ECOLOGICAL ENGINEERING 32 (2008) 347–359

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ecoleng

The impacts of re-introducing Mississippi River water on the hydrologic budget and nutrient inputs of a deltaic estuary

Emily C.G. Hyfield, John W. Day, Jaye E. Cable, Dubravko Justic*

Department of Oceanography and Coastal Sciences, School of the Coast and Environment, Louisiana State University,
Baton Rouge, LA 70803, United States

ARTICLE INFO

Article history:
Received 6 August 2007
Received in revised form
11 December 2007
Accepted 22 December 2007

Keywords:
Freshwater diversion
Mississippi deltaic estuary
Nutrient budget
River re-introduction
Water budget

ABSTRACT

Most wetlands of the Mississippi deltaic plain are isolated from riverine input due to flood control levees along the Mississippi River. These levees have altered hydrology and ecology and are a primary cause of massive wetland loss in the delta. River water is being re-introduced into coastal basins as part of a large-scale ecological engineering effort to restore the delta. We quantified freshwater, nitrogen, and phosphorus inputs to the Breton Sound Estuary for three climatically different years (2000, 2001, and 2002). Water budgets included precipitation, potential evapotranspiration, the diversion, stormwater pumps, and groundwater. Precipitation contributed 48–57% of freshwater input, while the diversion accounted for 33–48%. Net groundwater input accounted for less than 0.05% of freshwater inputs. Inputs of ammonium (NH_4-N), nitrate (NO_3-N), total nitrogen (TN), and total phosphorus (TP) were determined for each of the water sources. Atmospheric deposition was the most important input of NH_4-N (57–62% or 1.44×10^5–2.32×10^5 kg yr^{-1}) followed by the diversion. The diversion was the greatest source of NO_3-N (67–83%, 7.78×10^5–1.64×10^6 kg yr^{-1}) and TN (60–71%). The diversion contributed 41–60% of TP input (1.17×10^5–2.32×10^5 kg yr^{-1}). Annual loading rates of NH_4-N and NO_3-N were 0.17–0.27 and 1.2–2.3 g N m^{-2} yr^{-1}, respectively, for the total basin indicating strong retention of nitrogen in the basin. Nitrogen retention through denitrification and burial was estimated for the upper basin.

1. Introduction

Coastal wetland productivity and sustainability are influenced by the quality and quantity of water, sediments, and biogeochemical inputs, human activity in and around the wetland, and the hydrology of the wetland system. Inputs of point and non-point sources of water and nutrients have been calculated for many types of systems, including fresh and marine wetlands (Degobbis et al., 1986; Jaworski et al., 1992; Owen, 1995; Moustafa et al., 1998; Drexler et al., 1999; Mortazavi et al., 2000a,b; Motz et al., 2001; Sutula et al., 2001). Freshwater and nutrient budgets provide critical information on wetland function and human impacts that provides input to restoration strategies for coastal ecosystems (Day et al., 2000a,b, 2007; Glasgow and Burkholder, 2000; Oenema et al., 2003; Bowen and Valiela, 2004). For example, increased nitrogen loading from urban development to Waquoit Bay, Massachusetts, led to the development of various conservation and restoration scenarios which address nitrogen loading from different sources (Bowen and Valiela, 2004). Similar to Waquoit Bay, extensive wetlands along the Louisiana deltaic coastline suggest that wetland assimilation of nutrients is an important sink for nutrient inputs (Bowen and Valiela, 2004; Day et al., 2004).

---

* *Corresponding author.* Tel.: +1 225 578 6508; fax: +1 225 578 6326.
E-mail addresses: ecghkeenan@pbsj.com (E.C.G. Hyfield), johnday@lsu.edu (J.W. Day), jcable@lsu.edu (J.E. Cable), djusti1@lsu.edu (D. Justic).

0925-8574/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecoleng.2007.12.009

Globally, few relatively unmodified riverine ecosystems remain (e.g., the Orinoco River). Human activities such as dam construction, freshwater withdrawals, agriculture, population growth, and urban development have altered inputs to many coastal systems due to decreased freshwater and sediment inputs and an increase in the delivery of nutrients and toxins, e.g., the Colorado River (Stromberg, 1995), the Nile (Fanos, 1995), the Rhone (Pont et al., 2002), the Po and Venice Lagoon (Day et al., 2005), the Ebro (Ibanez et al., 1997), the Santee (Stephens et al., 1976), the Indus (Milliman et al., 1984), the Yangtze (Yang et al., 2002), and the Everglades (Perry, 2004). Restoration of natural functioning to impacted river systems has been shown to maintain and enhance functioning of coastal systems (Mitsch et al., 2001). Recently, the re-introduction of river water to coastal systems has become an important restoration focus (e.g., Everglades, Sklar et al., 2005; Mississippi delta, Day et al., 2000b, 2007; Rhone, Pont et al., 2002). This is ecological engineering where most of the work of sediment and water transport is done by natural energies (Mitsch and Jorgensen, 2004).

The Mississippi delta contains approximately 40% of the coastal wetlands in the contiguous United States. Additionally, much of the Louisiana wetland ecosystem is unusual in that it contains extensive areas of both microtidal fresh and marine coastal wetlands over a small spatial scale (less than 60 km). Almost all of these wetlands are isolated from riverine input due to flood control levees along the Mississippi River that have been in place since the early 20th century (Day et al., 2007). As a result of the reduction of freshwater input, saltwater intrusion is more pervasive in coastal systems (Han et al., 2001; Sanders and Piasecki, 2002), causing vegetative stress and death, shifts in vegetation composition, and coastal erosion (Milliman et al., 1984; Ibanez et al., 1997; Pont et al., 2002; Day et al., 2000a). To address such hydrologic modifications in the Mississippi delta, freshwater diversions have been constructed to restore riverine input to coastal wetlands. One important site is the Caernarvon Freshwater Diversion, a large-scale project that diverts Mississippi River water to the Breton Sound Estuary. While this gated diversion was originally designed for salinity management for oyster production, recent research indicates the river water inputs have increased sedimentation rates in the upper basin, reduced salinity, and increased marsh productivity and sustainability (Lane et al., 1999, 2006; DeLaune and Pezeshki, 2003; DeLaune et al., 2003; Wheelock, 2003). This previous research indicates diversions serve a broader purpose than oyster production, contributing to wetland restoration along this critically important coastline, thus preserving areas important to flood attenuation and fishery nursery grounds.

Nitrogen and phosphorus are important macronutrients affecting marsh productivity (Mendelssohn and Morris, 2000), and river diversions can promote this productivity if nutrient inputs are not excessive. However, high nutrient inputs can result in eutrophication of estuarine and coastal waters (Cloern, 2001; Paerl et al., 2003). One notable manifestation of eutrophication is the formation of seasonally hypoxic waters in coastal and estuarine systems, such as Long Island Sound (e.g., Parker and O'Reilly, 1991; Anderson and Taylor, 2001), the Mobile River (May, 1973), and Chesapeake Bay (e.g., Officer et al., 1984). Seasonal hypoxia on the northern Gulf of Mexico continental shelf is due to excessive nutrient inputs from the Mississippi River and has resulted in high phytoplankton growth and low oxygen concentrations in bottom waters similar to these other coastal systems (Justic et al., 1995; Rabalais et al., 2002). Concentrations of nitrogen, especially nitrate, and phosphorus have increased in the Mississippi River over the past half century due to increases in fertilizer application, extensive wetland reclamation, and highly efficient farm drainage systems (Rabalais et al., 1996; Justic et al., 2003; Mitsch et al., 2001). Thus, where river diversions may provide an important mechanism for increasing marsh productivity, concern also exists that introduced river water will lead to increased estuarine eutrophication. Construction of nutrient and water budgets can aid in the formulation of better ecologically engineered coastal management plans by quantifying the major sources of freshwater and nutrients. Investigations into the harmful effects of eutrophication due to nutrient enrichment versus the potential benefits to wetland productivity are important especially in relation to river diversions.

In this study, we developed a freshwater budget and determined the nutrient inputs for the Breton Sound Estuary, which has been receiving freshwater re-introduction from the Mississippi River since 1992. Additionally, we discuss denitrification and burial as sinks for nitrogen loss. The objectives of this study were: (1) to construct annual water budgets for 3 years with low, average, and high precipitation; (2) to evaluate the magnitude of nutrient sources and some potential removal mechanisms in the estuary; (3) evaluate the magnitude and variability of water sources and sinks for the estuary for long-term ecosystem sustainability.

2. Study site

The Breton Sound Estuary is located southeast of New Orleans, Louisiana, on the east side of the River and is bounded to the east by the natural levee of Bayou Terre Aux Boeufs and to the west by the Mississippi River levee (Fig. 1). The estuary is part of the Mississippi Delta, which formed over the past 6000–7000 years as a series of overlapping delta lobes. Two of these lobes, the St. Bernard (of which Bayou Terre Aux Boeufs is a relic channel) and the modern Balize delta, encompass the study area (Scruton, 1960; Roberts, 1997). Over the past century, wetlands in the basin have deteriorated due to retreat of the St. Bernard deltaic lobe, leveeing of the Mississippi River, and hydrologic alteration within the estuary (Russel, 1936; Penland et al., 1988; Day et al., 2000a). The present-day estuary is dominated by wetlands in the upper reaches, while the lower estuary is primarily open water of Breton Sound. The study area for the water budget analysis was an 848 km^2 zone of fresh, brackish, and marine marshes north of the sound. Two major water routes in the basin, Bayou Terre Aux Boeufs and River Aux Chenes, exchange water between the upper and lower estuarine reaches. There is also extensive interaction with the wetlands due to water level variations caused by the diversion, tides and storms.

