

Article

Restoration and Management of a Degraded Baldcypress Swamp and Freshwater Marsh in Coastal Louisiana

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Abstract: The Central Wetlands Unit (CWU), covering 12,000 hectares in St. Bernard and Orleans Parishes, Louisiana, was once a healthy baldcypress–water tupelo swamp and fresh and low salinity marsh before construction of levees isolated the region from Mississippi River floodwaters. Construction of the Mississippi River Gulf Outlet (MRGO), which funneled saltwater inland from the Gulf of Mexico, resulted in a drastic ecosystem change and caused mortality of almost all trees and low salinity marsh, but closure of the MRGO has led to decreases in soil and surface water salinity. Currently, the area is open water, brackish marsh, and remnant baldcypress stands. We measured hydrology, soils, water and sediment chemistry, vegetation composition and productivity, accretion, and soil strength to determine relative health of the wetlands. Vegetation species richness is low and above- and belowground biomass is up to 50% lower than a healthy marsh. Soil strength and bulk density are low over much of the area. A baldcypress wetland remains near a stormwater pumping station that also has received treated municipal effluent for about four decades. Based on the current health of the CWU, three restoration approaches are recommended, including: (1) mineral sediment input to increase elevation and soil strength; (2) nutrient-rich fresh water to increase productivity and buffer salinity; and (3) planting of freshwater forests, along with fresh and low salinity herbaceous vegetation.

Keywords: baldcypress swamp; saltwater intrusion; Louisiana; wetland restoration; wetland assimilation; coastal marsh

1. Introduction

The Pontchartrain Basin is a 1.2 million-ha coastal watershed in southeast Louisiana and southwest Mississippi. The hydrology of the Basin has been extensively altered due to construction of levees along the Mississippi River, closure of old distributaries [1–6], dredging of canals for navigation and oil and gas development [4,7–9], drainage of upland areas (as in the case of the New Orleans metropolitan

area), creation of spoil banks and impoundments [10,11], and construction of the Mississippi River Gulf Outlet (MRGO) [5,12,13]. These hydrologic alterations decreased freshwater input and increased saltwater intrusion, along with changing the way that water moves through the Basin. As a result, many freshwater wetland species, such as baldcypress (*Taxodium distichum*) and water tupelo (*Nyssa aquatica*), have had massive die offs. Herbivory, primarily by nutria (*Myocastor coypus*), has also negatively impacted these coastal wetlands [14–16].

The Central Wetlands Unit (CWU), located in the Pontchartrain Basin, consists of about 12,000 ha of public and privately owned wetlands and open water in coastal Louisiana, east of New Orleans (Figure 1). The CWU once contained nearly 6000 ha of forested wetlands that were an important buffer for storm surge for Orleans and St. Bernard Parishes, but now the area is primarily brackish marsh and open water. The objectives of this paper are: (1) to describe historical and current conditions of the CWU; (2) to present results of a recent ecological baseline study of the CWU; and (3) to discuss options for restoration of the CWU, focusing on restoring freshwater emergent marshes and forested wetlands.



Figure 1. Location of the Central Wetlands Unit (CWU) and primary features. “o” indicates stormwater pumping stations. The study was carried out in three sub-units of the CWU. Sampling sites A1 and A2 are located between the East Bank Sewage Plant and a highway embankment. Sites A3 and B3 are located between the highway embankment and Violet Canal. Sites B1 and B2 are located south of Violet Canal. Sites identified with a sediment elevation table (SET) are where wetland surface elevation change and accretion were measured.

2. Materials and Methods

2.1. Study Area

There are many important structural and hydrologic features within and adjacent to the CWU. The area is bordered completely by levees; to the north by a levee along the Intracoastal Waterway, to the east by the levee along the MRGO, to the south by a levee along the Bayou La Loutre Ridge, and to the west by a flood control back-levee that protects developed areas of St. Bernard and Orleans Parishes (Figure 1). There are four freshwater sources to the area, including rainfall, stormwater, the Violet river siphon, and treated municipal effluent.

The northernmost portion of the CWU was once forested wetlands and fresh to low salinity emergent marsh but the area was drained and soil oxidation occurred and now it is mainly open water of about one meter depth. Bayou Bienvenue flows across the northern part of the CWU and discharges through a floodgate in the MRGO levee. The area below Violet Canal is mostly brackish marsh, with the exception of an area surrounding the Gore Pumping Station and the Riverbend Oxidation Pond where one of the few remaining stands of baldcypress is located. The pumping station and pond have discharged fresh water to this area for over four decades. The Violet Canal-Bayou Dupre flows

from the Mississippi River across the CWU where it exits the area through a second floodgate in the MRGO levee.

The MRGO, built in the 1960s as a shorter route to New Orleans than the Mississippi River, caused significant modifications to the hydrology, salinity gradient, and sedimentation patterns of the Pontchartrain Basin [12,13,17]. The MRGO spoil deposit and flood control back-levee largely isolated the CWU from riverine, estuarine, and marine influences. Construction of the MRGO, which was over 100 m wide and 15 m deep, severed Bayou La Loutre, an old distributary of the Mississippi River, which had a ridge that served as a natural barrier to saltwater intrusion from the Gulf of Mexico into the wetlands to the north. Severing Bayou La Loutre allowed saltwater into previously freshwater and low salinity areas of the Pontchartrain Basin, killing thousands of hectares of freshwater forested and emergent wetlands, especially in the CWU [13]. During Hurricane Katrina and the levee failures that followed, the MRGO exacerbated the damage by increasing the height and speed of the storm surge and waves [13,17,18]. The absence of forested and emergent wetlands to buffer waves and storm surge contributed to levee failures and flooding in Orleans and St. Bernard parishes [13,19]. The MRGO was closed by a rock dam in 2009 [20].

The Violet Siphon was constructed in 1979 so that Mississippi River water could flow into the Violet Canal and then into the southern CWU during high water periods. The Violet siphon is located on the east bank of the Mississippi River at river mile 85.0 (136.8 km; Figure 1). The water-control structure consists of two 1.3-m diameter siphon tubes with a combined maximum discharge capacity of 8.5 m³/s. The siphon is currently operated and managed by the Louisiana Department of Natural Resources based on the head differential between the river and the wetland [21]. River water from the Violet siphon is initially channeled for several kilometers before merging with Bayou Dupre.

