all data are in μM. Gaps in TN and TP data are missing values.
Figure 4.3. Monthly mean nutrient concentrations by salinity. Units for all nutrient concentrations are in μM. No salinities greater than 15 were recorded in April.
from 1 to 224 (Figure 4.4a) with 76% of calculated DIN:DIP ratios greater than the Redfield ratio indicating potential phosphorus limitation for the majority of the study period. Higher DIN:DIP ratios occurred when there was an input of Atchafalaya River water high in NO$_2$+NO$_3$ concentration, while lower ratios were indicative of more saline Gulf water with lower NO$_2$+NO$_3$ content (see chapter 2). Average monthly ratios decreased over time with February, March, and April ratios of 49, 39, and 26, respectively, reflecting a decrease in riverine influence and stabilized DIP. All three months were significantly different from one another (Wilcoxon, p<0.001).

Separating DIN into its two components, NO$_2$+NO$_3$ and NH$_4$, and examining the N:P ratios (Figures 4.5a and b) shows that the higher ratios are mainly driven by NO$_2$+NO$_3$ from February to mid-April [Julian Day (JD) 35-100] with February and March significantly higher than April (Tukey, p<0.0001). NH$_4$ was the dominant nitrogen source during periods of low river influence and tidally-driven hydrodynamics (JD 50-55, 100-120) as evidenced by the significantly higher mean ratio of NH$_4$:PO$_4$ seen in April (Tukey, p<0.0001). In fact, during April DIN:DIP ratios dropped below the Redfield ratio indicating potential nitrogen limitation due to changes in bay hydrodynamics. Mean monthly DIN:DIP ratios in the Atchafalaya River were 72, 49, and 41 for February-April averaging 54 for the three months (Table 4.1; Garrison et al., 1995). River values were significantly higher than the Redfield ratio and those measured in Oyster Bayou suggesting N retention within the bay and surrounding marshes.

Ratios of TN:TP in Oyster Bayou remained relatively stable over the study averaging 16 which is suggestive of a stoichiometrically balanced system with a range
Figure 4.4. (a) Atomic ratios of DIN:DIP and (b) TN:TP in Oyster Bayou. Gaps in TN:TP are missing data values.
Figure 4.5. (a) Atomic ratios of $\text{NO}_2^+:\text{NO}_3^-:\text{PO}_4^-$ and (b) atomic ratios of $\text{NH}_4^+:\text{PO}_4^-$ in Oyster Bayou.
Table 4.1. Mean monthly atomic N:P ratios in the Atchafalaya River and Oyster Bayou.

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* Data source: Garrison et al. (1995)

of 1 to 67 (Figure 4.4b). Monthly mean ratios ranged from 12 in February to 15 in March and 19 in April, each significantly different from the other (Wilcoxon, p<0.01). Lower N:P ratios as total nutrients compared to dissolved inorganic are due to the differences in dissolved and particulate fractions of N and P. Whereas total nitrogen is mainly composed of dissolved inorganic species, the phosphorus pool is dominated by particulates and dissolved organics (see chapter 2). Increased TN:TP ratios in late April are due to a change in both nitrogen and phosphorus dynamics. With decreased riverine influence in April both TN and TP inputs to the bay were reduced. NO₂+NO₃ reduction was the main cause of TN reduction, although NH₄ production did partially compensate thereby stabilizing TN concentrations. At the same time, TP shifted from a particulate P (PP) dominance to an increasing PO₄ fraction. The disproportionate loss of PP in relation to DIN thus resulted in increased TN:TP ratios. TN:TP ratios in the Atchafalaya River averaged 20 with mean monthly ratios of 15, 23, and 22 for
February-April, respectively (Table 4.1) which are similar to those measured in Oyster Bayou.

4.4.3 Chlorophyll $a$

Concentrations of chlorophyll $a$ ranged from $<1$ to $48$ µg l$^{-1}$ with a study mean of 13 (Figure 4.6a). Mean monthly concentrations for February, March, and April were 9, 14, and 14 µg l$^{-1}$, respectively. Concentration increases in late March and April were consistent with increased sea temperature (Figure 4.6b) and lower suspended sediment concentrations likely leading to non-light limiting conditions.

4.4.4 Nutrient Loading and Uptake Relationships

The percent uptake of nitrogen in Fourleague Bay varied with loading to the estuary from the Atchafalaya River. Lower loading rates corresponded with higher uptake rates, while higher loading showed decreases in uptake. Although the loading/uptake relationship of NO$_2$+NO$_3$ was not significant ($r^2=0.31$, $p<0.095$), uptake ranged from 35-99% and averaged 60% (Figure 4.7a). TN showed a similar response with removal rates between 29 and 97% averaging 50% throughout the study period ($r^2=0.45$, $p<0.037$; Figure 4.7b). Linear regressions of the flux of NO$_2$+NO$_3$ and TN input to the upper estuary versus the flux out of Oyster Bayou showed similar results with approximately 50% of each being removed within the estuary ($r^2=0.73$, $p<0.0016$ and $r^2=0.75$, $p<0.0012$, respectively; Figure 4.8).