In 1992, the freshwater diversion was constructed at Caernarvon, Louisiana (river mile 81.5), to maintain an optimum salinity regime for oyster production (Chatry and Chew,

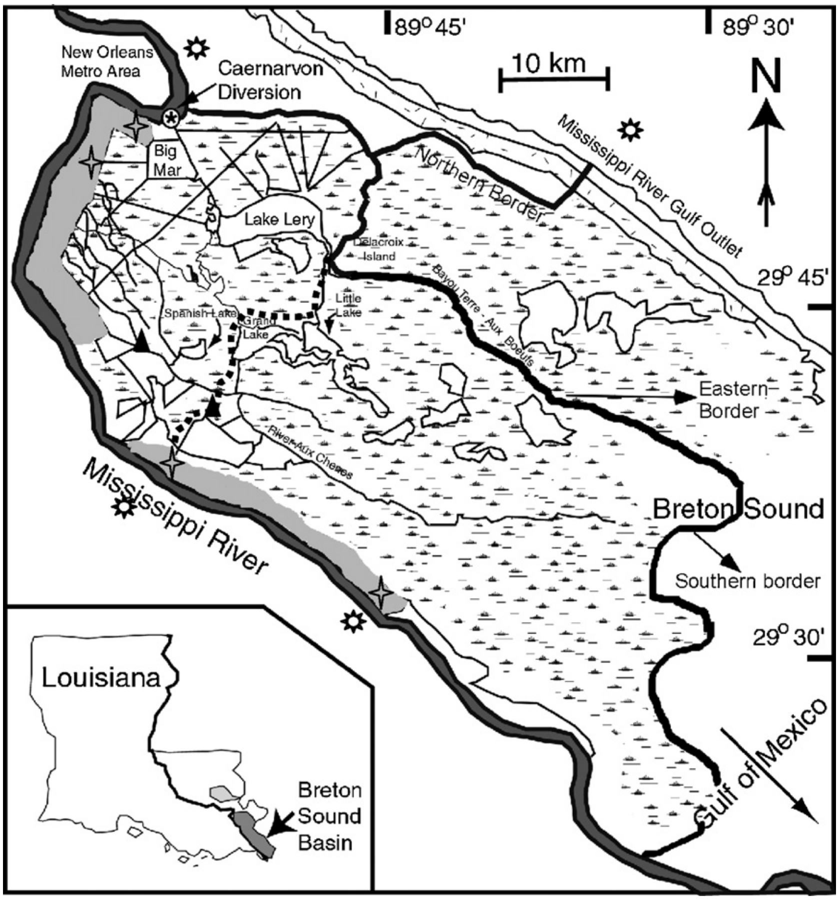

Fig. 1 – Map of Breton Sound Estuary, where Bayou Terre Aux Boeufs is the eastern boundary and the Mississippi River bounds the estuary to the west. The pumped drainage areas are shaded gray. The star is the location of the diversion structure, (▲) water level recorders used for groundwater calculation, (✧) stormwater pumps, and (✲) meteorological stations. The dashed black line represents the southern boundary for the upper estuary. The black line represents the down estuary extent of diversion-induced flooding from Snedden (2006).

1985). The diversion structure consists of five box culverts, each 4.6 m wide with vertical lift gates, capable of diverting up to 230 $m^3 s^{-1}$, though it typically discharges about 50 $m^3 s^{-1}$. The Mississippi River stage must reach a minimum level of approximately 1.2 m above sea level to allow adequate head differential for gravity flow through the culverts.

3. Materials and methods

3.1. *Water budget*

Water budgets were quantified by measuring or calculating all input and output components (e.g., Winter, 1981):

$$0 \pm \text{residual} = P - \text{PET} + \text{GW}_{\text{in}} - \text{GW}_{\text{out}} + \text{SW}_{\text{in}} - \text{SW}_{\text{out}} \pm \Delta S \tag{1}$$

where P is precipitation; PET is potential evapotranspiration; GW is groundwater input (+) or output (−); SW is surface water input (+) or output (−); and ΔS is the change in storage. In the case of Breton Sound Estuary, the water budget was modified to accommodate differences in this hydrologically altered system:

$$0 \pm \text{residual} = P - \text{PET} \pm \text{GW}_{\text{net}} + \text{SWP} \pm T_{\text{net}} - \text{GOM} + D \pm \Delta S \tag{2}$$

where GW was simplified to a net term because the low permeability deltaic clay substrate suggested this term would be small; and SW was subdivided into four components to assess their relative importance to the budget, T_{net}, SWP, D, and GOM. T_{net} is the net tidal effect, SWP is the stormwater pump drainage input to the estuary, D is the diversion input, and GOM is the loss of water to the Gulf of Mexico. The methods utilized to determine each component are discussed in detail in the following sections.

3.1.1. *Tides and change in storage*

Assessment of an accurate water budget is predicated on having reliable estimates of each water budget component, as well as the size of the study area. The study site area (848 km^2) was determined using a 30-m resolution geo-referenced thematic mapper (TM) image of the region taken on February 27, 2002, provided by the U.S. Geological Survey (Steyer, personal communication). Change in storage represents the volume of water present within a study area per unit time. Both change in storage and tides are an important component of any water budget over a short time interval. However, in a steady state system, such as over an annual cycle, no net change in storage in the estuary will occur, and thus, we did not include this term in our budget (e.g., Hoos, 1990). A current meter was installed in River Aux Chenes in mid-2001 and 1 full year (2002) of discharge data at the Breton Sound marine boundary overlapped this study. Measurements of the discharge at this gauge were evaluated as total flow (including all flow components: tides, river water, pumps, groundwater inputs, direct precipitation) and subtidal flow, where the tidal signal frequency of the total flow is removed using a 25-h low-pass filter (e.g., Dronkers, 1964; Bloomfield, 1976). When the total annual discharge at this gauge (17,835 $m^3 s^{-1}$) was compared to the subtidal annual discharge (17,663 $m^3 s^{-1}$), we found the net tidal effect (T_{net}) on the estuarine water balance was less than 1% of the total. Thus, the net water flux associated with the tidal ebb and flood at the marine boundary will be essentially zero over an annual cycle as well.

3.1.2. *Precipitation (P) and potential evapotranspiration (PET)*

Precipitation data were obtained from the Southern Regional Climate Center (SRCC) in Baton Rouge, Louisiana, for the four closest weather stations to the study area: Chalmette, Myrtle Grove, Buras, and St. Bernard (http://www.srcc.lsu.edu; Fig. 1). Using these precipitation data, weighted averages of monthly and annual precipitation at each station were calculated using Thiessen's Polygon method (Watson and Burnett, 1995) and summed to obtain total precipitation of the total basin for each year.

There were no stations measuring evaporation in the basin, thus Thornwaite's equation was used to calculate potential evapotranspiration (PET) for the basin (McCabe et al., 1985). Where there is always available water, PET and actual evaporation are very similar. Temperature data were obtained from the same four meteorological stations. Maximum possible sunshine hours were determined from the 30-year climate normal values for New Orleans airport meteorological station (NOAA, 2002). Annual and monthly PET was calculated for each station and area-weighted for the study area.

3.1.3. *Diversion and stormwater inputs*

Daily discharge from the diversion was obtained from the Louisiana Department of Natural Resources (Villarubia, personal communication; www.dnr.louisiana.gov) and summed to determine the monthly and annual contribution from the diversion. The discharge was divided by the surface area of the study site to determine the amount of water in meters evenly distributed over the study area. Additional surface water inputs to the estuary are runoff and stormwater pumps. Runoff was considered negligible because almost all precipitation that falls on the natural levee of the Mississippi River is pumped from the area by stormwater pumps. Four stormwater pumps are located along the western boundary of the study area at Bellevue, Braithwaite, East Pointe a La Hache, and Scarsdale in forced drainage areas surrounded by dikes (Fig. 1). Operational logs of all pumps except Scarsdale were obtained from the Plaquemines Parish Department of Drainage Pumps for 2000–2002. Since the pumps are either on at full capacity or turned off, the length of time they are operating multiplied by pump capacity equals total volume pumped. Stormwater pumps operate when surface water runoff accumulates in canals and generally the four pumps were operated simultaneously. Due to the close proximity between the Scarsdale and Braithwaite pump, the log for Braithwaite was used to approximate daily discharge from the Scarsdale pump. The monthly and annual input from the stormwater pumps was summed to obtain overall surface runoff to the Breton Sound Estuary study area.