There are five stormwater pumping stations along the 40 Arpent Canal that regularly pump surface water runoff into the CWU (Figure 1). These pumps are necessary because much of the developed area is below sea level. In addition, the Riverbend Oxidation Pond, located near the Gore Pumping Station, discharges about 1900 m³/day of secondarily treated, disinfected, non-toxic effluent into wetlands (Figure 1). This regular freshwater input has prevented the high soil salinities that have killed baldcypress in most other areas of the CWU and is the primary reason that baldcypress are still alive adjacent to the pump. With the exception of baldcypress growing near the Gore Pumping Station and the pumping station to the north, brackish and saline marshes with abundant *Spartina alterniflora* and *Spartina patens* now dominate the CWU, along with large areas of open water and ghost baldcypress trunks [4,21,22].

2.2. Sampling Design

To characterize the current ecological state of the CWU, we conducted an extensive study of the area. Seven study sites were selected to include near, mid, and far sites (relative to the interior flood protection levee) as well as a Reference site (Figure 1). Sites A1, A2, and A3 are located in the northern half of the CWU. A1 is open water and has no vegetation. Sites B1, B2 and B3 are in the southern half of the CWU, an area that drains via Violet Canal and Bayou Dupre (Figure 1). The “B” sites represent less disturbed wetlands compared to the “A” sites. The Reference site is a relatively undisturbed wetland area representative of natural conditions with little human influence.

2.3. Water Quality

Four separate field trips were conducted in 2011 to measure physiochemical variables of surface water and to collect samples for laboratory analysis. Dissolved oxygen, conductivity, pH, and salinity were measured *in situ* with a YSI meter (*i.e.*, YSI-85). Duplicate water column samples also were collected for analysis of total dissolved solids (TDS), total suspended solids (TSS), volatile suspended solids (VSS), total organic carbon (TOC), 5-day biochemical oxygen demand (BOD₅), ammonium (NH₄-N), nitrite + nitrate (NO_x-N), total Kjeldahl nitrogen (TKN), ortho-phosphate (PO₄-P), and total phosphorus (TP) using standard methods [23]. Total nitrogen (TN) is the sum of TKN and NO_x-N.

2.4. Vegetation

At each of the seven sites, two 625-m² replicate stations were established. Within each of the 14 replicate stations four 4-m × 4-m (16 m²) permanent herbaceous plots were established five m from the diagonal corners of each station. A 4-m² plot was established in the center of each 16-m² plot for cover value estimates and biomass clip plots. During each sampling in 2011, cover values were obtained by two independent estimates. Percentage cover of vegetation by species was determined by ocular estimation in 5% increments in July and October 2011 [24].

In September 2010 and 2011 end-of-season aboveground herbaceous biomass was estimated within each plot by clipping two randomly chosen (nonrepeating) replicate subplots (of 0.25 m² area) each season [25,26]. The pseudoreplicate subplots were pooled on site. Plant material was clipped at the soil surface, placed in a labeled bag, and transported to the lab, where it remained in cold storage until it could be separated into live and dead material, oven dried, and weighed. At the same time, belowground wetland biomass was collected using a 9.8 cm × 30 cm thin-walled stainless steel tube with a serrated and sharpened bottom [27]. Samples were collected at the same locations as aboveground biomass. Cores were sectioned in the field into 2.5-cm increments and brought to the laboratory. Roots and rhizomes were separated from small particulate material with a 2-mm mesh sieve under running water, and live and dead fractions separated using the criteria of live material being white and turgid and dead material being dark and flaccid [28–31]. The live fractions were then dried at 60 °C to a constant weight.

2.5. Soils/Sediments

Duplicate soil cores for analysis of bulk density were collected from all study sites on April 2011 using a 10-cm long, 2.5-cm diameter, 120-cm³ syringe with the top cut off. This allowed the application of suction as the core was collected, greatly reducing compaction. The soil sample was sliced into 2-cm sections, dried at 55 °C to a constant weight, and weighed for bulk density [32].

Soil interstitial pore water was collected for salinity analysis on 17–18 February, 28–29 April, 27–28 July, and 16–18 November 2011. Sample water was collected using an apparatus consisting of a narrow diameter plastic tube connected to a 50-mL syringe [33]. The rigid plastic tube (3-mm diameter) was perforated by several small holes at the end and was inserted into the soil to a 15-cm depth. Sixty to 80 ml of water was collected, stored in acid-washed 125-ml glass bottles, and analyzed for salinity. Additionally, salinity was measured using groundwater wells. Two 1-m long, 3.6-cm diameter PVC wells were inserted into the ground at each of the 14 stations. Wells were capped at both ends. Horizontal slits were cut into the wells every 2 cm from a depth of 5 cm to a depth of 70 cm below the soil surface to enable groundwater to enter. Well-water salinity was measured during site visits and averaged to yield quarterly mean salinity at each study plot.

Soil strength was measured using a penetrometer consisting of a 2.54-cm diameter PVC pipe and a hand-held scale. The capped pipe was pushed into the wetland soil at ten locations per site. A gauge attached to the top of the pipe measured the strength needed to push the pipe onto the marsh surface until penetration, at which point pressure was measured.

2.6. Surface Elevation

Wetland surface elevation monitoring stations were established approximately 50 m from the water's edge and measured using a sediment elevation table (SET) [34,35]. Vertical accretion was measured using feldspar marker horizons [36]. Three sites were established at increasing distance from the Violet siphon, including a Near site (2.4 km from the siphon), Mid (6.0 km from siphon), and Far (9.2 km from siphon). Although these sites do not match the sites established for this study, they provide a long-term measure of elevation dynamics in this area. Wetland elevation and accretion measurements were made every 6 to 12 months from summer 1996 through spring 1999 during a study reported by Lane *et al.* [21]. As part of the current study, these sites were re-measured during March 2011.

2.7. Hydrology

Hydrologic data were gathered from three existing Coastwide Reference Monitoring System (CRMS) sites located north and south of Violet Canal (Figure 1). CRMS site 3639 is located near monitoring site B2, 3641 is located near monitoring site B3, and 3664 is located south of Violet canal. All three sites are dominated by *Spartina patens*. Hydrology and salinity data for these sites between 28 November 2007 and 28 April 2012 were downloaded from the CRMS web site.

2.8. Statistical Analysis

To determine differences in variables (nutrient concentrations, salinity, accretion, etc.) among sites, one-way analysis of variance analysis (ANOVA, $\alpha = 0.05$) was conducted using JMP 7.0 statistical software (SAS Institute Inc., Cary, NC, USA, 1999) and SYSTAT 10.2 [37]. For significant ANOVA tests, comparisons of means were made using the Tukey-Kramer Honestly Significant Difference (HSD) test [38].

