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The effects of riverine discharge on temperature, salinity, suspended sediment and chlorophyll *a* in a Mississippi delta estuary measured using a flow-through system

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Abstract

The impact of diverted Mississippi River water on temperature, salinity, total suspended sediment (TSS) and chlorophyll *a* were monitored in the Breton Sound estuary from September 7, 2000, to August 28, 2002. Twenty-seven transects were carried out using a flow-through system to continuously measure temperature, salinity, turbidity and fluorescence, and discrete water samples were taken at 16 locations for calibration. Discharge from the river diversion structure ranged from 0 to 213 m^3/s, with several large pulses of water released during the spring of 2001 and 2002. There was a strong seasonal temperature signal in the estuary, with summer highs of >30 °C and winter lows of <12 °C. Incoming river water was usually cooler than estuarine waters, with temperatures as low as 6 °C, but generally equilibrated to the rest of the estuary within several kilometers. Salinity in the upper estuary was fresh throughout the study, and increased up to 14 and 30 PSU along Western and Eastern routes, respectfully, with distance from the diversion. Discharge from the river diversion greatly affected salinity, with the large spring pulses often causing the entire estuary to become fresh for a short period of time (<1 month). There was also a temporal lag of about two weeks between discharge and salinity in the lower estuary. River water entering the estuary had TSS concentrations ranging from 40 to 252 mg/L, with an average of 118 mg/L. Sediment from the river diversion reached about 10–15 km into the estuary during spring pulses. There were highly fluctuating TSS concentrations at the Gulf end of the estuary during winter and spring, due to wind resuspension. Chlorophyll *a* concentrations were highest in mid-estuary during summer and fall low discharge, and lowest during winter and spring high discharge. Chlorophyll *a* levels were generally less than 10 μg/L in the upper estuary, with concentrations rising in the mid-estuary generally to 20–30 μg/L during late summer and fall, and decreasing in the lower estuary. There were several periods of less than a month with unusually high chlorophyll *a* concentrations, ranging from 38 to >60 μg/L, that occurred during late summer and early winter.

Keywords: flow-through; river diversion; wetland restoration; water quality

1. Introduction

Overbank flooding and crevasses of the Mississippi River were major geological processes in the formation and maintenance of the Mississippi delta (Hatton et al., 1983; Kesel, 1988, 1989; Roberts, 1997; Davis, 2000; Day et al., 2000, 2007). Each year the river flood supplied a pulse of freshwater, suspended sediments, inorganic nutrients, and organic materials that stimulated primary and secondary production. This increased plant productivity provided higher rates of food production for consumers, and increased organic soil formation. Freshwater pulses also maintained a salinity gradient that

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supported a high diversity of wetland and aquatic habitats for estuarine species (Day et al., 1997, 2000).

The construction of flood control levees and closure of minor distributary channels began soon after colonization of New Orleans by the French in 1719 (Boesch, 1996; Colten, 2000). Since the early 1900s most of coastal Louisiana has been hydrologically isolated from the Mississippi River by the completion of massive flood control levees that have completely halted riverine input to coastal wetlands (Kesel, 1988, 1989; Mossa, 1996). As a consequence of this lack of river flooding, resuspended sediment from bay bottoms and eroded marsh edge have replaced fluvial sources of inorganic sediments in many regions of coastal Louisiana (Hatton et al., 1983; Baumann et al., 1984; Reed, 1988). In addition, canal dredging and spoil bank construction associated mainly with the oil and gas industry has further altered the natural hydrology of the delta, promoting saltwater intrusion events and limiting hydrological exchange (Bass and Turner, 1977; Swenson and Turner, 1987). These modifications to the coastal landscape have led to a massive loss of wetlands during the 20th century, with about 4500 km^2 lost by the end of the 20th century (Salinas et al., 1986; Boesch et al., 1994; Coast, 2050, 1998; Day et al., 2000, 2007).

Relative sea-level rise (RSLR), the combined effect of eustatic sea-level rise (1–2 mm/year, Gornitz et al., 1982) and coastal subsidence, in the Mississippi delta is in excess of 10 mm/year (Penland and Ramsey, 1990). This is much higher than reported for other deltas, such as the Nile (5 mm/year, Stanley, 1990), Ebre (3 mm/year, Ibanez et al., 1997) or Rhone (1–6.5 mm/year, L'Homer, 1992). This high rate of regional subsidence and extensive human modifications make the Mississippi River delta an excellent laboratory to study the effects of global change and human impact on deltas worldwide.

There is a strong consensus in the scientific and management community that the long-term survival of Louisiana's coastal wetlands depends, as one of the major restoration strategies, on the reintroduction of river flow into the interdistributary basins to stem salinity intrusion and supply nutrients and sediments for wetland restoration (Templet and Meyer-Arendt, 1988; Kesel, 1989; Boesch, 1996; Day et al., 2000, 2007; Gosselink, 2001). The State of Louisiana and Federal Government have developed a plan for river diversions that will mimic flooding events of the Mississippi River (Chatry and Chew, 1985; Coast, 2050, 1998). This study focuses on the second largest diversion structure in operation in Louisiana, located at Caernarvon, and the effect of diverted river water on several key water quality parameters in Breton Sound estuary, a large expanse of coastal wetlands between the diversion structure and the Gulf of Mexico. This region is greatly affected by the Caernarvon diversion that allows up to 226 m^3/s of Mississippi River water to enter the estuary (Lane et al., 1999, 2004, 2006).