3.1.4. *Groundwater input and sensitivity analysis*

River water infiltration under the levee system from the Mississippi River channel is classified as groundwater in this study. Groundwater movement into the study area is a function of the soil type and the head differential between the river stage and the estuarine water levels across the containment levee barrier. Groundwater input was modeled using continuous records of river stage and estuarine water levels to evaluate seasonal and annual variations in this seepage movement. Darcy's Law was used to estimate the volume of groundwater seepage under the Mississippi River levee (Hornberger et al., 1998):

$$q = -KA\,\frac{dh}{dl} \tag{3}$$

where q is groundwater discharge ($m^3 s^{-1}$), K is the hydraulic conductivity of the sediments ($m s^{-1}$), A is the cross-sectional area of the seepage zone (m^2), dh is the change in head between the Mississippi River and the estuarine basin water level (m), and dl represents the path length of water passage between the Mississippi River and areas within the basin (m). Some groundwater discharge may leak into the diked areas, collect in the drainage canals, and subsequently be pumped out by the stormwater pumps. To avoid counting this water volume twice as an input, groundwater infiltration from the Mississippi River to the Breton Sound basin was calculated only where no pumped drainage occurred adjacent to the river (Fig. 1). The cross-sectional area was determined by measuring the length of the river (7000 m) adjacent to the estuary where infiltration was possible and the estimated 30-m depth of a higher permeability layer beneath the levee (Carlson, personal communication). The resulting cross-sectional area (A) of 2.1×10^5 m^2 assumes a uniform zone of aquifer flow along the river length. The range in hydraulic conductivities for silty sand mixtures was estimated to be between 9×10^{-8} and 2×10^{-5} $m s^{-1}$ (Hornberger et al., 1998). Daily change in head (dh) was determined using two water level gages in the estuary and the Mississippi River stage at West Point a la Hache (Fig. 1). Groundwater discharge was calculated for both water level recorders and compared for reproducibility. Results from the water level recorders yielded similar groundwater discharge.

A sensitivity analysis was carried out by varying the path length (l) of potential groundwater discharge from 500 to 6500 m away from the levee and using the most conservative value of K (i.e., the value that would result in the highest

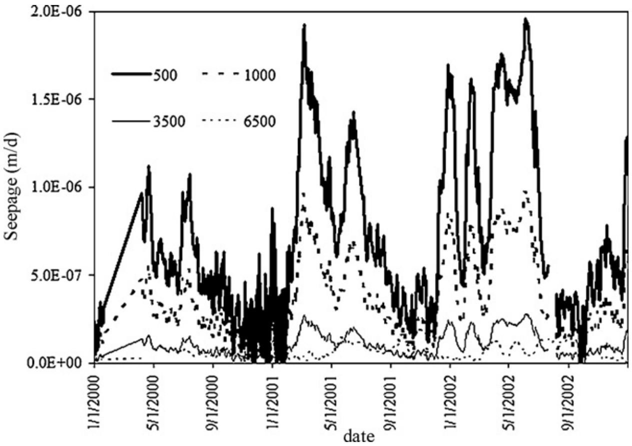

Fig. 2 – Sensitivity analysis of groundwater seepage to the estuary is given with varying path lengths (*l* = 500, 1000, 3500, and 6500 m).

groundwater flow, $2 \times 10^{-5}\,\mathrm{m\,s^{-1}}$). Darcy's Law was used to calculate the daily maximum and minimum groundwater seepage for each path length (Fig. 2). The maximum value for each year (e.g., highest *K*, shortest *l*) was used for groundwater seepage (GW_{net}) in the budget.

3.1.5. *Upper basin water inputs*

We also calculated water budgets for the upper basin to determine the importance of the diversion on the area of the basin most affected by the diversion. The water inputs for the three major freshwater sources to the upper basin (370 km^2) were determined for the area north of Grand Lake using the same methods as mentioned for the total basin (Fig. 1). Only two of the stormwater pumps were considered in these calculations based on their location within the estuary: Braithwaite and Scarsdale. Additionally, precipitation was determined from the meteorological station in Chalmette. The Caernarvon Freshwater Diversion daily discharge data were used, and the area used for groundwater input was the same since this area is in the upper basin.

Freshwater export from the Breton Sound Estuary–marsh system was evaluated in the water budget as the net system-wide export to the Gulf of Mexico (GOM). First, the residual of the total water budget was calculated from a sum of the inputs and outputs (Table 1). Next, a cumulative error for the budget was calculated by summing the associated error of each source or sink. This cumulative error was subtracted from the residual and export to the Gulf of Mexico was assumed to represent all of the residual unaccounted for after removing the cumulative error. About 15–25% of the residual was estimated to be associated with this cumulative budget error. Thus, we were able to estimate the annual freshwater export from the estuary between 1999 and 2001.

3.2. *Nutrient inputs*

Four nutrient inputs were evaluated for the estuary: atmospheric, river diversion, groundwater, and stormwater. We calculated nutrient inputs rather than a nutrient budget because nutrient export from the system was not measured. As opposed to unidirectional nutrient inputs to the system, the lower part of the system is tidal and thus nutrient flows are bidirectional. Also, unlike the water budget, nutrient concentrations in the basin are changed by several biogeochemical transformations.

The monthly and annual concentrations of total nitrogen (TN), NH_4-N and NO_3-N from atmospheric deposition were obtained from meteorological stations in Terrebonne and Iberia Parishes (National Atmospheric Deposition Program; http://nadp.sws.uiuc.edu) for each year. Annual TP atmospheric data was calculated using data from the literature. TP deposition data from Florida coastal wetlands ranging from 5 to 30 $\mathrm{mg\,P\,m^{-2}\,yr^{-1}}$ with an annual precipitation of 1.5 m resulted in a concentration range of 0.0033–0.02 mg/l (Redfield, 2002; Fitz and Trimble, 2006). This data range is consistent with unpublished atmospheric TP deposition data in Terrebonne parish, Louisiana (Cable, personal communication). Monthly atmospheric TP deposition data was not available; therefore, only annual estimates for atmospheric TP input are included. Atmospheric deposition data were used to calculate the nutrient input to the system via precipitation. Nutrient concentrations collected from stormwater pumps located just north of the study area in St. Bernard Parish were used to calculate nutrients inputs from runoff (Day et al., 1997).

The annual average and monthly concentrations of NH_4-N, NO_3-N, TN, and TP in Mississippi River water were calculated from monthly data collected by the USACE at Luling, Louisiana, about 50 km north of the diversion structure (Mach, personal communication). The annual and monthly nutrient input from the diversion and the annual groundwater input was determined using the nutrient concentration of the Mississippi River multiplied by the freshwater input of the diversion structure or groundwater seepage, respectively. The total annual loading rates of nitrogen and phosphorus were calculated for each constituent over each of the 3 study years for the total study area (848 km^2) and for the upper basin (370 km^2; Fig. 1).

3.3. *Nitrogen retention*

Nitrogen retention through burial and denitrification was estimated for the upper basin (370 km^2) based on previous studies which indicated the majority of nitrogen loss occurred north of Grand Lake (Lane et al., 1999; Baker, 2005; Bond, 2006). Denitrification rates from laboratory experiments, instantaneous and potential rates for the wetlands in Breton Sound were obtained from the literature (DeLaune and Jugsujinda, 2003; Baker, 2005; Day et al., 2004). Burial was calculated using ^{137}Cs accretion rates, bulk density and% N concentration in the upper 9 cm of the marsh surface in Breton Sound sediments (DeLaune et al., 2003).

3.4. *Error estimation*

The error analysis associated with each budget component is important in the development of a valid budget and assessment of magnitude or variability when comparing budget years. As discussed earlier, a sensitivity analysis was carried out for groundwater input to evaluate this error estimate. Here

Table 1 – A summary of the annual water budget showing the magnitude of each source and sink to the estuary (m) and the estimated annual export of water from the estuary to the Gulf of Mexico

Budget term	2000 (m) drought		2001 (m) normal		2002 (m) wet	
	Budget	Error	Budget	Error	Budget	Error
Inputs						
Precipitation (*P*, 5%)	1.045	0.052	1.574	0.079	1.874	0.094
Diversion (*D*, 10%)	1.061	0.106	0.967	0.097	1.072	0.107
Stormwater pumps (SWP, 5%)	0.086	0.004	0.183	0.0092	0.347	0.017
Groundwater (GW, 10%)	4.1×10^{-4}	4.1×10^{-5}	7.0×10^{-4}	7.0×10^{-5}	7.2×10^{-4}	7.2×10^{-5}
Subtotal	2.192	0.162	2.725	0.185	3.294	0.218
Outputs						
Potential evapotranspiration (PET, 10%)	−1.157	0.116	−1.114	0.111	−1.115	0.112
Residual	1.035		1.611		2.179	
Cumulative error	−0.278	0.278	−0.296	0.296	−0.330	0.330
Export to the Gulf of Mexico (GOM)	0.757		1.315		1.849	
Water inputs exported to GOM (%)	35		48		56	

The percent error associated with each source/sink is provided in parentheses.

we discuss the error analyses of the remaining components. The error associated with the diversion structure discharge measurement is approximately 10% based on USACE rating curves. Monthly *P* and PET area-weighted values contain errors estimated to be 5 and 10%, respectively, based on the size of the study area and the number of climate stations used in the analyses (Winter, 1981). The error associated with the stormwater pumps was undetermined. However, the relative importance of stormwater contribution suggests that even a significant error would not substantially alter the interpretation of the results. The error in the atmospheric deposition concentrations of NO_3-N and NH_4-N collected from the NADP were 3 and 6%, respectively (Lehmann, personal communication). The atmospheric deposition concentrations of TN and TP had an associated analytical error of 5%. The combined error of precipitation and atmospheric deposition results in an overall error of 8, 11, 10 and 10% for nitrate, ammonium, TN, and TP atmospheric deposition, respectively. The Mississippi River concentrations collected by the USACE had an error of 5% when combined with the diversion error, the total error in nutrient addition through the diversion structure was 15%. The analytical error in nutrient concentrations for stormwater pumps was 5%.

