WETLANDS, Vol. 26, No. 4, December 2006, pp. 1130–1142

WETLAND SURFACE ELEVATION, VERTICAL ACCRETION, AND SUBSIDENCE AT THREE LOUISIANA ESTUARIES RECEIVING DIVERTED MISSISSIPPI RIVER WATER

Robert R. Lane[1], John W. Day Jr.[1,2], and Jason N. Day
[1]*School of the Coast and Environment*
[2]*Department of Oceanography and Coastal Sciences*
School of the Coast and Environment
Louisiana State University
Baton Rouge, Louisiana, USA 70803
E-mail: rlane@lsu.edu

Abstract: Wetland surface elevation and vertical accretion were measured from 1996 to 1999–2000 using a sediment elevation table (SET) and feldspar marker horizons in nine paired wetlands receiving Mississippi River water from the Caernarvon, West Pointe a la Hache (WPH), and Violet river diversions. The Caernarvon study sites had wetland surface elevation change rates ranging from 0.16±0.31 to 0.42±0.21 cm y^{-1}. Vertical accretion ranged from 0.75±0.04 to 1.57±0.05 cm y^{-1}, and shallow subsidence ranged from 0.59 to 1.21 cm y^{-1}. Wetland surface elevation at the WPH study sites initially increased 2.3 to 3.3 cm during the first seven months of the study and then steadily decreased over the following year. The overall rate of elevation change ranged from 0.27±0.09 to 0.70±0.11 cm y^{-1}. Vertical accretion and shallow subsidence ranged from 1.24±0.08 to 1.84±0.07 cm y^{-1} and 0.54 to 1.27 cm y^{-1}, respectively. The Violet sites lost elevation and had the highest subsidence rates in this study, most likely due to a combination of hydrologic alteration and low diversion discharge. Wetland elevation decreased throughout the study, with rates ranging from −1.10±0.24 to −2.34±0.41 cm y^{-1}. Vertical accretion and shallow subsidence rates at the Violet-Near and Far sites were 0.44±0.10 and 0.44±0.11 cm y^{-1} and 2.78 to 1.54 cm y^{-1}, respectively. The Violet-Mid site wetland was burned in Winter 1999, leading to more than 4.0 cm decrease in material measured over the marker horizon and contributing to the lowest accretion rate measured in this study of 0.34±0.05 cm y^{-1}. Analysis of regional relative sea-level rise (RSLR) indicates that all Caernarvon sites and the WPH-Near and Mid sites are keeping pace with RSLR. This study indicates that the use of river diversions can be an effective coastal restoration tool, with efficiency related to the proximity to riverine source and degree of hydrologic alteration, quantity of river water released, and land uses of the receiving wetland basin. Landscape modifications such as spoil banks associated with oil and gas access canals negate the benefits of river water introduction by limiting wetland-water interaction and should be removed in conjunction with river diversion implementation for effective wetland restoration.

Key Words: SET, wetland restoration, river diversion, wetland elevation, accretion, subsidence

INTRODUCTION

Prior to human modification, the Mississippi River was hydrologically connected to the deltaic plain by several major distributaries, such as Bayou LaFourche (Roberts 1997), and many minor distributaries, such as Bayou Terra aux Boeufs, River aux Chenes (Oak River), and Grande Bayou located in our study areas (Welder 1959). Although partially filled with sediment and obscured or deteriorated at their seaward ends by wave erosion and subsidence, the remnants of these minor distributaries are easily distinguishable in many places (Figure 1). These minor distributaries supplied river water to broad areas of the deltaic plain during high river stage, and crevasses supplied exceptionally large quantities of river water to wetlands directly surrounding the Mississippi River (Welder 1959, Hatton et al. 1983, Kesel 1988, 1989, Roberts 1997, Davis 2000, Day et al. 2000). Davis (2000) documented 16 recurring crevasse sites of the Mississippi River from 1750 to 1927 located between New Orleans, Louisiana, USA, and the mouth of the river. This yearly input of fresh water, suspended sediments, and nutrients stimulated primary and secondary production throughout the delta (Delaune et al. 1983, Hatton et al. 1983, Day et al. 2001, DeLaune and Pezeshki 2003, DeLaune et al. 2003) and maintained a salinity gradient that supported a high diversity of wetland and aquatic habitats for estuarine species (Day et al. 1997).

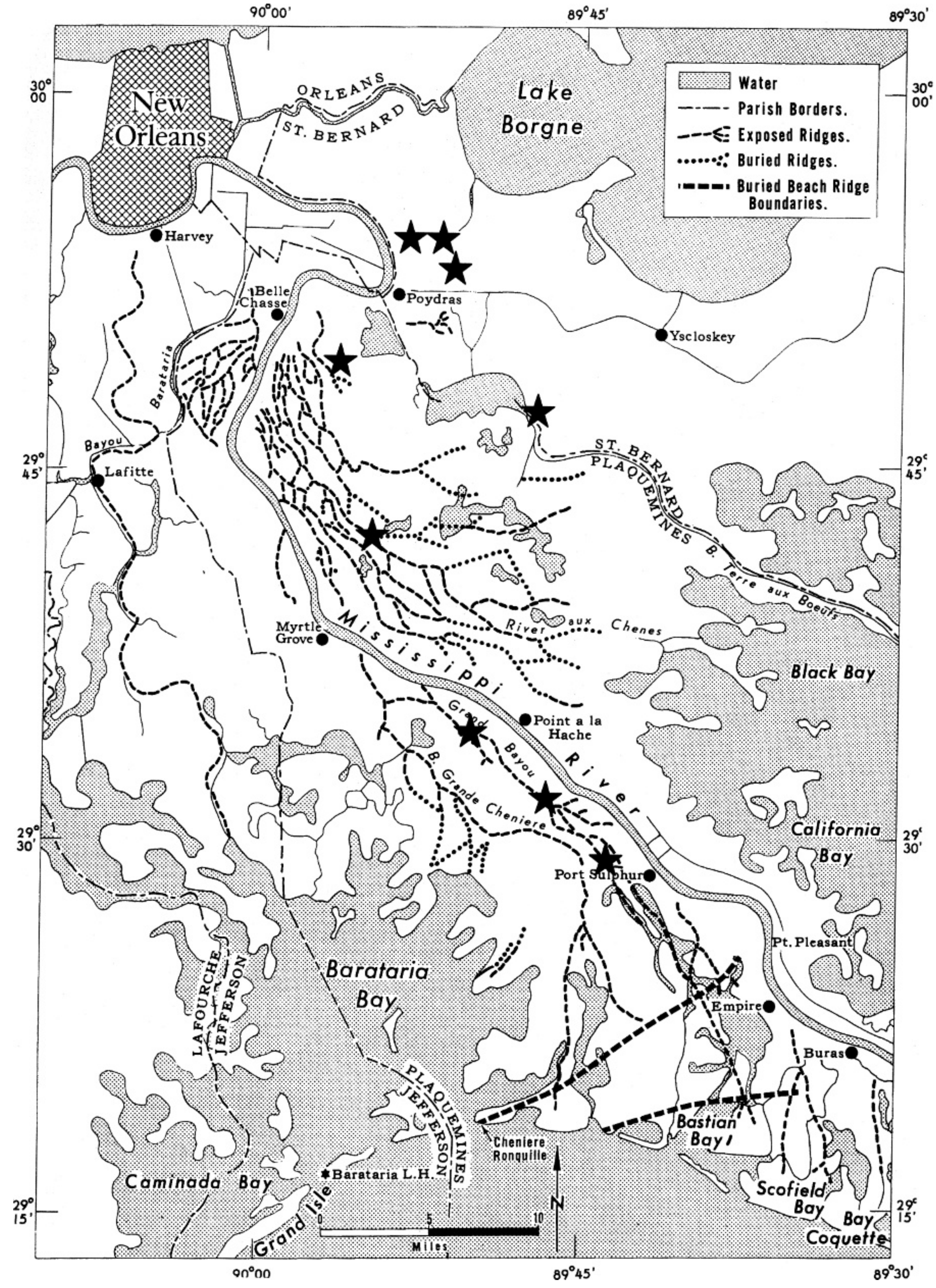

Figure 1. Abandoned minor distributaries of the Mississippi River, as indicated by buried ridges (taken from Welder 1959). Stars indicate locations of study sites.

