water

MDPI

Review

A Review of 50 Years of Study of Hydrology, Wetland Dynamics, Aquatic Metabolism, Water Quality and Trophic Status, and Nutrient Biogeochemistry in the Barataria Basin, Mississippi Delta—System Functioning, Human Impacts and Restoration Approaches

John W. Day [1,4], William H. Conner [2], Ronald D. DeLaune [1], Charles S. Hopkinson [3], Rachael G. Hunter [4], Gary P. Shaffer [5], Demetra Kandalepas [5], Richard F. Keim [6], G. Paul Kemp [1], Robert R. Lane [4,*], Victor H. Rivera-Monroy [1], Charles E. Sasser [1], John R. White [1] and Ivan A. Vargas-Lopez [1]

[1] Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA
[2] Baruch Institute of Coastal Ecology and Forest Science, Box 596, Clemson University, Georgetown, SC 29442, USA
[3] Department of Marine Sciences, University of Georgia, Athens, GA 30602, USA
[4] Comite Resources, PO Box 66596, Baton Rouge, LA 70896, USA
[5] Department of Biological Sciences, Southeastern Louisiana University, Hammond LA 70402, USA
[6] School of Renewable Natural Resources, Louisiana State University, Baton Rouge LA 70803, USA
* Correspondence: rlane@comiteres.com

Citation: Day, J.W.; Conner, W.H.; DeLaune, R.D.; Hopkinson, C.S.; Hunter, R.G.; Shaffer G.P.; Kandalepas, D.; Keim, R.F.; Kemp, G.P.; Lane, R.R.; et al. A Review of 50 Years of Study of Hydrology, Wetland Dynamics, Aquatic Metabolism, Water Quality and Trophic Status, and Nutrient Biogeochemistry in the Barataria Basin, Mississippi Delta—System Functioning, Human Impacts and Restoration Approaches. *Water* **2021**, *13*, 642. https://doi.org/10.3390/w13050642

Academic Editor: Maria Mimikou

Received: 21 January 2021
Accepted: 19 February 2021
Published: 27 February 2021

Abstract: Here we review an extensive series of studies of Barataria Basin, an economically and ecologically important coastal basin of the Mississippi Delta. Human activity has greatly altered the hydrology of the basin by decreasing riverine inflows from leveeing of the river and its distributaries, increasing runoff with high nutrient concentrations from agricultural fields, and channelization of wetlands of the basin interior that has altered flow paths to often bypass wetlands. This has resulted in degraded water quality in the upper basin and wetland loss in the lower basin. Trophic state analysis found the upper basin to be eutrophic and the lower basin to be mesotrophic. Gross aquatic primary production (GAPP) was highest in the upper basin, lowest in the mid basin, and intermediate in the lower basin. Forested wetlands in the upper basin have degraded over the past several decades due to increased periods of flooding, while there has been massive loss of emergent wetlands in the lower basin due to increasing water levels and pervasive alteration of hydrology. Restoration will entail reconnection of waterways with surrounding wetlands in the upper basin, and implementation of river sediment diversions, marsh creation using dredged sediments and barrier island restoration. Findings from this review are discussed in terms of the functioning of deltas globally.

Keywords: Barataria Basin; Mississippi Delta; trophic state; denitrification; eutrophication; forested wetlands; restoration

1. Introduction

The Barataria Basin is one of eight large coastal basins comprising the Mississippi Delta. The delta includes two geologic provinces—the deltaic plain formed by direct deposition of sediments and wetland growth and the Chenier Plain formed by the westward drift of Mississippi River sediments [1–3]. The basins in the deltaic plain are interdistributary, located between current and abandoned distributary ridges of the Mississippi River. The Barataria Basin is located between the Mississippi River and Bayou Lafourche, an abandoned distributary channel. Over the past half century, there has been dramatic wetland loss in the lower basin [4,5], but wetland area has remained relatively unchanged in the upper, freshwater part of the basin.

Over the past half century, there has been extensive study of Barataria Basin. Much of the earlier work performed in the basin was synthesized by [6,7]. Reference [6] reviewed early studies of saline waters and wetlands in the southwestern part of the basin surrounding Caminada Bay. This monograph reviewed composition and production rates of primary producers, composition of faunal communities in salt marshes, submerged sediments and the water column, microbiology, detrital dynamics and developed an ecosystem carbon budget. Reference [7] reviewed the ecology of the entire basin, as part of the US Fish and Wildlife Service Estuarine Profile series. This review covered water level variability, sediment dynamics, chemistry and nutrient dynamics, aquatic and wetland composition and productivity, fauna, modeling and management issues. These two publications are largely unavailable so information from these publications plus more recent studies is summarized here.

2. Overview Conceptual Model of the Barataria Basin

To better illustrate the changes in the Barataria Basin, we developed a simple conceptual model of how the basin functioned in a natural state and how human activities have changed this functioning (Figure 1). This model represents the triangular shape of the basin in natural and current conditions.