We carried out 27 transects in the Breton Sound estuary from September 7, 2000, to August 28, 2002, using a flow-through system to continuously measure temperature, salinity, turbidity, and fluorescence. The work presented in this paper was part of a large interdisciplinary project, PULSES, studying the effects of the Caernarvon diversion on the Breton Sound estuary (http://www.lsu.edu/cei/pulses_numan.html). The purpose of this project was to extend our understanding of the effect of pulsed riverine input into coastal wetlands. Our specific objectives were to examine this effect by measuring the fine scale spatial and temporal distribution of temperature, salinity, suspended sediments, and chlorophyll *a* in the Breton Sound estuary. We hypothesized there would be: (1) rapid reduction of suspended sediment concentration with distance from the diversion structure; (2) low chlorophyll *a* levels in areas of high suspended sediment, with higher chlorophyll levels immediately after suspended sediment concentrations decreased; and (3) a negative effect on salinity and temperature throughout the estuary associated with structure discharge.

2. Study area

The Caernarvon river diversion structure is located on the east bank of the Mississippi River at river mile 81.5 (Fig. 1), and consists of five 4.6 m wide box culverts with vertical lift gates, with a capability of passing up to 225 m^3/s. The structure was completed in 1991 and freshwater discharge began in August of that year. Discharge since structure completion to January 2000 averaged 21 m^3/s, with great variation throughout the year. Between the Caernarvon diversion and the Gulf of Mexico there are about 1100 km^2 of fresh to brackish wetlands. Diverted water must travel 30–40 km through two major routes dominated by wetlands before reaching the open waters of Breton Sound, and an additional 50 km before reaching Gulf waters (Fig. 1). The two major routes are via (1) Lake Leary and Bayou Terra aux Boeufs to the east (referred to as the Eastern route), which carries approximately 2/3 of the flow, and (2) Manuel's Canal and River aux Chene to the west (referred to as the Western route), which carries the remaining 1/3 of flow (Chuck Villarubia, personal communication, Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge, LA 70802, USA). Water depths range from 3 to 3.5 m in the main channels and from 1 to 1.25 m in the surrounding lakes and bayous (Hassan Mashriqui, personal communication, LSU Hurricane Center, Louisiana State University, Baton Rouge, LA 70803, USA). The water column is well mixed throughout the estuary, and there is considerable interaction between diverted river water and estuarine wetlands due to tides, northerly wind events and storms. Levees prevent Mississippi River water from entering most of Breton Sound estuary. However, river water can flow directly into Breton Sound Bay below the point where artificial levees end on the eastern bank of the river, and affects water quality in the outer bays of the estuary (Fig. 1).

3. Methods

3.1. Structure discharge

Discharge from the structure was calculated from a rating curve developed by the Louisiana Department of Natural Resources (Chuck Villarubia, personal communication). Discharge from the structure was also measured episodically by the USGS using an acoustic doppler velociometer deployed