4. Results

4.1. *Water budget*

Climate patterns were dramatically different in each of the 3 years for which water budgets were evaluated. The midwestern and eastern United States experienced a moderate to severe drought in 1999 and 2000 (NCDC, 2005). In southern Louisiana, this drought was classified as moderate, but parts of the state had extreme drought conditions. Breton Sound had 1.05 m of precipitation (*P*) and 1.16 m of potential evapotranspiration (PET) in 2000. By 2001, conditions had improved to moderately moist and the drought appeared to be abating (1.57 m *P* and 1.11 m PET), while 2002 was marginally a wet year (1.87 m *P* and 1.11 m PET). Conditions in 2001 were similar to the 30-year normal (1971–2000; 1.63, *P* and 1.09 m PET). Precipitation and the diversion were consistently the largest contributors of freshwater to the Breton Sound Estuary during the 3-year study (Table 1). Precipitation contributed 48–57% of freshwater input while the diversion structure accounted for 33–48%. The diversion freshwater input exceeded precipitation over the whole basin only during the 2000 drought. Freshwater input from the diversion was relatively constant for all 3 years (2000, 2001, and 2002) at 1.06, 0.97, and 1.07 m, respectively. Interannual freshwater input variability was primarily driven by precipitation. The relationship between precipitation and PET reflects this interannual precipitation variability where 2000 was the only year with a water deficit (−0.11 m) and 2001 and 2002 had surpluses of 0.46 and 0.76 m, respectively.

The net input of freshwater by groundwater was 3–4 orders of magnitudes less than diversion input and precipitation. Groundwater accounted for 0.02–0.03% of total freshwater input and is a negligible source term for the estuary. Because of this, groundwater inputs were not considered for nutrient input analysis. The contribution of freshwater from stormwater pumps was directly related to the annual precipitation and accounted for 0.09, 0.18, and 0.35 m, respectively, over the 3-year period, or 4–11% of freshwater input to the system. The water budget for the upper basin (370 km^2) was constructed to demonstrate the importance of the area used in calculations of freshwater inputs (Figs. 1 and 3). For this smaller area, the impact of diverted water (51–70%) was greater than precipitation (29–42%) and stormwater pump inputs (2–10%) for all 3 years. These small-scale water budget calculations demonstrate the impact the diversion has in the upper part of the basin.

Freshwater export from the marine end of the study area was linked directly to climatic conditions. When the region was experiencing a drought (2000), more water was retained by the wetlands and less was exported to the Gulf of Mexico

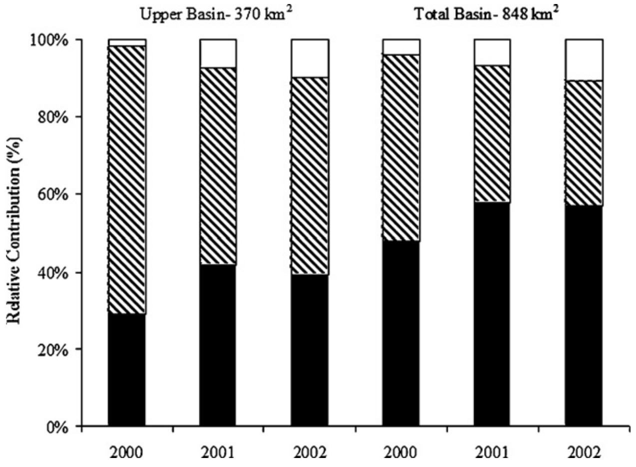

Fig. 3 – Comparison of relative contribution of the major freshwater sources at different spatial scales shows that the diversion was a more important source of freshwater in the upper basin. The black portion of the bars represents precipitation, the striped portion is the diversion and white represents the stormwater pumps.

(0.757 m) to compensate for the lower precipitation. Likewise during wet years (e.g., 2002), the estuary exported to the gulf (1.849 m) a greater percentage of the total water entering the estuary. Overall, the average export from Breton Sound to the Gulf of Mexico is about 46% of the total freshwater inputs.

4.2. *Nutrient inputs*

Atmospheric deposition was the largest contributor of NH_4-N in the estuary, accounting for 57–62% of the total NH_4 budget (Fig. 4A). NH_4-N input increased annually from 8.28×10^4 kg in 2000 to 1.36×10^5 kg in 2002 as the drought abated. Additionally, the mean annual concentration of NH_4-N was greater in atmospheric deposition than river water (Table 2). The river diversion contributed 12–31% of NH_4-N inputs, with 4.47×10^4, 3.97×10^4, and 2.76×10^4 kg, respectively, during the 3 years. The stormwater pumps accounted for 12–30% of NH_4-N inputs with the highest input in the wet year 2002. Nitrate-N input to the Breton Sound Estuary was an order of magnitude greater than NH_4-N input. Most inorganic nitrogen in both precipitation and river water was present as NO_3-N, and the diversion was the most important source of nitrate to the study area (Fig. 4B). Nitrate-N input from the river was 7.78×10^5, 1.64×10^6, and 1.04×10^6 kg, respectively, for the 3 years and contributed 67–83% of total nitrate input. Atmospheric deposition accounted for 10–17% of NO_3-N input and was 1.5×10^5, 2.05×10^5, and 2.69×10^5 kg for 2000, 2001, and 2002, respectively. The mean annual concentration of NO_3-N in the river was greater than the atmospheric deposition concentration by a factor of 8–10 (Table 2). Stormwater pumps contributed 6–16% of NO_3-N input with a maximum of 2.45×10^5 kg in 2002.

The diversion input was the largest contributor of TN: 1.26×10^6, 2.10×10^6, and 1.52×10^6 kg of TN, respectively, for the 3 years, representing 60–71% of TN input (Fig. 4C). The diversion input was nearly a factor of four greater than total nitrogen input through precipitation and stormwater pumps. Precipitation supplied 14–20% of TN with 3.45×10^5, 5.13×10^5, and 3.45×10^5 kg annually for 2000, 2001, and 2002, respectively. The stormwater pumps contributed 8–26% of TN over the 3-year period with a maximum occurring at 6.47×10^5 kg in 2002. The diversion discharge contributed 41–60% of TP input, which was the majority of TP input during 2000 and 2001. Diversion TP input was 1.17×10^5, 2.32×10^5, and 1.92×10^5 kg

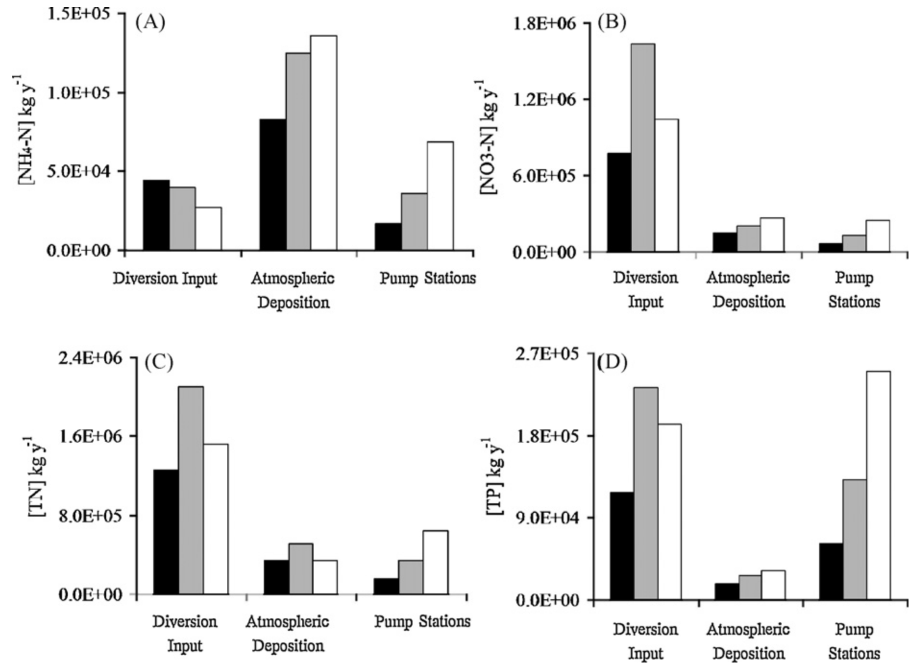

Fig. 4 – Nutrient sources to the Breton Sound Estuary for 2000 (black bars), 2001 (gray bars), and 2002 (white bars) are given for (A) ammonium-N, (B) nitrate-N, (C) total nitrogen, and (D) total phosphorus.