The construction of flood-control levees and closure of distributary channels began soon after colonization of New Orleans by the French in 1719 (Welder 1959, Boesch 1996, Colten 2000). After the great flood of 1927, levees were upgraded and made continuous almost to the mouth of the river, completing hydrologic separation of the delta from the river (Kesel 1988, 1989, Mossa 1996). In addition, canal dredging and spoil-bank construction associated primarily with the oil and gas industry further altered the natural hydrology of the delta, promoting saltwater intrusion events and limiting hydrologic exchange (Bass and Turner 1977, Deegan 1984, Swenson and Turner 1987). Also, massive clear-cut logging of Louisiana's forested wetlands eliminated virtually all old growth cypress-tupelo stands by 1950 (Mancil 1972). These modifications to the coastal landscape have led to the loss of about 4500 km^2 of wetlands during the 20^{th} century (Salinas et al. 1986, Boesch et al. 1994, LDNR 1998, Day et al. 2000).

Wetland elevation is directly influenced by a complex relationship between subsidence and accretion. Subsidence is defined as all local factors that contribute to the lowering of wetland elevation, including compaction and consolidation of sediments (both shallow and deep), tectonic activity, and human impacts such as oil and gas withdrawal (Callaway et al. 1996, Morton et al. 2002). Subsidence in some areas of the Mississippi delta is in excess of 10 mm y^{-1} (Penland and Ramsey 1990). Accretion is defined as the vertical accumulation of material on the wetland surface, as measured using a marker (i.e., feldspar, ^{137}Cs, ^{210}Pb; Callaway et al. 1996). Relative sea-level rise (RSLR) is defined as the sum of eustatic sea-level rise (l-2 mm y^{-1}, Gornitz et al. 1982) and subsidence. In order for a wetland to have long-term stability, wetland surface elevation gain must be equal to or greater than RSLR (Day et al. 1997).

There is a strong consensus in the scientific and management community that one of the major restoration strategies for the long-term survival of Louisiana's coastal wetlands depends on the reintroduction of river flow into the interdistributary basins of the Mississippi delta (Templet and Meyer-Arendt 1988, Kesel 1989, Boesch 1996, Day et al. 1997, 2000, 2005, Gosselink 2001, Boesch et al. 1994, 2006). The State of Louisiana and U.S. federal government have developed a plan for river diversions that will mimic flooding events of the Mississippi River (Chatry and Chew 1985, LDNR 1998). This study focuses three such diversions located at Caernarvon, West Pointe a la Hache (WPH), and Violet. These diversions are for the most part located where minor distributaries and crevasses of the Mississippi River occurred historically (Welder 1959, Davis 2000). The objective of this study was to measure wetland surface elevation, vertical accretion, and shallow subsidence in wetlands affected by the diversions, and evaluate the relative effect of the diversions on these parameters. We hypothesized that sites near diversions would have greater vertical accretion and wetland surface elevation gain than those further away.

STUDY AREAS

This study focuses on the Caernarvon, West Pointe a la Hache (WPH), and Violet Mississippi River diversions (Figure 2). These diversion projects vary widely in the amount of water being diverted and characteristics of the receiving wetlands. Below is a brief summary of each diversion structure and receiving basin.

Caernarvon

Caernarvon is one of the largest river diversions currently operational in the Mississippi delta. The structure was completed in 1991, and river water discharge began in August of that year. The diversion structure is located on the east bank of the Mississippi River near Caernarvon, Louisiana, at river mile 81.5 (131.2 km, Figure 2), and consists of five 4.6-m-wide box culverts with vertical lift gates. The structure has capability of passing 226 m^3s^{-1} of water, but flow averaged only 21 m^3s^{-1} from 1991 to 2000. Discharge from the Caernarvon structure is calculated from a rating curve developed by the Louisiana Department of Natural Resources (Chuck Villarubia, pers. comm.). The diversion discharges river water into a large artificial lake, Big Mar, caused by a failed agricultural impoundment, and then reaches the Gulf of Mexico through two main routes with considerable overland flow en route (Lane et al. 2003, Snedden 2006). Between the Caernarvon diversion and the Gulf of Mexico, there are about 1100 km^2 of fresh to saline marshes. The Breton Sound wetlands were first formed several thousand years ago as part of the Plaquemines-St. Bernard delta complex (Scruton 1960, Roberts 1997). Since then, approximately half of the original wetlands have disappeared by the processes of shore-face erosion and coastal subsidence (Penland et al. 1988). The remaining wetlands, however, are relatively stable and have not experienced as great a rate of land loss over the past several decades as other regions in coastal Louisi-