3. Results

3.1. Water Quality

Surface water salinity at all sites was typically below 4 parts per thousand (ppt), with the exception of an increase in salinity at most sites in the fourth sampling (November) period (Table 1). Conductivity, which is directly related to salinity, showed similar trends to salinity. pH was similar among all sites and fluctuated primarily between 7.0 and 8.0. DO concentrations fluctuated with season and ranged between 1.2 and 12.4 mg/L (Table 2). BOD₅ was typically less than 4 mg/L at all sites while TOC concentrations fluctuated greatly among sites and season (Table 2). TDS, TSS, and VSS concentrations were higher near the 40 Arpent Canal, and generally decreased when moving towards the MRGO levee (Table 3). Dissolved solids decreased during the third sampling event due to dilution from precipitation events preceding sampling and then increased in the fourth sampling event. High TSS concentrations were due primarily to inorganics as evidenced by low VSS to TSS ratios and were related to material pumped into the area.

Table 1. Surface water salinity, conductivity, and pH measured at sampling sites in the CWU.

Site	Sampling Date				Mean \pm Std err
	17-February-2011	28-April-2011	28-July-2011	16-November-2011	
Salinity (ppt)					
A1	3.60	3.60	0.60	2.67	2.62 \pm 0.55
A2	3.60	3.60	0.80	6.16	3.54 \pm 0.85
A3	3.40	3.40	0.50	5.84	3.29 \pm 0.85
B1	1.00	1.00	0.70	3.68	1.59 \pm 0.54
B2	0.20	0.20	0.50	5.99	1.72 \pm 1.10
B3	1.50	1.80	0.30	6.02	2.41 \pm 0.97
Reference	4.30	4.30	1.65	6.12	4.09 \pm 0.71
Conductivity (μ S/cm)					
A1	6416	6412	1298	4090	4554 \pm 942
A2	6444	6437	1647	9627	6039 \pm 1274
A3	6302	6354	1022	9919	5899 \pm 1420
B1	1717	1564	1485	6423	2797 \pm 937
B2	400	416	979	8625	2605 \pm 1558
B3	2798	3389	580	9244	4003 \pm 1432
Reference	7913	7973	3475	10,257	7405 \pm 1099
pH					
A1	7.70	7.70	7.30	8.90	7.90 \pm 0.27
A2	8.00	8.10	7.60	7.40	7.78 \pm 0.13
A3	8.60	8.60	7.35	7.80	8.09 \pm 0.24
B1	7.60	8.30	6.90	7.85	7.66 \pm 0.23
B2	8.20	8.80	6.90	7.90	7.95 \pm 0.31
B3	7.50	7.50	7.00	7.90	7.48 \pm 0.14
Reference	8.40	8.40	7.70	7.70	8.05 \pm 0.16

Table 2. Surface water dissolved oxygen, total organic carbon, and 5-day biochemical oxygen demand measured at sampling sites in the CWU.

Site	Sampling Date				Mean \pm Std err
	17-February-2011	28-April-2011	28-July-2011	16-November-2011	
Dissolved oxygen (mg/L)					
A1	6.50	6.20	3.50	12.40	7.15 \pm 1.45
A2	8.20	8.30	3.70	7.40	6.90 \pm 0.84
A3	9.20	8.80	3.75	7.50	7.31 \pm 0.96
B1	5.60	3.40	3.60	7.00	4.90 \pm 0.66
B2	9.10	9.80	1.20	8.70	7.20 \pm 1.56
B3	6.10	6.90	2.20	9.05	6.06 \pm 1.11
Reference	7.90	8.20	4.85	8.20	7.29 \pm 0.63
5-day Biochemical oxygen demand (mg/L)					
A1	2.90	2.80	3.65	2.10	2.86 \pm 0.25
A2	2.10	1.70	1.75	2.25	1.95 \pm 0.10
A3	1.60	1.10	1.35	1.30	1.34 \pm 0.08
B1	3.60	3.60	4.10	2.35	3.41 \pm 0.29
B2	3.00	1.50	2.35	1.95	2.20 \pm 0.25
B3	2.00	1.40	2.15	1.45	1.75 \pm 0.15
Reference	1.20	1.70	1.65	1.30	1.46 \pm 0.10
Total organic carbon (mg/L)					
A1	107.00	99.60	9.85	15.35	57.95 \pm 20.33
A2	14.20	8.70	8.90	10.10	10.48 \pm 0.99
A3	7.70	4.00	8.20	6.65	6.64 \pm 0.73
B1	38.80	45.50	23.10	20.25	31.91 \pm 4.72
B2	2.30	16.70	17.70	8.05	11.19 \pm 2.84
B3	20.00	26.20	7.85	6.45	15.13 \pm 3.71
Reference	4.30	4.00	8.40	5.70	5.60 \pm 0.78

Table 3. Surface water total dissolved solids, total suspended solids, and volatile suspended solids measured at sampling sites in the CWU.

Site	Sampling Date				Mean \pm Std err
	17-February-2011	28-April-2011	28-July-2011	16-November-2011	
Total dissolved solids (mg/L)					
A1	4258	4251	793	3211	3128 \pm 632
A2	4245	4238	1021	7030	4134 \pm 951
A3	4102	4208	618	6718	3912 \pm 971
B1	1268	1125	894	4356	1911 \pm 634
B2	267	271	598	6848	1996 \pm 1254
B3	1834	2171	358	6834	2799 \pm 1085
Reference	5064	5964	2042	7011	5020 \pm 828
Total suspended solids (mg/L)					
A1	78.50	72.80	19.85	30.75	50.48 \pm 11.43
A2	44.00	46.30	28.95	36.80	39.01 \pm 3.03
A3	16.20	11.70	11.80	41.70	20.35 \pm 5.57
B1	10.90	10.10	15.35	9.90	11.56 \pm 0.99
B2	24.30	26.30	6.40	17.10	18.53 \pm 3.48
B3	9.20	5.50	10.55	14.45	9.93 \pm 1.43
Reference	65.50	55.70	18.65	36.20	44.01 \pm 8.07
Volatile suspended solids (mg/L)					
A1	20.10	18.00	8.20	6.85	13.29 \pm 2.61
A2	14.70	12.00	8.15	19.15	13.50 \pm 1.79
A3	5.30	4.20	4.15	13.50	6.79 \pm 1.75
B1	5.20	4.80	7.60	4.80	5.60 \pm 0.52
B2	3.90	5.20	4.50	6.75	5.09 \pm 0.48
B3	3.60	2.20	4.55	6.00	4.09 \pm 0.62
Reference	12.60	10.70	5.60	8.55	9.36 \pm 1.16

$\text{NO}_x\text{-N}$ concentrations of surface waters ranged between 0.01 to 1.51 mg/L and $\text{NH}_4\text{-N}$ concentrations ranged from 0.01 to 1.59 mg/L (Figure 2). TN concentrations ranged from 0.17 to 3.31 mg/L. $\text{PO}_4\text{-P}$ concentrations in surface water ranged from 0.01 to 0.59 mg/L and TP concentrations ranged from 0.04 to 0.43 mg/L. TSS concentrations ranged from 0.9 to 187.0 mg/L. Elevated nutrient concentrations generally occurred close to pumping stations after rain events and near the Violet Canal when it was discharging river water.

