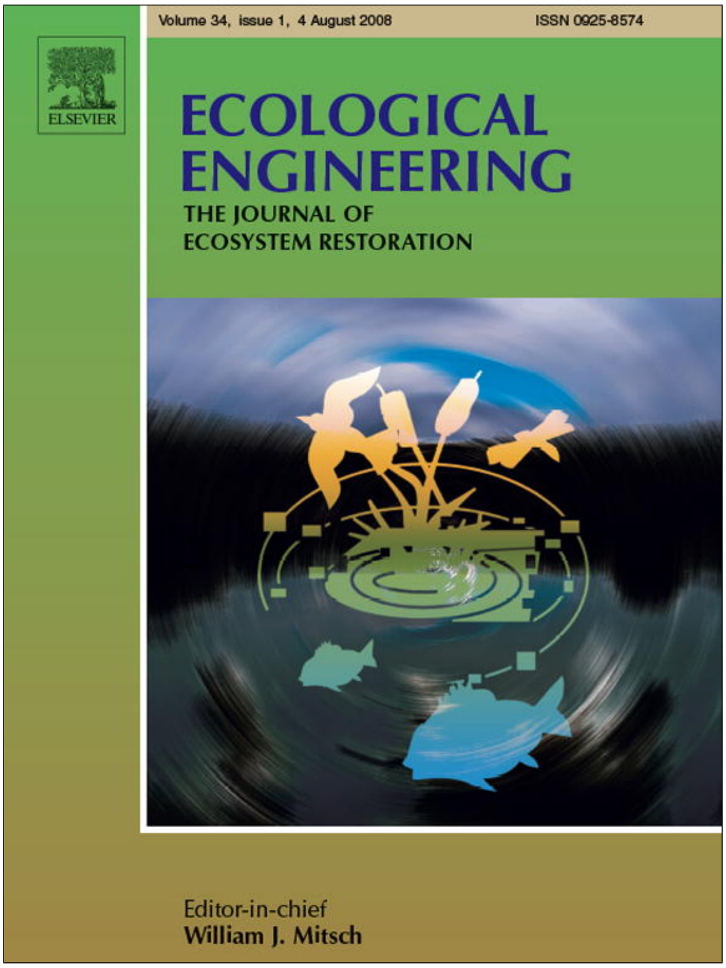
Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright

Author's personal copy

ECOLOGICAL ENGINEERING 34 (2008) 7–22

available at www.sciencedirect.com

ScienceDirect

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

Primary production, nutrient dynamics, and accretion of a coastal freshwater forested wetland assimilation system in Louisiana

Christopher G. Brantley[a,b,*], *John W. Day Jr.*[a], *Robert R. Lane*[a], *Emily Hyfield*[a], *Jason N. Day*[a], *Jae-Young Ko*[a]

[a] *Department of Oceanography and Coastal Sciences, School of the Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, United States*
[b] *U.S. Army Corps of Engineers, New Orleans District, PO Box 60267, New Orleans, LA 70160-0267, United States*

ARTICLE INFO

Article history:
Received 14 November 2007
Received in revised form
25 April 2008
Accepted 18 May 2008

Keywords:
Nutrients
Loading rate
Retention time
Wastewater treatment
Wetlands
Forest productivity
Louisiana
USA

ABSTRACT

This study reports on the response of a tidal, freshwater forested wetland ecosystem to long-term input of secondarily treated municipal effluent from the City of Mandeville, LA. Measurements of hydrology, nutrients, and aboveground net primary productivity were made from September 1998 through March 2002. Accretion measurements were made in October 2000 and October 2004. The major hydrologic inputs to the system were the effluent, precipitation, and back water flooding from Lake Pontchartrain. Nutrient levels were generally low except in the immediate vicinity of the outfall. Mean net primary production of the freshwater forest system was significantly higher downstream of the effluent discharge (1202 $g\,m^{-2}\,yr^{-1}$) compared to the control site (799 $g\,m^{-2}\,yr^{-1}$). Downstream of the outfall, accretion rates were double the rate of relative sea level rise in the area. Removal efficiencies of N and P were as high as 75% and 95%, respectively. The relatively constant flow of secondarily treated municipal effluent buffered the downstream area from salinity intrusion during a region-wide drought. Re-direction of nutrient-enhanced effluents from open water bodies to wetland ecosystems can maintain plant productivity, sequester carbon, and maintain coastal wetland elevations in response to sea-level rise in addition to improving overall surface water quality, reducing energy use, and increasing financial savings.

Published by Elsevier B.V.

1. Introduction

The coastal zone of Louisiana is experiencing tremendous change due to natural and anthropogenic processes. Increasing human populations and global climate change will likely exacerbate problems of degraded water quality, subsidence, and coastal wetland loss in the coastal zone (Day et al., 2000a,b, 2004). Increasingly, natural or constructed wetlands are being used for wastewater assimilation. Although wetlands have been used to treat wastewater for centuries, only in the past several decades has the response to such use been studied in a comprehensive, scientific manner (Richardson and Davis, 1987; Kadlec and Knight, 1996; Day et al., 2004). The ability of wetlands to perform water purification functions has been well established for natural watersheds (Khalid et al., 1981a,b; Kemp et al., 1985; Nichols, 1983; Richardson and Nichols, 1985;

* *Corresponding author at*: U.S. Army Corps of Engineers, New Orleans District, PO Box 60267, New Orleans, LA 70160-0267, United States. Tel.: +1 985 764 7484.
E-mail address: Christopher.G.Brantley@mvn02.usace.army.mil (C.G. Brantley).
0925-8574/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.ecoleng.2008.05.004

Author's personal copy

Knight et al., 1987; Richardson and Davis, 1987; U.S. EPA, 1987; Conner et al., 1989; Faulkner and Richardson, 1989; Kadlec and Alvord, 1989; Kadlec and Knight, 1996; Day et al., 2004). Studies in the southeastern United States have shown that wetlands chemically, physically, and biologically remove pollutants, sediments and nutrients from water flowing through them (Wharton, 1970; Shih and Hallett, 1974; Kitchens et al., 1975; Boyt et al., 1977; Nessel, 1978; Yarbro, 1979; Tuschall et al., 1981; Yarbro et al., 1982; Nessel and Bayley, 1984; Kuenzler, 1987; Hesse et al., 1998; Day et al., 2004; Lane et al., 1999, 2001; Zhang et al., 2000; Rybczyk et al., 2002).

From an ecological perspective, interest in wetlands to assimilate effluent is based on the principle that the free energies of the natural system are both capable of and efficient at driving the cycle of production, use, degradation, and reuse (Odum, 1978; Breaux and Day, 1994; Mitsch and Jorgenson, 2004). The basic idea underlying wetland wastewater assimilation is that the rate of application must balance the rate of decay or immobilization, and the primary mechanisms by which this balance is achieved are physical settling and filtration, chemical precipitation and adsorption, and biological metabolic processes resulting in eventual burial, storage in vegetation, and denitrification (Conner et al., 1989; Kadlec and Alvord, 1989; Patrick, 1990). Municipal effluent discharge generally introduces nutrients as NO_3, NH_4, PO_4, and organic forms, and these nutrients can be removed in the short-term by plant uptake, and in the long-term by peat and sediment accumulation, and in the case of nitrogen, by the process of denitrification (Hemond and Benoit, 1988; Day et al., 2004). For wetlands permitted to receive treated effluent in Louisiana, levels of heavy must be below state and federal standards (Day et al., 2004).

Wetlands have the ability to remove nutrients from inflowing water, primarily dependent on the volume and nutrient concentration of the input water, and the area of the receiving wetlands (Mitsch et al., 2001). This is expressed as the loading rate that is non-linearly related to nutrient uptake (Richardson and Nichols, 1985; Faulkner and Richardson, 1989; Mitsch et al., 2001). Nutrient uptake is also influenced by temperature and the hydrology of the specific wetland site (Blahnik and Day, 2000).

In Louisiana, there are sites that have received discharges from 10 to 50 years and continue to have high nutrient removal rates (Zhang et al., 2000; Day et al., 2004; Blahnik and Day, 2000). In addition, as long as peat accumulation remains below the water surface, nutrients can continue to be processed in natural wetland systems (Deghi et al., 1980; Rybczyk et al., 2002). In the Louisiana coastal zone, a high rate of relative sea level rise (RSLR) due to geologic subsidence gives rise to a high burial rate as a permanent loss pathway for nutrients (Rybczyk et al., 2002; Day et al., 2004).

Coastal wetlands have been shown to persist in the face of RSLR when vertical accretion equals or exceeds the rate of subsidence (Delaune et al., 1983; Baumann et al., 1984; Stevenson et al., 1986). In the past, seasonal overbank flooding of the Mississippi River deposited large amounts of sediments into the interdistributary wetlands of the delta plain (Roberts, 1997). Not only did these floods provide an allochthonous source of mineral sediments, which contributed directly to vertical accretion, but also the nutrients associated with these sediments promoted vertical accretion through increased autochthonous organic matter production and deposition due to organic soil through increased root growth (Delaune et al., 1983). This sediment and nutrient source was largely eliminated by the early 20th century with the completion of levees along the entire course of the lower Mississippi (Mossa, 1996), resulting in vertical accretion deficits (RSLR > accretion) throughout the coastal region (Hatton et al., 1983; Day et al., 2000a,b).

Recently, there have been renewed efforts to restore or enhance wetlands in the subsiding delta region of Louisiana. These attempts have focused on eliminating vertical accretion deficits by either physically adding sediments to wetlands using diversions or dredged material (Day et al., 2004; DeLaune et al., 2003; DeLaune and Pezeshki, 2003), or by installing sediment trapping mechanisms (i.e. sediment fences, Boumans et al., 1997), thus increasing elevation and relieving the physiochemical flooding stress (Boesch et al., 1994, Mendelssohn and Morris, 2000). There have been numerous studies indicating that treated wastewater will stimulate productivity and increase accretion in wetlands (Odum, 1975; Mudroch and Capobianco, 1979; Bayley et al., 1985; Knight, 1992; Craft and Richardson, 1993; Hesse et al., 1998; Rybczyk et al., 2002). Day et al. (1992) proposed using a complementary restoration strategy in coastal Louisiana by adding nutrient-rich, secondarily treated wastewater to hydrologically isolated and subsiding wetlands, in an effort to promote vertical wetland accretion through increased organic matter production and deposition.

This study reports on the investigation of nutrient retention and forest productivity in a wetland system north of Lake Pontchartrain, near the City of Mandeville, St. Tammany Parish, LA (Fig. 1). Specific objectives with this research were to: (1) quantify nutrients introduced from a wastewater treatment facility into a forested wetland as well as the loading rate and removal efficiency for N and P; (2) measure the impact of this nutrient-enhanced wastewater on plant productivity and accretion in the area.