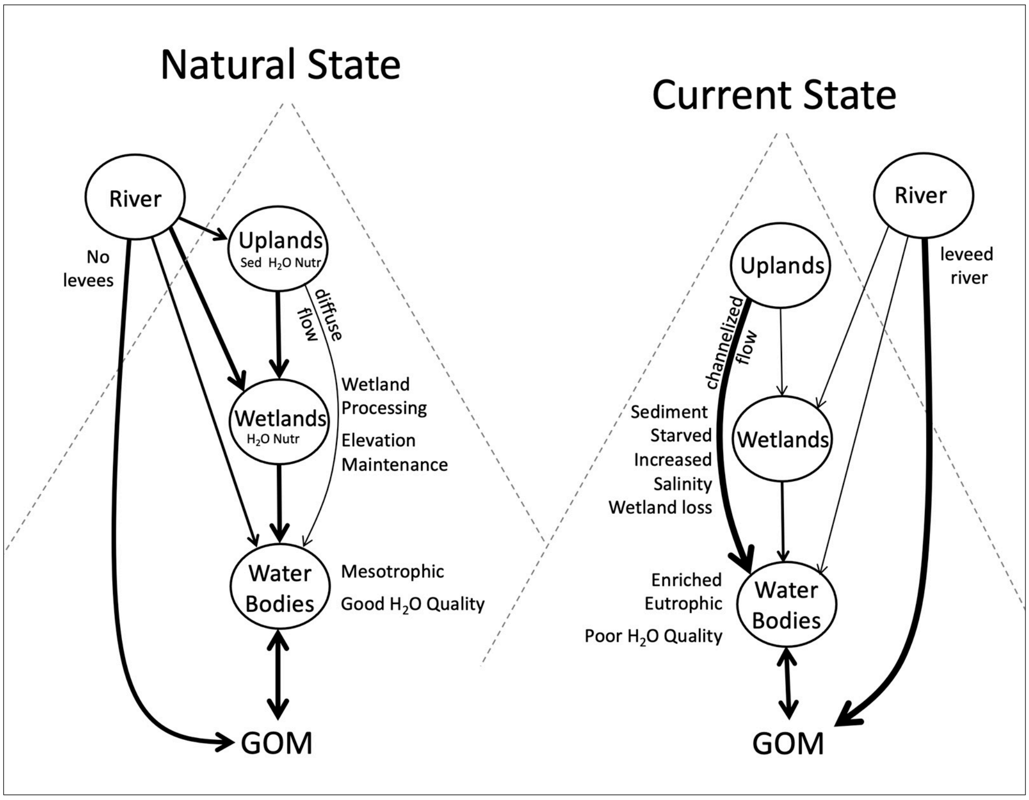

Figure 1. Simplified conceptual model of the Barataria Basin reflecting the triangular shape of the basin. There is net water flow from the upper basin to the Gulf of Mexico (GOM). Under natural conditions, river water entered the basin episodically, and rainfall runoff from elevated natural levees flowed mostly through wetlands to water bodies. Under current conditions, almost no river water enters the basin and upland runoff bypasses most wetlands.

The Mississippi Delta and its estuarine ecosystems have evolved over the past several thousand years largely in the absence of any human intervention. Interdistributary basins were formed and deteriorated as part of the shifts in Mississippi River deltaic lobes. There was a pattern of wetland expansion within the interdistributary basins followed by degradation as riverine input and sediment supplies waxed and waned. Until European colonization, the natural levees of the Mississippi and Bayou Lafourche isolated the Barataria Basin from other parts of the deltaic plain. River water, however, regularly entered the basin via overbank flooding, crevasse formation, and a dense network of minor distributary channels. The natural levees were densely forested and nutrient inputs via runoff from these natural levees were low. Most upland runoff from rainfall slowly flowed through creeks and bayous, with overbank sheet-flow through adjacent wetlands where nutrients, especially nitrate, and sediments were taken up. Flow reaching water bodies further down basin had relatively low nutrient concentrations and little stochiometric variability. River water that entered the basin in episodic pulses followed similar flow paths such that nutrient and sediment loading to mid reaches of Barataria Basin were relatively low. During years without these inputs, turnover time of water bodies in much of the basin was months up to more than a year. Aquatic primary productivity was likely moderate throughout the basin.

Freshwater surplus from the upper basin flowed to the lower basin and mixed with Gulf and estuarine plume water via tidal pumping. Sheet flow was important to tidal wetlands with a somewhat regular diurnal ebb–flood cycle accentuated by frontal passage and episodic events such as hurricanes. This resulted in one of the greatest expanses of tidal saline and coastal freshwater wetlands in the US. Sediment input to tidal wetlands and their regular draining worked together to consolidate sediments and add soil strength. Aquatic metabolism was likely heterotrophic in the upper basin due to high levels of organic matter flowing from wetlands but more balanced in the lower basin. Wetlands were sustained by regular inputs of riverine sediments and in situ organic soil formation.

Human activity has drastically changed the hydrology and landscape of the basin. River input to the basin is greatly reduced. There has been a change in land use on the natural levees bordering the basin from forest to intensive row crop agriculture and industrial/urban land covers. Channelization of bayous and waterways draining the natural levees has resulted in the rapid flow of water down basin with much less contact with adjacent wetlands. Natural hydrology has been altered by channel dredging related to drainage, navigation, and oil and gas activity throughout the basin. These changes pervasively altered the hydrology of the basin, restricting water movement on and off wetlands, and increasing the rate and extent of downstream runoff, and intrusion of salt water up the basin.