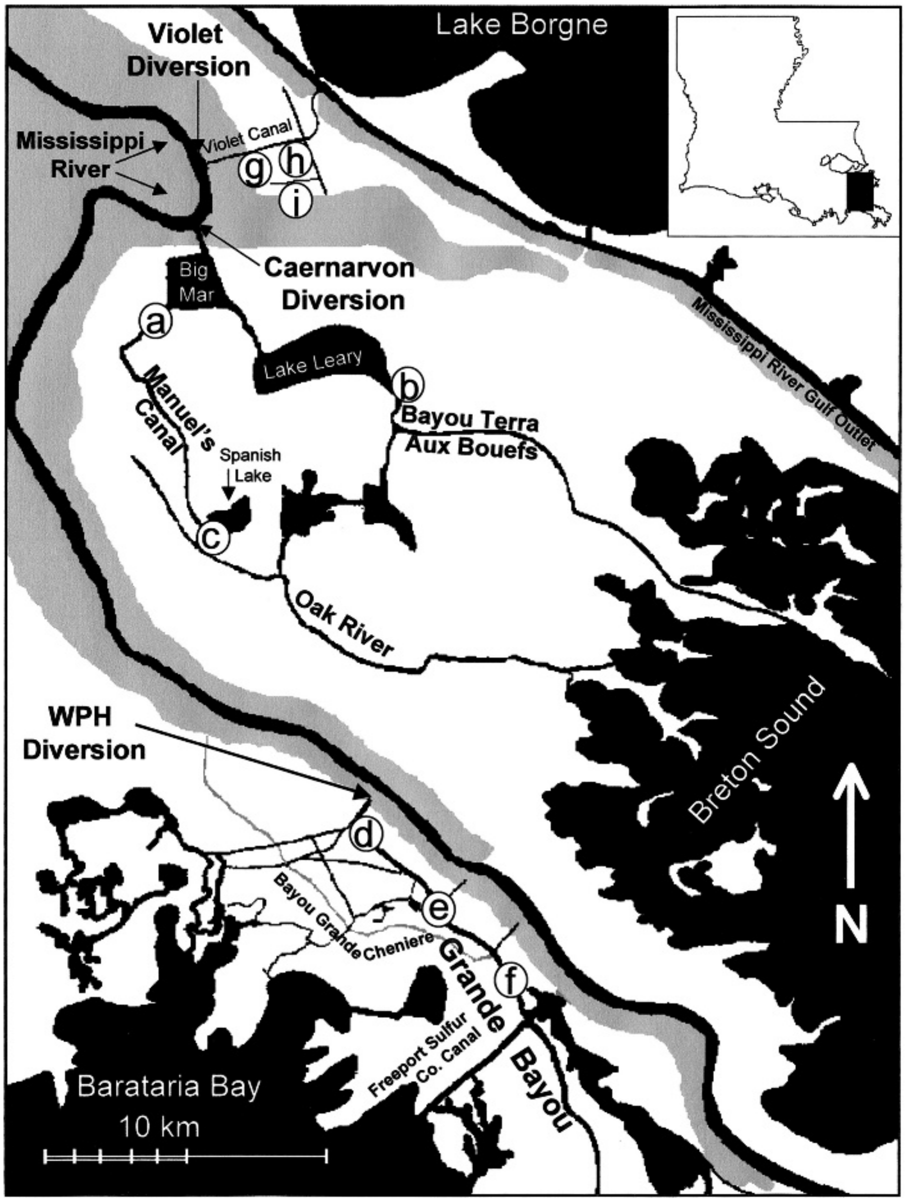

Figure 2. Locations of marsh elevation monitoring stations at Caernarvon (a) Big Mar, (b) Lake Leary, (c) Spanish Lake; West Point a la Hache (d) Near, (e) Grande Bayou Village, (f) Port Sulfur; and Violet (g) Levee, (h) Bayou, (i) Pipeline Canal.

ana, such as the Barataria and Terrebonne Basin (Britsch and Dunbar 1993, Barras et al. 2003).

West Pointe a la Hache

The West Pointe a la Hache (WPH) diversion structure is located on the west bank of the Mississippi River at river mile 48.9 (78.7 km, Figure 2), and consists of eight 1.8-m-diameter siphon tubes. Daily siphon discharge is determined by the Louisiana Department of Natural Resources from the head differential between the river and wetland and the number of pipes in operation (Haywood and Boshart 1998). The structure has been in operation since 1993, with a maximum discharge capacity of 64 m^3s^{-1}, but with an average flow of 21 m^3s^{-1}. Diverted river water flows into Grand Bayou on the eastern edge of Barataria Bay, where there are many connections for water exchange with the surrounding coastal complex. The WPH diversion has a design project area of approximately 68 km^2, delineated by Bayou Grande Cheniere (Haywood and Boshart 1998) but could potentially impact over 280 km^2 of wetlands located between the diversion structure and Barataria Bay. Barataria Bay wetlands, in contrast to the Breton

Table 1. Coordinates of study sites (mid-point between two subplots), distance from diversion structure (km), and dominant vegetation species.

		Near	Mid	Far
Caernarvon	Coordinates:	N 29.82172 W 89.92691	N 29.78135 W 89.79204	N 29.70300 W 89.90575
	Distance from diversion:	5.6	16.9	22.0
	Dominate Vegetation Species:	*Spartina patens* (Aiton) Muhl. *Sesbania drummondii* (Rydb.)Cory *Ipomoea sagittata* Poir.	*Spartina patens* *Panicum repens* L.	*Spartina patens* *Panicum repens* *Lythrum lineare* L.
	Comments:			On natural levee of River aux Chene
WPH	Coordinates:	N 29.55569 W 89.81034	N 29.51151 W 89.76590	N 29.49948 W 89.75248
	Distance from diversion:	1.1	8.1	14.5
	Dominate Vegetation Species:	*Spartina alternaflora* Loisel. *Distchlis spicata* L. *Lythrum lineare* *Ammania coccinea* Rottb. *Polygonum sp.*	*Spartina alterniflora* *Distchlis spicata*	*Spartina alterniflora*
	Comments:	On natural levee of Grande Bayou	On natural levee of Grande Bayou	On natural levee of Grande Bayou
Violet	Coordinates:	N 29.90075 W 89.87789	N 29.90466 W 89.85156	N 29.88868 W 89.84656
	Distance from diversion:	2.4	6.0	9.2
	Dominate Vegetation Species:	*Spartina alterniflora* *Lythrum lineare*	*Spartina alterniflora* *Spartina patens* *Aster tinuifolius* L.	*Spartina alterniflora* *Spartina patens* *Polygonium sp.*
	Comments:	Hydrologically isolated from diverted water by nearby levee	Burned during the Winter of 1998	

Sound wetlands, are being lost at a very high rate (Britsch and Dunbar 1993, Barras et al. 2003), and the region surrounding the WPH diversion has large expanses of open water that were wetlands several decades ago (Haywood and Boshart 1998).

Violet

The Violet river diversion structure is located on the east bank of the Mississippi River at river mile 85.0 (136.8 km, Figure 2). The water-control structure began operation in 1979 and consists of two 1.3-m-diameter siphon tubes with a combined maximum discharge capacity of 8.5 m^3s^{-1}. Daily siphon discharge is managed by the Louisiana Department of Natural Resources based on the head differential between the river and wetland. Siphoned river water is initially channeled for several km before impacting an approximately 50 km^2 area of *Spartina alterniflora* Loisel. dominated wetlands. These wetlands are largely hydrologically isolated from the surrounding landscape by levees associated with flood protection, oil and gas access canals, and the Mississippi River Gulf Outlet (MRGO, see Figure 2). The MRGO was completed in 1963 as an alternative shipping channel to the Mississippi River. Soon after completion, saltwater intrusion caused the death of most of the extensive forested wetlands that formally occurred in the region, converting it to what is presently a mixture of open water, *Spartina alterniflora* Loisel. marsh, and ghost cypress trunks (Day et al. 2000). Land loss in the Violet region, however, has been minimal during recent decades (Britsch and Dunbar 1993, Barras et al. 2003).

METHODS

At each study area, three study sites were selected with increasing distance from the diversion structures, classified as Near, Mid, and Far (Table 1). Two wetland surface elevation monitoring stations were established at each study site approximately 50 m from the waters edge. Wetland surface elevation was measured using a sediment elevation table (SET; Boumans and Day 1993, Cahoon et al. 2000), and vertical accretion was measured using feldspar marker horizons (Cahoon and Turner 1989). Wetland elevation and accretion measurements were begun in summer 1996. Measurements were made every 6 to 12 months until Spring 1999 at the Violet study area, and Spring 2000 at the Caernarvon and WPH study areas.

Wetland Surface Elevation

A platform was constructed at each wetland surface elevation monitoring station to minimize disturbance of the sediment surface during construction and sampling. Each SET site consisted of a supporting aluminum base pipe (7.5-cm diameter, 1-mm wall thickness) that was driven vertically 4–6 m until refusal with a hand-held pipe driver and/or vibracorer. The upper end of the base support pipe was fitted with a smaller pipe designed to receive the upper portable part of the SET. The portable part of the SET is a precisely machined device that can be leveled in two planes and positioned in four directions around the base support pipe. Once leveled, the plate at the end of the SET was assumed to be in the exact same position during every measurement, providing a constant reference plane in space from which the distance to the sediment surface was measured repetitively through time (Boumans and Day 1993). Nine 3-mm diameter, 91-cm-long metal rods were used to measure the distance to the wetland surface in the four quadrants, providing 36 measurements per sampling effort. The accuracy of this technique is ± 1.5 mm (Boumans and Day 1993, Cahoon et al. 2002).