Loading and uptake relationships for NH$_4$, TP, and PO$_4$ are not included here due to imports from the Gulf and surrounding marshes.
Figure 4.6. (a) Chlorophyll a concentration and (b) water temperature measured in Oyster Bayou.
Figure 4.7. Linear regressions of nutrient loading from the Atchafalaya River versus % uptake for (a) NO$_2$+NO$_3$ and (b) TN. All data points are net weekly values.
Figure 4.8. Linear regressions of NO$_2$+NO$_3$ and TN input from the Atchafalaya River versus output of Oyster Bayou. All data points are net weekly values.
4.4.5 TN Export versus Residence Time

The mean residence time of Fourleague Bay during the 89-day study was approximately 8 days ranging from 3 to >100 d (Figure 4.9) depending upon prevailing hydrologic and meteorologic conditions. Regressions of the percent of total nitrogen exported weekly from the bay as a function of log mean residence time indicated that with increased residence time less TN was exported to the Gulf (Figure 4.10). In order to compare our data to that of Nixon et al. (1996) residence times were calculated in months rather than days. Net weekly rates of flushing and TN export were calculated with only those time periods of net export (10 out of 12 weeks) entered into the regression. Due to high riverine influence the majority of the weekly estimates had residence times between 0.14 and 0.27 months (4-8 days) with residence times increasing in the latter part of April to a high of 3.9 months (118 days). TN export ranged from <3% at high residence times to >85% at low residence times (Figure 4.10). The relationship with the highest $r^2$ (0.91) was a power rather than linear function suggesting that as residence times increased past a certain point a disproportionate percent export of TN results.

4.5 DISCUSSION

4.5.1 Nitrogen and Phosphorus Concentrations

Study results indicate that concentrations of NO$_2$+NO$_3$ increase when associated with pulses of Atchafalaya River water influence and decrease when associated with Gulf water influenced characterized by periods of tidally-driven hydrodynamics. Higher NO$_2$+NO$_3$ concentrations in our study exceeding 40 $\mu$M are within the range of Madden’s (1988) findings and are consistent with river water being
Figure 4.9. Flushing time of Fourleague Bay in days.
$f(x) = a \cdot (x^{-1.08})$

where $a = \exp(2.29)$

$R^2 = 0.91$

$p < 0.0245$

Figure 4.10. Percent of total nitrogen input from the Atchafalaya River that is exported from Fourleague Bay as a function of log mean water residence time. Each data point is a 7-d mean value to assure net export of water and TN.
diverted into the upper bay by north and northwest winds associated with the passage of cold fronts. NO$_2$+NO$_3$ concentrations decreased to <5 μM with changes in estuarine hydrology from a riverine/wind forced to a tidally-dominated system as a result of moderate southerly winds, limited freshwater input, and increased residence times in the bay. Denitrification is likely a significant pathway of NO$_2$+NO$_3$ loss during these times accounting for approximately 50% of the annual NO$_3$ entering the estuary (Smith et al., 1985). Concentrations of NH$_4$ measured in Oyster Bayou were highly variable and, on average, greater than the concentrations entering the bay via the Atchafalaya River. This indicates that the bay and surrounding marshes are a source of NH$_4$ and that the river is not controlling the lower bay concentrations. TN concentrations were higher at lower salinities indicating a riverine source, but concentrations measured in Oyster Bayou were lower than those in the Atchafalaya River signifying a loss within the estuary. Important TN loss pathways include denitrification of NO$_2$+NO$_3$ and burial in surrounding marshes.

PO$_4$ concentrations were low and remained relatively constant throughout the study which is consistent with previous work in the bay (Madden et al., 1988; Stern et al., 1991) and in other Louisiana estuaries (Lane et al., 1999). PO$_4$ concentrations were somewhat higher during periods of riverine influence, but elevated concentrations at other times suggest benthic remineralization (Twilley et al., 1999), marsh export (Heinle and Flemmer, 1976; Nixon, 1980; Dame et al., 1986; Childers and Day, 1990), and the Gulf (Madden, 1986; Sutula, 1999) as potential sources.
4.5.2 Comparisons of N:P Stoichiometry in Coastal Systems