In this paper, we document how changes in hydrology and water flow paths in the Barataria Basin have altered the creation and sustainability of wetlands, nutrient biogeochemistry, aquatic metabolism, and the pattern of eutrophication throughout the basin. The changes discussed above have had the following impacts:

- Human impacts in the basin include high rates of relative sea-level rise, loss of riverine input, and pervasive alteration of hydrology and nutrient enrichment.
- The hydrology of the basin has been pervasively altered with elimination of riverine surface input, clearing of natural levees and excavation of a dense network of drainage canals in agricultural fields, and extensive channelization of wetlands so that most upland runoff flows directly to open water bodies. The wet-dry season and tidal flooding of wetlands have been altered, especially with spoil banks created during channelization.
- Nutrient processing has changed dramatically with fertilizer application and rapid nutrient runoff, especially nitrate, that is discharged directly to open water bodies. The role of wetlands in buffering nutrient concentrations and stoichiometry has been greatly reduced.
- Because of high nutrient input due to wetland bypassing, water bodies in the upper and mid basins receiving high nutrient inputs have become very productive, more

heterotrophic due to high organic input from wetlands and uplands, and eutrophic to hyper-eutrophic. Water bodies with low agricultural input are less productive and slightly autotrophic, and more mesotrophic. Water quality in the upper basin is highly degraded while that in the lower basin is less so.

- Wetlands in the basin have become degraded and there has been extensive wetland loss in the lower basin due to increasing water levels, lack of riverine input, saltwater intrusion, and pervasive alteration of hydrology. Marsh productivity has declined due to these human impacts. The impacts of oil and gas activity have contributed significantly to marsh loss. The upper basin is dominated by bald cypress-water tupelo swamps and some freshwater marshes, but there has been relatively little loss of wetland area. However, forested wetlands are now mostly permanently flooded so that productivity is declining, and recruitment is limited so that there is a slow deterioration of these wetlands. Low to no natural recruitment because of increased flooding has made logging unsustainable.

In summary, there has been severe water deterioration in the upper basin and extensive wetland loss in the lower basin. We address causes of these problems and potential solutions throughout this paper. We focus more intensively on the upper basin because we believe that water quality can be substantially improved and extensive wetland loss can be prevented by a return to a more natural system functioning.

3. Description of the Barataria Basin

The Mississippi Delta was formed over the past approximately 6000 years as the river sequentially occupied different distributary channels and formed a series of large delta lobes (Figure 2). Sale-Cypremont was the first active lobe until approximately 4600 years BP and formed as sea level was still rising. As the Sale-Cypremont Delta was abandoned, the river subsequently occupied the Cocodrie (4600–3500 years BP), and Teche (3500–2800 years BP) channels. These distributaries discharged to the central and western parts of the deltaic plain. It was not until the development of the St. Bernard lobe (2800–1000 years BP), with discharge to the eastern part of the deltaic plain, that the river occupied the channel that would become the current Mississippi River. The river then shifted back west and occupied the Lafourche distributary channel (1000–300 years BP) and the Barataria Basin became a distinct landscape feature. The river then shifted east to the present channel forming the Plaquemines lobe (750–500 years BP) and finally the Balize (Birdsfoot) Delta at the mouth of the river. The Atchafalaya delta lobe became subaerial in 1973 initiating a new delta lobe formation. Thus, by approximately 1000 years ago, the Barataria Basin had been largely enclosed by the Lafourche and current Mississippi channels.

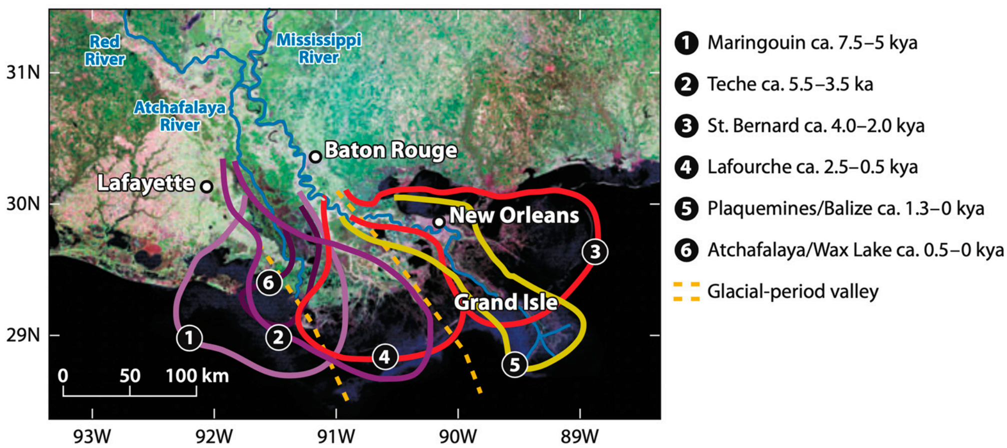

Figure 2. Holocene deltas of the lower Mississippi River (modified from [8]).

Even though these distributary channels and delta lobes were most active during the periods indicated, most of the distributaries carried water well into the late 19th century. Reference [9] used journals and charts of 16th- and 17th-century explorers to describe what they have called the "last natural delta" of the Mississippi as it existed just prior to European settlement. They stated that the delta was a seaward-advancing arc that occupied, through four distributaries, all of the five most recent delta complexes of the Mississippi River (Teche, St. Bernard, Lafourche, Modern, and Atchafalaya) and extended across the deltaic plain. It was characterized by plumes of fresh water that extended for more than 10 km into the Gulf of Mexico during the spring flood and by a vast offshore oyster reef.