Wetland Vertical Accretion

Feldspar marker horizons were established at the same time as the first SET measurements (summer 1996) and were measured three times at the Caernarvon study sites and twice at the WPH and Violet study sites, always in conjunction with SET measurements. Powdered feldspar clay was laid on the wetland surface 1 cm thick in three randomly placed 0.25 m^2 plots next to each SET platform. The thickness of material deposited on top of the feldspar marker was measured destructively by taking a 20 cm x 20 cm plug using a shovel, cleanly slicing the core into several sections to reveal the horizon, then measuring the thickness of material above the surface of the horizon at 10 different locations. The rate of vertical accretion was calculated by dividing the thickness of material above the surface of the horizon by the amount of time the horizon had been in the sediment. The rate of shallow subsidence was calculated by subtracting the rate of vertical accretion from that of surface elevation change (Cahoon et al. 1995).

Statistics

Statistical analyses were carried out to determine changes in wetland surface elevation and vertical accretion over time. Mean wetland elevation at each station for each date was tested against the initial measurement (zero), as well as against all other dates, for each respective station using the Tukey-Kramer group comparison method (Sall and Lehman 1985). The Tukey-Kramer group comparison method was also used to detect differences in the rates of wetland surface elevation and vertical accretion between study sites. In addition, the slope of mean wetland elevation versus time was tested against a slope of zero. An alpha value of 0.05 was used to signify a significant difference for all tests.

RESULTS

River Diversion Discharge

The three diversions in this study delivered pulsed and highly seasonal riverine discharge into the receiving estuaries (Figure 3). The Caernarvon diversion had an average flow of 31 m^3s^{-1} and a peak flow of 225 m^3s^{-1}, with total yearly discharge volume ranging from 0.37 to 1.55 km^3. The WPH diversion had an average flow of 19 m^3s^{-1}, peak flow of 62 m^3s^{-1}, and total yearly discharge volume ranging from 0.51 to 0.90 km^3. The Violet diversion had an average flow of 4 m^3s^{-1}, a peak flow of 8 m^3s^{-1} from 1996–1999, and total yearly discharge volume ranging from 0.04–0.08 km^3.

Wetland Surface Elevation

Wetland surface elevation generally increased or remained stable at the Caernarvon and WPH diversions but decreased considerably at the Violet diversion (Figure 4). The Caernarvon study sites had elevation change rates ranging from 0.16 ± 0.31 to 0.42 ± 0.21 cm y^{-1} (Table 2, Figure 5). The Near site at the Caernarvon study area had significantly higher wetland elevation at the end of the study, while elevations at the Mid and Far sites did not change significantly (Figure 4a-c). The WPH study sites had 2.3 to 3.3 cm of increased elevation during the first seven months of the study (Figure 4 d–f), with the largest increase occurring at the Near site,

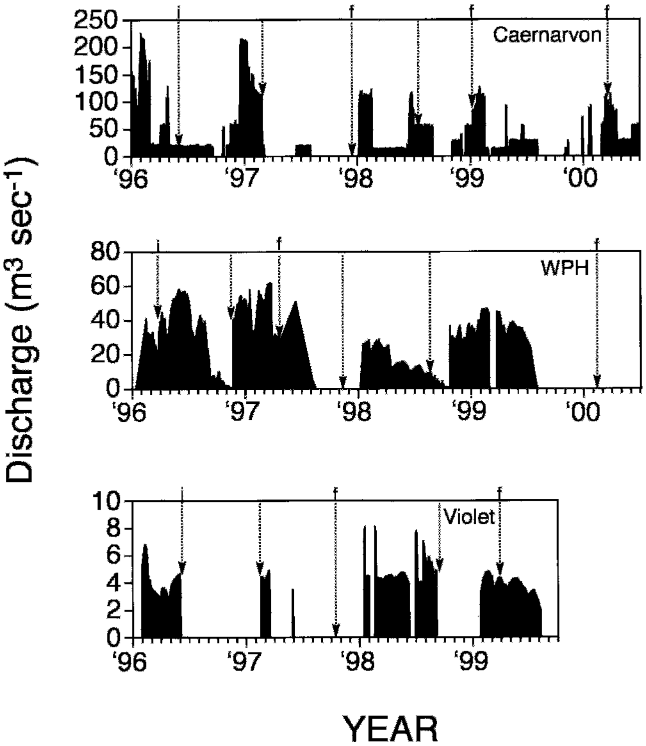

Figure 3. Discharge from the Caernarvon, West Point a la Hache (WPH), and Violet freshwater diversions. Measurement of marsh elevation is indicated by arrows, initial accretion measurement by 'i's and subsequent measurement by 'f's.

followed by the Mid and Far sites. The rate of surface elevation change at WPH ranged from 0.27±0.09 to 0.70±0.11 cm y^{-1} (Table 2, Figure 5). All of the WPH study sites had significantly higher wetland elevation at the end of the study compared to initial measurements. In contrast, all of the Violet sites had significantly lower wetland elevation at the end of the study (Figure 4 g–i), with elevation rates ranging from −1.10±0.24 to −2.34±0.41 cm y^{-1} (Table 2, Figure 5). The Violet-Near site had the highest rate of elevation loss of the nine sites in this study, with elevation significantly ($p<0.01$) decreasing (slope: −2.2 cm y^{-1}) throughout the study, having a final elevation of −6.44 cm (Figure 4g).

Wetland Vertical Accretion

Wetland vertical accretion at the Caernarvon study sites ranged from 0.75±0.04 to 1.57±0.05 cm y^{-1} (Table 2, Figure 5). Decrease in feldspar marker depth at the Caernarvon-Mid site during the last measurement indicates erosional processes were active during the later period of the study (Figure 4b). Vertical accretion rates at the WPH study sites ranged from 1.24±0.08 to 1.84±0.07 cm y^{-1}. Accretion at the Near and Far sites of the Violet study sites were 0.44±0.10 and 0.44±0.11 cm y^{-1}, respectively (Table 2, Figure 5). The Violet-Mid site marsh was burned during Winter 1999 leading to more than 4.0 cm decrease in material over the marker horizon (Figure 4h), contributing to the lowest accretion rate of 0.34±0.05 cm y^{-1} measured in this study.

Shallow Subsidence

Shallow subsidence ranged from 0.59 to 1.21 cm y^{-1} at the Caernarvon Study areas, 0.54 to 1.27 cm y^{-1} at the WPH regions, and 1.54 to 2.78 cm y^{-1} at the Violet study areas, with an overall average of 1.24 cm y^{-1} (Table 2).

DISCUSSION

Generally, sites that received the greatest volume of river water and were nearer the diversions had the highest rates of wetland surface elevation increase and vertical accretion. Other studies have shown a similar relationship between riverine input, accretion, and elevation. Baumann et al. (1984) found greater accretion in wetlands near the mouth of the Atchafalaya River, Louisiana compared to those not near a riverine source. The same was found for several deltas in the northern Mediterranean (Ibanez et al. 1997, Day et al. 1999, Hensel et al. 1999, Pont et al. 2002).