Ratios of nitrogen to phosphorus are commonly used in estuarine and coastal systems as estimates of potential nutrient limitation of algal growth. Riverine discharge is a major source of N and P to estuaries and is likely to control aquatic primary production if one or more nutrients are potential limiting factors on both seasonal and annual time scales (Sin et al., 1999). In Fourleague Bay DIN:DIP ratios were higher than 16:1 when associated with increased Atchafalaya River influence suggesting potential P limitation, often severe, for the majority of the study. As riverine influence lessened and temperatures increased in the latter part of April, DIN:DIP ratios decreased below 16:1 indicating periods of potential N limitation. Patterns of potential DIP limitation in spring due to high concentrations of inorganic nitrogen via freshwater runoff and DIN limitation in the warmer summer months as a result of lower “new” nutrient inputs have been documented by previous investigators in Fourleague Bay (Madden, 1986; Madden et al., 1988; Childers and Day, 1990) as well as in other estuaries including the Ems (van Beusekom and de Jonge, 1998), York River (Sin et al., 1999), Tidal Hudson River (Lampman et al., 1999), Caminada Bay (Ho and Barrett, 1977), and Barataria Bay (Childers and Day, 1990). Similarly, Malone et al. (1996) showed shifting N and P limitation over an annual cycle in Chesapeake Bay. In fact, Sin et al. (1999) stated that during high flow years large winter-spring blooms of phytoplankton following peak discharge may lead to potential N limitation earlier than normal. N:P ratios for various estuarine systems are given in Table 4.2.
Table 4.2. Comparison of N:P ratios from published studies in estuarine systems. Wi=winter, Sp=spring, Su=summer, Fa=fall. *designates PN:PP ratio. ♦designates TKN:TP ratio.

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Table 4.2 continued
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<th>Rhone River Delta, France</th>
<th>Wetland-Lagoon</th>
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References:
1. Boynton et al., 1995
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8. Lane et al., 1999
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Lower TN:TP ratios measured in Fourleague Bay during the spring flood are indicative of the large proportion of the TN load lost in the estuary and surrounding marshes compared to that of the TP load. Approximately 50% of TN entering the estuary was retained in or removed from the water column, mostly due to NO$_2$+NO$_3$ loss, whereas the loss of TP was much less. Another factor which may have led to lower TN:TP ratios is high concentrations of particulate P entering the bay in riverine water coupled with remobilization of PP in suspended particulate matter previously buried on the bay bottom. During our study a number of powerful cold fronts led to high rates of resuspension (i.e., suspended sediment concentrations in excess of 1500 mg l$^{-1}$) and caused large volumes of Atchafalaya River water to enter the bay (Perez et al., 2000). TN:TP decreases in response to storm events have been documented as a result of scouring and transport of phosphorus rich sediment with flood waters. Over a 60 month period 11% of N and 31% of P was delivered to the Potomac estuary in one month due to a tropical storm resulting in a monthly mean N:P ratio of 9 as opposed to the 5 year mean of 33 (Magnien et al., 1992). Large percentages of the total P load input to estuaries in particulate form are not uncommon as noted in the Ems estuary where 75% of P import is comprised of particulates (van Beusekom and de Jonge, 1998).

As riverine influence and high wind events decreased in the latter part of April, TN:TP ratios increased. Nearly balanced water fluxes and tidally-driven hydrodynamics which are more indicative of summertime patterns resulted in lower concentrations of both dissolved inorganic and particulate N and P in the bay. Although overall TN and TP concentrations were lower, benthic remineralization in
the bay coupled with Gulf sources probably led to the increase in NH$_4$ concentration which in turn resulted in higher TN:TP ratios. Thus, on average, an indirect relationship between DIN:DIP ratios and TN:TP ratios exists in Fourleague Bay during our study period due to the temporal changes in nutrient composition (i.e., dissolved inorganic or particulate) as regulated by riverine, bay, marsh, or Gulf influences as well as biological and geochemical processes.

4.5.3 Implications of Changing N:P Stoichiometry in Coastal Systems

Increased nutrient loading to coastal waters via riverine sources not only leads to enhanced productivity and potential eutrophication but may also bring about changes in planktonic species composition. In the Mississippi River it has been reported that while P and N concentrations have increased 2- and 3-fold, respectively, since 1960, levels of silicon have declined (Turner and Rabalais, 1991, Justic et al., 1995). These changes have led to waters in coastal Louisiana near stoichiometric balance which is suitable for diatom growth. However, with depletion of Si by diatom assimilation and further increases in N and P via the Mississippi, a shift in phytoplankton dominance from diatoms to non-siliceous, often toxic, forms may result (Justic et al., 1995). Similarly, long-term increases of N and P loadings to the northern Adriatic from the Po River have led to nutrient concentrations near stoichiometric balance which likely caused increased primary productivity and subsequent bottom water oxygen depletion (Justic et al., 1995).