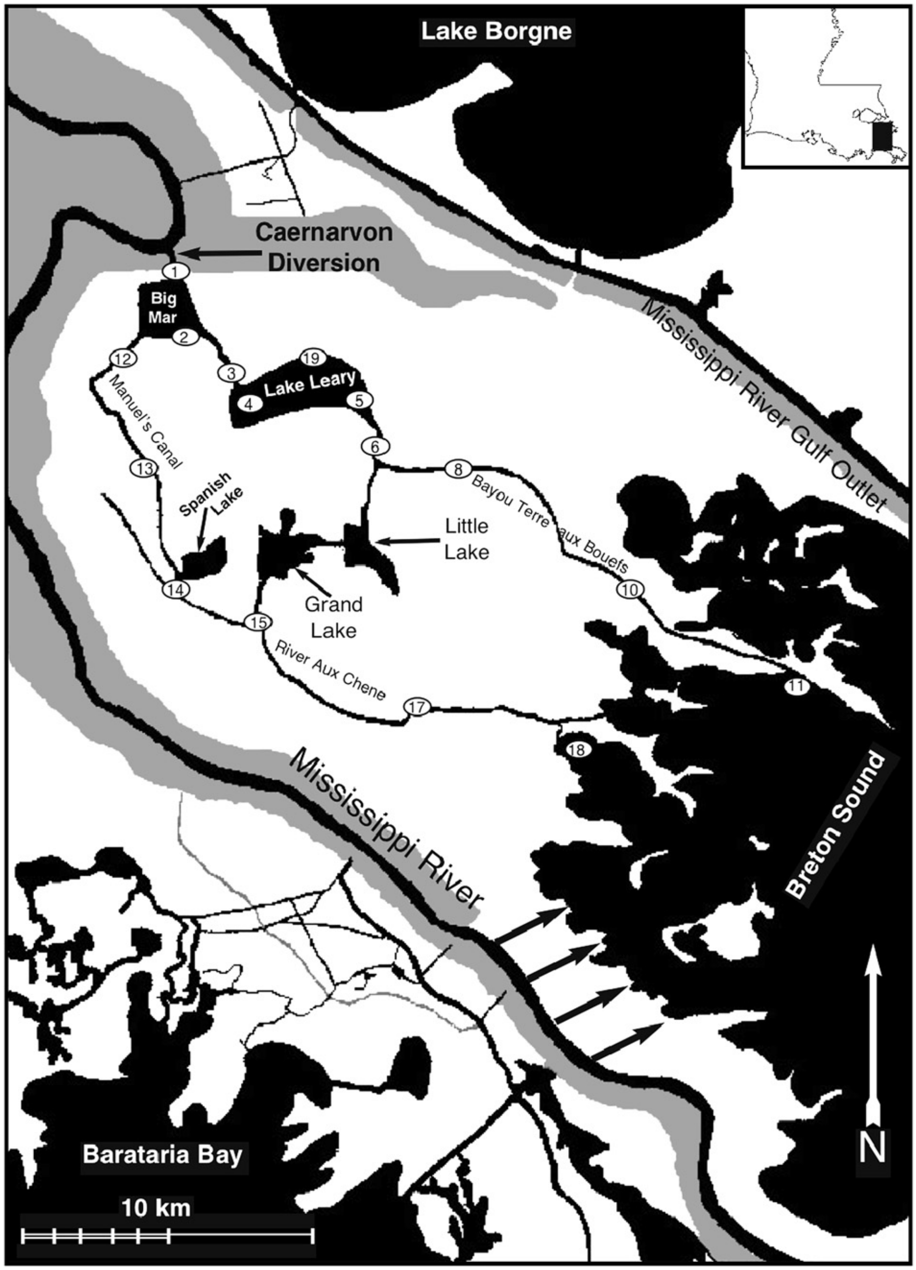

Fig. 1. Site map with water quality monitoring transects in the Breton Sound estuary. Gray shading indicates upland habitats, black open water, white wetlands. Large arrows along the east bank of the Mississippi River indicate where river water can flow directly into Breton Sound Bay during high stage. The numbered circles indicate where water samples were taken for calibration of the flow-through system.

in the discharge channel located between the Caernarvon structure and Big Mar. The instrument collected hourly velocity and water height measurements. Water heights were then converted to volume using a stage-to-discharge relationship calibrated several weeks earlier using an acoustic doppler current profiler. Regression analysis found a linear relationship between the two methods ($R^2 = 0.98$, $p < 0.01$), and the resulting equation was used to back-calculate the flows determined using the Doppler velocimeter, which was thought to be a more accurate estimate of flow than the head differential equation (Gregg Snedden, personal communication, USGS-NWRC, Coastal Restoration Field Station, Baton Rouge, LA 70802, USA).

3.2. Flow-through system

The flow-through system consisted of a 1.5 cm diameter pipe mounted on the transom of an outboard motor boat that scooped water from just below the surface at planing speed, routed the water into a bubble trap where a submersible pump moved water past environmental sensors, and eventually flushed out where it was either sampled or discarded en route (Lorenzen, 1966; Madden and Day, 1992). All continuous measurements were taken using a YSI-6600 probe modified for flow-through measurement (http://www.ysi.com). The probe measured temperature, salinity, turbidity, and fluorescence every 5 s. The average speed of the boat was 50 km/h, providing a reading approximately every 70 m. Prior to each transect the YSI-6600 probe was calibrated for turbidity and conductivity using known standards, and the time synchronized with an onboard digital time device. The flow-through system was run through the Eastern and Western routes described above and discrete samples were taken at 16 locations for additional calibration (Fig. 1). The transects were completed in 4–6 h, covering approximately 210 km, providing an essentially synoptic survey of the estuary.

3.3. Discrete sample analysis

Water samples were taken at 16 sampling locations from water exiting the flow-through system and immediately stored at 4 °C for preservation. Total suspended sediments were determined by filtering 100–200 mL of sample water through pre-rinsed, dried and weighed 47 mm 0.7 μm Whatman GF/F glass fiber filters. Filters were then dried for 1 h at 105 °C, weighed, dried for another 15 min, and reweighed for quality assurance (Greenberg et al., 1992). Chlorophyll *a* was determined using a modified version of Strickland and Parsons (1972) technique. Pigments were extracted with a 40:60 ratio of dimethyl sulfoxide (DMSO):90% acetone (Burnison, 1980). The extract was measured with a Turner Designs model 10-AU fluorometer.

3.4. Statistical analysis

Temperature and salinity data were taken directly from the YSI-6600 Sonde instrument, while turbidity and fluorescence were converted to TSS and chlorophyll *a*, respectively, using linear regression. Simple linear regression analysis was carried out for each transect using turbidity and fluorescence as independent variables and TSS and chlorophyll *a* as dependent variables. JMP statistical software (Sall et al., 2005) was used to test for significant differences between the slope of the regression and the mean (alpha <0.05), provide R^2 correlation coefficients, and the regression equations that were used to calculate TSS and chlorophyll *a* values from turbidity and fluorescence data, respectively, from the flow-through system.

In addition, an analysis of variance was carried out on the discrete water samples, with the factors of interest being structure discharge, season, route, and distance from the diversion structure. Discharge was smoothed using a 2-week running average, and divided into three categories: low flow ($\leq$19 m^3/s), medium flow (20–59 m^3/s), and high flow ($\geq$60 m^3/s). Seasons were designated according to solar solstice and equinox designations. The routes were the Eastern and Western described above. Distance from the diversion structure was divided into three categories: D1 (1–8 km), D2 (9–18 km), and D3 (19–40 km). Data were available for all treatment combinations, but the number of replications was unbalanced. Least square means were calculated for significant interactions and main effects. Statements about interaction plots reflect an experiment wise Type 1 error rate (falsely finding significance) controlled at the 5% level, using Bonferroni adjustment, and only significant interactions were reported in the text.

4. Results

Simple linear regression analysis found significant correlations between *in situ* signals measured by the flow-through system and discrete samples analyzed in the laboratory for all transects. R^2 coefficients of correlation had a mean of 0.76 (min 0.45; 0.03 SE) for TSS and 0.73 (min. 0.50; SE 0.03) for chlorophyll *a* (Table 1). There was no relationship found between R^2 coefficients and season or structure discharge. Individual transect data for each parameter can be found online in Lane (2003). The data were separated into the two routes, Eastern and Western, and graphed (see Fig. 3).