2. Study area

Bayou Chinchuba and Bayou Castine form the western and eastern boundaries of the City of Mandeville, respectively, and each discharges into the northern portion of Lake Pontchartrain. Both of these streams are similar in size and discharge and are typical of other streams with forested wetlands in the Gulf Coastal plain (Ewel and Odum, 1984; Felley, 1992; USGS, 1998). Both the Bayou Chinchuba and Bayou Castine lower drainage basins are seasonally flooded cypress-tupelo and bottomland hardwood forests, with a forest floor approximately 0.6 m above Mean Sea Level (MSL). The streams are tidal near the lake. Soils are classified as an Arat silty clay loam (fine silty, siliceous, non-acid, thermic Typic Hydraquents; Trahan et al., 1990). The floodplains of Bayou Chinchuba and Bayou Castine are hydrologically distinct from adjacent wetland areas due to higher elevation ridges that border each side of the floodplain area.

Bayou Chinchuba and Bayou Castine are broadleaf and needle-leafed deciduous forested wetlands dominated by water tupelo (*Nyssa aquatica*), swamp blackgum (*Nyssa biflora*)

Author's personal copy

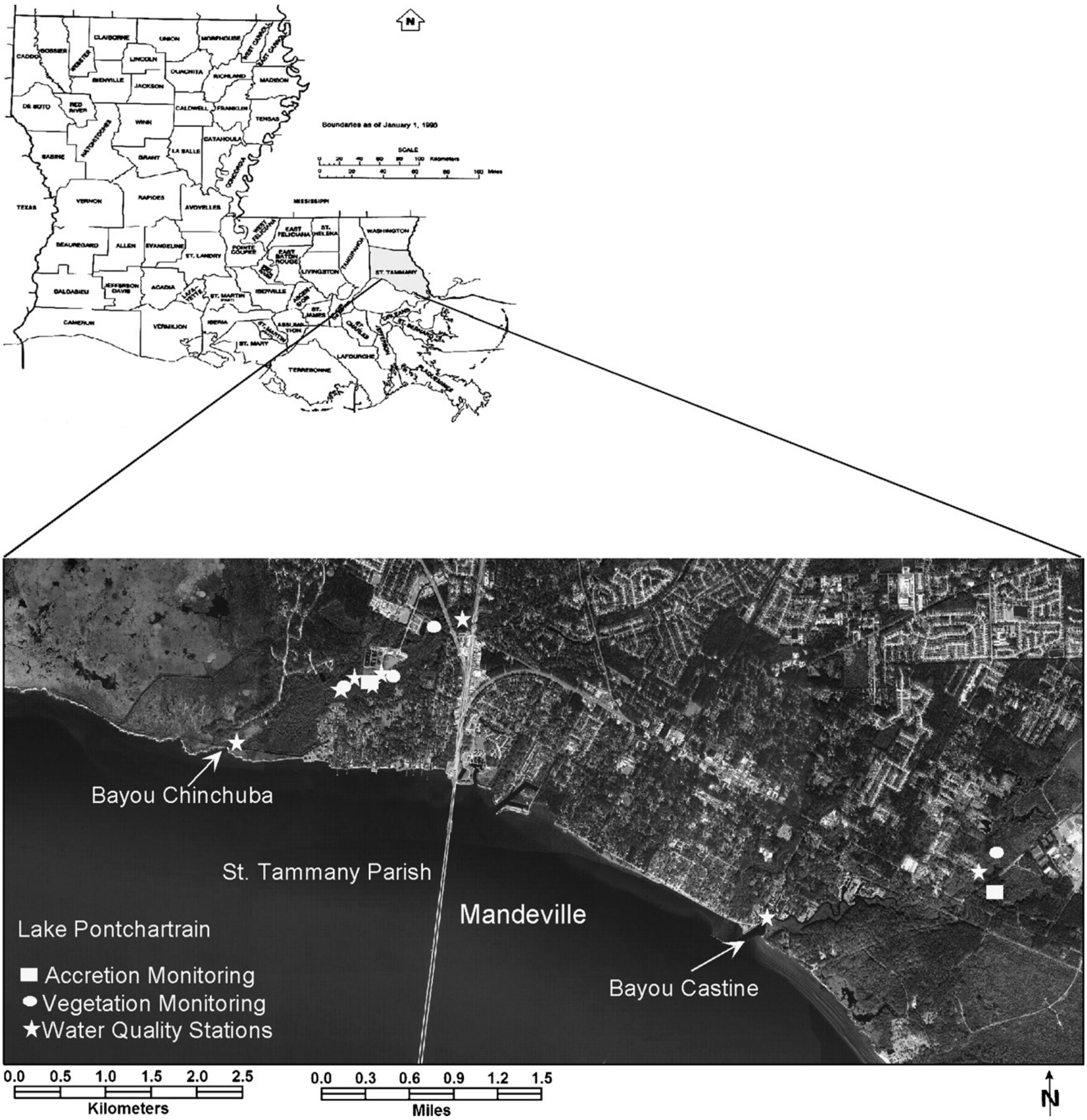


Fig. 1 – Map of study area. Bayou Chinchuba received treated municipal effluent and Bayou Castine served as the control area. The Mandeville treatment plant is just north of the white square indicating the accretion monitoring location in Bayou Chinchuba. This is the location of the effluent discharge to the bayou.

and baldcypress (*Taxodium distichum*). Bayou Chinchuba and to a lesser degree Bayou Castine exhibit vegetation zonation from the upper portion of the watershed to the lower portion. Swamp blackgum typically dominates the upper floodplain portion of both watersheds, and water tupelo and baldcypress become much more dominant downstream (Rheinhardt et al., 1998; Brantley, 2005). As the bayou becomes deeper and the floodplain wider, baldcypress becomes the dominant forest tree in the lower floodplain of both tidal streams (Rheinhardt et al., 1998). Water tupelo may also be sensitive to low salinity water in the lower reaches of both streams (Brantley, 2005).

The area has a subtropical climate, with a mean annual air temperature of 21.1 °C and mean annual rainfall of 151.4 cm yr^{-1} (U.S. Geological Survey (USGS), 1998). Stream flows in Bayous Chinchuba and Castine vary greatly. USGS measurements during 1998 indicated that during a majority of the year in Bayou Chinchuba, there was no discernible flow downstream from approximately 1500 m upstream of the treatment facility outfall). However, after two rainfall events measuring 25.1 cm on 6–7 March 1998 and 8.5 cm on 14–15 July 1998, flow in Bayou Chinchuba at West Causeway Approach was 1.8 $m^3 s^{-1}$ on 10 March 1998 and 1.0 $m^3 s^{-1}$ on 15 July 1998

Author's personal copy

(USGS, 1998). The Bayou Chinchuba and Bayou Castine floodplains are swamps hydrologically controlled by stream flow and back flooding from Lake Pontchartrain. The area immediately downstream of the wastewater treatment facility does not have a well-defined channel area and flow from the plant spreads out through the surrounding forest areas. Average water depth in Bayou Chinchuba over most of its length is less than 30 cm.

Flood tides from Lake Pontchartrain can typically enter through the mouth of Bayou Chinchuba and Bayou Castine and cause backwater flooding. Tides at Manchac Pass to the west typically show a 9–12 cm range (Gibson and Gill, 1988), however storm tides associated with tropical disturbances in the summer and fall can increase tides to much higher levels.

Little is known about near-surface groundwater interactions in the area, but in general there is little lateral groundwater movement in the fine-grained sediments of south Louisiana (USGS, 1998). The low conductivity of clays (10^{-6} mm s^{-1}, Terzaghi and Peck, 1968) coupled with the low topographic gradient indicates that horizontal and vertical groundwater velocities are more likely dominated by surface water pressure (head) and density (salinity) gradients than gravity or soil permeability. Vertical exchange of surface and groundwater is also likely minimal. During prolonged periods of dryness, some loss of surface water to the ground would be expected when water levels rise and surface soils were not yet saturated. The lack of flow in Bayou Chinchuba during dry periods suggests that ground water input is low.

Since 1989, the City of Mandeville has discharged secondarily treated municipal effluent into the Bayou Chinchuba wetland (7195.5 m^3 day^{-1}). The wastewater facility currently consists of three (61 m × 183 m) aerated lagoon cells, a three-celled rock reed filter, and an ultraviolet disinfection system. In 1998, the City of Mandeville was issued a discharge permit by US EPA with the following criteria: 30 day average BOD of 10 mg l^{-1} with daily maximum of 15 mg l^{-1}; 30 day average TSS of 15 mg l^{-1} with daily maximum of 23 mg l^{-1}; 30 day average NH_4 of 5 mg l^{-1} with daily maximum of 10 mg l^{-1}; 30 day average fecal coliforms of 200 colonies/100 ml with daily maximum of 400 colonies/100 ml (US EPA, 1998). The effluent is disinfected and metals must be below state and federal criteria.

3. Methods

3.1. Hydrology

Precipitation was monitored daily with a gauge located near the wastewater facility outfall. These data were compared on a monthly basis to 30-year average precipitation records at Covington, LA, approximately 11 km north (NOAA, 2003). Evapotranspiration was calculated on a monthly basis using Thorntwaite's equation and utilizing average monthly air temperature at the Covington, LA, weather station. Water balance was determined by subtracting monthly precipitation from the monthly adjusted evapotranspiration rate. Data from a USGS gauging station on Bayou Chinchuba upstream of the wastewater facility outfall and the measured rate of flow from the wastewater facility were used to determine these additional hydrologic inputs.

3.2. Water chemistry

Samples for water chemistry analysis were collected in September and November, 1998; January, March, April, May, July, October, and December 1999; and April and October 2000. Water samples were collected in 500 ml acid-washed polyethylene bottles, stored on ice and taken to the laboratory for analysis. Nutrient analyses were performed using standard methods outlined by the Environmental Protection Agency and the Louisiana Department of Environmental Quality, (U. S. Environmental Protection Agency, 1979) and included the following: nitrate-nitrite, (NO_x-N); ammonium, (NH_4-N); total N, (TN); phosphate, (PO_4-P); and total phosphorus, (TP). Chlorophyll *a* samples were analyzed by a modified version of the method suggested by Strickland and Parsons (1972). Chlorophyll was extracted as described by Burnison (1980) and was measured fluorometrically with a Turner Designs model 10-AU fluorometer (Greenburg et al., 1985). Within one week of sample collection, total suspended sediment (TSS) was determined by filtering 100–200 ml of sample water through pre-rinsed, dried and weighed 47 mm 0.45 um 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 (Greenburg et al., 1985). To analyze for differences in nutrient concentrations during drought versus normal rainfall amounts, averages by station of the first six sample dates were compared with the final five nutrient collections (Fig. 4). Statistical analyses were carried out to determine changes in nutrient concentration with distance. Mean nutrient concentrations at each distance were tested against all other distances using the Tukey-Kramer group comparison method (Sall et al., 2005; alpha < 0.05). The two different time periods were tested independently.