The mean DIN:DIP ratio measured in Oyster Bayou in this study (37:1) was lower than the ratio in the Atchafalaya River (54:1) indicating that as riverine water flows through a shallow bay surrounded by marshes changes in N:P ratios result.
Although we do not have Si data in Oyster Bayou, it is likely that with a 50% reduction in NO$_2$+NO$_3$ and potentially low uptake of Si evidenced by fairly low chlorophyll $a$ concentrations the Si:DIN ratio may have increased. In the Atchafalaya River the mean Si:DIN ratio during this study was 4.5:1 suggesting potential DIN limitation upon entering the bay. Thus, a further increase in the ratio due to DIN losses would supply Si to the northern Gulf in excess of algal demand.

4.5.4 Chlorophyll $a$

The pattern of increasing chlorophyll $a$ concentrations over the study period are likely due to more favorable environmental conditions. February and the beginning of March were characterized by low temperatures (Figure 4.6b), high concentrations of TSS (see Perez et al., 2000) which likely resulted in light limitation (Madden et al., 1988), and high flushing rates of the bay advecting phytoplankton cells out of the estuary with little time to increase biomass (Dagg, 1995). The combination of these factors likely acted to suppress phytoplankton growth regardless of ample nutrient concentrations. In late March and April more favorable conditions prevailed including high nutrient concentrations, warmer temperatures, lower TSS, more stable water levels and salinity, and increased estuarine residence time. As a result chlorophyll concentrations increased. Around April 10 (JD 100) concentrations began to decrease likely in response to N-limitation (Figure 4.6a). As NH$_4$ concentrations increased (JD 110) DIN was no longer a potentially limiting factor and chlorophyll concentrations increased with a quick decline likely due to increased grazing pressure. Previously, Day et al. (1995) suggested that winter zooplankton stocks in Fourleague Bay were low as a result of lower temperatures and high wash-out due to short flushing times.
4.5.5 Factors Influencing Nutrient Retention

Nutrient retention in estuarine and wetland systems is indirectly related to the nutrient loading rate, as loadings increase removal efficiencies decrease (Mitsch and Gosselink 1993; Kadlec and Knight, 1996). Our results indicate that at low loading rates less than 22 gm$^{-2}$y$^{-1}$ nearly 100% of NO$_2$+NO$_3$ is removed from the Fourleague Bay water column. This is similar to that calculated in Caernarvon, Louisiana where 88-97% of NO$_2$+NO$_3$ was removed from the estuary at loading rates less than 10 gm$^{-2}$y$^{-1}$ (Lane et al. 1999). Lower rates have been reported for the Hudson River (15% retention; Lampman et al., 1999) and for Ems estuary (17% retained; van Beusekom and de Jonge, 1998). Smith et al. (1985) reported that approximately 50% of the NO$_2$+NO$_3$ entering Fourleague Bay was lost via denitrification. This rate of denitrification is higher than those reported for the Potomac (13%), Chesapeake (25%), Patuxent (31%; Boynton et al., 1995), and Ems (19%; van Beusekom and de Jonge, 1998) but lower than the Choptank (79%; Boynton et al., 1995). Boynton et al. (1995) suggested that high removal of nitrogen inputs via denitrification may be a function of the percentage of TN entering an estuary as nitrate. At low TN loading rates, NO$_3$ and organic matter may limit denitrification with rates increasing with additional TN loading until hypoxia or anoxia hinders nitrification and thus a source of nitrate (Boynton et al., 1995). Two data points of moderate NO$_2$+NO$_3$ loading in figure 4.7a reveal lower percent uptake rates (35-40%) than others with similar and higher loadings. One possible explanation for the lower uptake rates may be lower temperatures as both of these points were from the first 2 weeks of the study period [February 5-11 (JD 36-42) and 12-18 (JD 43-49); Figure 4.6b]. Biological processes.
regulating nitrate removal and uptake including denitrification, dissimilatory nitrate reduction, and assimilation are temperature dependent and were likely not efficient removal mechanisms during this time period. In the Ems estuary plankton uptake and remineralization were also found to be at a minimum during the winter months (van Beusekom and de Jonge, 1998).

The relationship between loading and percent uptake of TN shows similar results to that of NO$_2$+NO$_3$ ranging from 29-97% removal with the highest uptake rates at low loading. In Chesapeake Bay uptake of TN was qualitatively proportional to TN loading rates (Boynton et al., 1995) while in the Tidal Hudson River 15% of the TN load was retained (Lampman et al., 1999).