Table 2 – Range of nutrient concentrations (mg/l) for the three major sources from 2000 to 2002

	TN	TP	NH_4	NO_3
Diversion	1.9–2.3	0.18–0.26	0.03–0.07	1.2–1.8
Stormwater pumps	2.2	2.2	0.23	0.83
Atmospheric deposition	0.22–0.39	0.02	0.086–0.093	0.15–0.17

in 2000, 2001, and 2002, respectively (Fig. 4D). Stormwater pump inputs had the majority of TP during the wet year of 2002 (56%; 2.51×10^5 kg). The diversion and stormwater pumps were an order of magnitude greater than precipitation, which accounted for only 7–9% of the TP input. The seasonal variation in nutrient concentrations of the different sources resulted in the highest input of nutrients from the diversion in the late winter–early spring and the lowest during the low discharge summer months (Fig. 5). In contrast, atmospheric deposition was greatest in the summer and the lowest during the winter (Fig. 5). The nutrients associated with the stormwater pumps remained relatively constant.

For the total study area, the maximum loading rates of NH_4-N and NO_3-N were 0.27 and 2.3 g N m^{-2} yr^{-1}, respectively (Table 3). Total nitrogen loading ranged from 2.1 to 3.5 g N m^{-2} yr^{-1} and TP ranged from 0.24 to 0.53 g P m^{-2} yr^{-1}. Riverine inputs from the diversion were the overall largest loading factor of NO_3-N, TN, and TP to the estuary. Ammonium-N loading from atmospheric deposition exceeded that from the diversion in all 3 years. For the upper basin, TN and TP loading ranged from 4.8 to 8.0 g N m^{-2} yr^{-1} and 0.53 to 1.3 g P m^{-2} yr^{-1}, respectively and NO_3 loading ranged from 2.7 to 5.3 g N m^{-2} yr^{-1}.

5. Discussion

5.1. *Magnitude and variability of freshwater and nutrient inputs*

Freshwater is the primary process for nutrient delivery to many aquatic systems, and rivers are important sources of freshwater, sediment, and nutrients to coastal systems (e.g. Nixon et al., 1995; Degobbis et al., 1986; Mortazavi et al., 2000a,b; Moustafa et al., 1998). Water budgets are particularly important in examining nutrient budgets of aquatic systems because the magnitude of water discharge influences the delivery rate for nutrients, which is affected by seasonal change, and impacts the residence time of the system being considered. Input variability and residence time can impact the efficiency of nutrient processing and an ecosystems response to change. The efficiency can be particularly affected by anthropogenically enhanced loading due to altered

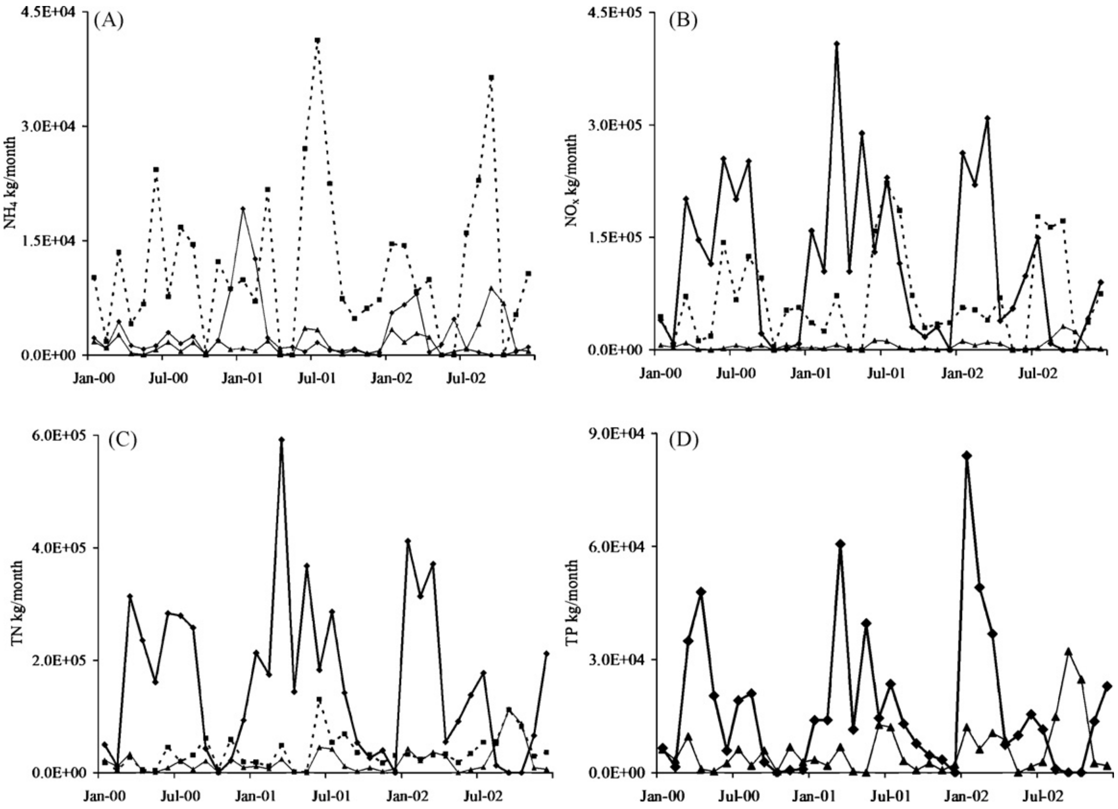

Fig. 5 – Monthly nutrient inputs to the Breton Sound Estuary for the three major sources of input. Atmospheric deposition (dashed line with squares), diversion (solid line with diamond), and stormwater input (solid line with triangle). (A) Ammonium-N, (B) nitrate-N, (C) total nitrogen, and (D) total phosphorus.

Table 3 – Annual loading rate of NH_4-N, NO_3-N, TN and TP ($g^{-2}\ yr^{-1}$)

	Year	Basin total	Diversion input	Atmospheric deposition	Pump station	Groundwater	Upper basin total
NH_4-N	2000	0.17	0.053	0.10	0.02	9.6E−06	0.39
	2001	0.24	0.047	0.15	0.043	1.2E−05	0.54
	2002	0.27	0.033	0.16	0.081	1.1E−05	0.63
NO_3-N	2000	1.2	0.92	0.18	0.072	1.7E−04	2.7
	2001	2.3	2.00	0.24	0.15	4.9E−04	5.3
	2002	1.8	1.20	0.32	0.29	4.0E−04	4.2
TN	2000	2.1	1.50	0.41	0.19	2.7E−04	4.8
	2001	3.5	2.50	0.61	0.40	6.3E−04	8.0
	2002	3.0	1.80	0.41	0.76	5.8E−04	6.8
TP	2000	0.23	0.14	0.02	0.073	2.5E−05	0.53
	2001	0.46	0.27	0.03	0.16	6.9E−05	1.06
	2002	0.56	0.23	0.038	0.30	7.4E−05	1.3

Total annual loading rate for the upper basin and total basin ($g^{-2}\ yr^{-1}$).

land uses. Very few riverine environments exist today that have not been altered in some manner to suit agriculture (e.g., irrigation, drainage), industry (e.g., cooling waters, hydroelectric power), communities (e.g., potable water supplies), and flood control (e.g., dams, levees). Each hydrologic alteration may impact downstream environments by increasing or decreasing sediment and nutrient loads.

Our results show that diverted Mississippi River water is the primary source of freshwater, nitrate, TN and TP to the Breton Sound Estuary, Louisiana. This input plays a role in freshwater residence time, marsh productivity, and nutrient retention in the estuary. Additionally, it is clear that seasonality is important to the delivery of constituents, especially during the winter and spring. This is consistent with a number of other studies. Pumped river water provided greater than 99% of TN and 94% of TP to the Boney Marsh in southern Florida (Moustafa et al., 1998). Nixon et al. (1995) reported that rivers input over 50% of the total phosphorus (TP) to Narragansett Bay, Rhode Island, and are the major pathway for nitrogen to the system. The Po River, Italy, one of several discharging into the Adriatic Sea, contributes more than 50% of the total nitrogen to the Sea (Degobbis et al., 1986). The Apalachicola River contributes 92% of the dissolved inorganic nitrogen (DIN) and 78% of the TP entering Apalachicola Bay, Florida (Mortazavi et al., 2000a,b). In the following discussion, the major sources and sinks of the Breton Sound Estuary water budget and associated nutrient inputs are considered in coastal Louisiana.

While the major source of inorganic nitrogen to the estuary was nitrate from the river diversion, atmospheric deposition was the primary source of ammonium to the estuary. Atmospheric deposition has been reported as a significant component in nitrogen inputs to several U.S. watersheds: Chesapeake Bay Estuary (MD-VA) – 19% of NO_3-N and 40% of TN (Fisher, 1991); Upper Potomac River basin (VA) – 28% of the total N (Jaworski et al., 1992); Waquoit Bay watershed (MA) – 30% of nitrogen (Valiela et al., 1997); and Neuse River Estuary (NC) – 50% of nitrogen (Whitall et al., 2003). Additionally, Sutula et al. (2001) showed atmospheric phosphorus deposition was a major contributor to the phosphorus-limited wetlands of the southeastern Everglades. In contrast, atmospheric TP inputs were relatively minor for Breton Sound. Interannual and seasonal variability in precipitation can change the relative inputs of freshwater and nutrients, as demonstrated by Sutula et al. (2001) who reported strong seasonal and interannual variability of freshwater and nutrient inputs to the southeastern Everglades. They indicated this variability impacts estimates of loading and should be considered in development of management plans for the Everglades restoration and future use.