For the loading rate analysis at Mandeville, we used concentrations and discharge from the treatment plant and the area of receiving wetlands. Total amounts of nitrogen and phosphorus discharged from the treatment plant were calculated based on TN and TP concentrations and the average discharge of the treatment plant (0.083 m^3 s^{-1}). The effective area of wetlands used in the loading rate calculations was based on the floodplain area downstream of the treatment plant outfall on Bayou Chinchuba (approximately 98 ha).

3.3. Forest composition and productivity

In July 1998, two 20 m × 20 m plots were randomly established in four separate swamp areas, 1500 m upstream of the outfall treatment area along Bayou Chinchuba, at the treatment area outfall along Bayou Chinchuba, 200 m downstream of the treatment area along Bayou Chinchuba, and at a reference site along Bayou Castine. The upstream plots were located in an area of Bayou Chinchuba floodplain not affected by water flow from the treatment plant outfall. Within each plot, all trees >2.5 cm in diameter at breast height (dbh) were tagged. Average diameter, basal area, relative dominance, absolute density, relative density, survivorship, and importance value (IV) were calculated for each tree species (Barbour et al., 1980). The IV of each major tree species in the plots was based on relative density (total number) and relative dominance (basal area) in

Author's personal copy

each of the plots according to the following equation (ref):

$$IV = \frac{\text{Relative density} + \text{relative dominance}}{200}$$

Mortality rates in each plot were calculated as an exponential decay rate:

$$\text{Average annual mortality rate} = 1 - \left(\frac{S}{N_o}\right)\left(\frac{1}{y}\right);$$

where S is the number of survivors; N_o is the number of original stems; y is the number of years between samples.

Data were square-root transformed to normalize data and analysis of variance (ANOVA) used to determine if average annual rates differed.

In forested sites, biomass production is defined as the sum of litterfall and wood production (Newbould, 1967). To estimate aboveground productivity within each plot, litterfall was collected from 5–0.25 m^2 litter traps with 1 mm mesh bottoms for a total of 10 litter traps at each monitoring site. The boxes were elevated to a height of 2 m above the forest floor to prevent inundation during high water periods. Litterfall was collected monthly from August 1998 to March 2002. Litter was separated into leaves, reproductive material, and woody material, dried at 60 °C for 48 h, and weighed. Individual litterfall-trap data were converted to $g\,m^{-2}$ and then log transformed to normalize the data and reduce correlations between means and variance. A 2-way ANOVA was conducted to determine if litterfall varied among the eight plots over the three years, and an a-posteriori Tukey multiple comparisons test was employed to detect any significant differences.

Initial dbh measurements were taken in February 1999 when trees were dormant and trees were re-measured again in December 1999, January 2001, and January 2002 during the dormant season. Algorithms from Megonigal et al. (1997) were used to calculate biomass for each tree species. Change in biomass represents annual wood production and when used with annual leaf litterfall determines the aboveground net primary production in each plot. Data were log transformed and a 2-way ANOVA (4 × 3 factorial) was employed to determine if aboveground net primary productivity varied. Tukey multiple comparisons was used to detect any significant differences in the four reference areas or by years.

3.4. *Sediment accretion*

Accretion was monitored at 2 swamp forest locations, one in Bayou Chinchuba and another at Bayou Castine (Cahoon et al., 1995). Feldspar was laid out 1 cm thick in three separate 0.25 m^2 plots in April 1999 and the sediment layer thickness was measured in October 2000 and again in October 2004. The three plots at each site were spaced linearly in the swamp forest along a transect from the bayou edge to the edge of the floodplain adjacent to the elevated ridge bordering the site. At the end of each sampling period, measurements of the depth of material above the marker to the nearest mm were made at 10 random locations within each plot. Each plot was considered an experimental unit and ANOVA was used to test for total accretion between sites. Data were square-root transformed to normalize the data and an a-posteriori Tukey multiple comparisons test was employed to detect any significant differences.

Table 1 – Contribution of hydrologic inputs to Bayou Chinchuba, Mandeville, LA

Input source	Potential hydrologic contribution ($cm\,day^{-1}$)
Precipitation[a]	0.43
Bayou Chinchuba (low normal)[b]	0.0
Bayou Chinchuba (high flow)[b]	13.0
Effluent to Bayou Chinchuba[c]	0.7

Data are annual average from 1998–2002. Floodplain area downstream of outfall is approximately 100 ha.

[a] Data from rain gauge at Chinchuba.

[b] Data from USGS gauge.

[c] Daily records from city of Mandeville.

4. Results

4.1. *Hydrology*

The area receives water from several primary sources, specifically rainfall, periodic stream flow from Bayou Chinchuba, local runoff, flood tides from Lake Pontchartrain, and effluent from the wastewater facility (Table 1). During the study, average annual precipitation in the Bayou Chinchuba watershed area was 149.5 cm. Comparison with the 30-year rainfall averages at Covington indicates rainfall deficits in the area from October 1998 until November 2000 during an extended regionwide drought (Fig. 2). Evapotranspiration (ET) rates in the area ranged from 16.7 cm in July 1998 to 9.3 cm in December 1999. In general, evapotranspiration rates exceeded precipitation for much of the first two years of the study; rainfall began to approximate normal levels again in June 2000 (Fig. 3). High rainfall events occurred during November 2000, March 2001, and June 2001, although much of the precipitation that fell in June 2001 was due to the effects from Tropical Storm Allison (Fig. 3). Typically in south Louisiana, ET slightly exceeds P from May through August (Keim et al., 1995).

Downstream of the wastewater facility outfall, the floodplain area of Bayou Chinchuba receives approximately 7191.5 $m^3\,day^{-1}$ (0.083 $m^3\,s^{-1}$) of freshwater input from the treatment plant. This amount of water delivered to the wetlands can be substantial during low precipitation periods, but it can also be overwhelmed during periods of high rainfall (Table 1). During the course of the study, flow from Bayou Chinchuba upstream of the outfall discharge was low and we observed the effluent stream from the wastewater treatment facility generally bypassed the outfall vegetation plots due to low water levels during most of the study. This resulted in the Bayou Chinchub downstream plot being most affected by the effluent discharge.

4.2. *Water chemistry*

Nutrient levels in the study area were generally low with the exception of the outfall from the facility into Bayou Chinchuba (Fig. 4). In general, nutrient concentrations peaked at the plant

Author's personal copy

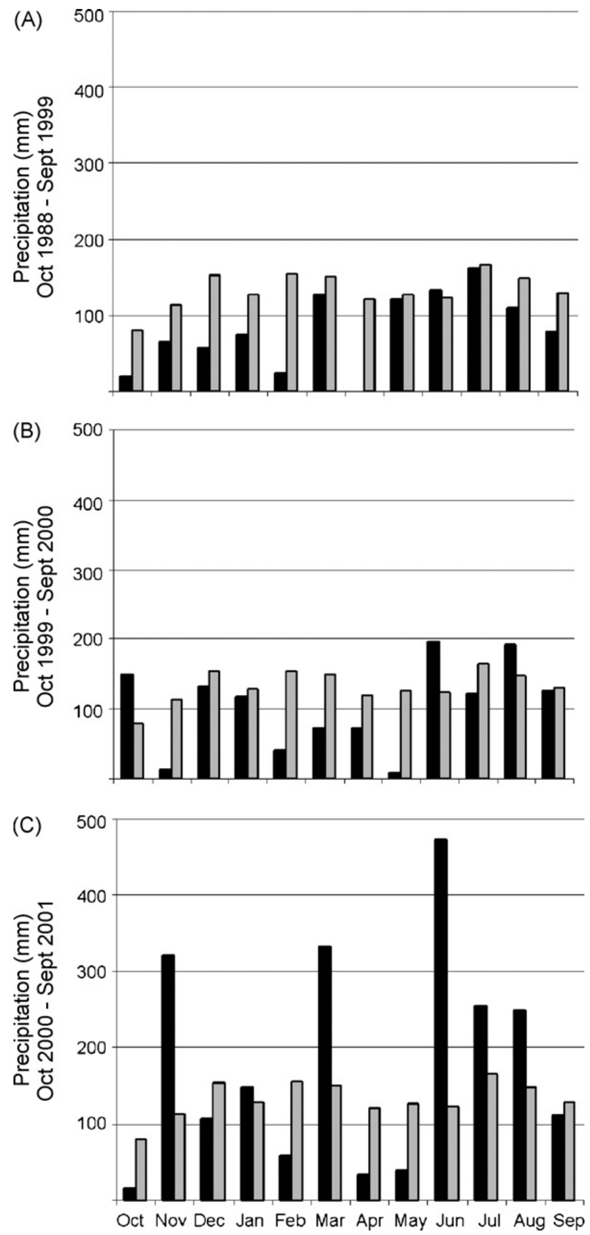


Fig. 2 – Mandeville precipitation (black bars) vs. 30-year average precipitation at Covington, LA (shaded bars). (A) 1999, (B) 2000 and (C) 2001.

discharge location, and decreases in nutrient concentrations occurred downstream of the plant. The plant operated within the established permit criteria over the course of this study for the permitted constituents. For samples collected in July, October and December 1999, the TSS concentration at the outfall sampling location averaged 78 mg l^{-1}, but was likely due to input from upstream as that location averaged 135 mg l^{-1} for those three sample dates. The upstream sample location consistently had the lowest concentration of nitrogen species and total phosphorus along Bayou Chinchuba (Fig. 4), in part due to the infrequent flows at this location during the region-wide drought. Samples collected in late 1999 and 2000 were sometimes associated with precipitation events.

Nitrate concentrations averaged 1.8 mg-N l^{-1} at the outfall location, decreased to 0.2 mg-N l^{-1} at the lake, and averaged 0.3 mg-N l^{-1} in the control area (Fig. 4A). On average, nitrate concentrations declined by 82% within 1200 m of the outfall location (Fig. 4A). Average decrease in nitrate concentration within 1200 m of the outfall over the entire sampling effort was approximately 82%. Significant differences in nitrate were noticed for the outfall location, the stations nearest the outfall, and the stations furthest downstream from the outfall ($P < 0.05$).

Ammonium concentrations ranged from near detection limits upstream of the outfall to an average high of 2.2 mg-N l^{-1} at the outfall location (Fig. 4B). Ammonium concentration at the control locations on Bayou Castine averaged 0.2 mg-N l^{-1}. Ammonium nitrogen concentrations decreased by an average of 45% from the outfall to the 1200 m station (Fig. 4B). During the 1998–1999 part of the study, no significant differences ($P > 0.05$) were noticed for ammonium nitrogen between sampling locations along Bayou Chinchuba. However, between 1999 and 2000 there was a significant difference between the outfall location and the remaining downstream locations ($P < 0.05$).