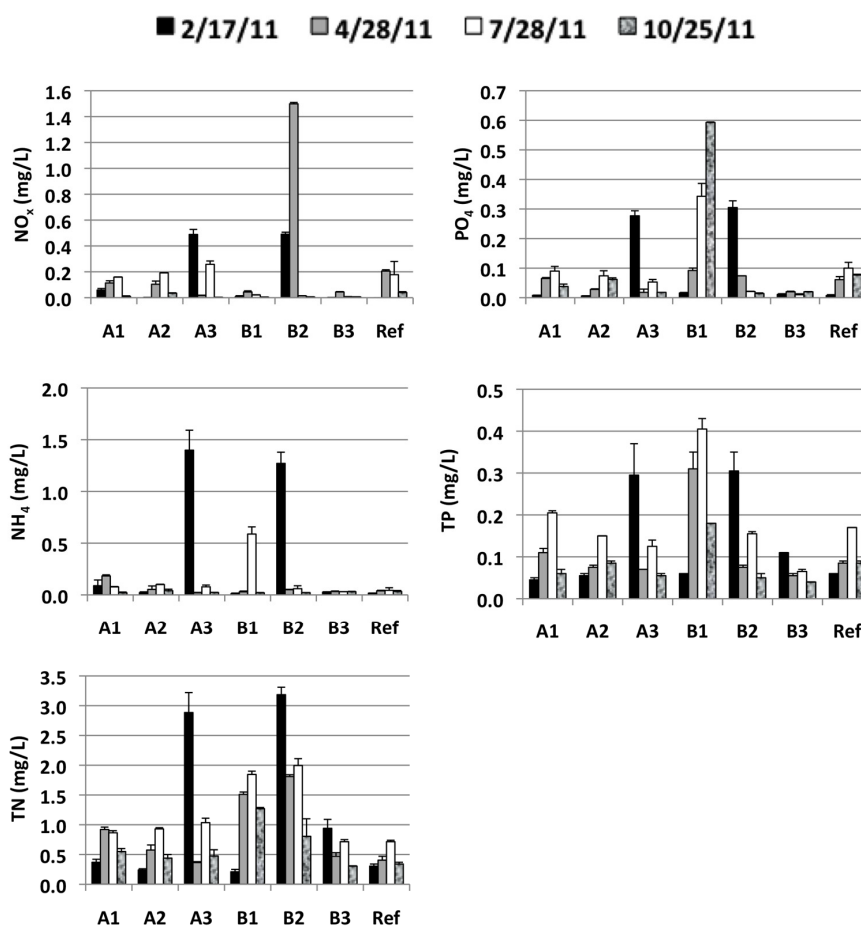


Figure 2. Nitrate + Nitrite ($\text{NO}_x\text{-N}$), ammonium ($\text{NH}_4\text{-N}$), total nitrogen (TN), phosphate ($\text{PO}_4\text{-P}$), total phosphorus (TP), and total suspended solids (TSS) at the CWU sampling stations. Error bars represent standard error of the mean.

3.2. Vegetation

Vegetative species richness was low throughout the CWU, generally limited to about four salt-tolerant species. Total vegetative cover was significantly lower in Sites B1 and B3 than in the other sites. The entire marsh is precariously perched on a matrix of dead baldcypress stumps and fallen trunks that are generally just below the surface. These trunks are the result of the trees killed by salinity when the MRGO was opened. All sites contain significant areas of open water, with site A3 approaching 50% and A1 at 100%. The Reference site has substantially greater cover of the salt marsh species *Spartina alterniflora*, whereas site B1 (the site receiving stormwater runoff from the Gore pumping station) was the only area with substantial shrub-scrub habitat dominated by *Iva frutescens* and baldcypress.

Peak aboveground biomass ranged from about 1500 g·dry·weight/m² to about 2000 g·dry·weight/m² and belowground biomass ranged from about 1000 g·dry·weight/m²

to about 4000 g·dry·weight/m² (Figure 3). The lowest values for above- and belowground biomass generally occurred in areas where the marsh is breaking up.