Approximately 50% of both the TN and NO$_2$+NO$_3$ input to Fourleague Bay via the Atchafalaya River was retained within the estuary (Figure 4.8). Processes discussed above including denitrification, dissimilatory nitrate reduction, and assimilation into organic matter are likely responsible for the removal of NO$_2$+NO$_3$. Sedimentation and burial of particulate N within the bay and on surrounding marshes as well as microbial uptake likely account for the remainder of TN retained in the estuary not accounted for by NO$_2$+NO$_3$ removal. Burial of nitrogen in estuarine systems can be significant with 28-53% of particulate N input reported for the Chesapeake (Boynton et al., 1995) but as little as 3% of N input to the Ems was estimated to be buried (van Beusekom and de Jonge, 1992). Burial is especially important in deltaic environments such as coastal Louisiana marshes where relative sea level rise (RSLR) rates are estimated at approximately 1 cm y$^{-1}$ (Penland and Ramsey, 1990). High rates of deposition are necessary to offset RSLR leading to high
rates of burial. In the Barataria Bay, Louisiana marshes DeLaune et al. (1981) showed an accumulation of 21 gNm⁻²y⁻¹.

Estuarine residence time is another major determinant of the magnitude of nutrients exported to the coastal ocean (Nixon et al., 1996). As residence time increases, processes governing the fate of nutrients have more time to take place whereas during periods of high flushing estuaries and wetlands are more likely to act conservatively with respect to nutrient removal (Kadlec and Knight, 1996; Nixon et al., 1996; Eyre, 1998). The mean flushing time of Fourleague Bay during our study was approximately 8 days with complete turnover occurring in as little as 3 days and as high as 118. Madden et al. (1988) reported mean residence times of approximately 7 days during the spring discharge of the Atchafalaya River and 65 days during the low-flow summer-fall months. Reported residence times of other estuaries include >300 d for Corpus Christi and Aransas Bays in Texas (Solis and Powell, 1999); 20 d for the Ems estuary (van Beusekom and de Jonge, 1998); 7, 40, and 77 d for Sabine Lake, Louisiana, Galveston Bay, Texas, and Matagorda Bay, Texas, respectively (Armstrong, 1982); and 1.5-13 d for the Norminde Fjord (Nielsen et al., 1995).

Nixon et al. (1996) reported that residence time was a good predictor for N exported to the ocean for a number of estuarine environments. Direct calculations of fluxes measured in Oyster Bayou over the 89-d period resulted in a net export of 56% of the TN imported to Fourleague Bay from the Atchafalaya River at a mean residence time of 0.26 mo. By comparison, using the regression equation in Nixon et al. (1996) with a mean residence time of 0.26 months yields an export of 81% of TN input. Net weekly estimates of TN export in Fourleague Bay were also compared to residence.
times (Figure 4.10). The regression with the highest $r^2$ (0.91) was a power function suggesting that as residence time increases a disproportionate amount of TN will be retained in Fourleague Bay. These results indicate that Fourleague Bay exports a much lower percentage of TN input than the estuaries used in Nixon’s regression.

There are several differences between the estuaries included in Nixon et al. (1996) and Fourleague Bay which help to explain the difference in retention. Fourleague Bay is a shallow, microtidal, completely mixed estuary surrounded by extensive fresh, brackish, and saline marshes. During the vast majority of this study, the bay hydrodynamics were dominated by Atchafalaya River discharge and high energy winds associated with the passage of cold fronts which cause high sediment resuspension and large perturbations in water levels often inundating the marsh surface. The tight coupling of the water column with the shallow benthic sediment and surrounding marsh likely enhance the sinks for N removal via denitrification, sedimentation, burial, and phytoplankton and macrophyte assimilation. This is in contrast to many of the estuaries included in Nixon et al.’s analysis which were deeper and stratified, had lower rates of burial, and often did not have extensive wetlands.

4.6 REFERENCES


CHAPTER 5

CONCLUSIONS AND MANAGEMENT IMPLICATIONS
5.1 SUMMARY

The results of this study have shown that during the late winter to early spring months Fourleague Bay is predominantly controlled by riverine and wind-driven processes. Peak Atchafalaya River discharge and peak atmospheric cold front activity act in concert to dominate the bay hydrodynamics causing large perturbations in water levels and enhancing the flux of water, sediment and nutrients out of Oyster Bayou to the Gulf of Mexico. The clockwise rotation of winds associated with the passage of cold fronts caused water level variations up to 0.90 m in Lower Fourleague Bay which is nearly triple the mean astronomical tide range. Pre-frontal, southerly winds cause a coastal set-up of Gulf water along the Louisiana coast and a net inflow of water through Oyster Bayou thereby raising water levels in the Lower Bay, often flooding the surrounding marshes. With the passage of a cold front, winds quickly shift to the northerly quadrant driving additional Atchafalaya River water into the Upper Bay thereby leading to the highest water levels in the Lower Bay due to a temporary bottleneck in drainage at the Oyster Bayou entrance. Subsequently, the bay and adjacent marshes are rapidly drained as a result of north winds blowing the water out of this north-south trending estuary.