Total nitrogen concentrations averaged 4.3 mg-N l^{-1} at the outfall location while concentrations upstream and downstream were between 1.4–3.1 mg-N l^{-1} (Fig. 4C). Total nitrogen at the control locations on Bayou Castine averaged 0.6 mg-N l^{-1}. On average, TN declined by 59% from the outfall to the 1200 m station (Fig. 4C). Statistically, TN was different significantly ($P < 0.05$) at all Chinchuba stations in the 1999–2000 part of the study except for the upstream and 1800 m downstream location.

Total phosphorus concentrations ranged from below 0.5 mg-P l^{-1} upstream and downstream of the outfall to an average of 1.1 mg-P l^{-1} at the outfall location (Fig. 4D). Decreases in total phosphorus were noted downstream of the outfall in a range from 25–93%, and averaged 69% reductions over all sample dates (Fig. 4D). Total phosphorus levels at the control stations on Bayou Castine were also low, ranging from below detection limits to 0.5 mg-P l^{-1}. Between 1998 and 1999, P concentrations were significantly different at the outfall, 30 m and 250 m downstream locations, than from the 1200 m and 1800 m downstream locations ($P < 0.05$).

Total suspended sediment concentrations ranged from less than 10 mg l^{-1} to 221 mg l^{-1} over the course of the study (Fig. 4E). In general, TSS at the outfall location was low and within the plant permit criteria. TSS at the control sites on Bayou Castine ranged from 10–80 mg l^{-1}. Group comparisons tests for TSS revealed no statistical differences ($P > 0.05$) (Fig. 4E).

Chlorophyll *a* levels on Bayou Chinchuba varied from 1–10 μg l^{-1} (Fig. 4F). There were no statistical differences among time periods and sampling stations in the level of chlorophyll *a* in Bayou Chinchuba (Fig. 4F). The sample sites on Bayou Castine had similar chlorophyll *a* values from 4–10 μg l^{-1}. The high productivity and dense canopy of the forested wetlands resulted in shaded conditions at the sample sites that probably contributed to the relatively low levels of chlorophyll.

In summary, for the water chemistry data along Bayou Castine and Bayou Chinchuba, there were no significant dif-

Author's personal copy

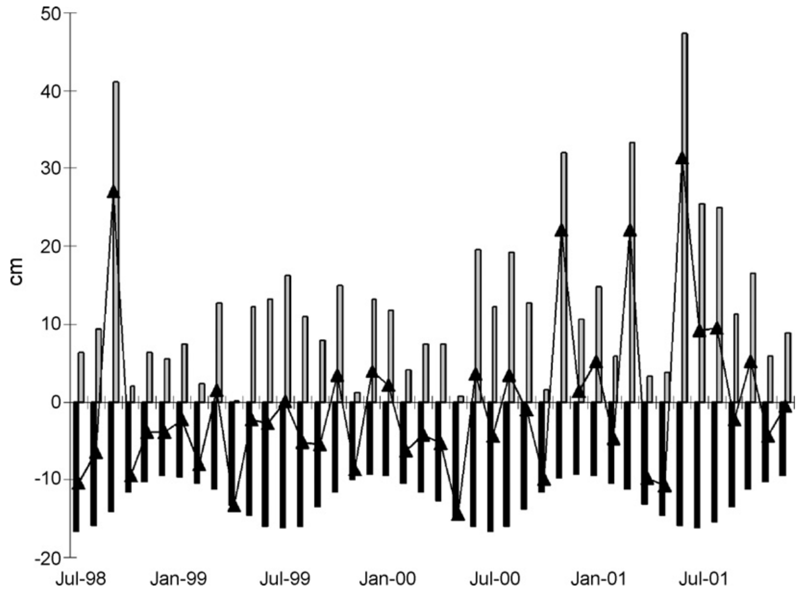


Fig. 3 – Water budget for study area. Black bars are adjusted evapotranspiration, shaded bars are Mandeville precipitation and the black triangles indicate water surplus or deficit each month. Units are cm month^{-1}.

ferences for parameters measured between the Bayou Castine and the upstream location of Bayou Chinchuba. At Bayou Chinchuba, there was a significant input of N and P forms into the forested wetland at the outfall location and significant reductions of N and P forms downstream from the treatment plant (Fig. 4).

4.3. *Forest composition and productivity*

The forest canopy community structure at Bayou Chinchuba and Bayou Castine (Table 2) is largely comprised of baldcypress (*Taxodium distichum*), tupelo gum (*Nyssa aquatica*), and swamp blackgum (*Nyssa biflora*). Average tree diameter and basal area were similar between areas (Table 3). Midstory was composed of ash and red maple, understory was sparse general ground cover. Litterfall peaked during September in the plots with a swamp blackgum component; otherwise litterfall peak was December or bimodal with a peak in the fall and winter. Litterfall contribution by species reflected the composition and IV for each plot (Table 2). Tree mortality over the first two years was low, however, after the third growing season, mortality rates increased over all areas, but this increase was not significant ($F = 5.1$, $P = 0.6$) (Fig. 5).

Leaf litter from the downstream plots was significantly higher than the other sampled areas for each of the years sampled (Table 3). Annual mean litterfall for Bayou Castine, Upstream Chinchuba, Outfall Chinchuba, and Downstream Chinchuba was 649, 498, 532, and 746 g m^{-2} yr^{-1}, respectively. There were significant litterfall differences between forest plots ($F = 35.54$, $P < 0.001$) (Table 3) but there was no effect by year ($F = 0.41$, $P = 0.8$). The interaction term was marginally significant between forest plots and year on leaf litter ($F = 1.64$, $P = 0.046$), possibly as a result of changing hydrological conditions between forest plots and increases or decreases in annual primary production.

Annual mean stem growth for Bayou Castine, Upstream Chinchuba, Outfall Chinchuba, and Downstream Chinchuba was 217, 462, 386, and 456 g m^{-2} yr^{-1}, respectively, but these differences were not significant. Total aboveground net primary production over the three study years averaged 959.9 g m^{-2} yr^{-1} for the upstream plots at Bayou Chinchuba; 917.1 g m^{-2} yr^{-1} for the Bayou Chinchuba outfall plots; 1202.7 g m^{-2} yr^{-1} for the Bayou Chinchuba downstream plots; and 799.2 g m^{-2} yr^{-1} for the Bayou Castine reference area (Fig. 6). There were significant differences between the sampled areas ($F = 7.01$, $P < 0.05$) (Table 3) and there was no effect by year ($F = 0.97$, $P = 0.4$). Comparisons test indicated the aboveground net primary productivity in the downstream area of Bayou Chinchuba was significantly higher than the other three reference areas ($P < 0.001$) (Table 3 and Fig. 6). There was no significant differences among the outfall, upstream, or Bayou Castine reference areas ($P > 0.5$) for aboveground net primary productivity (Table 3 and Fig. 6).

4.4. *Accretion*

Accretion at the two monitoring sites varied significantly (Table 4). There were significant differences in the plots after 1.5 years ($F = 20.4$, $P < 0.0001$) and after 5.5 years ($F = 220.2$, $P < 0.001$). Accretion rates along Bayou Chinchuba from 1999 to 2004 ranged from 9.3 mm yr^{-1} along the elevated ridge plot location to 11.8 mm yr^{-1} at the bayou edge plot (Table 4), and this increase was significantly higher than Bayou Castine ($F = 81.5$, $P < 0.001$). The natural levee ridge at Bayou Castine also showed a relatively high accretion rate; however, the remaining accretion plots were near or below 3 mm yr^{-1}

Author's personal copy

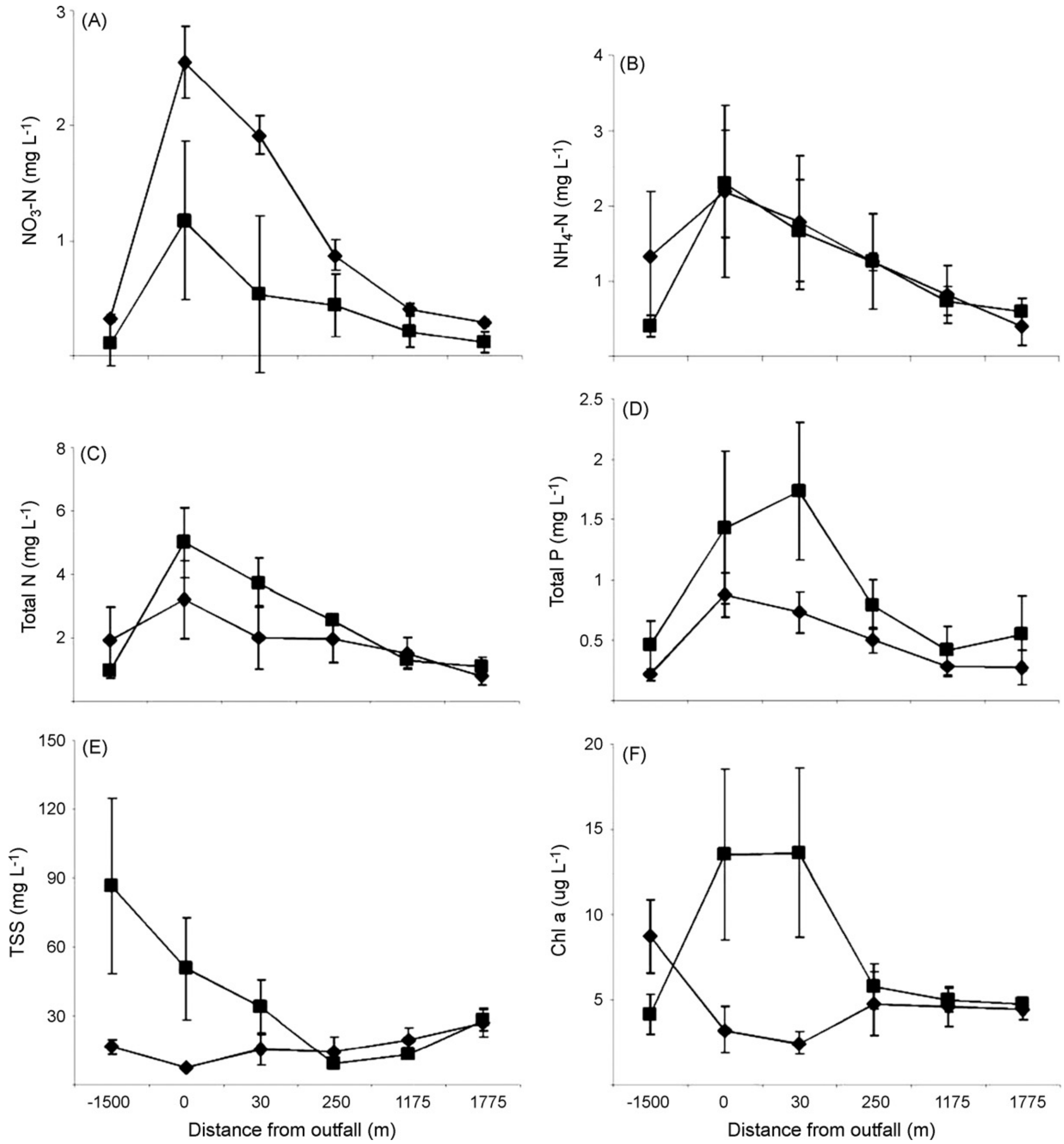


Fig. 4 – Nutrient concentrations (mean ± S.E.) in the study area for two periods (■, September 1998–May 1999; ♦, July 1999–October 2000) with increasing distance from the outfall. (A) NO_3-N, (B) NH_4-N, (C) Total N, (D) Total P, (E) TSS, and (F) Chl a.