The Barataria Basin (Figure 3) is a 6600 km^2 interdistributary basin located between the natural levees of the Mississippi River and Bayou Lafourche. The aquatic portion of the basin is dominated by wetlands in the upper basin and open water in the lower basin adjacent to the Gulf of Mexico. Hydrologically, the basin can be divided into three subbasins. The upper basin is fresh and dominated by bald cypress-water tupelo swamps and fresh marshes. There are two water bodies: Lake Boeuf and Lac des Allemands. The latter receives most runoff from the upper basin from Bayous Boeuf and Chevreuil. These two streams carry most agricultural runoff to Lac des Allemands, and water flows down basin via Bayou des Allemands which is the only outlet to the mid basin. The mid basin occupies the area between Highway 90 and the Gulf Intracoastal Waterway (GIWW). Water flows from Bayou des Allemands to Lake Salvador and then through two outlets to the lower basin. Lake Salvador also receives flow from the Lake Cataouatche subbasin, which receives runoff from the west bank of the New Orleans metropolitan area. Since approximately 1940, the Intracoastal Waterway has connected the Barataria Basin to the Atchafalaya River, from which there is net eastward flow into the Barataria Basin [10]. Since 2002, the Davis Pond freshwater river diversion has introduced Mississippi River water to Lake Cataouatche [11]. Mississippi River water also enters the basin by subsurface pathways; [12] estimated the contribution via this pathway was 14–28% of all water discharging to the Gulf in the modern basin. Wetlands of the mid basin are mostly fresh to low salinity marshes and small areas of swamp forest. Water leaving the mid basin flows through a series of shallow water bodies (Bayous Perot, Rigolettes, and Barataria, and Little Lake) before entering Barataria Bay. Wetlands of the lower basin are dominated by brackish and saline marshes. Water is exchanged between Barataria and Caminada bays and the Gulf of Mexico through several deep tidal passes.

The astronomical tide range is approximately 30 cm near the coast. There is little daily astronomical tidal variability in the upper basin, but there is longer-term water level variability due to such factors as heavy rainfall runoff, frontal passages and seasonal water level changes in the Gulf of Mexico. Water bodies in the basin are shallow, ranging from 1 to 3 m, and are generally unstratified [13]. Water turnover is low in the upper basin (months) and a few days near the Gulf [14,15]. Mississippi River water enters the lower basin from the Gulf of Mexico during high discharge [16]. Wetland loss has been low in the upper basin but very high in the lower basin ([17] see discussion below).

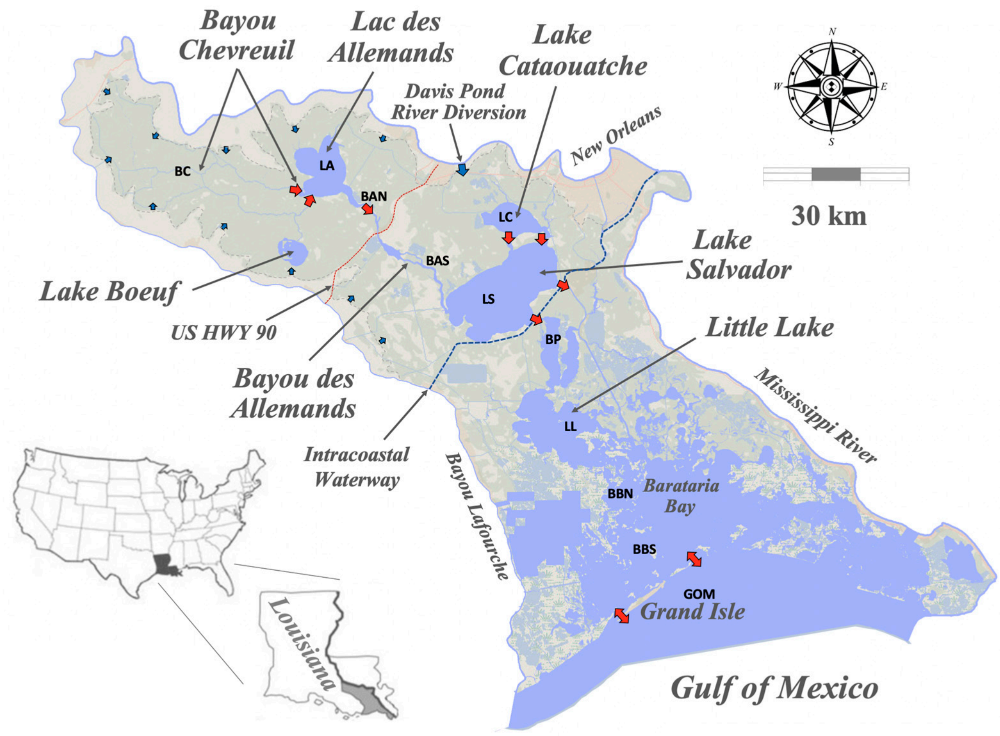

Figure 3. Map of the Barataria Basin (blue-water, green-wetlands, tan-uplands). Arrows indicate general hydrologic flow. Letters indicate station groupings used by [18] for water quality analysis of the basin: BC—Bayou Chevreuil, LA—Lac des Allemands, BAN—Bayou des Allemands north, BAS—Bayou des Allemands south, LS—Lake Salvador, LC—Lake Cataouatche, BP—Bayou Perot, LL—Little Lake, BBN—Barataria Basin north, BBS—Barataria Bay south, and GOM—Gulf of Mexico.