In Breton Sound, monthly precipitation was highly variable and the highest precipitation events occurred in the summer months associated with large tropical storms. A previous study in south Louisiana in Terrebonne Parish found similar results, i.e., the composition of atmospheric deposition was highly dependent on storms, climate, and the inundation of wetlands (West and Feagley, 1995). In an environment such as coastal Louisiana where marsh hydroperiods are a function of riverine inputs (either diversions or natural flow), wind-driven and lunar tides, and precipitation, warm summer months can promote microbial activity in moist soils and sediments. Volatilization of nitrogen in wetlands during the summer is enhanced and will increase the delivery of NO_x to the atmosphere (West and Feagley, 1995). The importance of atmospheric nitrogen sources complicates nutrient reduction programs in estuaries and demonstrates why elemental mass balances for coastal systems are necessary. Management of atmospheric deposition can only be controlled by regulation of industrial, agricultural and fossil fuel combustion processes that introduce nutrients and other constituents to the atmosphere (McDevitt, 1999; Burns, 2002).

In Breton Sound, the river diversion is the only manageable input to the basin, but temporal and spatial differences in inputs occur due to both precipitation and the diversion. When considered on a seasonal basis, the diversion input was much greater during the winter and spring when the Mississippi River discharge is greatest (Fig. 5). The impact of the diversion was also greater in the upper estuary where most sediment is deposited (Wheelock, 2003; Snedden et al., 2007) and circulation was dominated by river inputs (Snedden, 2006). In general, riverine input to temperate estuaries is the most important source of freshwater and nutrients during the winter and spring (e.g., Boynton and Kemp, 2000). Diversion operations are managed, and as such, nutrients and freshwater input are dependent on operation schedules and the seasonal nutrient concentration in the river source water. Structure operation can be utilized for management purposes so that the input of dissolved and particulate constituents and freshwater are optimal for the downstream marsh and estuary.

Another minor, though still measurable, portion of the freshwater inputs came from stormwater pumps, which are intermittent, event-driven inputs. Stormwater inputs probably affected freshwater and nutrient dynamics in the immediate outfall area of the pumps, but these inputs are minimal to the overall estuarine water budget when compared to diversion and precipitation inputs. As with the diversion, stormwater pumps are controlled inputs but they are also climate dependent since their operation is limited to high precipitation periods.

While characterization of point source riverine inputs to the ocean is relatively easy, marsh–tidal creek systems covering broad geographic areas pose a more problematic environment for quantifying flow into the coastal ocean. The complex geometry of these systems can accommodate highly productive ecosystems, but determining the best location for measurement stations is difficult. The marine end of the Breton Sound is characterized by an expansive salt marsh (*Spartina alterniflora*), many minor and two main channels (River Aux Chenes and Bayou Terre Aux Boeufs). Thus it was not possible to develop a complete nutrient budget because nutrient export from the marine end was not possible with existing information.

Just as quantification of freshwater export is important to the overall water budget assessment, quantification of nutrient uptake and removal pathways provides insights into the functioning of the estuarine system and guidance for management of the diversion. We focus here on nitrogen because it is normally considered limiting in coastal systems (Day et al., 1989). Important estuarine sinks for nutrients include direct burial of particulate nutrients, plant uptake and subsequent burial of organic nutrients, and denitrification. Measurement of these processes in the Breton Sound system indicates they are all significant sinks for nutrients. Denitrification rates in Mississippi deltaic estuarine and wetland environments can be as high as 21–36 $\mathrm{g\,N\,m^{-2}\,yr^{-1}}$ (DeLaune and Jugsujinda, 2003; Bond, 2006; Day et al., 2004). These rates indicate denitrification is an important process in Breton Sound. The loss of nitrogen via plant uptake occurs through organic soil formation and subsequent burial. Burial in sediments is an important nitrogen sink. Based on data in DeLaune et al. (2003), we calculated that N burial in Breton Sound sediments ranged from 7.6 to 23 $\mathrm{g\,N\,m^{-2}\,yr^{-1}}$ and averaged 12.5 $\mathrm{g\,N\,m^{-2}\,yr^{-1}}$ (DeLaune et al., 2003). This high capacity for N burial reflects the subsidence rate in the area which is estimated to be about 0.5 cm/yr (Gagliano, 1999).

Fluctuations in nitrogen removal occur because of variations in temperature, nitrate concentration, and the amount of over-marsh flooding. Rick et al. (2003) showed in coastal Louisiana that denitrification rates increase with increasing temperature and high nitrate concentrations. In Breton Sound, diverted river water in the spring is generally less than 12 °C, in contrast to estuarine waters which are generally higher than 15 °C higher (Lane et al., 2007). Lane et al. (2007) reported that as cold diverted water flowed over the marsh surface during the winter–spring period in Breton Sound, temperature increased rapidly, often by more than 10 °C, resulting in high rates of nitrate removal from the water column.

The loading rate analysis showed that annual loadings for nitrogen and phosphorus were low compared the range of values reported in the literature (Richardson and Nichols, 1985; Mitsch and Gosselink, 2007; Mitsch et al., 2001, 2005; Day et al., 2004). These low loading rates are reflected in the high rates of removal of N and P reported by Lane et al. (2004). The mechanisms of nutrient removal were discussed in the preceding paragraph.

5.2. *Implications and conclusions*

Several studies have indicated that re-introduction of river water in the Mississippi delta may be beneficial. Benefits include higher rates of sediment deposition to offset relative sea level rise, enhanced marsh productivity, and rapid nutrient assimilation (Lane et al., 1999, 2004, 2006; Day et al., 2003; DeLaune et al., 2003, 2005; DeLaune and Pezeshki, 2003; Wheelock, 2003; Snedden, 2006). Diverted river water may also have deleterious effects on water quality in estuaries such as Breton Sound (i.e., eutrophication, harmful algal blooms, and hypoxia; Justic et al., 1995, 2003; Rabalais et al., 2002). These concerns highlight the importance of carefully quantifying hydrologic and biogeochemical budgets to examine those sources and/or sinks which may be influenced by anthropogenic activities. The relative differences in the seasonal and annual budgets highlight the importance of the river diversion as a resource for management of the Breton Sound Estuary. The control and utilization of the diversion structure to compensate for reductions in “normal” or historical freshwater and nutrient input are important for marsh restoration. While records of the freshwater inputs to the basin are not well quantified prior to the construction of containment levees in the early 20th century, evidence that periodic spring flooding occurred can be found in the modern estuarine geomorphology shaped by crevasses and distributary channels. Our results indicate the diversion can be managed to achieve a number of desired objectives including: (1) increasing the potential for nutrient uptake via plant growth and denitrification, (2) increased overmarsh flow to enhance sediment capture efficiency, marsh productivity, and organic soil formation, and (3) decreased residence time. A decrease in residence time would be especially beneficial during late spring/early summer when phytoplankton blooms may occur. Thus it is possible that the diversion could be managed to minimize the potential for algal blooms.

In a broader context, insight into how managed flow may reduce the impacts of global climate change in coastal areas emerges from this study. Two important climate change drivers that will likely impact the Breton Sound Estuary are accelerated sea level rise and reductions in local freshwater inflow (McCarthy et al., 2001). To survive rising sea levels, coastal marshes must accrete vertically at the same rate sea level increases (e.g., Day et al., 1997; Morris et al., 2002). This is especially important in the Mississippi River and other deltas where subsidence results in rates of relative sea level rise that are higher than eustatic sea level rise. In addition, it is predicted that climate change will likely result in reduced local freshwater input to the northern Gulf of Mexico (Wolock and McCabe, 1999). Results from this study and others (Wheelock, 2003; Snedden et al., 2007) show that the diversion is an important source of freshwater, sediments, and nutrients. These inputs all contribute to enhanced marsh sustainability and reduced salinity (Day et al., 2003; DeLaune et al., 2003, 2005; Lane et al., 2006), both of which ultimately may lead to enhanced marsh survival with global warming. In summary, our results show that development of water and nutrient budgets provide valuable insights into the functioning of a large ecologically engineered restoration effort for the Mississippi delta.

Acknowledgements

Funding for this work was provided by grants to John Day, Jaye Cable, and Dubravko Justic from the EPA/USDA/NSF Water and Watersheds Research Program (#R828009) and the USDA/CSREES/EPA Nutrient Science for Improved Watershed Management Program (#2002-00561). This work would not have been possible without the generosity of the Delacroix Corporation and the cooperation of the Louisiana Department of Natural Resources. In addition, we thank Gregg Snedden for help with field data collection, Eric Swenson for help in calculating the net tidal effect, and Ron DeLaune for help with burial calculations.

REFERENCES

Anderson, T.H., Taylor, G.T., 2001. Nutrient pulses, phytoplankton blooms and seasonal hypoxia in Western Long Island Sound. Estuaries 24, 228–243.

Baker J., 2005. A flume technique to measure marsh nutrient flux in coastal wetlands associated with a Mississippi River Diversion. Masters Thesis. University Louisiana at Lafayette. Lafayette, Louisiana.

Bloomfield, P., 1976. Fourier Analysis of Time Series, An Introduction. John Wiley, New York.

Bond, D., 2006. A modified batch core technique to measure potential marsh nutrient flux in coastal wetlands associated with a Mississippi River Diversion. Masters Thesis. University of Louisiana at Lafayette. Lafayette, Louisiana.

Bowen, J.L., Valiela, I., 2004. Nitrogen loads to estuaries: using loading models to assess the effectiveness of management options to restore estuarine water quality. Estuaries 27, 482–500.