(Table 4). The high accretion at the ridge site was due to litterfall rather than mineral sediments.

5. Discussion

During a three year monitoring study at Mandeville, LA, the discharge of secondarily treated effluent into Bayou Chinchuba resulted in nutrient reduction, enhanced wetland forest productivity, and increased accretion downstream of the outfall. The effluent stream appeared to buffer the downstream floodplain from drought effects but was overwhelmed during high bayou discharges, usually associated with precipitation events.

5.1. *Hydrology*

Hydrology in the study area was dominated for most of the study period by the effluent from the wastewater treatment facility. This constant source of nutrient enhanced freshwater served to buffer the downstream portion of Bayou Chinchuba from a region wide drought (Table 1, USGS, 1998). Reductions in salinity were noted in St. Bernard Parish where discharge of secondarily treated effluent is maintaining a cypress stand in a brackish marsh area (Day et al., 2004). Other studies from south Louisiana indicate that freshwater can offset salinity induced stress to coastal plant communities (Martin and Shaffer, 2005, Myers et al., 1995, Shaffer et al., 2001, McKee et

Author's personal copy

Table 2 – Forest community structure at Bayou Chinchuba and Bayou Castine, St. Tammany Parish, LA, USA

Plot	Species	DBH (cm)	Stem density (number ha^{-1})	BA (m^2 ha^{-1})	IV
Castine A	*Taxodium distichum*	39.5	125	18.5	24.2
	Nyssa aquatica	25.8	175	10	17.1
	Nyssa sylvatica	16.7	550	13.6	35.1
	Acer rubrum	11.5	250	3.3	12.9
	Fraxinus caroliniana	9.5	225	2	10.6
	Living trees		1325	47.6	
	Dead trees		75	0.4	
Castine B	*Taxodium distichum*	34.5	175	17.9	25.2
	Nyssa aquatica	35	300	30.7	43.1
	Nyssa sylvatica	22.2	250	11	23.8
	Acer rubrum	5.6	100	0.3	6.2
	Fraxinus caroliniana	9.6	25	0.2	1.6
	Living trees		850	60.3	
	Dead trees		25	0.2	
Upstream A	*Taxodium distichum*	–	0	0	0
	Nyssa aquatica	33.5	475	48.1	50.4
	Nyssa sylvatica	16.3	625	15.8	32.2
	Acer rubrum	13.8	175	4.1	8.8
	Fraxinus caroliniana	5.7	225	0.7	8
	Living trees		1500	69.6	
	Dead trees		25	0.2	
Upstream B	*Taxodium distichum*	22.3	75	3.7	4.5
	Nyssa aquatica	29.1	400	31.8	32.1
	Nyssa sylvatica	22.5	625	31.4	37.5
	Acer rubrum	9.5	375	3.5	11.9
	Fraxinus caroliniana	6.7	400	1.6	11.3
	Living trees		1975	72.6	
	Dead trees		125	0.6	
Outfall A	*Taxodium distichum*	40	125	16.5	22.2
	Nyssa aquatica	27.9	475	34	59.3
	Nyssa sylvatica	22.1	125	4.9	12.1
	Acer rubrum	15.2	75	1.7	6.2
	Fraxinus caroliniana	–	0	0	
	Living trees		800	57.4	
	Dead trees		50	0.45	
Outfall B	*Taxodium distichum*	22.7	175	13.3	19.7
	Nyssa aquatica	32.4	400	38.8	51.9
	Nyssa sylvatica	22.1	200	9	17.5
	Acer rubrum	3	125	0.4	6.7
	Fraxinus caroliniana	7.1	75	0.3	4.1
	Living trees		975	61.9	
	Dead trees		75	9.8	
Downstream A	*Taxodium distichum*	39.1	100	14.9	14.7
	Nyssa aquatica	25	750	43.9	60.6
	Nyssa sylvatica	19	175	5.6	10.7
	Acer rubrum	10.6	175	3	8.8
	Fraxinus caroliniana	6.3	75	0.2	3
	Living trees				
	Dead trees		75	1.2	
Downstream B	*Taxodium distichum*	30.9	325	27.4	37.6
	Nyssa aquatica	24.8	350	18.6	31.1
	Nyssa sylvatica	16.5	150	3.6	9.6
	Acer rubrum	17.5	225	8.2	16.8
	Fraxinus caroliniana	6.4	100	0.4	4.7
	Living trees		1150	58.4	
	Dead trees		250	2	

DBH = diameter at breast height, BA = basal area, IV = importance value. IV = (Relative density + Relative dominance)/200.

Author's personal copy

Table 3 – Aboveground net primary production (g m^{-2} yr^{-1}) at Bayou Chinchuba and Bayou Castine, St. Tammany Parish, LA, USA

	1999			2000			2002		
	Stem	Leaf	Total	Stem	Leaf	Total	Stem	Leaf	Total
Bayou Castine									
A	297.8	604.9	902.7	163.9	611.1	775.0	191.6	730.0	921.6
B	204.4	548.1	752.5	182.7	627.0	809.7	260.6	773.0	1033.6
Upstream Chinchuba									
A	623.0	446.0	1069.0	466.6	366.1	832.7	494.2	457.9	952.1
B	369.1	592.2	961.3	348.7	501.0	849.7	470.2	624.1	1094.3
Outfall Chinchuba									
A	333.0	577.6	910.6	420.8	538.8	959.6	319.0	647.0	966.0
B	524.6	446.9	971.5	301.6	493.5	795.1	414.4	485.5	899.9
Downstream Chinchuba									
A	724.3	743.8	1468.1	672.1	745.0	1417.1	254.1	827.5	1081.6
B	425.6	670.5	1096.1	370.7	714.2	1084.9	292.4	775.6	1068.0

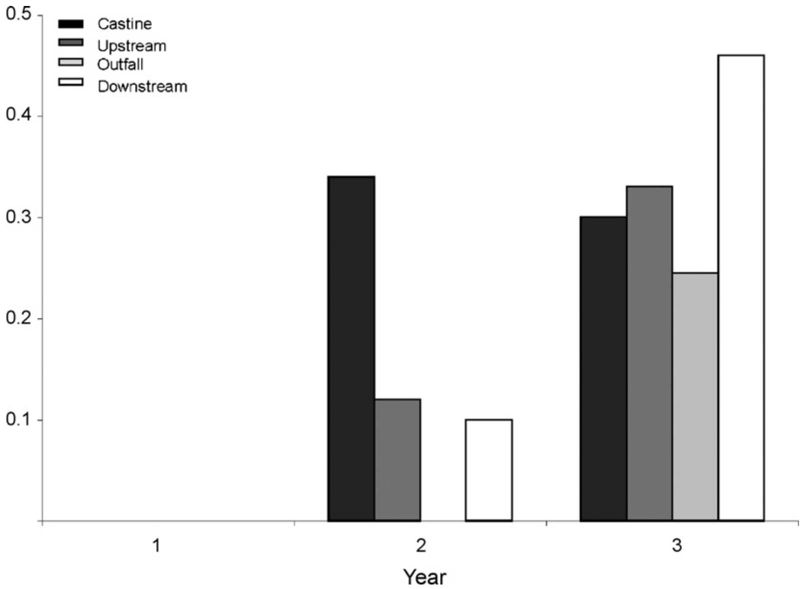


Fig. 5 – Tree mortality in the study area. Units are percent per year.

al., 2004). For coastal wetland forests in Louisiana, fresh water from municipal effluent and riverine discharges can be important in buffering salinity intrusion, especially in drought years (Day et al., 2000a; Martin and Shaffer, 2005; Myers et al., 1995; Shaffer et al., 2001; McKee et al., 2004).

5.2. *Water chemistry*

There were reductions in nutrient concentrations in Bayou Chinchuba with distance from the plant, indicating nutrient assimilation in the swamp system. This is consistent with

Table 4 – Total accretion (mm) and accretion rates (mm yr^{-1}) (mean ± S.E.) utilizing feldspar technique for wetland plots near Mandeville, St. Tammany Parish, LA, USA

	Total accretion (April 99–October 00)	Accretion rate (April 99–October 00)	Total accretion (April 99–October 04)	Accretion rate (April 99–October 04)
Chinchuba Ridge	8.0 ± 1.7	5.3 ± 1.2	51.3 ± 0.8	9.3 ± 0.1
Chinchuba Mid	9.0 ± 1.5	6.0 ± 1.0	55.5 ± 0.8	10.1 ± 0.2
Chinchuba Bayou	23.0 ± 4.0	15.3 ± 2.7	65.1 ± 1.3	11.8 ± 0.3
Castine Ridge	36.0 ± 2.7	24.0 ± 1.8	43.5 ± 2.0	7.9 ± 0.4
Castine Mid	13.9 ± 1.0	9.3 ± 0.7	14.8 ± 0.7	2.7 ± 0.1
Castine Bayou	7.9 ± 0.7	5.3 ± 0.5	11.6 ± 1.4	2.1 ± 0.3

Author's personal copy

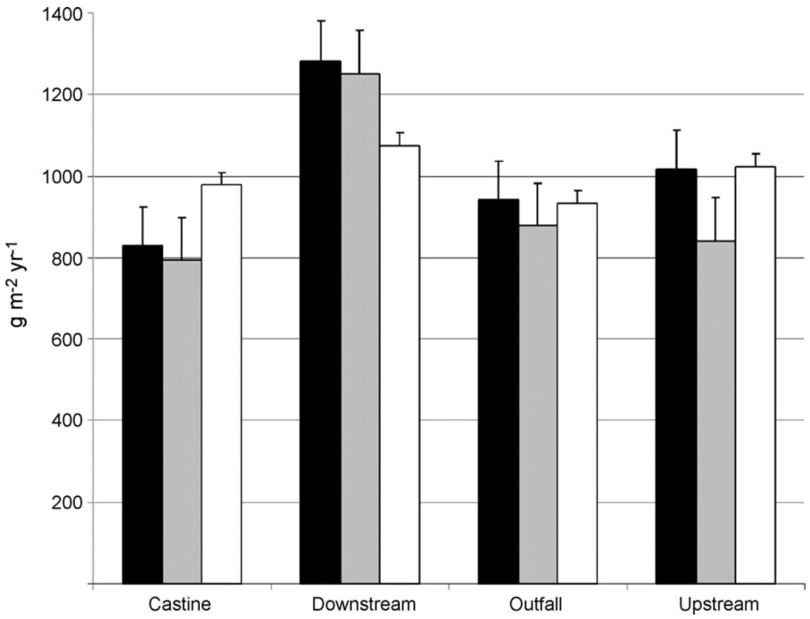


Fig. 6 – Aboveground net primary productivity at paired forest plots near Mandeville, LA for three annual periods. 1999—black bars, 2000—shaded bars, and 2001—white bars.

findings for other wetlands in Louisiana and elsewhere (Zhang et al., 2000; Blahnik and Day, 2000; Day et al., 2004; Mitsch et al., 2001, 2005; Lane et al., 1999, 2001, 2003). The results for nutrient concentrations were similar to values reported for other wetland forests in Louisiana and other areas (Kemp and Day, 1984; Zhang et al., 2000; Day et al., 2004; Lane et al., 2003). Water chemistry parameters measured at control sites along Bayou Castine were not significantly different to those collected at the upstream location of Bayou Chinchuba.