4.1. Discharge

Discharge from the Caernarvon structure ranged from 0 to 213 m^3/s (Fig. 2). Most of the discharge in 2000 occurred between March and September, with flows peaking at 139 m^3/s on March 14, decreasing to about 37 m^3/s for the rest of March, and rapidly rising to 68 m^3/s in June that continued for the rest of the summer. There was no water discharged during several months in fall 2000, but starting in late November, three moderate sized ($\approx$100 m^3/s) pulses were released, followed by a large ($\approx$200 m^3/s) in the spring of 2001. Discharge decreased and remained relatively constant ($\approx$40 m^3/s) during summer and fall, with short interruptions of no flow. Discharge increased again in December 2001, and continued to increase, with short interruptions in flow, peaking in February 9, 2002, at 166 m^3/s. Discharge decreased and peaked again on March 15 at 181 m^3/s. Flow decreased to $\approx$20 m^3/s, rising briefly to $\approx$37 m^3/s, and then falling to zero for the remainder of the study.

4.2. Temperature

There was a strong seasonal signal in temperature in the Breton Sound estuary, with summer highs of >30 °C and winter lows of <12 °C (Fig. 3). Incoming Mississippi River water temperature was usually cooler than estuarine waters, with temperatures as low as 6 °C, but generally equilibrated to the rest of the estuary within several kilometers. During large structure discharges there were several times when cooler water from the diversion propagated through the entire estuary. This was evident during the pulses of January 2001, January 2002 and February 2002, when water temperature throughout the estuary ranged from 6.3 to 10.2 °C.

4.3. Salinity

Salinity in the upper estuary was fresh throughout the study, and increased in the outer estuary up to 14 and 30 PSU along the Western and Eastern routes, respectively (Fig. 3). The analysis of variance detected this effect with a significant ($p < 0.001$) route $\times$ distance class interaction (Fig. 4), indicating decreased

Table 1
R^2 correlation coefficients, and the regression equations used to calculate TSS and chlorophyll *a* values from turbidity and fluorescence data, respectively, from the flow-through system

Date	TSS	CHL*a*
09/07/00	TSS = 1.70Turb − 30.07 $r^2 = 0.52$	CHL*a* = 4.68Fluor − 5.12 $r^2 = 0.71$
10/12/00	TSS = 1.06Turb − 8.95 $r^2 = 0.89$	CHL*a* = 4.29Fluor − 6.16 $r^2 = 0.83$
11/10/00	TSS = 1.09Turb − 9.45 $r^2 = 0.45$	CHL*a* = 4.47Fluor − 9.83 $r^2 = 0.75$
01/25/01	TSS = 0.67Turb − 2.21 $r^2 = 0.78$	CHL*a* = 4.30Fluor − 2.11 $r^2 = 0.96$
02/16/01	TSS = 0.80Turb − 7.37 $r^2 = 0.65$	CHL*a* = 5.26Fluor − 6.68 $r^2 = 0.81$
02/23/01	TSS = 0.73Turb − 23.57 $r^2 = 0.75$	CHL*a* = 3.14Fluor − 2.32 $r^2 = 0.91$
03/02/01	TSS = 0.52Turb + 4.90 $r^2 = 0.89$	CHL*a* = 4.27Fluor − 5.00 $r^2 = 0.69$
03/09/01	TSS = 0.59Turb − 6.03 $r^2 = 0.94$	CHL*a* = 4.89Fluor − 5.68 $r^2 = 0.84$
03/15/01	TSS = 0.53Turb + 3.06 $r^2 = 0.91$	CHL*a* = 7.15Fluor − 10.01 $r^2 = 0.93$
03/22/01	TSS = 0.48Turb − 1.99 $r^2 = 0.80$	CHL*a* = 5.85Fluor − 5.38 $r^2 = 0.81$
03/30/01	TSS = 0.44Turb + 6.96 $r^2 = 0.75$	CHL*a* = 5.63Fluor − 4.84 $r^2 = 0.75$
05/10/01	TSS = 0.59Turb − 24.84 $r^2 = 0.61$	CHL*a* = 5.36Fluor − 4.83 $r^2 = 0.65$
07/18/01	TSS = 0.42Turb + 3.43 $r^2 = 0.78$	CHL*a* = 8.95Fluor − 18.58 $r^2 = 0.55$
08/21/01	TSS = 0.82Turb − 4.86 $r^2 = 0.75$	n.a.
09/25/01	TSS = 1.22Turb − 3.74 $r^2 = 0.76$	CHL*a* = 4.91Fluor − 3.36 $r^2 = 0.84$
10/30/01	TSS = 0.97Turb − 2.77 $r^2 = 0.60$	CHL*a* = 5.23Fluor − 6.50 $r^2 = 0.62$
12/20/01	TSS = 0.94Turb − 7.25 $r^2 = 0.91$	n.a.
01/08/02	TSS = 0.92Turb − 25.99 $r^2 = 0.87$	CHL*a* = 8.73Fluor − 13.87 $r^2 = 0.81$
01/22/02	TSS = 0.61Turb − 8.03 $r^2 = 0.68$	CHL*a* = 5.83Fluor − 6.40 $r^2 = 0.75$
02/07/02	TSS = 0.79Turb − 25.96 $r^2 = 0.81$	CHL*a* = 0.17Fluor + 1.00 $r^2 = 0.53$
02/28/02	TSS = 0.63Turb + 2.86 $r^2 = 0.73$	CHL*a* = 14.71Fluor − 26.48 $r^2 = 0.50$
03/13/02	TSS = 0.70Turb + 3.47 $r^2 = 0.92$	CHL*a* = 6.17Fluor − 5.58 $r^2 = 0.66$
04/11/02	TSS = 0.89Turb − 10.31 $r^2 = 0.75$	CHL*a* = 5.04Fluor − 2.71 $r^2 = 0.81$
04/23/02	TSS = 0.59Turb − 1.26 $r^2 = 0.87$	CHL*a* = 0.90Fluor − 1.34 $r^2 = 0.66$
05/21/02	TSS = 3.62Turb − 47.88 $r^2 = 0.86$	CHL*a* = 10.21Fluor − 15.38 $r^2 = 0.79$
06/28/02	TSS = 1.08Turb + 3.03 $r^2 = 0.92$	CHL*a* = 9.88Fluor − 19.61 $r^2 = 0.50$
08/28/02	TSS = 3.52Turb − 80.72 $r^2 = 0.50$	CHL*a* = 10.01Fluor − 38.27 $r^2 = 0.56$