3.1. Wetland Change in the Barataria Basin

Coastal Louisiana has experienced dramatic wetland loss over the past 70–80 years as a result of a complex interaction of a variety of factors, all of which are related to isolation of most of the deltaic plain from riverine input and pervasive hydrologic alteration of coastal wetlands and water bodies [17,19–24]. As with most of the delta, almost all wetland loss in Barataria Basin has been coastal marshes.

We use the term wetland change because swamp forests and floating freshwater marshes have had much lower loss rates than saline marshes in the lower basin, although they have in many cases been modified to wetter or more-saline wetland types. The most important cause of wetland loss in saline marshes is increasing inundation due to relative sea-level rise (RSLR) and reduced ability of these marshes to accrete vertically to offset RSLR because of a reduction in mineral sediment input and lowered organic soil formation due to increasingly long-duration flooding [22,25,26].

By contrast, there has been relatively little loss of wetland area in the upper basin. Increased flooding affects freshwater forested wetlands due to RSLR in two main ways. As flooding duration increases, total forest productivity decreases. When flooding becomes permanent or near permanent, recruitment ceases because the tree seeds need periods of dryness to germinate. However, adult cypress and tupelo trees can persist for decades to centuries with permanent flooding. Freshwater marshes in the Bayou Boeuf Basin are predominantly floating so that they can survive with RSLR. Salinity intrusion is a threat to both forested wetlands and fresh marshes in the upper basin but the restricted hydrological exchange with the lower basin and surplus freshwater runoff has minimized salinity intrusion in the upper basin. If fresh conditions can be maintained and the long-term flooding conditions in forested wetlands can be reversed, those wetlands in the upper basin can persist as forested for decades.

4. Pervasive Changes in Hydrology

The wetland hydrology of the basin has been extensively modified due to canal dredging, resulting in the direct input of agricultural runoff to water bodies of the upper basin rather than mostly flowing through wetlands as it did when the system was natural. Before human alterations to the system, the basin received regular input of river water via crevasses, minor distributaries, and overbank flooding from both the Mississippi River and Bayou Lafourche. Bayou Lafourche was cut off from the Mississippi River in 1900 and the Mississippi River now has continuous levees that prevent river water input to the basin. River water has entered via the GIWW since approximately 1940, and the Davis Pond diversion since 2002, but quantities of water in both cases are relatively small (~62 m^3/sec from the GIWW and ~28 m^3/sec from the Davis Pond diversion) and are of more importance locally than for water budgets of the entire basin. High elevation natural levees (1 to 5 m) have almost all been cleared and converted to agricultural lands, as well as urban and industrial development. There are approximately 33,850 ha of farm fields above US 90, almost all devoted to sugarcane, and agricultural runoff is the major cause of water quality impairment in the upper basin.

By the time of European colonization, the natural levees of the Mississippi and Bayou Lafourche had isolated the Barataria Basin from other parts of the deltaic plain for approximately a thousand years. The map of [27] clearly shows the pervasiveness of major and minor channels in the deltaic plain (Figure 4a). For the Barataria Basin, the major distributaries of the Mississippi River and Bayou Lafourche confine the basin but at least six smaller distributary channel complexes flowed into the basin, from both Bayou Lafourche and the Mississippi. Some of the distributary ridges of these minor channels are still inhabited today, especially in the upper basin. Crevasses (low spots in natural levees that allowed frequent river flow) were very common all along the lower river distributaries. Figure 4b shows crevasses along the Mississippi River and Bayou Lafourche that were active during the colonial period [28–31].

In years without large floods, the hydrology of the basin was largely controlled by rainfall and water level variability of the Gulf. Most runoff from forested uplands flowed into wetlands and then into water bodies. There is strong seasonality of water export from the upper basin [32] (Figure 5a). Water export is highest in the cooler months due to high rainfall and low evaporation and can decrease to zero in the summer due to high rates of evaporation leading to a water deficit. Bayous Boeuf and Chevreuil drain into Lac des Allemands, and Bayou des Allemands is the sole outlet from the upper basin and drains into Lake Salvador. This seasonal pattern of water export is the primary factor influencing materials export to the lower basin and also reflects nutrient losses due to denitrification and burial (Figure 5b).