Boynton, W.R., Kemp, W.M., 2000. Influence of river flow and nutrient loading on selected ecosystem processes and properties in Chesapeake Bay. In: Hobbie, J. (Ed.), Estuarine Science: A Synthetic Approach to Research and Practice. Island Press, Washington, DC, pp. 269–298.

Burns, D.A., 2002. The effects of atmospheric nitrogen deposition in the Rocky Mountains of Colorado and southern Wyoming—a synthesis and critical assessment of published results. Water-Resources Investigations Report 02-4066, U.S. Geological Survey.

Chatry, M., Chew, D., 1985. Freshwater diversion in coastal Louisiana: recommendations for development of management criteria. In: Fourth Coastal Marsh Estuary Management Symposium, pp. 71–84.

Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. Mar. Ecol. Progr. Ser. 210, 223–253.

Day, J.W., Hall, C.A.S., Kemp, W.M., Yanez-Arancibia, A., 1989. Estuarine Ecology. John Wiley and Sons, New York, 558 pp.

Day, J.W., Rybczyk, J., Pratt, R., Sutula, M., Westphal, A., Blahnik, T., Delgado, P., Kemp, P., 1997. A use attainability analysis of long term wastewater discharge on the Poydras-Verret wetland in St. Bernard Parish, LA. Final Report to the Lake Pontchartrain Basin Foundation and St. Bernard Parish, 60 pp.

Day, J.W., Britsch, L.D., Hawes, S.R., Shaffer, G.P., Reed, D.J., Cahoon, D.R., 2000a. Pattern and process of land loss in the Mississippi Delta: a spatial and temporal analysis of wetland habitat change. Estuaries 23, 425–438.

Day, J.W., Psuty, N.P., Perez, B.C., 2000b. The role of pulsing events in the functioning of coastal barriers and wetlands: implications for human impact, management and the response to sea level rise. In: Weinsten, M.P., Kreeger, D.A. (Eds.), Concepts and Controversies in Tidal Marsh Ecology. Kluwer Academic Publishers, Dordrecht, 633 pp.

Day, J.W., Ko, J., Cable, J., Day, J.N., Fry, B., Hyfield, E., Justic, D., Kemp, P., Lane, R., Mashriqui, H., Reyes, E., Rick, S., Snedden, G., Swenson, E., Templet, P., Twilley, R., Wheelock, K., Wissel, B., 2003. Pulses: the importance of pulsed physical events for Louisiana floodplains and watershed management. In: First Interagency Conference on Research in the Watersheds, October 27–30, pp. 693–699.

Day, J.W., Ko, J., Rybczyk, J., Sabins, D., Bean, R., Berthelot, G., Brantley, C., Cardoch, L., Conner, W., Day, J.N., Englande, A.J., Feagley, S., Hyfield, E., Lane, R., Lindsey, J., Mitsch, J., Reyes, E., Twilley, R., 2004. The use of wetlands in the Mississippi delta for wastewater assimilation: a review. Ocean Coast. Manage. 47, 671–691.

Day, J.W., Abrani, G., Rybczyk, J., Mitsch, W., 2005. Venice Lagoon and the Po Delta: system functioning as a basis for sustainable management. In: Fletcher, C.A., Spencer, T. (Eds.), Flooding and Environmental Challenges for Venice and its Lagoon: State of Knowledge. Cambridge University Press, Cambridge, pp. 445–460.

Day, J., Boesch, D., Clairain, E., Kemp, P., Laska, S., Mitsch, W., Orth, K., Mashriqui, H., Reed, D., Shabman, K., Simenstad, C., Streever, B., Twilley, R., Watson, C., Wells, J., Whigham, D., 2007. Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. Science 315, 1679–1683.

Degobbis, G.D., Gilmartin, M., Revelante, N., 1986. An annotated nitrogen budget calculation for the northern Adriatic Sea. Mar. Chem. 20, 159–177.

DeLaune, R.D., Jugsujinda, A., Peterson, G.W., Patrick, W.H., 2003. Impact of Mississippi River freshwater reintroduction on enhancing marsh accretionary processes in a Louisiana estuary. Estuarine Coast. Shelf Sci. 58, 653–662.

DeLaune, R.D., Jugsujinda, A., 2003. Denitrification potential in a Louisiana wetland receiving diverted Mississippi River water. Chem. Ecol. 19 (6), 411–418.

DeLaune, R.D., Pezeshki, S.R., 2003. The role of soil organic carbon in maintaining surface elevation in rapidly subsiding U.S. Gulf of Mexico marshes. Water Air Soil Pollut. 3, 167–179.

DeLaune, R.D., Pezeshki, S.R., Jugsujinda, A., 2005. Impact of Mississippi River freshwater reintroduction on *Spartina Patens* Marshes: response to nutrient input and lowering of salinity. Wetlands 25 (1).

Drexler, J.Z., Bedford, B.L., DeGaetano, A.T., Siegel, D.I., 1999. Quantification of the water budget and nutrient loading in a small peatland. J. Am. Water Resour. Assoc. 35, 753–769.

Dronkers, J.J., 1964. Tidal Computations in Rivers and Coastal Waters. North Holland Publishing Company, Amsterdam.

Fanos, A.M., 1995. The Impact of human activities on the erosion and accretion of the Nile delta coast. J. Coast. Res. 11, 821–833.

Fisher, T., 1991. Atmospheric nitrogen deposition and the Chesapeake Bay Estuary. Ambio 20, 102–108.

Fitz, H.C., Trimble, B., 2006. Documentation of the Everglades Landscape Model: ELM v 2.5. South Florida Water Management District. West Palm Beach, Florida.

Gagliano, S.M., 1999. Faulting, subsidence and land loss in coastal Louisiana. In: Coast 2050: Toward a Sustainable Coastal Louisiana, The Appendices. Louisiana Department of Natural Resources, Baton Rouge, La.

Glasgow, H., Burkholder, J., 2000. Water quality trends and management implications from a five-year study of a eutrophic estuary. Ecol. Appl. 10, 1024–1046.

Han, Z.C., Pan, C.H., Yu, J., 2001. Effects of large-scale reservoir and river regulation/ reclamation on saltwater intrusion in Qiantang Estuary. Sci. China Ser. B-Chem. 44, 221–229.

Hornberger, G.M., Raffensperger, J.P., Wiberg, P., Eshleman, K.N., 1998. Elements of Physical Hydrology. John Hopkins Press, Baltimore.

Hoos, A.B., 1990. Recharge rates and aquifer hydraulic characteristics for selected drainage basins in middle and east Tennessee. USGS Water-Resources Investigations Report 90-4015.

Ibanez, D., Pont, D., Prat, N., 1997. Characterization of the Ebro and Rhone Estuaries: a basis for defining and classifying salt-wedge estuaries. Limnol. Oceanogr. 42, 89–101.

Jaworski, N.A., Groffman, P.M., Keller, A.A., Prager, J.C., 1992. A watershed nitrogen and phosphorus balance: the upper Potomac River Basin. Estuaries 15, 83–95.

Justic, D., Rabalais, N.N., Turner, R.E., Dortch, Q., 1995. Changes in nutrient structure of river-dominated coastal waters: stoichiometric nutrient balance and its consequences. Estuarine Coast. Shelf Sci. 40, 339–356.

Justic, D., Turner, R.E., Rabalais, N.N., 2003. Climatic influences on riverine nitrate flux: implications for coastal marine eutrophication and hypoxia. Estuaries 26, 1–11.

Lane, R.R., Day, J.W., Justic, D., Reyes, E., Marx, B., Day, J.N., Hyfield, E., 2004. Changes in stoichiometric Si, N, and P ratios of Mississippi River water diverted through coastal wetlands to the Gulf of Mexico. Estuarine Coast. Shelf Sci. 60, 1–10.

Lane, R.R., Day, J.W., Thibodeaux, B., 1999. Water quality analysis of a freshwater diversion at Caernarvon, Louisiana. Estuaries 22, 327–336.

Lane, R., Day, J.W., Day, J.N., 2006. Wetland surface elevation, vertical accretion, and subsidence at three Louisiana estuaries receiving diverted Mississippi River water. Wetlands 26, 1130–1142.

Lane, R., Day, J.W., Marx, B., Reyes, E., Hyfield, E., Day, J.N., 2007. The effect of riverine discharge on temperature, salinity, suspended sediment, and chlorophyll *a*, in a Mississippi delta estuary measured using a flow-through system. Estuarine Coast. Shelf Sci. 74, 145–154.

May, E.B., 1973. Extensive oxygen depletion in Mobile Bay, Alabama. Limnol. Oceanogr. 18, 353–366.

McCabe, G.J., McLaughlin, J.D., Muller, R.A., 1985. Thornwaite continuous monthly water budget: Louisiana Office of State Climatology, Climate Paper 85-1, 19.

McCarthy, J.J., Canziani, O., Leary, N., Dokken, D., White, K., 2001. Climate Change 2001: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge.

McDevitt, W., 1999. Status Report on Emissions and Deposition of Atmospheric Nitrogen Compounds from Animal Production in North Carolina. North Carolina Department of Environment and Natural Resources.