salinities along the Western route compared to the Eastern route at distance class D3, with no significant differences found at distance classes D1 and D2. The analysis of variance also found a significant three-factor interaction for discharge × season × distance ($p = 0.04$), with higher discharge decreasing salinities in the outer estuary in the fall and winter (see Lane, 2003, Appendix B, Fig. B1). Discharge from the diversion greatly affected salinity throughout the estuary, with the large spring pulses often causing the entire estuary to become fresh, but only for a short period of time (<1 month). There was also a temporal lag between discharge and effect on salinity in the lower estuary. For example, there was a 2-week lag from the onset of high discharge (211 m^3/s) on March 9, 2001, and the effect on salinity at the end member stations on March 22, suggesting a water residence time of approximately 2 weeks during peak discharge (Fig. 5).

4.4. Total suspended sediment

Total suspended sediment of Mississippi River water entering the estuary ranged from 40 to 252 mg/L, with an average of 118 mg/L (Fig. 3). The lowest concentrations (<40 mg/L) occurred during late summer/early fall, and the highest concentrations (>200 mg/L) during winter and spring high discharge. Sediment derived from the diversion reached ≈10–15 km into the estuary during the spring pulses of 2001 and 2002. There were also elevated and fluctuating TSS concentrations at the southern end of the estuary on the Eastern route during fall, winter and spring, likely due to wind resuspension related to storms. The analysis of variance found a significant ($p = 0.02$) discharge × season × route interaction, with elevated TSS concentrations in the outer estuary during fall high discharge (see Lane, 2003, Appendix B, Fig. B3).

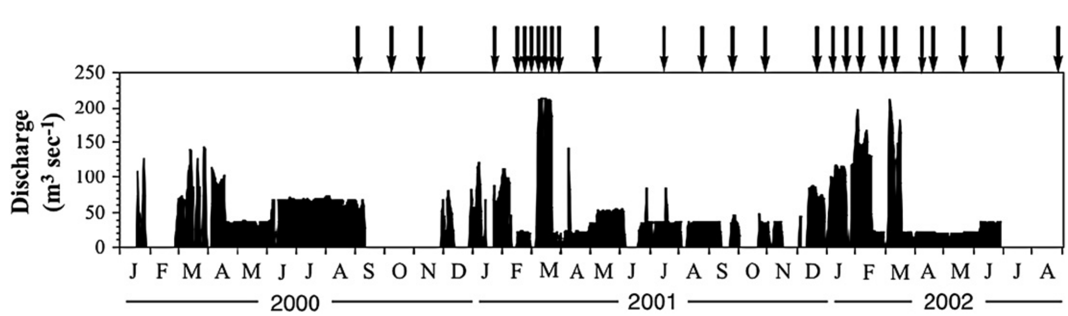

Fig. 2. Mississippi River discharge through the Caernarvon diversion structure. Arrows indicate when water quality data were taken.

4.5. Chlorophyll a

Chlorophyll *a* levels were generally less than 10 μg/L in the upper estuary, with concentrations rising in the mid-estuary generally to 20–30 μg/L during late summer and fall, and decreasing in the lower estuary (Fig. 3). There were several periods of less than a month with high chlorophyll *a* concentrations, peaking at 38 μg/L in 2001 and >60 μg/L in 2002, and also during the fall of 2000 and early winter of 2001, with peak concentrations ranging from 40–56 μg/L. Highest chlorophyll *a* levels occurred during periods of low or no discharge from the Caernarvon structure (Fig. 3), in low salinity (1–5 PSU) waters located in mid-estuary with TSS concentrations less than 75 mg/L (Fig. 6). The chlorophyll *a*/TSS ratio, an indicator of vegetal food availability (Burdloff et al., 2000), was highest (Chla/TSS: >20 mg/g) in low salinity (<10 PSU) waters in the mid-estuary (Fig. 7), reflecting both high chlorophyll and decreasing TSS concentrations in the middle estuary (Fig. 6). These observed trends are corroborated by the analysis of variance, which found a significant ($p < 0.0001$) main effect for distance