The large volumes of water input to the bay from the Atchafalaya River coupled with high velocity northerly winds resulted in the export of $1.02 \times 10^9$ m$^3$ of water from Fourleague Bay to the Gulf over the 89-day study. The largest ebb-directed fluxes were in response to strong cold fronts with over 56% of the bay volume being exported in one day as a result of 45 h of post-frontal north-northwest winds. In contrast, water fluxes were nearly balanced during periods of tidally-driven
hydrodynamics in late April. This is evidenced by rapid flushing of the bay averaging approximately 8 days for the study with values ranging from <3 d to >100 d in response to riverine and cold front-dominated or tidally-dominated hydrodynamics, respectively.

Total suspended sediment concentrations and fluxes were largely determined by physical forcings. Although high concentrations of TSS were input to the bay from the Atchafalaya (300-400 mgl⁻¹), resuspension of shallow benthic sediment via high velocity post-frontal winds were the impetus for concentrations exceeding 1500 mgl⁻¹. The greatest instantaneous exports of TSS were in association with high riverine influence and cold front passage with a net export of 1.72 x 10⁸ kg of sediment to the Gulf measured over the study. Lower TSS concentrations, 50-100 mgl⁻¹, and fluxes were measured during calm weather and tidally-influenced periods (i.e., mid to late April). Higher particulate organic carbon concentrations coincided with high TSS but the highest percent organic carbon was associated with marsh flushing.

High NO₂⁺NO₃, TN, and TP concentrations were mainly derived from the Atchafalaya River. NH₄ concentrations, on the other hand, were higher in association with higher salinity Gulf water and with periods of normal tidal influence which allowed for benthic regeneration. PO₄ sources included riverine, marine, and remineralization from within the bay and surrounding wetlands. These multiple sources led to relatively stable concentrations throughout the study and are important in maintaining annual P availability in the bay for organismal and macrophyte usage. Net exports of all nutrients were measured over the study, however, temporal variations were evident in response to hydrodynamic forcings.
Based on Redfield ratios, the DIN:DIP ratios measured over the study (mean 37:1) revealed a potential P-limitation for the majority of the period due to higher concentrations of N entering the bay from the Atchafalaya River. However, during low riverine influence and tidally-driven hydrodynamics, potential N-limitation was evident. TN:TP ratios were fairly consistent and near Redfield ratios mainly due to composition differences (dissolved inorganic and particulate).

Approximately 50% of both NO2+NO3 and TN that entered the bay from the Atchafalaya River were lost or retained within the estuary and surrounding wetlands. Processes including denitrification, dissimilatory nitrate reduction, biological assimilation, and burial in the bay and surrounding marshes are likely reasons for such high loss rates. The nutrient removal efficiency of Fourleague Bay was dependant upon the loading rate with high uptake occurring during periods of low loading and visa versa. Nutrient retention is also inherently tied to estuarine residence time and the geomorphic characteristics of the area. Longer residence times in the bay allow for greater nutrient uptake and transformation processes to take place leading to higher nutrient retention in the system. Approximately 44% of TN was retained within the estuary which is less than reported for other estuaries with similar flushing times. Reasons for greater uptake in Fourleague Bay compared to other estuaries may be related to the tight coupling of the shallow, well-mixed water column of the bay along with the interactions between the bay and extensive wetland surroundings.

5.2 MANAGEMENT IMPLICATIONS FOR COASTAL LOUISIANA

The ecologic and economic importance of coastal systems has gained attention and greater understanding over the past several decades. However, increasing
pressures for coastal development and diversified use can be detrimental if not managed properly. Coastal marsh stability and sustainability are closely intertwined with the supply of freshwater, sediment, and nutrients (DeLaune et al., 1983; Day et al., 2000). Natural pulsing events are efficient dispersal mechanisms which provide sediment and nutrient rich waters to back marshes (Stern et al., 1991; Day et al., 2000) providing the essential components necessary for accretion and healthy vegetation. Integration of natural pulsing mechanisms into coastal management plans are effective ways of enhancing coastal productivity and sustainability.