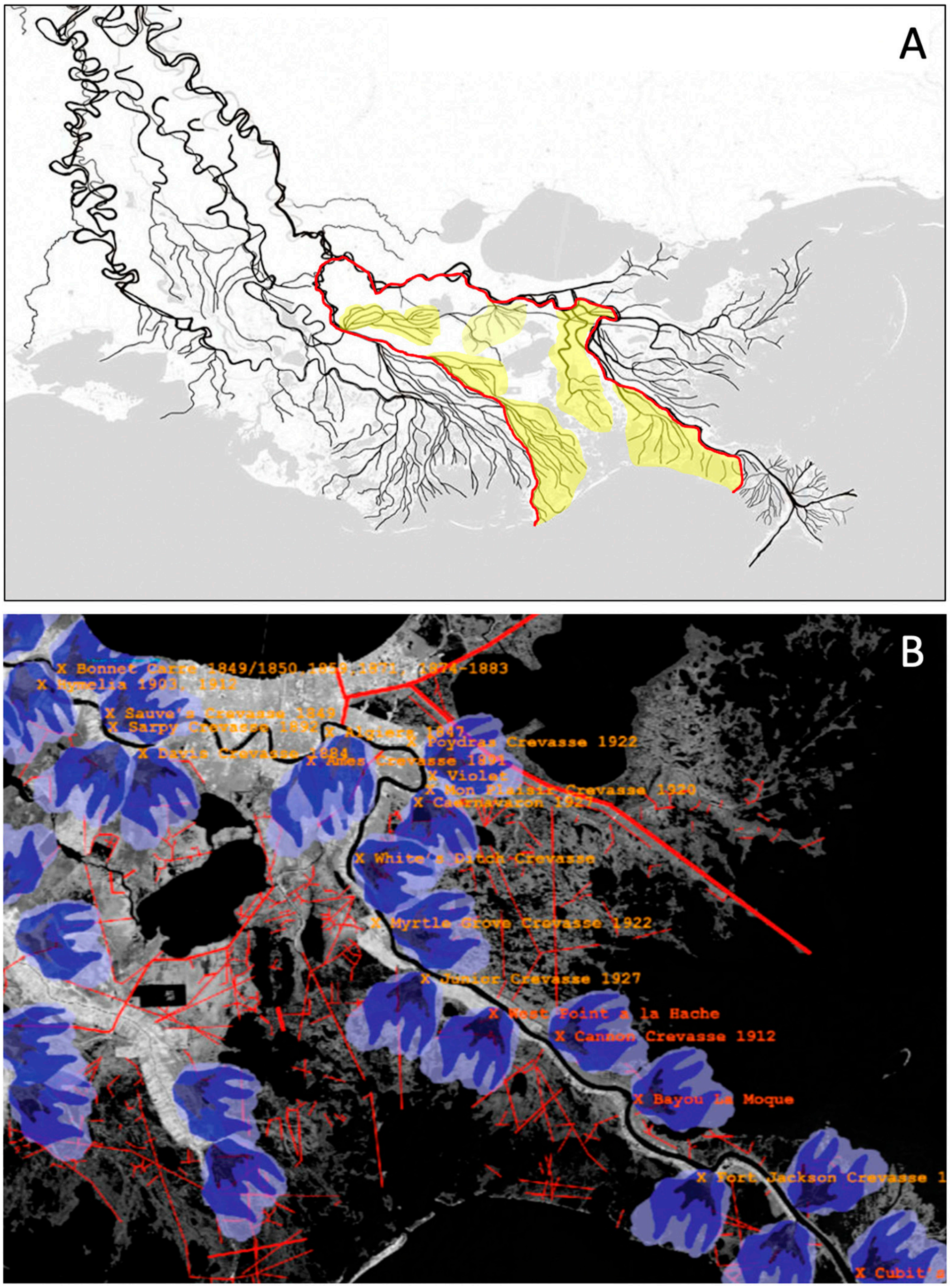

Figure 4. (**A**) Historical distributary channels of the Mississippi deltaic plain. The Barataria Basin is outlined in red. There are at least six minor distributary channel complexes in the basin (highlighted yellow areas). Modified from [27,33]. (**B**) Map of crevasses along the lower Mississippi River and Bayou Lafourche that functioned during the historical period (from [34] as modified from [28,29]).

Droughts influence salinity of the basin by reducing freshwater fluxes toward the Gulf and thereby allowing influx of salt water farther up the basin. The importance of drought-associated saline spikes prior to the extensive hydrologic modification of the basin is not well known, but they have recently been responsible for widespread vegetation changes in marshes in the Barataria Basin [35] and conversion of swamp forest to marshes in the nearby Lake Pontchartrain Basin [36]. Forest mortality from salinity is the major causes of forest loss in the delta [37], and persistence depends on sufficient freshening between drought events [38]. Frequent tropical cyclones and shallow bathymetry of the Gulf of Mexico results in relatively frequent periodic storm surge floods in the basin [39]. These events bring salt water but typically have minor effects on soil salinity [40] unless surge water is impounded and cannot freely drain [41].