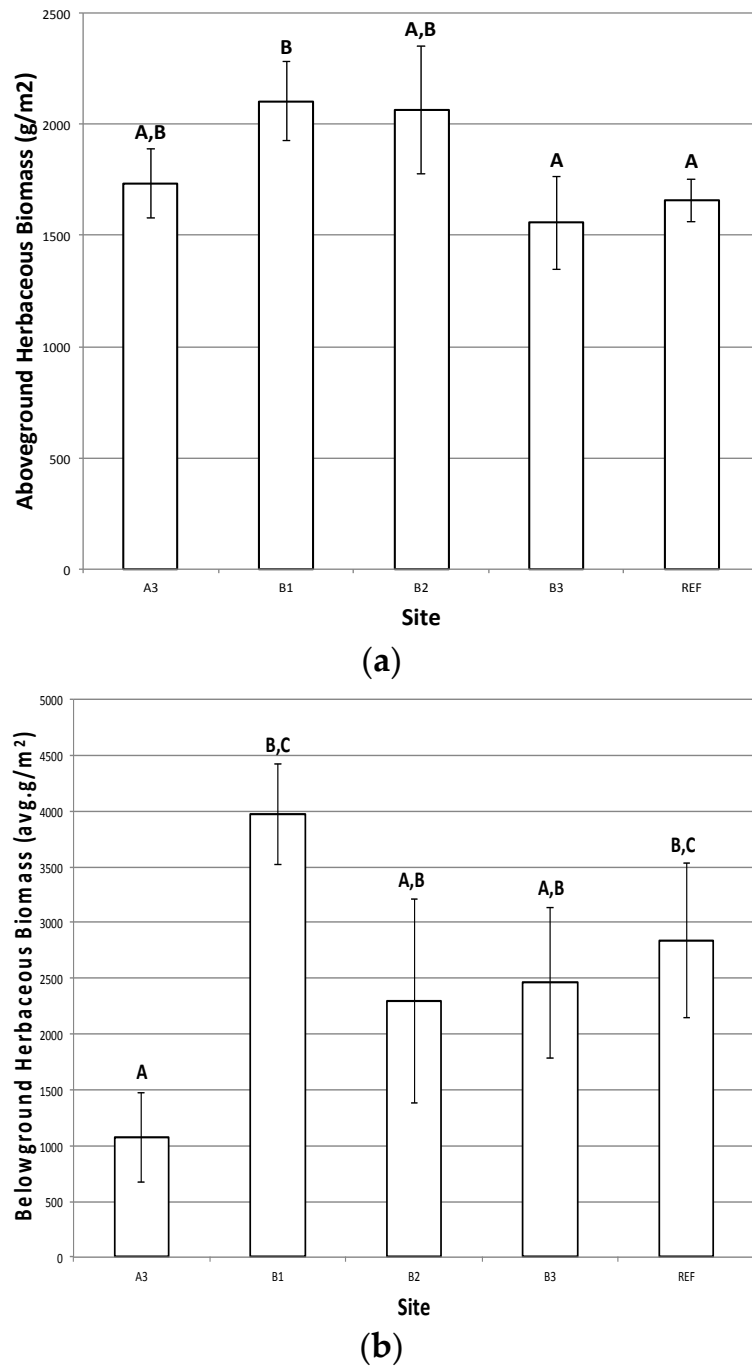


Figure 3. Aboveground (a); and belowground (b) herbaceous biomass at study sites in the CWU. Different letters indicate a significant difference $\alpha = 0.05$. Error bars represent standard error of the mean.

3.3. Soils

Bulk density ranged from 0.13 to 0.42 g/cm³, with an overall mean of 0.22 ± 0.2 g/cm³. Bulk density was significantly higher at site B1, which is the site that has been receiving fresh water from the Gore Pumping Station and the Gore Oxidation Pond, than any of the other sites except A2 ($p < 0.0060$; Figure 4).

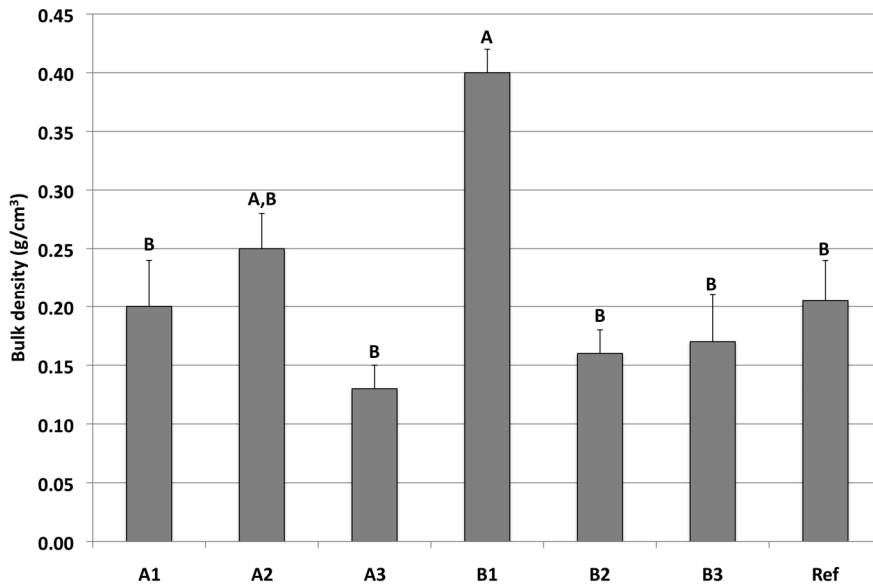


Figure 4. Soil bulk density at the sampling sites in the CWU. Different letters indicate a significant difference $\alpha = 0.05$. Error bars represent standard error of the mean.

Soil strength was significantly higher at sampling site B1, adjacent to the Gore pumping station, than at any other site ($p < 0.0060$; Figure 5). The lowest strength soils were found at site B3, an area that is actively degrading.

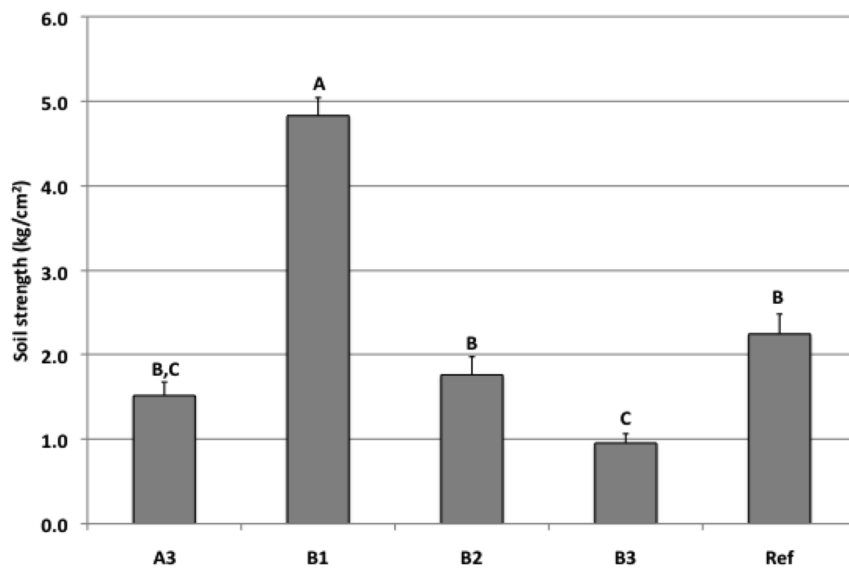


Figure 5. Surface soil strength using a hand held penetrometer. Different letters indicate a significant difference $\alpha = 0.05$. Error bars represent standard error of the mean.

Wetland surface elevation south of the Violet Siphon increased at all sites compared to the historical measurements taken in 1996–1999 [21]. The Near site had an elevation 8.3 cm lower in 1999 than initial measurements made in 1996, however, measurements made in 2011 indicate elevation has risen 10.9 cm since 1999 (Figure 6). The Mid site elevation decreased 1.62 cm during the 1996–1999 period, but has since increased 5.2 cm and is now 3.6 cm above initial measurements made in 1996. Elevation at the Far site decreased 3.7 cm from 1996 to 1999, but then increased 11.6 cm from 1999 to 2011 to be 7.9 cm above initial measurements. Accretion measured during spring 2011, which

encompasses all accretion since 1996, was 10.4 ± 0.31 cm at the Near site, 6.4 ± 0.37 cm at the Mid site, and 4.12 ± 0.34 cm at the Far site.