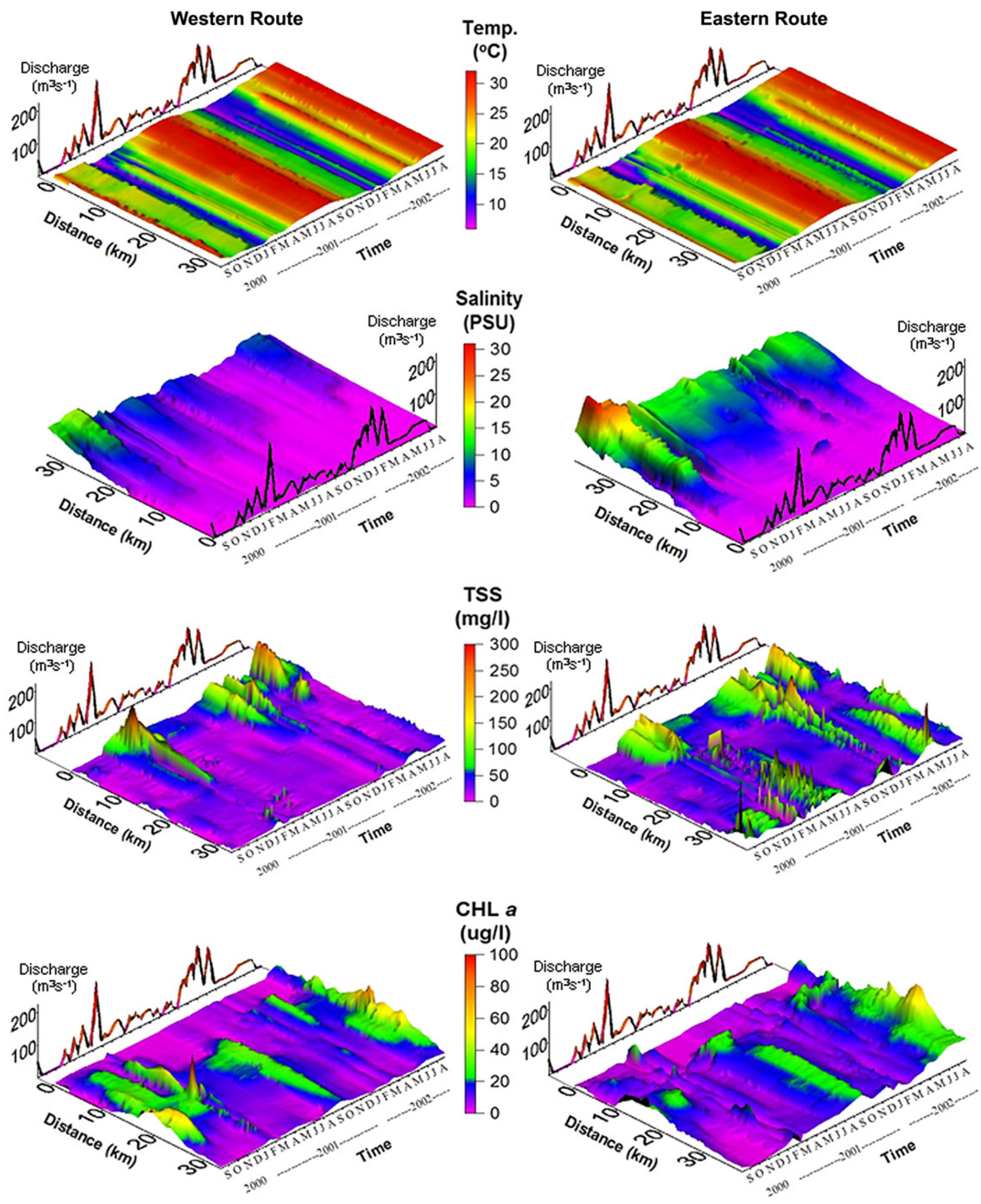

Fig. 3. Spatial–temporal graphs of temperature, salinity, total suspended sediment (TSS) and chlorophyll a (CHL *a*) in the Breton Sound estuary. Time is shown on the *x*-axis and distance from the Caernarvon structure on the *y*-axis. Discharge from the Caernarvon diversion is indicated by the red line superimposed on the *x*-axis. Note that for clarity, the distance axis for salinity is opposite the other parameters.

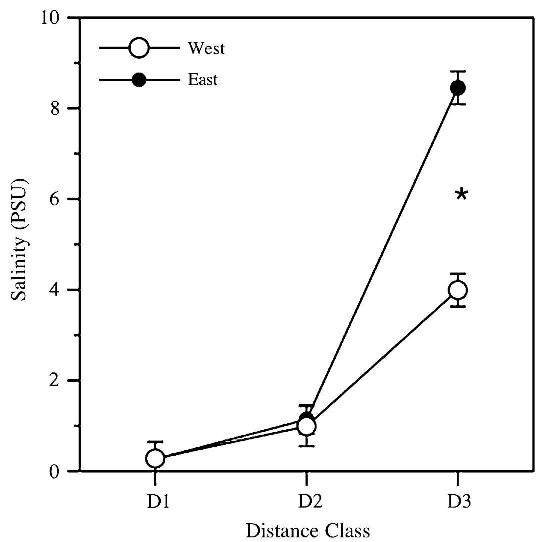

Fig. 4. Route × distance class interaction for salinity. Asterisk indicates a significant difference between Eastern and Western routes.

class, with the D2 distance class (mid-estuary) having higher chlorophyll *a* concentrations than either D1 or D3, and a moderately significant ($p = 0.06$) discharge × season interaction, with the highest chlorophyll *a* concentrations occurring at low flow during summer and fall (Fig. 8).