Vertical accretion was always greater than surface elevation gain (Figure 5), with the difference due to shallow subsidence caused by compaction and consolidation of the substrate between the wetland surface and the end of the SET pipe (Cahoon et al. 1995). Shallow subsidence rates at the Caernarvon, WPH, and Violet diversions ranged from 0.54 to 2.78 cm y^{-1}, with an overall average of 1.24 cm y^{-1} for this study. This is comparable to other reports of shallow subsidence in Louisiana and other deltas. Cahoon et al. (1995, 1999) reported shallow subsidence of 0.5 and 1.5 cm y^{-1} for Old Oyster Bayou and Bayou Chitigue, respectfully, located in coastal Louisiana. In Willapa Bay, Washington, USA, shallow subsidence was 1.0–1.2 cm y^{-1} (Cahoon et al. 1999). Shallow subsidence in the Rhone, Po, and Venice wetlands ranged from 0.1 to 0.9 cm y^{-1} (Ibanez et al. 1997, Day et al. 1999, Hensel et al. 1999, Pont et al. 2002)

Penland and Ramsey (1990) analyzed tide-gauge data to calculate relative sea-level rise (RSLR), the combined affect of subsidence and eustatic sea-level rise, which ranged from 0.36 to 1.11 cm y^{-1} in the

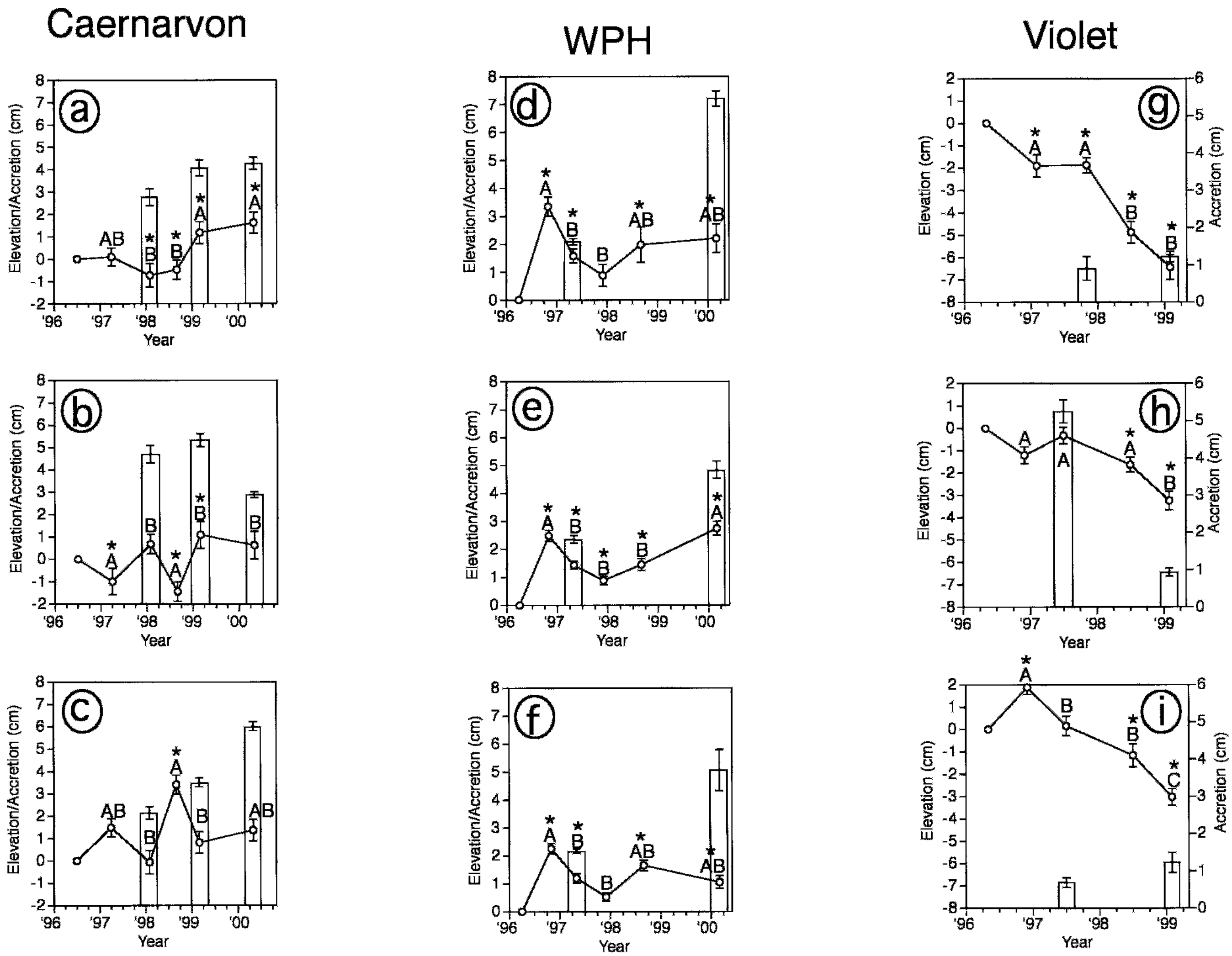

Figure 4. Marsh elevation (line) and accretion (bars) in receiving wetlands of the Caernarvon, West Point a la Hache (WPH), and Violet freshwater diversions. Asterisks indicate significant differences in elevation compared to the initial measurement, and letters indicate statistical differences in elevation between dates at each station ($p<0.05$).

southeastern portion of the Mississippi delta. Gagliano (1999) used a similar analysis to produce a contour map of RSLR in Louisiana (Figure 6). Using this map, we estimated that RSLR at the Caernarvon study sites ranged from 0.15 to 0.45 cm y^{-1} and 0.55 to 0.85 cm y^{-1} at the WPH study sites and 0.45 to 0.75 cm y^{-1} at the Violet study sites. In order for a wetland to have long-term sustainability,

Table 2. Months since station instillation, marsh elevation and accretion, and rates of elevation, accretion and shallow subsidence at the Caernarvon study sites (s.e. = standard error).

Site	Ending Surface Elevation (cm ± s.e.)	Ending Vertical Accretion (cm ± s.e.)	Elevation Change (cm/y)	Accretion Rate (cm/y)	Shallow Subsidence (cm/y)
C-Near	1.63±0.48	4.27±0.27	0.42±0.21	1.11±0.07	0.69
C-Mid	0.62±0.62	2.88±0.13	0.16±0.31	0.75±0.04	0.59
C-Far	1.37±0.45	6.02±0.20	0.36±0.25	1.57±0.05	1.21
W-Near	2.21±0.52	7.21±0.27	0.56±0.26	1.84±0.07	1.27
W-Mid	2.75±0.25	4.84±0.31	0.70±0.11	1.24±0.08	0.54
W-Far	1.06±0.23	5.06±0.73	0.27±0.09	1.29±0.19	1.02
V-Near	−6.44±0.58	1.22±0.27	−2.34±0.41	0.44±0.10	2.78
V-Mid	−3.24±0.41	0.93±0.14	−1.18±0.26	0.34±0.05	1.52
V-Far	−3.03±0.38	1.20±0.31	−1.10±0.24	0.44±0.11	1.54