Louisiana is currently experiencing a loss of coastal marshes at a rate of approximately 90 km²y⁻¹ (1978-1990 loss rates; Barras et al., 1994). Much of the land loss is a result of canal dredging for oil and gas activities and the leveeing of the Mississippi River which allows salt water intrusion and cuts off the natural source of sediment, nutrients and fresh water to the surrounding marshes, respectively (Day and Templet, 1989; Day et al., 1997). The Atchafalaya delta region is an area in the Louisiana coastal zone which is actively accreting and keeping pace with the rate of relative sea level rise (RSLR; Boumans and Day, 1994; Cahoon et al., 1995) due to a direct riverine source of sediment and nutrients. In areas not directly influenced by a major riverine source along the coast, such as Bayou Chitigue in northern Terrebonne Bay, the marshes are fragmented and are mostly reliant on organic production for accretion. In order to combat coastal land losses, river diversions are being initiated to re-introduce the natural pulse of sediment, nutrients, and fresh water which is necessary for long-term survival of the coastal system. These diversions are intended to mimic the annual overbank flooding cycle of the river which occurred every spring.
during peak discharge months but have essentially been removed by leveeing. The impact of present and future planned diversions of Mississippi River water into coastal marshes and bays is an area of ongoing debate. For instance, issues of eutrophication in coastal Louisiana are of major concern due to high nutrient loading rates from the Mississippi and Atchafalaya Rivers. As a result of increased nutrient loading, hypoxic zones in continental shelf waters as large as 9500 km² during the summer have been documented in the northern Gulf of Mexico (Rabalais et al., 1991; Rabalais et al., 1994). To combat potential problems, Day et al. (1997) suggested that management strategies should include the utilization of wetlands and shallow waters to assimilate nutrients at a rate which would increase estuarine and wetland productivity but reduce coastal eutrophication. Using this approach, reintegrating the natural energy subsidy of pulsing events into management plans is essential.

Vertical accretion, through mineral sediment input or via organic production, is necessary to offset eustatic sea level rise if marshes are to remain healthy and survive (Mitsch and Gosselink, 1993; Cahoon et al., 1995). This is especially important in the Mississippi delta where rates of relative sea level rise (eustatic sea level rise plus subsidence, RSLR) are approximately 1 cm y⁻¹ (Penland and Ramsey, 1990). In Fourleague Bay, the combination of winter frontal passages and high Atchafalaya River influence resulted in large water level fluctuations and very high suspended sediment concentrations. As the marsh is flooded during these events greater potential for the advection and deposition of sediment onto the marsh surface exists. In fact, in microtidal areas such as the Mississippi delta it has been shown that atmospheric cold fronts and tropical storms supply most of the sediment deposited to the marsh surface.

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If the natural pulse of sediment via storm events is restricted short-term sedimentation is reduced and the marsh is not as likely to keep pace with RSLR (Boumans and Day, 1994).

Increased loading of nutrients to coastal Louisiana via the Mississippi and Atchafalaya Rivers has resulted in cases of eutrophication and offshore hypoxic zones (Turner and Rabalais, 1991; Justic et al., 1995; Rabalais et al., 1996). If managed properly, the use of coastal wetlands and shallow bays may provide a buffering mechanism for nutrient rich river water prior to reaching offshore waters. The results from this study indicate that at low nutrient loading rates and high estuarine residence times nearly all (>95%) of the nitrogen input to Fourleague Bay was lost or retained within the estuary or adjacent wetlands. On average, approximately 45-50% of both NO$_2$+NO$_3$ and TN were retained. The tight coupling of the shallow, well-mixed water column to the benthic community and surrounding wetlands which enhance processes such as denitrification, burial, and biological assimilation are likely reasons for such high loss/retention rates. Since these measurements were obtained in late winter and early spring, it is likely that the mean annual retention of N in the Fourleague Bay system would increase with measurements taken in the summer and fall when temperatures and biological activity are greatest.

The data presented in this dissertation indicate that pulsing events are important to the sustainability of coastal systems. In addition, the data lend support to the concept that when properly managed, shallow estuarine and wetland environments can and should be used in coastal restoration ventures. Using Fourleague Bay as a
model of a geologically young, stable marsh-estuarine system with regular riverine inflow, the sediment and nutrient data from this study suggest that diversions of Mississippi River water into shallow estuarine systems may have several beneficial results. These include: 1) enhanced productivity of estuaries and surrounding marshes, 2) stabilization of surrounding marshes via inorganic sediment delivery and increased organic production, and 3) reduction of excess nutrients and sediment from the water column prior to reaching offshore waters.

5.3 REFERENCES


Dear Dr. Perez,

Your paper will appear in the February issue of ECSS (Estuarine, Coastal and Shelf Science). Your 150 reprints will be dispatched shortly after publication and sent via surface mail so will take several weeks to reach you.

I have also had a query passed onto me regarding using your paper in your dissertation. According to the copyright form which you have signed, you "May include the Work as part of your dissertation, for non-commercial distribution only".