5. Discussion

Chlorophyll *a* concentrations were significantly higher in mid-estuary during summer and fall during low discharge, and lower during winter and spring during high discharge (Fig. 8). This was likely caused by an interaction between water residence time, turbidity, salinity and temperature. As indicated by the salinity data in this study, as well as Lane et al. (2004), high riverine discharge leads to reduced residence time, leading to increased flushing of phytoplankton biomass out of the estuary, as well as high turbidity, which is inversely related to chlorophyll concentration (Fig. 6). Conversely, as riverine discharge decreased during summer and fall, there was lower turbidity and an increase in water residence time, allowing the buildup of phytoplankton biomass as reflected in higher chlorophyll *a* concentrations, especially at salinities less than 5 psu (Fig. 6). The mid-estuary peak is clearly related to salinity and turbidity. High chlorophyll generally occurred at salinities less than 5 psu and TSS less than about 75 mg/L. In the upper basin, salinities were low, indicating high nutrients (Lane et al., 1999), but high TSS limited algal development. In the lower basin, TSS was generally low, but salinities were high. Conditions of low salinity and TSS most often occurred in the mid-basin. This increased biomass was likely supported by an increase in benthic regeneration of nutrients associated with higher summer water temperatures since riverine input is low during this period (Kemp and Boynton, 1984; Day et al., 1989; Cowan and Boyton, 1996). This is corroborated by increases in ammonium and phosphate concentrations in the estuary during the two summers of this study (Emily Hyfield, personal communication, Post, Buckley, Schuh & Jernigan, Inc., Tampa, FL 33607, USA) and high summer remineralization of nutrients (Robert Twilley, personal communication, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA). Such decoupling between riverine nutrient input during spring and peak phytoplankton productivity during summer has been observed in many other estuaries (Nixon, 1981; Boynton et al., 1982; Fisher et al., 1988; Madden et al., 1988).

The Caernarvon diversion structure had a significant effect on salinity throughout the Breton Sound estuary, with statistical analysis showing decreased salinities along the Western route compared to the Eastern route in the lower estuary (Fig. 4). This freshening of the Western route was likely caused by Mississippi River water flowing into the region below where flood protection levees end (Fig. 1). Lane et al. (1999) analyzed a 7-year data set from the Breton Sound estuary and found salinities in the estuary to be significantly lowered in response to diversion discharge. The original goal of the Caernarvon diversion was to establish optimal salinity conditions for oyster production (Chatry et al., 1983; Chatry and Chew, 1985), but in addition, the Caernarvon diversion can also be managed to prevent saltwater intrusion during storms and drought. Freshwater pulses can be used to form a buffer against saltwater intrusion, while simultaneously allowing the coastal system to remain open to the movement of fishery species and important energetic pulses originating from the sea in the form of tides and storms (Day et al., 1997, 2001). This is opposite to other coastal salinity management techniques, such as the use of levees, weirs and flap gates (Cowan et al., 1988; Boyer, 1997; Reed, 1992; Reed et al., 1997).

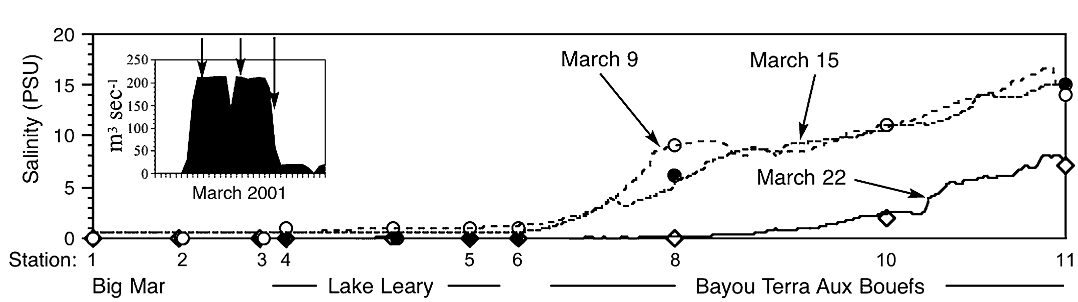

Fig. 5. Salinity along the Eastern route on March 9, 15 and 22, 2001. Individual data points indicate discrete sample concentrations. Arrows in subplot indicate discharge for respective dates.

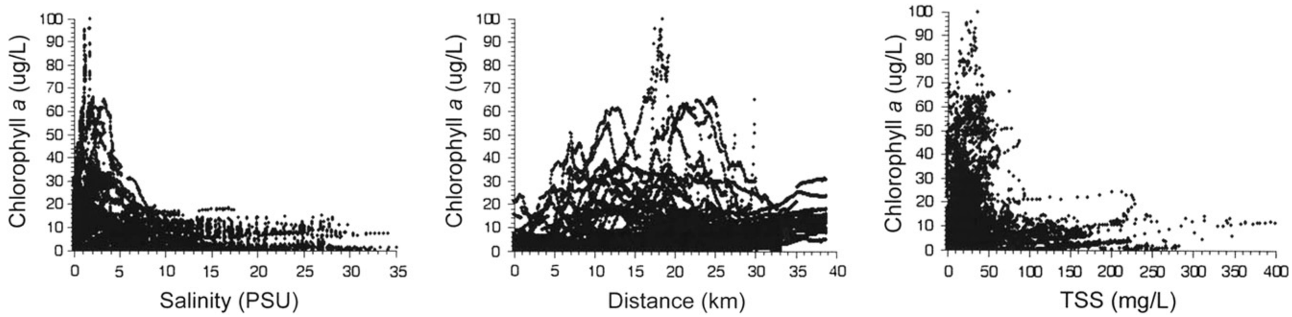

Fig. 6. Graphs of chlorophyll *a* versus salinity, distance from diversion structure, and TSS.