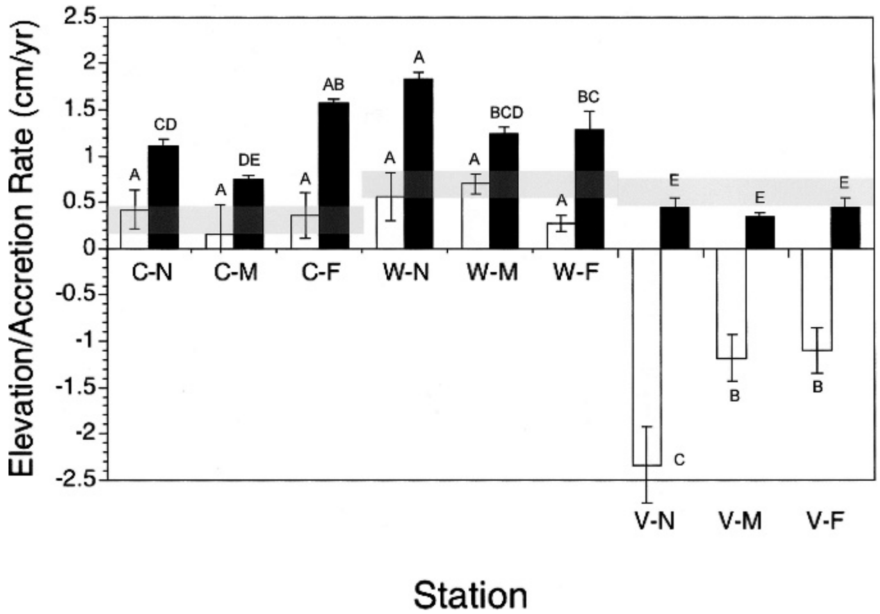

Figure 5. Rates of wetland surface elevation (white) and accretion (black): C-N (Caernarvon-Near); C-M (Caernarvon-Mid); C-F (Caernarvon-Far); W-N (WPH-Near); W-M (WPH-Mid); W-F (WPH-Far); V-N (Violet-Near); V-M (Violet-Mid); V-F (Violet-Far). Letters above the bars indicate statistical analysis: means with the same letter failed to be statistically different. Shaded lines indicate the range of RSLR at the various regions based on Figure 6.

wetland surface elevation must be at or greater than RSLR (Cahoon et al. 1995, Day et al. 1997). This analysis indicates that all of Caernarvon study sites are keeping pace with RSLR, as well as the WPH-Near and Mid study sites (Figure 5). Conversely, surface elevation rates are not keeping pace with RSLR at any of the Violet study sites, or the WPH-Far study site (Figure 5).

The Violet-Near study site had the highest rate of elevation loss of any site in this study (Figure 5). This site was also the most hydrologically isolated, being impounded by the Violet Canal spoil bank and other features in the area. Spoil banks have been found to decrease the net flux of materials to and from nearby wetlands, making these areas prone to excessive inundation (Swenson and Turner 1987, Bryant and Charbreck 1998). Not only do spoil banks decrease the quantity of sediments and nutrients available to maintain wetland elevation (Boumans and Day 1994, Reed et al. 1997), but they also can increase flooding and lower soil Eh levels such that anoxic conditions and high sulfide concentrations cause vegetation dieback (Mendelssohn et al. 1981, Mendelssoln and Morris 2000). Cahoon and Turner (1989) reported 40% less annual accretion in a wetland behind canal spoil banks compared to a wetland adjacent to a natural waterway. In addition to canals, the wetlands surrounding the Violet river diversion have also been modified by the installation of fixed-crest weirs. A number of studies have shown that such management leads to lower water exchange and reduction in sediment deposition and vertical accretion in coastal wetlands (Reed 1992, Boumans and Day 1994, Reed et al. 1997). Cahoon (1994) measured significantly lower accretion in two brackish impoundments compared to adjacent unmanaged wetlands (7 vs. 30 mm y^{-1}). These two impoundments also had lower short-term sedimentation and lower materials fluxes between the impoundments and adjacent wetlands (Boumans and Day 1994). Even though the Violet-Near site is very close to a sediment source, it is hydrologically disconnected from it by a spoil bank. This clearly demonstrates that the introduction of river water has much less restoration benefit without proper hydrologic restoration and outfall management. The removal of spoil banks and weirs should be implemented as an integral part of using river diversions for wetland restoration.

Fire is a widely used management tool to improve habitat quality for wildlife in coastal Louisiana (Nyman and Chabreck 1995) and may have occurred spontaneously prior to human intervention (Viosca 1931). There has been little research into the effect of marsh burning on wetland elevation or accretion, but 'root burns' and 'deep peat burns' that in some cases have burned the wetland down to the underlying clay subsoil have been documented in coastal Louisiana (Lynch 1941). Other studies have

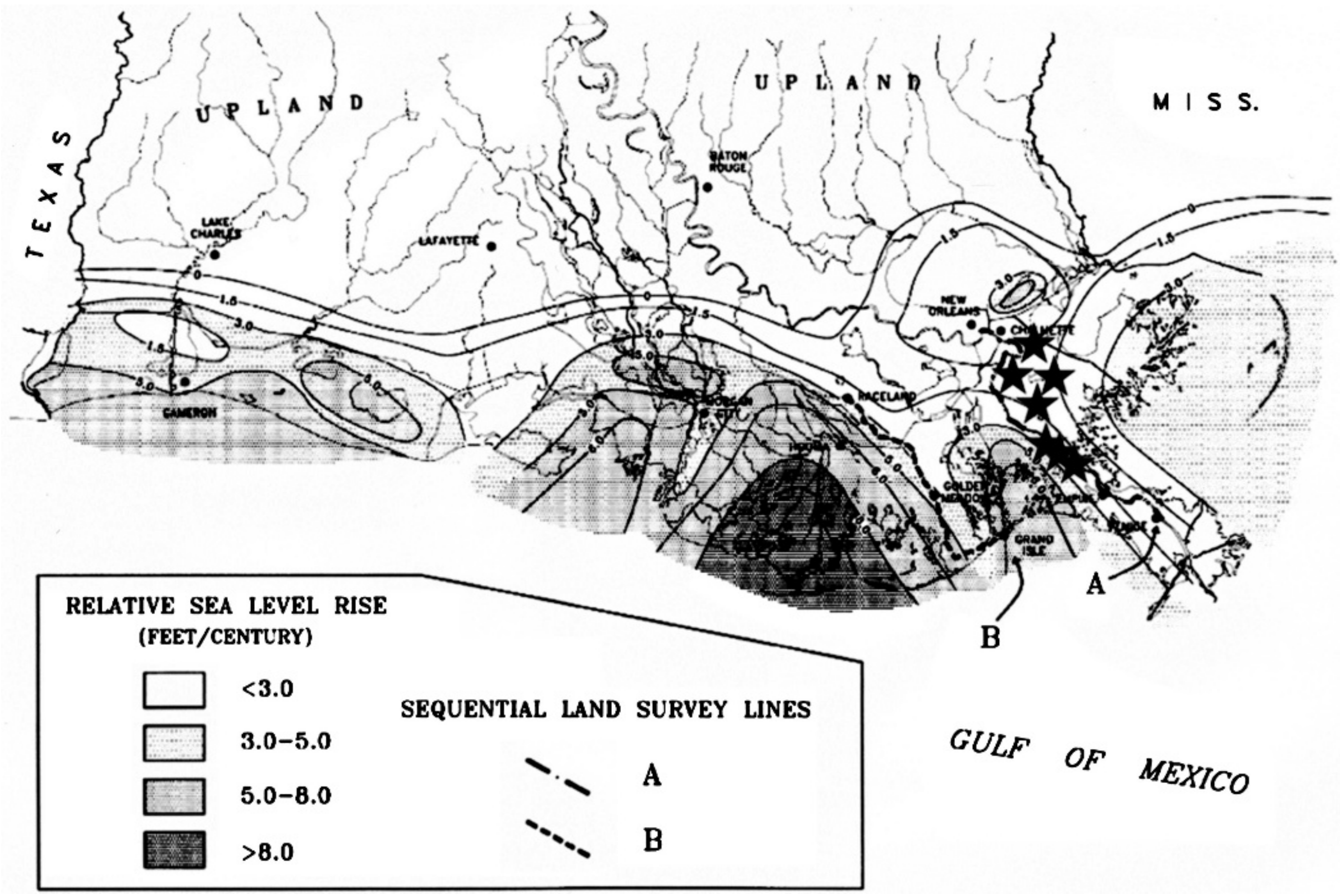

Figure 6. Isopleth map of relative sea level rates in coastal Louisiana based on 1962–1982 tide gauge data (adapted from Ramsey and Moslow 1987, taken from Gagliano 1999). Stars indicate locations of study sites.

found increases in aboveground productivity associated with burns along the Gulf coast (Whipple and White 1977, Hackney and de la Cruz 1983). The Violet-Mid site was burned prior to the summer 1998 measurement (Figure 4h). There was burned organic matter on the wetland surface, and the boardwalks, made of 5-cm-thick lumber, were destroyed. This fire was likely started in the late winter or early spring to burn off dead vegetation from the previous year, allowing room for new growth. Wetland accretion at this site decreased by over 4 cm due most likely decreasing the ability of the wetland to maintain elevation in face of relative sea-level rise.