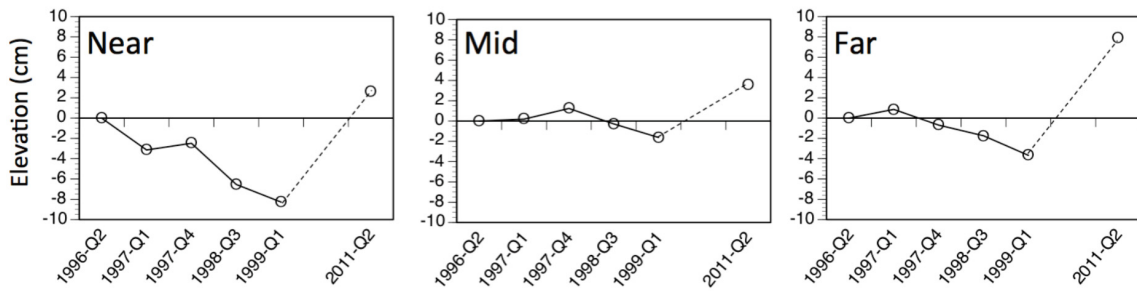


Figure 6. Wetland surface elevation change at the Violet monitoring stations. Q1, Q2, etc. indicate which quarter of the year samples were collected.

Surface water and interstitial soil salinity did not differ among sites. Across sites, surface water salinity was near fresh during most of the 2011 growing season (Figure 7). Interstitial soil salinity, however, ranged between about 5 and 7 ppt and was much greater than water salinity in Spring and Summer (Figure 7).

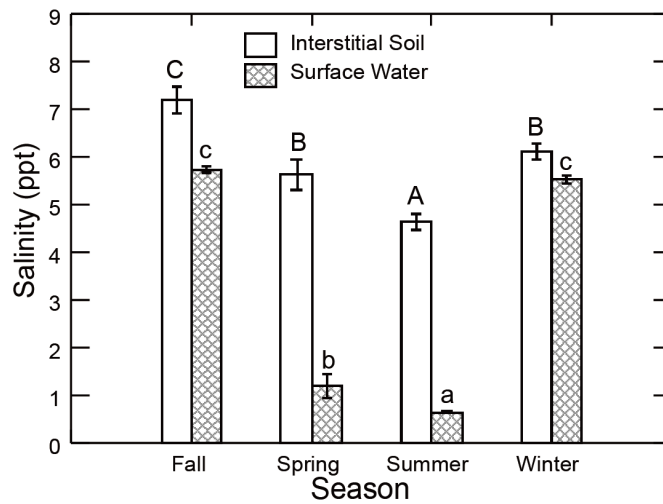


Figure 7. Mean surface water and interstitial soil salinity measured in the CWU in 2011. Different letters indicate a significant difference $\alpha = 0.05$. Error bars represent standard error of the mean.

3.4. Hydrology

There was 138 cm of rainfall during 2011 in the CWU area, with the majority falling during the summer months. The largest storm event occurred from 2 to 5 September 2011, with a maximum daily rainfall of 16 cm and a combined event total of 28 cm.

During this study, discharge from the Violet Siphon ranged from about 1.5 to 7.0 m³/s (Figure 8), with peak discharge in May and June 2011, and no flow from September 10th through the end of 2011.

Water levels fluctuated regularly at all three CRMS sites, but sites were constantly flooded with about 15 cm of water (Figure 9). Prior to the closing of the MRGO in mid-2009, surface water salinity fluctuated between about 2 and 12 ppt. However, since the closing of the navigation channel, surface water salinities have steadily declined and did not exceed 6 ppt in any of the three CRMS sites after 2009 (Figure 9).

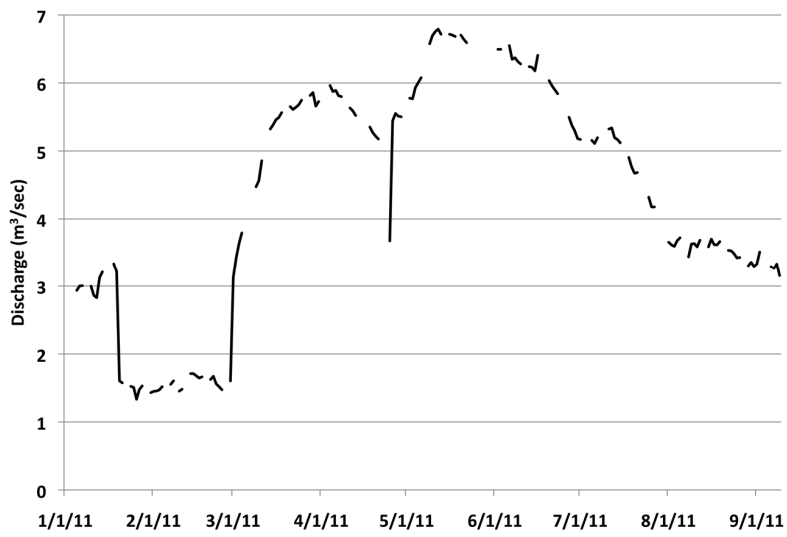


Figure 8. Discharge of Mississippi River from the Violet Siphon during the study.