There was large seasonal variation in water temperature in the Breton Sound estuary, which likely affected a broad array of physiological and geochemical estuarine processes. Water temperature affects denitrification and nitrification rates (Bachand and Horne, 2000; Nowicki et al., 1997), with temperatures below 15 °C having a much more pronounced effect compared to temperatures between 15–35 °C (Reddy and Patrick, 1984). Temperature of water entering the Breton Sound estuary during the large spring pulses was less than 12 °C, possibly decreasing the metabolism of the estuary, especially during periods of prolonged flow. However, flows higher than 100 m^3/s lead to a considerable amount of river water flowing over wetlands rather than in channels (Snedden et al., 2007), increasing the temperature of the water by 10–15 °C, and leading to increased rates of denitrification (Robert Twilley, personal communication). Thus, nutrient reduction potential may be greatly enhanced by discharging water into the estuary in the form of several large pulses rather than as a lower continuous flow.

The use of the flow-through system revealed detailed dynamics of temperature, salinity, TSS and chlorophyll *a* that could not have been captured by discrete sampling alone. The peak chlorophyll *a* concentrations found in the mid-estuary would most likely have been overlooked, or understated, since discrete sampling may not have occurred either spatially or temporally at the chlorophyll *a* maximum. Another example of the fine detail recorded by the flow-through system was the highly variable TSS measurements recorded in the outer reaches of the estuary, most likely the result of wind induced resuspension of bay bottom sediments. Further development of the flow-through system, such as the addition of nutrient and water column light attenuation parameters, would be of great value in understanding the complex biogeochemical processes occurring in estuarine ecosystems.

6. Conclusions

This study revealed the very dynamic behavior of temperature, salinity, TSS and chlorophyll *a*, and their interactions in the Breton Sound estuary. The estuary efficiently trapped sediments and did not lead to persistent and widespread high chlorophyll levels. Chlorophyll *a* concentrations were highest in mid-estuary during summer and fall during low discharge, and lowest during winter and spring during high discharge, most likely caused by an interaction between water residence time and temperature. Salinity throughout the Breton Sound estuary was greatly influenced by the diversion structure during high discharge, suggesting that saltwater intrusion events may be controlled with proper management of structure discharge. Continuous sampling of environmental data has merits over discrete sampling in being able to gather data over very short temporal and spatial scales, thus providing a detailed synoptic view of the system at work. This study demonstrated that the use of a flow-through system greatly enhanced the resolution of data compared to discrete sampling, allowing scientists and managers alike to better understand and visualize critical processes in the estuarine system.

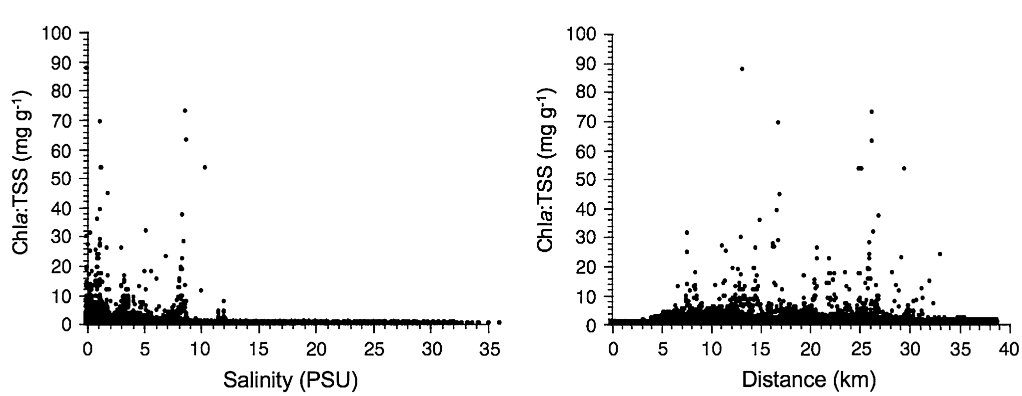

Fig. 7. Graphs of chlorophyll *a*/TSS ratio versus salinity and distance from diversion structure.

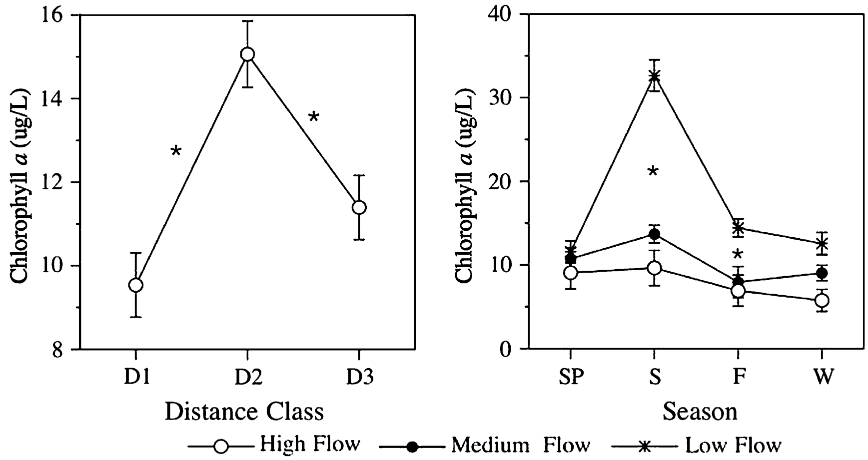

Fig. 8. Distance main effect (left) and discharge × Season interaction (right) for chlorophyll *a*. Asterisks indicate a significant difference for points above and below.

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