The Caernarvon-Spanish Lake study site had the most stable elevation of any of the Caernarvon sites, most likely due to this site resting on the natural levee of Oak River, a former distributary of the Mississippi River prior to levee construction (Welder 1959). This same stability was evident at the WPH sites that were located on the natural levee of Grande Bayou, another former distributary channel (Welder 1959). These former distributary channel levees are low-lying levees with heights ranging from 5 to 10 cm above the surrounding landscape (Mendelssohn and McKee 2000). The greater stability of areas along natural levees, compared to back wetland areas, is due to greater availability of sediments and nutrients leading to increased mineral matter accumulation and primary productivity (DeLaune et al. 1979).

We calculated the wetland area that could be maintained by each diversion using mineral accumulation rates needed for wetland sustainability and the sediment load discharged from each of the three diversions during this study. Hatton et al. (1983) reported that fresh and brackish wetlands require at least 280 and 478 g m^2 y^{-1} of sediment, respectively, to keep pace with RSLR. Sediment loads for our calculations were calculated as the product of diversion discharge and Mississippi River suspended sediment concentration (USGS data from St. Francisville, Louisiana, http://nwis.waterdata.usgs.gov). On average, the Caernarvon and WPH diversions introduced 259 and 151 million kg of sediment per year, respectively, into their receiving basins. The

Violet diversion introduced 8.1 million kg of sediment per year. Using the mineral sediment requirements given by Hatton et al. (1983) and assuming even distribution of sediments, the Caernarvon diversion could maintain 541 to 923 km^2 of fresh and brackish wetlands, the WPH diversion 316 to 540 km^2, and the Violet diversion 17 to 29 km^2. The Caernarvon diversion discharges into approximately 1100 km^2 of fresh to brackish wetlands, substantially more than the capacity of the diversion. This calculation is consistent with the results of Lane (2003) and Wheelock (2003), who reported that most mineral sediment was deposited within 15 km of the diversion structure. Results were similar for the Violet diversion, which discharges into approximately 50 km^2 of wetlands. In contrast, the WPH diversion has a design project area of 68 km^2 and potentially could impact over 280 km^2 of wetlands located between the diversion structure and Barataria Bay. This analysis shows that WPH is the most appropriately sized of the three river diversion projects in this study and that the Caernarvon and Violet diversions are undersized for their respective receiving basins. It should be noted, however, that both the Caernarvon and Violet diversions have much greater discharge capacity than was realized during this study and that increased discharge could improve restoration effectiveness.

CONCLUSIONS

This study indicates that the use of river diversions can be an effective coastal restoration tool, with efficiency related to the proximity to riverine source, degree of hydrologic alteration, quantity of river water released, and land uses of the receiving wetland basin. Landscape modifications such as spoil banks and weirs reduce the benefits of river water introduction by limiting wetland-water interaction and should be removed or breeched as part of outfall management in conjunction with river diversion implementation for effective wetland restoration.

ACKNOWLEDGMENTS

This study was funded by Louisiana Sea Grant College program. We thank Delacroix Corp. for permission to access field sites and for use of their beautiful camp that was destroyed by Hurricane Katrina. We also thank Cary and Christopher Bush who greatly helped in the field, and the Bush family for the use of their camp (not destroyed).

LITERATURE CITED

Barras, J., S. Beville, D. Britsch, S. Hartley, S. Hawes, J. Johnston, P. Kemp, Q. Kinler, A. Martucci, J. Porthouse, D. Reed, K. Roy, S. Sapkota, and J. Suhayda. 2003. Historical and projected coastal Louisiana land changes: 1978–2050. USGS Open File Report 03-334 (Revised January 2004).

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

Boesch, D. F. 1996. Science and management in four U.S. coastal ecosystems dominated by land-ocean interactions. Journal of Coastal Conservation 2:103–114.

Boesch, D. F., M. N. Josselyn, A. J. Mehta, J. T. Morris, W. K. Nuttle, C. A. Simenstad, and D. J. P. Swift. 1994. Scientific assessment of coastal wetland loss, restoration and management. Journal of Coastal Research Special Issue No. 20.

Boumans, R. M. J. and J. W. Day. 1993. High precision measurements of sediment elevation in shallow coastal areas using a sedimentation-erosion table. Estuaries 16: 375–380.

Boumans, R. M. and J. W. Day. 1994. Effects of two Louisiana marsh management plans on water and materials flux and short-term sedimentation. Wetlands 14:247–261.

Bryant, J. C. and R. H. Chabreck. 1998. Effects of impoundment on vertical accretion of coastal marsh. Estuaries 21:416–422.

Cahoon, D. R., J. W. Day, and D. J. Reed. 1999. The Influence of Surface and Shallow Subsurface soil Processes on Wetland Elevation: a Synthesis. Current Topics in Wetland Biogeochemistry 3:72–88.

Cahoon, D. R., P. E. Marin, B. K. Black, and J. C. Lynch. 2000. A method for measuring vertical accretion, elevation, and compaction of soft, shallow-water sediments. Journal of sedimentary research 70:1250–1253.

Cahoon, D. R. and D. J. Reed. 1994. Relationships among marsh surface topography, hydroperiod , and soil accretion in a deteriorating louisiana salt marsh. Journal of Coastal Research 11:357–369.

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

Cahoon, D. R. and R. E. Turner. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries 12:260–268.

Chatry, M. and D. Chew. 1985. Freshwater diversion in coastal Louisiana: recommendations for development of management criteria. p. 71–84, *In* 4th Coastal Marsh and Estuary Mgt. Symposium.

Chatry, M., R. J. Dugas, and K. A. Easley. 1983. Optimum salinity regime for oyster production on Louisiana's state seed grounds. Contributions in Marine Science 26:81–94.

Childers, D. L., F. H. Sklar, B. Drake, and T. Jordan. 1993. Seasonal measurements of sediment elevation in three mid-atlantic estuaries. Journal of Coastal Research 9:986–1003.

Colten, C. (ed.) 2000. Transforming New Orleans and its Environs. University of Pittsburgh Press, Pittsburgh, PA, USA.

Crandall, M. E. and J. L. Lindsey. 1981. Establishment of controlled freshwater diversion of the Mississippi River into Louisiana coastal zone. p. 139–146, *In* R. D. Cross and D. L. Williams (eds.) Procedings of the National Symposium on Freshwater Inflow to Estuaries, Slidell, LA, USA.

Davis, D. W. 2000. Historical perspective on crevasses, levees, and the Mississippi River. p. 84–106, *In* C. E. Colten (ed.) Transforming New Orleans and its Environs. University of Pittsburgh Press, Pittsburgh, PA, USA.