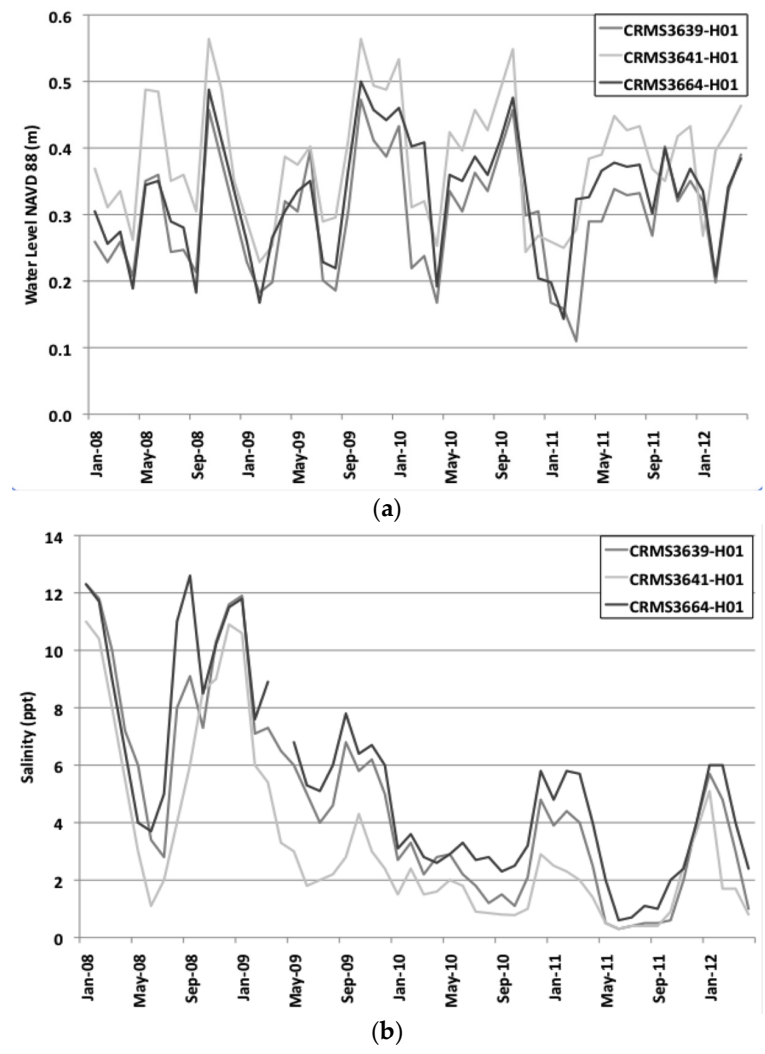


Figure 9. Surface water level (NAVD 88; a); and surface water salinity (b) measured at three Coastwide Reference Monitoring System (CRMS) sites in the CWU.

3.5. Nutria

Nutria (*Myocastor coypus*) were observed throughout the CWU, as were signs of grazing. Nutria are largely nocturnal and are very cryptic herbivores. Previous studies indicate that for every nutria spotted, far more go undetected [14,31,39]. This is most likely the case in the CWU, as nutria scat was prevalent at all sites during all visits. Nutria were also observed foraging on submerged aquatic vegetation (SAV) in the water column of the eastern portion of the CWU.

4. Discussion

4.1. Current State of the CWU

The CWU is a highly degraded coastal wetland that is largely isolated from riverine and estuarine influences. There are four freshwater sources to the area, including rainfall, stormwater, the Violet river siphon, and treated municipal effluent. Stormwater is dependent on rainfall and during wet periods there is ample fresh water from these sources. During drought periods, however, there may be no freshwater input for months. During the extreme drought of 2000–2001, high salinities in Lake Pontchartrain led to widespread death of freshwater vegetation [24,31].

The majority of the original fresh and low salinity forested and herbaceous wetlands were killed by saltwater intrusion resulting from opening of the MRGO, and much of the remaining brackish and saline wetlands have low vegetation diversity and biomass and soil strength. Prior to the closing of the MRGO in mid-2009, surface water salinity fluctuated between about 2 and 12 ppt and vegetation mapping of 32 areas in the CWU over the past several decades [40–42] shows changes that reflect these salinity fluctuations. In 1997, vegetation at the 32 areas was dominated by low salinity and intermediate marsh. By 2001 these sites were all brackish marshes and in 2007 they were a mixture of intermediate and brackish marsh. Vegetation composition changes with salinity, which causes plant death if salinity exceeds salt tolerance. It is likely that a large area of vegetation die off near the pumping station just north of the Violet canal is due to salinity fluctuations reflecting low salinity to fresh conditions during wet periods and high salinity during droughts.

Surface water salinities generally ranged between 0 and 6 ppt for this study and these results are consistent with other measurements of salinity in the area [20]. Interstitial soil salinity ranged between about 4 and 8 ppt in 2011, but both soil and water salinities in the CWU increased somewhat in 2012 [20]. Hillmann *et al.* [20] also recorded soil salinities below 2 ppt in areas surrounding each of the pumping stations in the CWU. Other data show that soil salinity has dropped below 2 ppt since 2013 (G. Shaffer, unpublished data). After soil salinities below 2 ppt were measured, 3000 baldcypress seedlings were planted in 2014 near the Gore pumping station as part of a grant from the Louisiana Coastal Protection Restoration Authority and funds from the Southeast Louisiana Flood Protection Authority.

Overall, water quality of the study area did not differ significantly among sampling sites within the CWU for any of the parameters measured, and almost all parameters were lower than criteria required by the Louisiana Department of Environmental Quality (LDEQ) at all sampling times and sites [43]. Nutrient concentrations of surface water at sites in the CWU (0.17–3.31 mg TN/L and 0.04–0.43 mg TP/L) were very similar to other wetlands in coastal Louisiana. In a review of surface water chemistry of freshwater forested wetlands, Hunter *et al.* [44] reported that TN concentrations ranged 0.11–3.09 mg/L and TP concentrations ranged 0.2–1.0 mg/L. In coastal marsh/estuarine systems, TN concentration generally range 0.5–5 mg/L and TP concentrations range 0.02–0.30 mg/L [45–50].

Measurements of wetland vegetation and soil characteristics indicate that the area is in a suboptimal state. Vegetative species richness is low in the CWU and throughout the area an unstable marsh platform has developed on a matrix of dead baldcypress trunks located just below the water surface. Aboveground herbaceous biomass is low (1500 to 2000 g·dry·weight/m²) compared to healthy coastal marshes in Louisiana (up to 4000 g·dry·weight/m²) [51]. Belowground live biomass ranged from about 1000 to 4000 g·dry·weight/m² whereas healthy herbaceous marsh generally has

8000 to 10,000 g·dry·weight/m² belowground biomass [31,51,52]. The highest above and belowground biomass occurred in the area with regular freshwater input (site B1).

Soil bulk density, strength, and belowground biomass were higher at site B1 (0.49 g/cm³, >4 kg/cm², and 4000 g/m², respectively) near the Gore Pumping Station than at any other study site (0.25 g/cm³, <2.5 kg/cm², and <2800 g/m², respectively). Site B1 also has one of only two remaining stands of baldcypress in the CWU due to consistent freshwater input from stormwater and the secondarily treated effluent from the Riverbend Oxidation Pond. Continuing discharge of treated effluent from the Riverbend Oxidation Pond (near the Gore Pumping Station) will help maintain freshwater conditions in this area. The lowest bulk density and soil strength occurred at sites with low vegetation biomass that are degrading to open water (e.g., sites A3 & B3). Day *et al.* [53] reported that marshes near Fourleague Bay impacted by the Atchafalaya River had soil strengths an order of magnitude higher than marshes with no riverine impact, much as occurs here.