Regards,

Alan Thomas
VITA

Brian Christopher Perez was born on August 28, 1970, in New Orleans, Louisiana. Brian is the son of Robert L. Perez, Sr. and Lauralee Perez, and is the third child of eight. After graduating from Jesuit High School in New Orleans, Brian began his undergraduate degree at the University of Alabama in Tuscaloosa in 1988. He graduated in 1992 with a bachelor of science degree in environmental sciences. Following graduation, Brian worked for a year and returned to school in 1993. He began his graduate academic career under the auspices of Dr. John W. Day, Jr. in the Department of Oceanography and Coastal Sciences at Louisiana State University. Brian entered the Department of Oceanography and Coastal Sciences in the masters' program, and in 1994 at the suggestion of Dr. Day, changed his enrollment status to pursue his doctoral program studying sediment and nutrient dynamics in the Fourleague Bay, Louisiana estuary. In 1995, Brian accepted a Research Associate position with Dr. Day working on a multi-year flux study project in south Florida. He is currently working as a post-doctoral researcher with Dr. Don Cahoon at the National Wetlands Research Center in Lafayette, Louisiana evaluating coastal wetland elevation and accretion rates in response to changes in sea level. Brian Perez will receive the Doctor of Philosophy degree in May 2000.
Influence of Atchafalaya River Discharge and Winter Frontal Passage on Suspended Sediment Concentration and Flux in Fourleague Bay, Louisiana

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Suspended sediment concentrations and fluxes between Fourleague Bay, Louisiana and the northern Gulf of Mexico were sampled every 3 h for 3 months to examine the importance of atmospheric cold fronts and riverine forcing on the functioning of this estuarine system. A cold front index was developed and used to identify major winter frontal passages likely to have the largest effects on material concentrations and transport. Suspended sediment concentrations ranged from 11 to 1527 mg \textsuperscript{-1} l; the highest values occurred during winter frontal passages and the lowest during calm periods. High concentrations are generated by a continuous source of sediment from the Atchafalaya River and resuspension of benthic sediment via high intensity winds associated with cold fronts along with sufficient duration to keep the sediment in suspension. Spring peak discharge of the Atchafalaya River increased water levels and sediment concentrations in the bay leading to strong seasonal net exports of water (1.02 \times 10^8 m\textsuperscript{3}) and sediment (1.72 \times 10^9 kg) into the Gulf of Mexico through Oyster Bayou over the 89-day study. Net fluxes associated with tidal forcing were nearly balanced with a small net export due to freshwater input. The combination of high volumes of water originating from the northern bay and the restricted outlet to the Gulf often cause increased water levels and inundation of the surrounding marshes and potential advection of sediments onto the marsh surface. The results suggest that marsh drainage often increases the particulate organic carbon export as a result of marsh flushing.

Keywords: sediment flux; cold fronts; pulsing; storms; Atchafalaya River; Fourleague Bay

Introduction

The mobilization, deposition and transport of sediment in coastal systems are very dynamic. Riverine input is a major sediment source to estuaries, but the input varies with discharge and the size and nature of the drainage basin. The resuspension and transport of sediment within estuaries is also largely related to high energy events (Baumann et al., 1984; Hsu & Blanchard, 1993; Cahoon et al., 1995; Day et al., 1995; Hensel et al., 1998). For example, Nichols (1991) reported that 73% of the sediment supply of the James River estuary, a tributary of Chesapeake Bay, is from fluvial input, and that 90% of the mean annual suspended sediment load for the James and Rappahannock River estuaries is transported in less than 11% of the year. Sediment can also be transported into estuarine systems from the nearshore ocean during storm events (Roberts, 1997). Sediment transport within estuaries is also influenced by tidal dynamics. Stevenson et al. (1988) reviewed sediment fluxes in marsh systems along the Gulf and Atlantic coasts and suggested that south-eastern estuaries of the U.S.A. are net exporters of water and sediment as a result of a tidal-velocity asymmetry which favours ebb-directed flows. Similarly, Leonard et al. (1995) concluded that sediment transport in Cedar Creek, Florida was influenced by time-velocity asymmetry of tidal currents, spring-neap tidal aberrations, and extra-tropical storm activity.

Marsh accretionary processes are related to sediment imported into estuarine systems and sediment dynamics within estuaries. Vertical accretion, whether from mineral sediment input or organic soil formation, is necessary to offset eustatic sea level if marshes are to remain healthy and survive (Mitsch & Gosselink, 1993; Cahoon et al., 1995). This is especially important for deltas where high rates of subsidence lead to relative sea-level rise which are much greater than eustatic sea-level rise (Baumann et al., 1984; Stanley & Warne, 1993; Cahoon et al., 1995). Sediment suspended in the water column is deposited on the marsh surface during periods of
DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Brian Christopher Perez

Major Field: Oceanography and Coastal Sciences

Title of Dissertation: Suspended Sediment and Nutrient Flux Dynamics in Fourleague Bay, Louisiana: The Role of Winter Cold Fronts and Atchafalaya River Discharge

EXAMINING COMMITTEE:

Date of Examination: March 16, 2000