Day, J. W., L. D. Britsch, S. Hawes, G. Shaffer, D. J. Reed, and D. Cahoon. 2000. 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., J. Martin, L. Cardoch, and P. Templete. 1997. System functioning as a basis for sustainable management of deltaic ecosystems. Coastal Management 25:115–153.

Day, J. W., N. P. Psuty, and B. C. Perez. 2001. 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. p. 633–659, *In* M. P. Weinstein and D. A. Kreeger (eds.) Concepts and Controversies in Tidal Marsh Ecology. Kuwer Acedemic Publishers, Boston, MA, USA.

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

Day, J. W. and P. H. Templet. 1989. Consequences of sea level rise: implications from the Mississippi delta. Coastal Management 17:241–257.

Deegan, L. A., H. M. Kennedy, and C. Neill. 1984. Natural factors and human modifications contributing to marsh loss in Louisiana's Mississippi River deltaic plain. Environmental Management 8:519–528.

DeLaune, R. D., R. H. Baumann, and J. G. Gosselink. 1983. Relationships among vertical accretion, coastal submergence, and erosion in a Louisiana Gulf Coast marsh. Journal of Sedimentary Petrology 53:0147–0157.

DeLaune, R. D., R. J. Buresh, and W. H. Patrick. 1979. Relationship of soil properties to standing crop biomass of Spartina alternafloria in a Louisiana marsh. Estuarine and Coastal Marine Science 8:477–487.

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

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

Gagliano, S. M. 1999. Faulting, subsidence and land loss in coastal Louisiana: in Coast 2050: Toward a Sustainable Coastal Louisiana, Appendix B, Section 3, p. 21–72, *In* Louisiana Coastal Wetlands Conservation and Restoration Task Force and Wetlands Conservation Restoration Authority. Louisiana Department of Natural Resources, Baton Rouge, LA, USA. (http://www.coast2050.gov/2050reports.htm).

Hackney, C. T. and A. A. de la Cruz. 1983. Effects of winter fire on the productivity and species composition of two brackish marsh communities in Mississippi. International Journal of Ecology and Environmental Science 9:185–208.

Hatton, R. S., R. D. Delaune, and J. W. H. Patrick. 1983. Sedimentation, accretion, and subsidence in marshes of Baritaria Basin, Louisiana. Limnology and Oceanography 28:494–502.

Haywood, E. L. and W. M. Boshart. 1998. West pointe a la hache freshwater diversion: three-year comprehensive report. Louisiana Department of Natural Resources/Coastal Restoration Division, Baton Rouge, LA, USA. Monitoring Series No. BA-04-MSTY-0498-1

Ibanez, C., A. Canicio, J. W. Day, and A. Curco. 1997. Morphologic evolution, relative sea level rise and sustainable management of water and sediment in the Ebre Delta. Journal of Coastal Conservation 3:191–202.

Kesel, R. H. 1988. The decline in the suspended load of the Lower Mississippi River and its influence on adjacent wetlands. Environmental and Geological Water Science 11: 271–281.

Kesel, R. H. 1989. The role of the lower Mississippi River in wetland loss in southeastern Louisiana, USA. Environmental and Geological Water Science 13:183–193.

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

Lane, R. 2003. The effect of water quality of riverine input into coastal wetlands. Ph.D. Dissertation. Deptartment of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA, USA.

LDNR. 1998. Coast 2050: Toward a Sustainable Coastal Louisiana Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority. Louisiana Department of Natural Resources, Baton Rouge, LA, USA.

Lynch, J. J. 1941. The place of burning in wildlife management of the Gulf coast wildlife refuges. Journal of Wildlife Management 5:454–457.

Mancil, E. M. 1972. An historical geography of industrial cypress lumbering. Ph.D. Dissertation. Louisiana State University, Baton Rouge, Louisiana.

Mendelssohn, I. A. and K. L. Mckee. 2000. Salt marshes and mangroves. p. 501–536, *In* M. G. Barbour and W. D. Billings (eds.) North American Vegetation. Cambridge University Press, New York, NY, USA.

Mendelssohn, I. A., K. L. McKee, and J. W. H. Patrick. 1981. Oxygen deficiency in *Spartina alterniflora* roots: metabolic adaption to anoxia. Science 214:439–441.

Mendelssohn, I. A. and J. T. Morris. 2000. Eco-physiological controls on the productivity of Spartina alterniflora loisel. p. 59–80, *In* M. P. Weinstein and D. A. Kreeger (eds.) Concepts and Controversies in Tidal Marsh Ecology. Kuwer Acedemic Publishers, Boston, MA, USA.

Mossa, J. 1996. Sediment dynamics in the lowermost Mississippi River. Engineering Geology 45:457–479.

Nyman, J. A. and R. H. Chabreck. 1995. Fire in coastal marshes: history and recent concerns. p. 135–141, *In* R. T. Engstrom, S. I. Cerulean, and R. T. Engstrom (eds.) Proceedings 19th Tall Timbers Fire Ecology Conference- Fire in wetlands: a management perspective. Tall Timbers Research, Inc. Tallahassee, FL, USA.

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

Penland, S. and K. E. Ramsey. 1990. Relative sea-level rise in Louisiana and the Gulf of Mexico: 1908–1988. Journal of Coastal Research 6:323–342.

Pont, D., J. Day, P. Hensel, E. Franquet, F. Torre, P. Rioual, C. Ibanez, and E. Coulet. 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.

Reed, D. J. 1992. Effect of weirs on sediment deposition in Louisiana coastal marshes. Environmental Management 16:55–65.

Reed, D. J., N. D. Luca, and A. L. Foote. 1997. Effect of hydrolic management on marsh surface sediment deposition in coastal Louisiana. Estuaries 20:301–311.

Roberts, H. H. 1997. Dynamic changes of the holocene Mississippi river delta plain: the delta cycle. Journal of Coastal Research 13:605–627.

Salinas, L. M., R. D. DeLaune, and W. H. Patrick. 1986. Changes occurring along a rapidly submerging coastal area: Louisiana. Journal of Coastal Research 2:269–284.

Sall, J. and A. Lehman. 1996. JMP Start Statistics, a Guide to Statistical and Data Analysis using JMP and JMP IN Software. Duxbury Press, New York, NY, USA.

Scruton, P. C. 1960. Delta building and the deltaic sequence. Recent Sediments, NW Gulf Coast of Mexico AAPG Symposium., p. 82–102.

Swenson, E. M. and R. E. Turner. 1987. Spoil banks: effects on a coastal marsh water-level regime. Estuarine, Coastal and Shelf Science 24:599–609.

Templet, P. H. and K. J. Meyer-Arendt. 1988. Louisiana wetland loss: a regional water management approach to the problem. Environmental Management 12:181–192.

Viosca, P. 1931. Spontaneous combustion in the Marshes of Southern Louisiana. Ecology 12:439–442.

Welder, F. A. 1959. Processes of deltaic sedimentation in the lower Mississippi River. Louisiana State University, Coastal Studies Institute Technical Report, Baton Rouge, LA, USA.

Wheelock, K. 2003. Pulsed river flooding effects on sediment deposition in Breton Sound estuary, Louisiana. M.S. Thesis. Deptartment of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA, USA.

Whipple, S. A. and D. White. 1977. The effects of fire on two Louisiana marshes. Association of Southeastern Biologists Bulletin. 24:95.

Manuscript received 10 June 2005; revision received 10 July 2006; accepted 20 September 2006.