We used these results to calculate nutrient loading and uptake for Bayou Chinchuba based on the initial loading amount from the outfall of the wastewater facility. For Bayou Chinchuba, the percent reduction of nitrate-nitrite was approximately 82% between the outfall station and Bayou Chinchuba at Lake Pontchartrain, for most sampling periods. The percent reduction of total nitrogen between these stations was approximately 59% for the study. Total phosphorus reductions ranged from 25% to 93% with an average reduction of 69% over the study. The lowest reduction percentages generally corresponded to times when high rainfall events decreased the residence time of water from Bayou Chinchuba into Lake Pontchartrain.

Nutrient inflow into a wetland is normally expressed as a loading rate, which integrates the nutrient concentration and volume of the inflow and the area of the receiving wetland, usually expressed as g N or P $m^{-2}\,yr^{-1}$. Most authors have shown that nutrient removal is inversely related to the loading rate (Richardson and Nichols, 1985; Kadlec and Knight, 1996; Mitsch et al., 2001, 2005; Fisher and Acreman, 2004). At low loading rates nutrient removal efficiency is high. But, as loading rates increase, nutrient removal efficiency decreases rapidly (Richardson and Nichols, 1985; Kadlec and Knight, 1996). Average total nitrogen loading rate for the 98 ha area below the outfall on Bayou Chinchuba was 20.1 g $m^{-2}\,yr^{-1}$ and the average loading rate for total phosphorus was 5.4 g $m^{-2}\,yr^{-1}$ (Table 5).

5.3. *Forest composition and productivity*

Bayou Chinchuba and Bayou Castine have stem densities and basal areas that are similar to other forested wetlands in the southeastern U.S. (Conner and Day, 1982). These forest structure indices are also similar to or higher than at the Amelia wetland assimilation site (Brantley, 2005) and the Breaux Bridge wetland assimilation site (Delgado-Sanchez, 1995), and much higher than at the Thibodaux wetland assimilation site (Rybczyk, 1997). The forest composition at Bayou Chinchuba and Bayou Castine appears to be correlated with the floodplain width and distance from Lake Pontchartrain (i.e., salinity). As noted by Rheinhardt et al. (1998), for other low-order streams in the coastal plain, swamp blackgum usually dominates these forested wetlands in the headwa-

Table 5 – Percent nutrient reductions from the outfall to the 1200 m station and loading rates for wastewater treatment at a 98 ha area near Mandeville, St. Tammany Parish, LA

Nutrient	Effluent concentration ($mg\,l^{-1}$)	Outlet % reduction	Loading rate ($g\,m^{-2}\,yr^{-1}$)
Total N	7.5	65	20.1
Total P	2	50	5.4

Author's personal copy

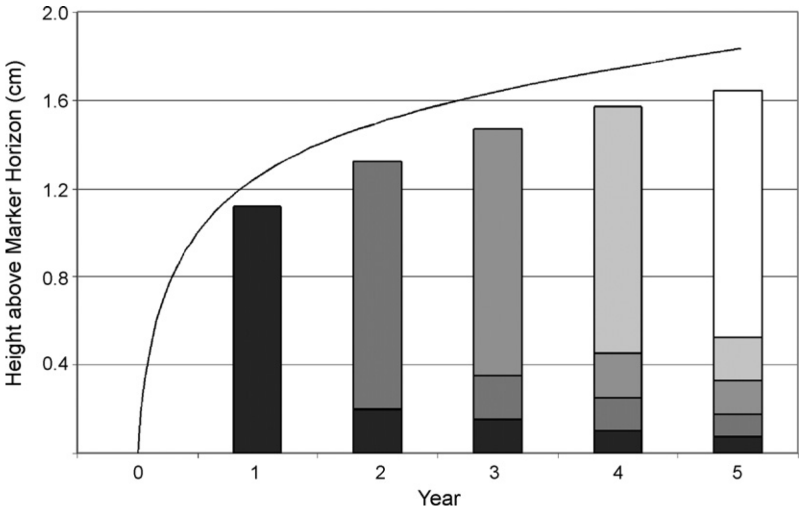


Fig. 7 – Marsh accretion near Mandeville, LA. Different shadings on the bars show compaction and consolidation of each year's cohort over time. Line indicates that compaction and consolidation is non-linear at this site.

ters, while water tupelo and baldcypress typically dominate mid-reach portions. This is readily apparent in the Bayou Chinchuba plots, as the relative density and relative dominance of swamp blackgum decreases from the upstream to the downstream plots, and both water tupelo and baldcypress dominate the outfall and downstream plots.

The litterfall at the four swamp sites were similar to levels found in other alluvial, flowing water systems in the southeastern U.S. These figures for aboveground production are above averages for similar forest habitats in the southeastern U.S. we noticed differences in the carbon allocation for the amount of stem and leaf growth in the vegetation plots by year which could be affected by the hydrology or the amount of carbon turnover. Clearly, the two downstream plots on Bayou Chinchuba were very productive, likely due to the fertilizing effects of the discharge. This enhanced productivity is similar to other studies involving wetland wastewater treatment, in that, wetland systems can effectuate high nutrient reduction and increase primary productivity (Ewel and Bayley, 1978; Lemlich and Ewel, 1984; Conner et al., 1989, 2002; Rybczyk et al., 1996). Forested wetland systems can provide an additional benefit by storing carbon on a long-term basis.

Tree mortality rates over the first two years were low, however, after the third growing season, rates increased at all areas along Bayou Chinchuba, presumably due to stresses associated with the region wide drought during the study. The mortality rates observed in this study were similar to rates observed by Conner et al. (2002) in areas where the hydrology of the swamp had not been altered. Although these mortality rate increases were not significant, what is of interest, however, is that the downstream receiving area, although experiencing greater mortality, also exhibited enhanced productivity, as surviving trees grew into available growing space. This finding can potentially provide another avenue for carbon sequestration, the rapid turnover, burial and compaction of plant material in wetland systems (Comins and McMurtrie, 1993; Craft et al., 1995; Hamilton et al., 2002; Luo and Reynolds, 1999). Increasing plant productivity from elevated nutrient availability and uptake can lead to rapid carbon turnover, but in a wetland system, the release of carbon back into the atmosphere from decomposition is reduced (Comins and McMurtrie, 1993; Hamilton et al., 2002; Melillo and Aber, 1984; Luo and Reynolds, 1999).

5.4. *Accretion*

Our study confirmed the findings of Rybczyk et al. (2002) that municipal effluent can significantly increase accretion rates and thus help offset RSLR. In their study, Rybczyk et al. (2002) presented a conceptual model of coastal sediment accretion dynamics over time where decomposition, dewatering, and compaction of sediments and organic matter reduce the volume and thickness of each yearly cohort. We modified this conceptual model to include treatment forested wetlands where the yearly cohort is not reduced by decomposition, dewatering and compaction, but instead is subject to high perennial plant productivity (both aboveground and belowground) and nutrient burial over time leading to a linear response as opposed to a curvilinear response in marsh habitats (Fig. 7). Rybczyk et al. (2002) posed several questions as to how the overall accretion balance would change and how the wetland system would respond to a surface that became subaerial. We agree that decomposition rates would increase as the soil became oxygenated and rates of mineral deposition would decrease also, as elevation increased (Rybczyk et al., 2002). However, if nutrient enhanced water were continuously placed over the surface of a forested wetland, high productivity and high rate of carbon turnover can lead to carbon burial, increasing soil elevations, and forcing water above the soil surface, thereby lowering the rate of decomposition (Rybczyk et al., 2002).

The downstream plots had significantly higher primary production as well as higher tree mortality rates. This served to provide more room for expansion of the remaining trees into available growing areas, and also served to place this stored carbon from stems and limbs into the wetland area

Author's personal copy

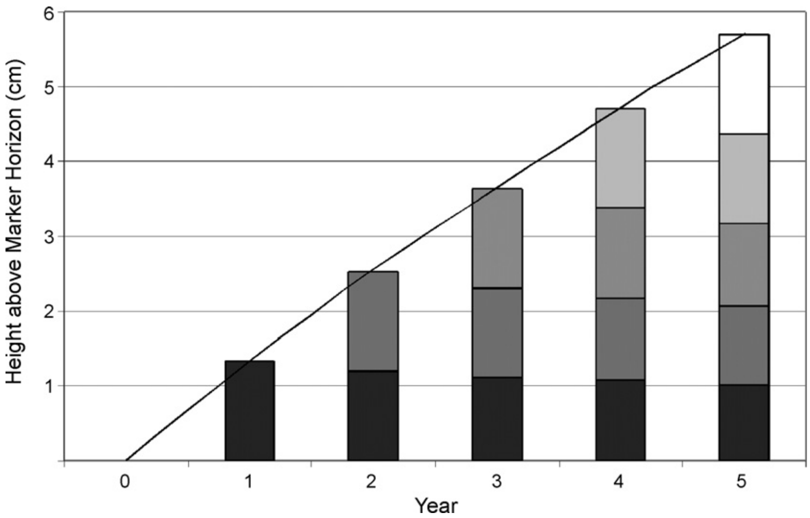


Fig. 8 – Swamp accretion near Mandeville, LA. Different shadings on the bars show compaction and consolidation of each year's cohort over time. Line indicates that compaction and consolidation is linear at this site.

for future burial. Leaf litter contributed significantly higher rates of accretion over time in these plots. The high accretion rate observed downstream of the outfall may be in part due to the mineral soils present at the study site, as this has been shown to increase relative elevation rates in coastal areas (Fig. 8; Day et al., 1999). RSLR in the Lake Pontchartrain basin has been estimated at 4.5 mm yr^{-1} based on tide gauge analysis (Turner, 1991). This area of the Louisiana coastal zone is experiencing lower overall rates of subsidence due to the proximity of Pleistocene sediments near the surface (Penland et al., 1988). RSLR rates are much higher in areas of the former Mississippi River alluvial plain (Turner, 1991). The increased accretion indicates that addition of treated effluent can help coastal forested wetland keep up with accelerated sea level rise.