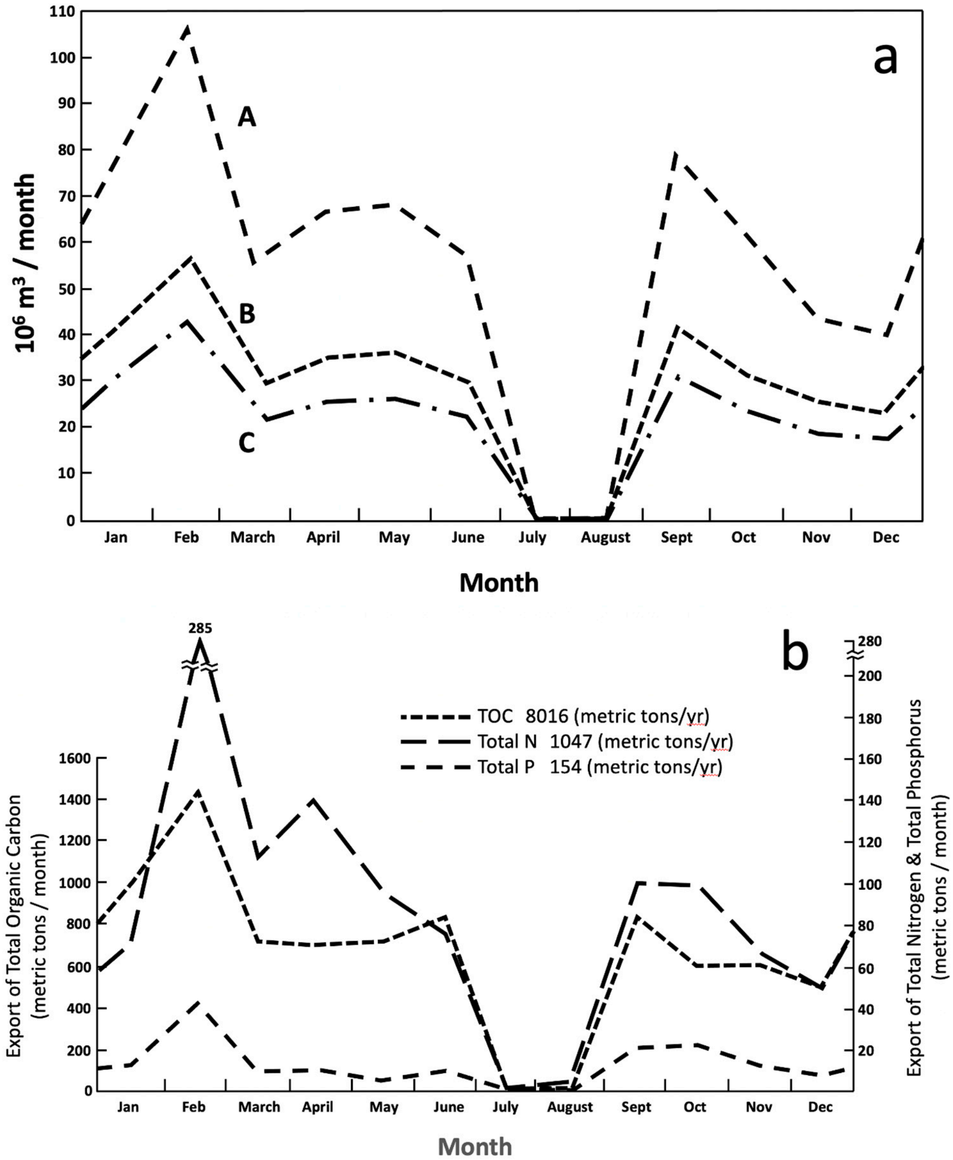

Figure 5. (**a**) Water flowing into and out of Lac des Allemands. Monthly mean water discharge at bayous des Allemands (A), Boeuf (B), and Chevreuil (C). Bayous Boeuf and Chevreuil account for most water flowing into Lake des Allemands, and Bayou des Allemands is the single outlet from the upper basin to the lower basin. Water discharge was zero in July and August because evapotranspiration exceeded precipitation (modified from [34]; data collected 1975–1976); (**b**) Materials export to the lower estuary measured at Bayou des Allemands, the only outlet from the upper basin (modified from [34]; data collected 1975–1976). The lines in the graph are monthly export values. Annual loadings for TOC, TN and TP are provided in the upper middle.

Reference [42] measured drainage density (length of channels per unit area) in the Barataria Basin (Figure 6) and compared it to trophic state index based on a multivariate analysis of Secchi depth, TN, TP, and chlorophyll following the approach of [43]. This is similar to the analysis of Seaton and Day discussed below that had similar results. Drainage density, which included both natural channels and dredged canals, varied by over an order of magnitude, ranging from approximately 1 km/km^2 in natural bayous to as high as 40 km/km^2 in agricultural fields. In the natural state, drainage density was less than 2–3 km/km^2 indicating how profoundly the hydrology of the basin has changed. The drainage density was related to trophic status as will be discussed later.