Wetland surface elevation south of the Violet Siphon increased at all sites compared to the measurements taken in 1996–1999 [21], and these increases reflect sediment deposition that occurred when levees broke and storm surge from Hurricane Katrina flooded the area. A number of studies have demonstrated that storm deposition is an important source of sediments that increases elevation gain in wetlands because hurricane surge causes extreme water level excursions of up to several meters [54–56]. This surge usually does not occur in the CWU because gates at Bayous Dupre and Bienvenue are closed during storms. Thus the potential for input of re-suspended sediments from storm passage has been eliminated.

Seasonal water level variability measured in the CWU (about 30 cm) is consistent with other reports from the Louisiana coast [57] but because the CWU is largely isolated from marine influence, daily astronomical water level changes are much less than on the open coast.

Nutria and/or nutria scat were seen throughout the CWU and these animals should be monitored and managed since overgrazing is a serious problem in Louisiana wetlands [14–16,24,58]. When vegetation is removed from the marsh surface by nutria, the fragile organic soils are exposed to erosion through tidal action. If damaged areas do not re-vegetate quickly, they become open water as tidal scour removes soil and lowers elevation. If root systems become damaged, regeneration is slow to absent.

4.2. Management and Restoration of the CWU

Restoration of the CWU should address the human impacts that led to its deterioration. The most important acute cause of decline was the opening of the MRGO that led to rapid saltwater intrusion and massive wetland loss, especially of freshwater forested wetlands [13]. With the closure of the MRGO in 2009 and construction of a surge barrier on the eastern side of the MRGO levee, the potential for saltwater intrusion has been greatly reduced. Most of the remaining wetland is subsiding brackish and saline herbaceous marsh with low soil strength. Restoration plans should include introducing fresh water to combat saltwater intrusion and mineral sediments to increase elevations and strengthen wetland soils, and re-establishing fresh and low salinity wetland vegetation.

Marshes in the CWU have low vegetation diversity and biomass and low soil strength compared to marshes with riverine influence (e.g., [31,52]), primarily because the CWU is isolated from many outside sources of fresh water and sediments. Marshes with regular input of re-suspended sediments have high soil strength (e.g., [44]), such as coastal marshes in the Atchafalaya and Wax Lake deltas [59]. Two options for introducing mineral sediments and fresh water to the CWU include pumping in dredged sediment and diverting fresh water from the Mississippi River. Currently, 12 ha are being filled in the northern portion of the CWU using sediment dredged from adjacent water bottoms. This created wetland will be planted with baldcypress and herbaceous vegetation and nourished with secondarily-treated municipal effluent from Orleans Parish. Dredged sediments would be beneficial to the wetlands of the CWU but may be cost prohibitive for the entire area. Estimates of pumping dredged sediment range from \$20 to \$105 per cubic meter [60].

Diversion of fresh water from the Mississippi River is a second option to bring in sediment and reduce the impact of salt water. Lopez *et al.* [61] documented the development of a small delta at the Caernarvon diversion in Big Mar, a shallow open water areas that formed in a failed reclamation, that grew to about 700 ha in less than a decade. Another diversion, the Bonnet Carré Spillway, has been opened ten times since 1933, or about 1% of the time. Opening the spillway has resulted in up to two meters of sediment deposition between U.S. Highway 61 and Lake Pontchartrain, an area with a highly productive forested wetland [31].

Any water diverted into the CWU would also have to leave but, currently, there are only two relatively small outlets from the CWU to coastal waters, the flood gates at Bayous Dupre and Bienvenue. To prevent impoundment, freshwater could be diverted for short periods of time so that water levels rise but then recede through the floodgates when the diversion is closed. Such a diversion would need to be coordinated with coastal water levels so that drainage would occur rapidly. After passage of cold fronts in the winter in Louisiana, water levels can decrease by a meter for up to a week [57,62], which would enhance drainage. To improve water drainage and circulation in the CWU, Hillmann *et al.* [20] recommended removing or breaching of spoil banks.

To increase vegetation species composition and biomass, fresh and low-salinity vegetation should be reintroduced into the area. In deeper areas, floating marsh can be created and vegetation such as giant bullwhip, *Schoenoplectus californicus*, can be planted. This plant can grow in nearly 1 m of water and is generally unaffected by nutria. Fresh and low-salinity vegetation require a consistent source of fresh water and, in addition to a diversion from the Mississippi River, another consistent freshwater source is secondarily treated effluent from one or more of the surrounding wastewater treatment plants. Secondarily treated and disinfected municipal effluent is discharged into natural wetlands throughout Louisiana [15,62–64]. This discharge is regulated by the LDEQ and the receiving wetland is monitored (e.g., surface water quality, vegetative productivity, soil metal accumulation) for the life of the project. About 1900 cubic meters per day of treated effluent has been discharged from the Riverbend Oxidation Pond near the Gore Pumping Station (Figure 1) for more than four decades, with the exception of a 10-year shut down after Hurricane Katrina. The only remaining baldcypress swamp in the CWU and freshwater herbaceous and shrub vegetation grow in the area receiving the effluent. There are four wastewater treatment plants within or adjacent to the CWU that could potentially discharge treated effluent into the wetlands.

Ialeggio and Nyman [65] showed that nutria are attracted to vegetation with higher nutrient content, such as that growing where nutrients are discharged through river diversions, stormwater, or secondarily-treated effluent. A marsh in Hammond, LA receiving treated effluent was decimated by nutria in one year but recovered after nutria were controlled [15]. Without sustained reduction of nutria populations, wetland restoration efforts may be significantly hampered.

5. Conclusions

Historically, the Central Wetlands Unit was a healthy baldcypress–water tupelo swamp and fresh to low salinity marsh. The area was severely degraded in the last century primarily due to hydrologic alterations and saltwater intrusion. Most of these wetlands are in a sub-optimal state and will be enhanced by well-managed wetland restoration efforts such as proposed here and by Hillmann *et al.* [20]. The addition of fresh water, sediments, and nutrients, combined with planting of forested and herbaceous wetland species, will lead to restoration of degraded habitats and forested wetlands will enhance hurricane protection in Orleans and St. Bernard Parishes. Measures to monitor and control nutria should be considered as part of any restoration plan. Without timely implementation of large-scale restoration measures, the CWU will continue to degrade and to increase the vulnerability of nearby populations.

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