5.5. *Summary*

In this study conducted on the impact of long-term input of secondarily treated effluent to a wetland ecosystem near the City of Mandeville, St. Tammany Parish, LA, there were positive responses related to nutrient reduction, increased plant productivity and higher accretion downstream of the discharge location. The effluent into the system was a major source of freshwater to the system during a period of drought and provided elevated levels of nutrients to the forested wetland. Removal efficiencies of N and P reached 87% and 93%, respectively. At Bayou Chinchuba, there was a significant input of N and P forms into the forested wetland at the outfall location and significant reductions of N and P forms downstream from the treatment plant. On average, the nitrogen loading rate for the 98 ha area below the outfall on Bayou Chinchuba was 20.1 g m^{-2} yr^{-1} and the loading rate for total phosphorus was 5.4 g m^{-2} yr^{-1}. Aboveground net primary production of the freshwater forest system and accretion rates were both high downstream of the effluent discharge. The aboveground production on the downstream forest plots at Bayou Chinchuba was significantly higher than the other three reference plots, likely due to the fertilizing effects of the discharge. This enhanced productivity is similar to other studies involving wetland wastewater assimilation. Accretion rates downstream of the outfall were significantly higher than the reference location. Management or re-direction of nutrient-enhanced effluents to wetland ecosystems can maintain plant productivity, sequester carbon, and maintain coastal wetland elevations in response to sea-level rise.

Acknowledgements

This study was funded by the City of Mandeville, LA. We acknowledge support of the personnel of the Department of Public Works of Mandeville, especially Mr. Joe Mistich. C. Coronado, B. Perez, R. Pratt and A. Westphal provided help in the field and laboratory. We appreciate the review of the manuscript by P. Templet, D. Justic, J. Cable and M. Levitan.

REFERENCES

Barbour, M.G., Burk, J.H., Pitts, W.D., 1980. Terrestrial Plant Ecology. Benjamin/Cummins Publishing Company, 604 pp.

Baumann, R.H., Day, J.W., Miller, C., 1984. Mississippi deltaic wetland survival: sedimentation versus coastal submergence. Science 224, 1093–1095.

Bayley, S.E., Zoltek Jr., J., Hermann, A.J., Tortora, L., 1985. Experimental manipulation of nutrients and water in a freshwater marsh: effects on biomass, decomposition and nutrient accumulation. Limnol. Ocean. 30, 500–512.

Blahnik, T., Day, J.W., 2000. The effects of varied hydraulic and nutrient loading rates on water quality and hydrologic distributions in a natural forested wetland. Wetlands 20, 48–61.

Boesch, D.F., Josselyn, M.N., Mehta, A.J., Morris, J.T., Nuttle, W.K., Simenstad, C.A., Swift, D.J.P., 1994. Scientific assessment of coastal wetland loss, restoration and management in Louisiana. J. Coast. Res. 20, 1–84.

Author's personal copy

Boumans, R., Day, J., Kemp, P., Kilgen, K., 1997. The effect of intertidal sediment fences on wetland surface elevation, wave energy and vegetation establishment on two Louisiana coastal marshes. Ecol. Eng. 9, 37–50.

Boyt, F.L., Bayley, S.E., Zoltek Jr., J., 1977. Removal of nutrients from treated municipal wastewater by wetland vegetation. J. Water Poll. Cont. Fed. 49, 789–799.

Brantley, C.G., 2005. Nutrient interactions, plant productivity, soil accretion, and policy implications of wetland enhancements in coastal Louisiana. Ph.D. Dissertation. Louisiana State University, Baton Rouge, LA.

Breaux, A.M., Day Jr., J.W., 1994. Policy considerations for wetland wastewater treatment in the coastal zone: a case study for Louisiana. Coast. Manage. 22, 285–307.

Burnison, B.K., 1980. Modified dimethyl sulfoxide (DMSO) extraction for chlorophyll analysis of phytoplankton. Can. J. Fish. Aquat. Sci. 37, 729–733.

Cahoon, D.R., Reed, D.J., Day Jr., J.W., 1995. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. Marine Geol. 128, 1–9.

Comins, H.N., McMurtrie, R.E., 1993. Long-term response of nutrient-limited forests to CO_2 enrichment-equilibrium behavior of plant–soil models. Ecol. Appl. 3, 666–681.

Conner, W.H., Day Jr., J.W., 1982. The ecology of forested wetlands in the southeastern United States. In: Wetlands: Ecology and Management. International Scientific Publications, Jaipur, India, pp. 69–87.

Conner, W.H., Day Jr., J.W., Bergeron, J.D., 1989. A Use Attainability Analysis of Wetlands for Receiving Treated Municipal and Small Industry Wastewater: A Feasibility Study Using Baseline Data from Thibodaux, LA. Center for Wetland Resources, Louisiana State University, Baton Rouge, LA, 78 pp.

Conner, W.H., Mihalia, I., Wolfe, J., 2002. Tree community structure and changes from 1987 to 1999 in three Louisiana and three South Carolina forested wetlands. Wetlands 22, 58–70.

Craft, C.B., Richardson, C.J., 1993. Peat accretions and phosphorus accumulation along a eutrophication gradient in the northern Everglades. Biogeochemistry 22, 133–156.

Craft, C.B., Vymazal, J., Richardson, C.J., 1995. Response of Everglades plant communities to nitrogen and phosphorus additions. Wetlands 15, 258–271.

Day, J.W., Breaux, A.M., Hesse, I.D., Rybczyk, J.M., 1992. Wetland wastewater treatment in the Louisiana coastal zone. In: Barataria-Terrebone National Estuary Program: Data Inventory Workshop Proceedings.

Day, J., Rybczyk, J., Scarton, F., Rismondo, A., Are, D., Cecconi, G., 1999. Soil accretionary dynamics, sea-level rise and the survival of wetlands in Venice Lagoon: a field and modeling approach. Estuar. Coast. Shelf Sci. 49, 607–628.

Day Jr., 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., Mistich, 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., Jr., Brantley, C.G., Kemp, G.P., Pratt, R., Day, J.N., Lane, R., Mistich, J.A., 2000a. A use attainability analysis of municipal wastewater discharge to coastal wetlands at Mandeville, Louisiana. Coastal Ecology Institute Report, Louisiana State University, prepared for City of Mandeville, Louisiana.

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

Deghi, G.S., Ewel, K.C., Mitsch, W.J., 1980. Effects of sewage effluent application on litter fall and litter decomposition in cypress swamps. J. Appl. Ecol. 17, 397–408.

Delaune, R.D., Baumann, R.H., Gosselink, J.G., 1983. Relationships among vertical accretion, coastal submergence, and erosion in a Louisiana Gulf Coast marsh. J. Sediment. Petrol. 53, 0147–0157.

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

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.

Delgado-Sanchez, P., 1995. Effects of long-term wastewater discharge in the Cypriere Perdue forested wetland at Breaux Bridge, Louisiana. M.S. thesis. LA State University, Baton Rouge, LA.

Ewel, K.C., Bayley, S.E., 1978. Cypress strand receiving sewage at Waldo. Cypress wetlands for water management, recycling, and conservation. Fourth Annual Report to National Science Foundation, pp. 750–801.

Ewel, C.E., Odum, H.T., 1984. Cypress Swamps. University Press of Florida, 472 pp.

Faulkner, S.P., Richardson, C.J., 1989. Physical and chemical characteristics of freshwater wetland soils. In: Constructed Wetlands for Wastewater Treatment. Lewis Publishers, MI, pp. 41–72.

Felley, J.D., 1992. Medium-low-gradient streams of the Gulf Coastal Plain. In: Biogeography of the Southeastern United States. John Wiley and Sons, pp. 233–269.

Fisher, J., Acreman, M.C., 2004. Wetland nutrient removal: a review of the evidence. Hydrol. Earth Syst. Sci. 8, 673–685.

Gibson, W.M., Gill, S.K., 1988. Analysis of tidal variations of Lake Pontchartrain and the Mississippi Sound. NOAA Technical Memorandum NOS OMA 36.

Greenburg, A.E., Trussell, R.R., Clesceri, L.S., Franson, M.A.H., 1985. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Washington, DC.

Hamilton, J.G., Delucia, E.H., George, K., Naidu, S.L., Finzi, A.C., Schlesinger, W.H., 2002. Forest carbon balance under elevated CO_2. Oecologia 131, 250–260.

Hatton, R.S., Delaune, R.D., Patrick, W.H., 1983. Sedimentation, accretion, and subsidence in marshes of Barataria Basin, Louisiana. Limnol. Ocean. 28, 494–502.

Hemond, H.F., Benoit, J., 1988. Cumulative impacts on water quality functions of wetlands. Environ. Manage. 12, 639–653.

Hesse, I.D., Day Jr., J.W., Doyle, T.W., 1998. Long-term growth enhancement of baldcypress (*Taxodium distichum*) from municipal wastewater application. Environ. Manage 22, 119–127.

Kadlec, R.H., Alvord Jr., H., 1989. Mechanisms of water quality improvement in wetland treatment systems. In: Wetlands: Concerns and Successes. Proceedings sponsored by American Water Resources Association, September 17–22, 1989, Tampa, FL, pp. 489–498.

Kadlec, R.H., Knight, R.L., 1996. Treatment Wetlands. Lewis Publishers, Boca Raton, FL, 893 pp.

Keim, B.D., Faiers, G.E., Muller, R.A., Grymes III, J.M., Rohli, R.V., 1995. Longterm trends of precipitation and runoff in Louisiana, USA. Int. J. Climatol. 15, 531–541.

Kemp, G.P., Conner, W.H., Day Jr., J.W., 1985. Effects of flooding on decomposition and nutrient cycling in a Louisiana swamp forest. Wetlands 5, 35–51.