Mendelssohn, I.A., Morris, J.T., 2000. Eco-physiological control on the productivity of Spartina alteriflora loisel. In: Weinstein, M.P., Kreeger, D.A. (Eds.), Concepts and Controversies in Tidal Marsh Ecology. Kuwer Academic Publishers, Dortrecht, The Netherlands, pp. 59–80.

Milliman, J.D., Quraishee, G.S., Beg, M.A., 1984. Sediment discharge from the Indus River to the ocean; Past, present and future. In: Haq, B.H., Milliman, J.D. (Eds.), Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan. Van Nostrand Reinhold Co., New York, NY, USA, pp. 265–270.

Mitsch, W., Gosselink, J., 2007. Wetlands. John Wiley & Sons, New York, 582 pp.

Mitsch, W., Jorgensen, W., 2004. Ecological Engineering and Ecosystem Restoration. John Wiley & Sons, New York, 411 pp.

Mitsch, W., Day, J., Gilliam, W., Groffman, P., Hey, D., Randall, G., Wang, N., 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River Basin: strategies to counter a persistent ecological problem. BioScience 51, 373–387.

Mitsch, W., Day, J., Zhang, L., Lane, R., 2005. Nitrate-nitrogen retention in wetlands in the Mississippi River basin. Ecol. Eng. 24, 267–278.

Morris, J.T., Sundareshwar, P., Nietch, C., Kjerve, B., Cahoon, D., 2002. Responses of coastal wetlands to rising sea level. Ecology 83, 2869–2877.

Mortazavi, B., Iverson, R.L., Huang, W., Lewis, F.G., Caffrey, J.M., 2000a. Nitrogen budget of Apalachicola Bay, a bar-built estuary in the northeastern Gulf of Mexico. Mar. Ecol. Progr. Ser. 195, 1–14.

Mortazavi, B., Iverson, R.L., Landing, W.M., Huang, M., 2000b. Phosphorus budget of Apalachicola Bay: a river-dominated estuary in the northeastern Gulf of Mexico. Mar. Ecol. Progr. Ser. 198, 33–42.

Motz, L.H., Sousa, D., Annable, M.D., 2001. Water budget and vertical conductance for Lowry (Sand Hill) Lake in north-central Florida, USA. J. Hydrol. 250, 134–148.

Moustafa, M.Z., Fountaine, T.D., Guardo, M., James, R.T., 1998. The response of a freshwater wetland to long-term 'low level' nutrient loads: nutrients and water budget. Hydrobiologia 364, 41–53.

NCDC, 2005. Worldwide Weather and Climate Events. NOAA Satellite and Information Center. http://www.ncdc.noaa.gov/oa/reports/weather-events.html.

Nixon, S.W., Granger, S.L., Nowicki, B.L., 1995. An assessment of the annual mass balance of carbon, nitrogen and phosphorus in Narrangansett Bay. Biogeochemistry 31, 15–61.

NOAA, 2002. Monthly Station Normals of Temperature, Precipitation, and heating and Cooling Degree Days 1971–2000. NOAA, Asheville.

Oenema, O., Kros, H., De Vries, W., 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Eur. J. Agron. 20, 3–16.

Officer, C.B., Biggs, R.B., Taft, J.L., Cronin, L.E., Tyler, M.A., Boynton, W.R., 1984. Chesapeake Bay anoxia: origin, development, and significance. Science 223, 22–27.

Owen, C.R., 1995. Water budget and flow patterns in an urban wetland. J. Hydrol. 169, 171–187.

Paerl, H., Valdes, L.M., Pinckney, J.L., Piehler, M.F., Dyble, J., Moisander, P.H., 2003. Phytoplankton photopigments as indicators of estuarine and coastal eutrophication. BioScience 53, 953–963.

Parker, C.A., O'Reilly, J.E., 1991. Oxygen depletion in Long Island Sound: a historical perspective. Estuaries 14, 248–264.

Penland, S., Boyd, R., Suter, J.R., 1988. Transgressive depositional systems of the Mississippi Delta Plain: a model for barrier shoreline and shelf sand development. J. Sediment. Petrol. 58, 932–949.

Perry, W., 2004. Elements of south Florida's comprehensive Everglades restoration plan. Ecotoxicology 13 (3), 185–193.

Pont, D., Day, J.W., Hensel, P., Franquet, E., Torre, F., Rioual, P., Ibanez, C., Coulet, E., 2002. Response scenarios for the deltaic plain of the Rhône in the face of an acceleration in the rate of sea level rise, with a special attention for Salicornia-type environments. Estuaries 25, 337–358.

Rabalais, N.N., Turner, R.E., Dortch, Q., Wiseman, W.J., Gupta, B.K.S., 1996. Nutrient changes in the Mississippi River and system response on the adjacent continental shelf. Estuaries 19, 386–407.

Rabalais, N.N., Turner, R.E., Scavia, D., 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi river. BioScience 52, 129–142.

Redfield, G., 2002. Atmospheric deposition of phosphorus to the Everglades: concepts, constraints, and published deposition rates for ecosystem management. Sci. World 2, 1843–1873.

Richardson, C.J., Nichols, D.S., 1985. Ecological analysis of wastewater management criteria in wetland ecosystems. In: Ecological Considerations in Wetlands Treatment of Municipal Wastewaters. Van Nostrand Reinhold Company, NY, pp. 351–391.

Rick, S., Rick, H.H., Twilley, R., 2003. Benthic and pelagic nutrient cycling in a coastal watershed influenced by river diversions (Caernarvon, Louisiana). In: ERF Conference Proceedings, Seattle, Washington, September 14–18, 2003.

Roberts, H.H., 1997. Dynamic changes of the holocene Mississippi River delta plain: the delta cycle. J. Coast. Res. 13, 605–627.

Russel, RJ., 1936. Physiography of lower Mississippi River Delta. In: Lower Mississippi River Delta, Reports on the Geology of Plaquemines and St. Bernard parishes. Department of Conservation, Louisiana Geological Survey, Geological Bulletin no. 8. New Orleans, Louisiana, pp. 3–199.

Sanders, B.F., Piasecki, M., 2002. Mitigation of salinity intrusion in well-mixed estuaries by optimization of freshwater diversion rates. J. Hydraul. Eng. 128, 64–77.

Scruton, P.C., 1960. Delta building and the deltaic sequence. In: Shepard, F.P., Phleger, F.B., van Andel, T.H. (Eds.), Recent Sediments, Northwest Gulf of Mexico. American Association of Petroleum Geologists, Tulsa, Oklahoma, pp. 82–102.

Sklar, F.H., Chimney, M.J., Newman, S., McCormick, P., Gawlik, D., Miao, S., McVoy, C., Said, W., Newman, J., Coronado, C., Crozier, G., Korvela, M., Rutchey, K., 2005. The ecological-societal underpinnings of Everglades restoration. Front. Ecol. Environ. 3 (3), 161–169.

Snedden, G.A., Cable, J.E., Swarzenski, C.M., Swenson, E.M., 2007. Sediment discharge into a subsiding Louisiana deltaic estuary through a Mississippi River diversion. Estuarine Coast. Shelf Sci. 71 (1–2), 181–193.

Snedden, G., 2006. River, tidal, and wind interactions in a deltaic estuarine system. Ph.D. Dissertation. Louisiana State University, Baton Rouge, Louisiana.

Stephens, D.G., Van Nieuwenhuise, D.S., Mullin, P., Lee, C., Kanes, W.H., 1976. Destructive phase of deltaic development: North Santee River delta. J. Sediment. Petrol. 46, 132–144.

Stromberg, J.C., 1995. Restoration of riparian vegetation in the south-western United States: importance of flow regimes and fluvial dynamism. J. Arid Environ. 11, 821–833.

Sutula, M., Day, J.W., Cable, J., Rudnick, D., 2001. Hydrological and nutrient budgets of freshwater and estuarine wetlands of Taylor Slough in Southern Everglades, Florida, USA. Biogeochemistry 56, 287–310.

Valiela, I., Collins, G., Kremer, J., Lajtha, K., Geist, M., Seely, B., Brawley, J., Sham, C., 1997. Nitrogen Loading from Coastal Watersheds to receiving estuaries: new method and application. Ecol. Appl. 7, 358–380.

Watson, I., Burnett, A.D., 1995. Hydrology: An Environmental Approach. Lewis Publishers, Boca Raton.

West, L.M., Feagley, S.E., 1995. The chemical composition of atmospheric deposition collected from six Louisiana sites from 1983 to 1992. Atmos. Environ. 29, 1211–1217.

Wheelock, K., 2003. Pulsed river flooding effects on sediment deposition in Breton Sound Estuary, Louisiana. Masters Thesis. Louisiana State University, Baton Rouge, LA.

Whitall, D., Hendrickson, B., Paerl, H., 2003. Importance of atmospherically deposited nitrogen to the annual nitrogen budget of the Neuse river estuary, North Carolina. Environ. Int. 29, 393–399.

Winter, T.C., 1981. Uncertainties in estimating the water balance of lakes. Water Resour. Bull. 17, 82–115.

Wolock, D.M., McCabe, G.J., 1999. Explaining spatial variability in mean annual runoff in the conterminous United States. Climate Res. 11, 149–159.

Yang, S., Zhao, Q., Belkin, I.M., 2002. Temporal variation in the sediment load of the Yangtze river and the influences of human activities. J. Hydrol. 263, 56–71.