Author's personal copy

Kemp, G.P., Day Jr., J.W., 1984. Nutrient dynamics in a Louisiana swamp receiving agricultural runoff. In: Ewel, K.C., Odum, H.T. (Eds.), Cypress Swamps, pp. 286–293.
Khalid, R.A., Gambrell, R.P., Patrick Jr., W.H., 1981a. An overview of the utilization of wetlands for wastewater organic carbon removal. In: Progress in Wetlands Utilization and Management. Proceedings of a Symposium, 9–12 June, 1981, Orlando, FL, pp. 405–423.
Khalid, R.A., Holford, I.C.R., Mixon, M.N., Patrick, W.H., 1981b. Nitrogen and phosphorus reactions in overland flow of wastewater. U.S. Environmental Protection Agency, EPA-600/S2-81-150.
Kitchens Jr., W.F., Dean, J.M., Stevenson, L.H., Cooper, J.H., 1975. The Santee Swamp as a nutrient sink. In: Mineral Cycling in Southeastern Ecosystems. ERDA Symposium Series 36. Energy Research and Development Administration, Washington, DC, pp. 349–366.
Knight, R.L., McKim, T.W., Kohl, H.R., 1987. Performance of a natural wetland treatment system for wastewater management. J. Water Poll. Cont. Fed. 59, 746–754.
Knight, R.L., 1992. Natural land treatment with Carolina bays. Water Environ. Tech. 4, 13–16.
Kuenzler, E.J. 1987. Impacts of sewage effluent on tree survival, water quality and nutrient removal in coastal plain swamps. Report no. 235 of the Water Resources Research Institute of the University of North Carolina, Chapel Hill, NC, 91 pp.
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.R., Day, J.W., Kemp, G.P., Demcheck, D.M., 2001. The 1994 experimental opening of the Bonnet Carre Spillway to divert Mississippi River water into Lake Pontchartrain, Louisiana. Ecol. Eng. 17, 411–422.
Lane, R.R., Mashriqui, H.S., Kemp, G.P., Day, J.W., Day, J.N., Hamilton, A., 2003. Potential nitrate removal from a river diversion into a Mississippi delta forested wetland. Ecol. Eng. 20, 237–249.
Lemlich, S.K., Ewel, K.C., 1984. Effects of wastewater disposal on growth rates of cypress trees. J. Environ. Qual. 13, 602–604.
Luo, Y., Reynolds, J.F., 1999. Validity of extrapolating field CO_2 experiments to predict carbon sequestration in natural ecosystems. Ecology 80, 1568–1583.
Martin, S.B., Shaffer, G.P., 2005. Sagittaria biomass partitioning relative to salinity, hydrological regime, and substrate type: implications for plant distribution patterns in coastal Louisiana, USA. J. Coast. Res. 21, 164–171.
McKee, K., Mendelssohn, I.A., Materne, M.D., 2004. Acute salt marsh dieback in the Mississippi River deltaic plain: a drought induced phenomenon? Global Ecol. Biogeogr. 13, 65–73.
Mendelssohn, I.A., Morris, J.T., 2000. Eco-physiological controls on the productivity of Spartina alterniflora loisel. In: Weinstein, M.P., Kreeger, D.A. (Eds.), Concepts and Controversies in Tidal Marsh Ecology. Kluwer Academic Publishers, Boston, MA, pp. 59–80.
Megonigal, J.P., Conner, W.H., Kroeger, S., Sharitz, R.R., 1997. Aboveground production in southeastern floodplain forests: a test of the subsidy-stress hypothesis. Ecology 78, 370–384.
Melillo, J.M., Aber, J.D., 1984. Nutrient immobilization in decaying litter: an example of C-nutrient interactions. In: Trends in Ecological Research for the 1980s. Plenum Press, pp. 193–215.
Mitsch, W.J., Day Jr., J.W., Gilliam, J.W., Groffman, P.M., Hey, D.L., Randall, G.W., Wang, N., 2001. Reducing N loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to counter a persistent ecological problem. BioScience 51, 373–388.
Mitsch, W.J., Jorgenson, S.E., 2004. Ecological Engineering and Ecosystem Restoration. J. Wiley, New York, 411 pp.
Mitsch, W., Day, J., Zhang, L., Lane, R., 2005. Nitrate-nitrogen retention in wetlands in the Mississippi River basin. Ecol. Eng. 24, 267–278.
Mossa, J., 1996. Sediment dynamics in the lowermost Mississippi River. Eng. Geol. 45, 457–479.
Mudroch, A., Capobianco, J.A., 1979. Effects of treated effluent on a natural marsh. J. Water Poll. Cont. Fed. 51, 2243–2256.
Myers, R.S., Shaffer, G.P., Llewellyn, D.W., 1995. Baldcypress restoration in southeast Louisiana: the relative effects of herbivory, flooding, competition, and macronutrients. Wetlands 15, 141–148.
Nessel, J.K., 1978. Distribution and dynamics of organic matter and phosphorus in a sewage enriched cypress swamp. M.S. thesis. University of Florida, Gainesville, FL.
Nessel, J.K., Bayley, S.E., 1984. Distribution and dynamics of organic matter and phosphorus in a sewage-enriched cypress swamp. In: Cypress Swamps. University Presses of Florida, Gainesville, FL, pp. 262–278.
Newbould, P.J., 1967. Methods for Estimating the Primary Productivity of Forests. Wilmer Brothers, Ltd, London.
Nichols, D.S., 1983. Capacity of natural wetlands to remove nutrients from wastewater. J. Water Poll. Cont. Fed. 55, 495–505.
NOAA, 2003. National weather data in electronic form. National Oceanographic and Atmospheric Administration, National Weather Service.
Odum, H.T., 1975. Energy quality and carrying capacity of the earth. Trop. Ecol. 16, 1–8.
Odum, H.T., 1978. Value of wetlands as domestic ecosystems. Cypress Wetlands for Water Management, Recycling, and Conservation. Fourth Annual Report to National Science Foundation and the Rockefeller Foundation, pp. 910–930.
Patrick, W.H., Jr., 1990. Microbial reactions of nitrogen and phosphorus in wetlands. The Utrecht Plant Ecology News Report, Utrecht, The Netherlands, pp. 52–63.
Penland, S., Ramsey, K.E., McBride, R.A., Mestayer, J.T., Westphal, K.A., 1988. Relative sea level rise and delta plain development in the Terrebone parish region. Coastal Geology Technical Report, Louisiana Geological Survey, Baton Rouge, LA, 121 pp.
Rheinhardt, R.D., Rheinhardt, M.C., Brinson, M.M., Fraser, K., 1998. Forested wetlands of low order streams in the inner coastal plain of North Carolina, USA. Wetlands 18, 365–378.
Richardson, C.J., Davis, J.A., 1987. Natural and artificial ecosystems: ecological opportunities and limitations. In: Aquatic Plants for Water Treatment and Resource Recovery. Magnolia Publishing, Inc., Orlando, FL, pp. 819–854.
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.
Roberts, H.H., 1997. Dynamic changes of the Holocene Mississippi river delta plain: the delta cycle. J. Coast. Res. 13, 605–627.
Rybczyk, J.M., 1997. The use of secondarily treated wastewater effluent for forested wetland restoration in a subsiding coastal zone. Ph.D. Dissertation. Louisiana State University, Baton Rouge, LA.
Rybczyk, J.M., Day Jr., J.W., Conner, W.H., 2002. The impact of wastewater effluent of accretion and decomposition in a subsiding forested wetland. Wetlands 22, 18–32.
Rybczyk, J.M., Day, J.W., Hesse, I.D., Delgado Sanchez, P., 1996. An overview of forested wetland wastewater treatment projects in the Mississippi River delta region. In: Kathryn Flynn (Ed.), Proceedings of the Southern Forested Wetlands Ecology and Management Conference. Clemson University, SC, pp. 78–82.
Sall, J., Creighton, L., Lehman, A., 2005. JMP Start Statistics: A Guide to Statistical and Data Analysis Using JMP and JMP IN

Author's personal copy

Software. Brooks/Cole-Thompson Learning, Belmont, CA.
Shaffer, G.P., Willis, J.M., Hoeppner, S.S., Parsons, A.C., Hester, M.W., 2001. Characterization of ecosystem health of the Maurepas Swamp, Lake Pontchartrain Basin, Louisiana: feasibility and projected benefits of a freshwater diversion. Diversion into the Maurepas Swamps: Complex Project Coastal Wetlands Planning, Protection, and Restoration Act. US EPA, Region Six Report WA #5-02.
Shih, S.F., Hallett, D.W., 1974. Impact of upland marsh on water quality. Internal Report, Department of Resource Planning, Central and Southern Florida Flood Control District, West Palm Beach, FL.
Stevenson, J.C., Ward, L.G., Kearney, M.S., 1986. Vertical accretion in marshes with varying rates of sea level rise. In: Estuarine Variability. Academic Press, NY, pp. 241–260.
Strickland, J.D.H., Parsons, T.R., 1972. A Practical Handbook of Seawater Analysis. Bulletin 167. The Fisheries Research Board of Canada.
Terzaghi, K., Peck, R.B., 1968. Soil mechanics and Engineering Practice, second ed. John Wiley and Sons, Inc., New York, 55 pp.
Trahan, L., Bradley, J.J., Morris, L., Nolde, R., 1990. Soil survey of St. Tammany Parish, Louisiana. USDA, Soil Conservation Service.
Turner, R.E., 1991. Tide gauge records, water level rise, and subsidence in the northern Gulf of Mexico. Estuaries 14, 139–147.
Tuschall, J.R., Brezonik, P.L., Ewel, K.C., 1981. Tertiary treatment of wastewater using flow-through wetland systems. In: Proceedings of 1981 Annual Conference of the American Society of Civil Engineers, Environmental Division.
U.S. Environmental Protection Agency, 1979. Standard methods.
U.S. Environmental Protection Agency, 1987. Report on the Use of Wetlands for Municipal Wastewater Treatment and Disposal. Office of Water, Office of Municipal Pollution Control. EPA 430/09-88-005.
U.S. Geological Survey, 1998. Water Resources Data, Louisiana, Water Year 1998. Water-Data Report LA-98-1.
Wharton, C.H., 1970. The southern river swamp—a multiple use environment. School of Business Administration, Georgia State University, Atlanta, GA.
Yarbro, L.A., 1979. Phosphorus cycling in the Creeping Swamp floodplain ecosystem and exports from the Creeping Swamp watershed. Ph.D. Dissertation. University of North Carolina, Chapel Hill, NC, 231 pp.
Yarbro, L.A., Kuenzler, E.J., Mulholland, P.L., Sniffen, R.P., 1982. The influence of swamp floodplain on exports of nitrogen and phosphorus from North Carolina coastal plain watersheds. In: Proceedings of the Symposium, Progress in Wetlands Utilization and Management, Coordinating Council on Restoration of Kissimmee River and Taylor Creek-Nubbin Slough Basin, pp. 225–241.
Zhang, X., Feagley, S.E., Day, J.W., Conner, W.H., Hesse, I.D., Rybczyk, J.M., Hudnall, W.H., 2000. A water chemistry assessment of wastewater remediation in a natural swamp. J. Environ. Qual. 29, 1960–1968.