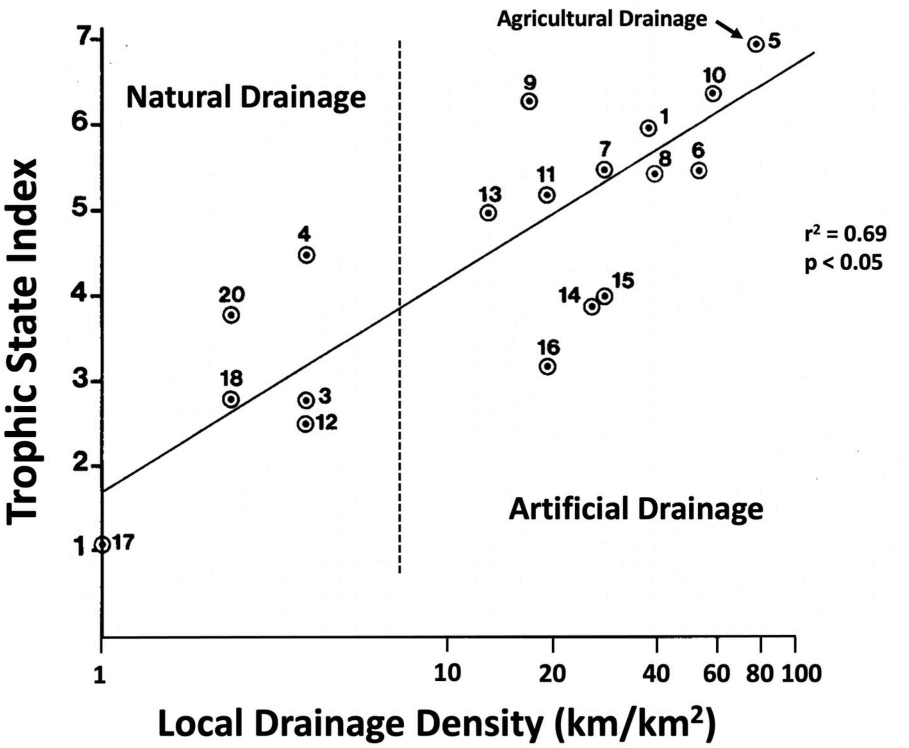

Figure 6. Local drainage density versus trophic status of stations in the Barataria Basin (modified from [42]; data collected 1977–1978).

The physical characteristics of water bodies in the basin reflect freshwater flowing down basin mixing with saline water from the Gulf of Mexico and the size of water bodies [44] (Table 1). Turnover of water bodies is related to their size, depth, drainage area, and tidal influence. In the upper basin, water body turnover ranges from one to 4.6 times per year which lower Barataria Bay turnover is 14.6 times per year. Salinity increases down basin due to mixing of fresh and salt water.

Table 1. Physical characteristics of water bodies in the Barataria Basin (modified from [44]; data collected 1973–1981; na: not available).

Ecological Zone	Example	Turnovers per Year	Mean Depth (m)	Salinity (‰)	Secchi Depth (cm)	Tidal Range (cm)	Upland to Wetland+ Water Ratio
Upper Basin	Lac des Allemands	4.6	2.0	0	33	3.2	1: 2.3
Middle Basin	Lake Cataouatche	1.5	2.0	0–3	30	na	1: 6.7
	Lake Salvador	1.0	2.5	0–6	72	8.5	
Lower Basin	Little Lake	na	1.5	0–15	72	12	1: 33.3
	Lower Barataria Bay	14.6	2.0	10–35	68	30	

5. Water Quality, Biogeochemistry, and Changes in the Trophic Status of Water Bodies of the Barataria Basin from the 1970s to 2015

Water quality in the basin depends on upland runoff, the degree of interaction with wetlands, biogeochemistry, especially the role of denitrification, and decreases in nutrient concentrations due to non-conservative uptake. We begin this discussion of nutrient dynamics with a review of two transect studies.

5.1. Temporal Changes in the Water Quality of the Basin Over Four Decades

Previous studies of nutrient chemistry in Barataria Basin from the upper freshwater swamp-dominated bayous to the near shore Gulf of Mexico include quarterly transects in 1977 and 1978 [45,46] and monthly transects from 1994 to 2016 [16] (see Figure 3 for station locations). Reference [16] added stations in 2005 in Lake Cataouatche and eastern Lake Salvador to capture the impacts of the Davis Pond diversion. Reference [18] analyzed both data sets to investigate spatial and temporal changes from the 1970s to 2016 focusing on trends down basin and the impact of the Davis Pond diversion (Figure 7). Reference [45] analyzed the transect data using multivariate statistics and developed a trophic state index (TSI) for Barataria Basin (see section 5.4) [46,47]. Reference [18] followed the same protocol and developed TSI scores using data from Seaton (1977–1978) [45] and pre- (1994–June 2002) and post-diversion (July 2002–2016) transects from [16].

The means for chlorophyll *a*, Secchi disk depth, total phosphorus (TP), total organic nitrogen (TON), total inorganic nitrogen (TIN), and NO_3 are shown in Figure 8. Reference [18] fit a two-way ANOVA model with interaction, and the interaction between station and time period was highly significant for every response ($p << 0.001$ for CHL, SD, TP, TIN and TON, and $p < 0.01$ for NO_3). This indicates that the main effect for time period varied over the station location. In all cases, the main effect for location was highly significant ($p < 0.0001$), indicating strong variation in the responses across stations. All of the pairwise comparison statements below have a Bonferroni comparison-wise protection at 0.05.

Chlorophyll *a* and nutrient levels were generally higher in the upper basin and decreased toward the lower basin (Figure 8). Mean chlorophyll *a* was highest in upper basin in non-shaded water bodies (Lac des Allemands and Bayou des Allemands), with the ranking (highest to lowest) of pre-diversion, post-diversion, and Seaton. These differences diminished, even becoming non-significant, toward the lower basin. In freshwater bayous bordered by swamp forest, chlorophyll *a* was lower due to light limitation. Mean chlorophyll *a* was 30 to 70 µg/L in fresh to low salinity water bodies strongly influenced by upland runoff. Turbidity was highest in the upper basin, as reflected by low Secchi depth values and that the water clarity increased down basin. Total phosphorous found highly significant differences in the upper basin, with significantly higher mean values for pre-diversion relative to post-diversion (and no differences to Seaton). However, there was a reversal in significance in the lower basin, with [45] exhibiting significantly higher mean TP than both pre- and post-diversion, especially in the lower basin. Mean nitrate was generally less than 0.3 mg/L in the central basin transects. NO_3 was elevated after runoff peaks from agricultural fields and where Mississippi River water entered the basin via the GIWW or the Davis Pond diversion.

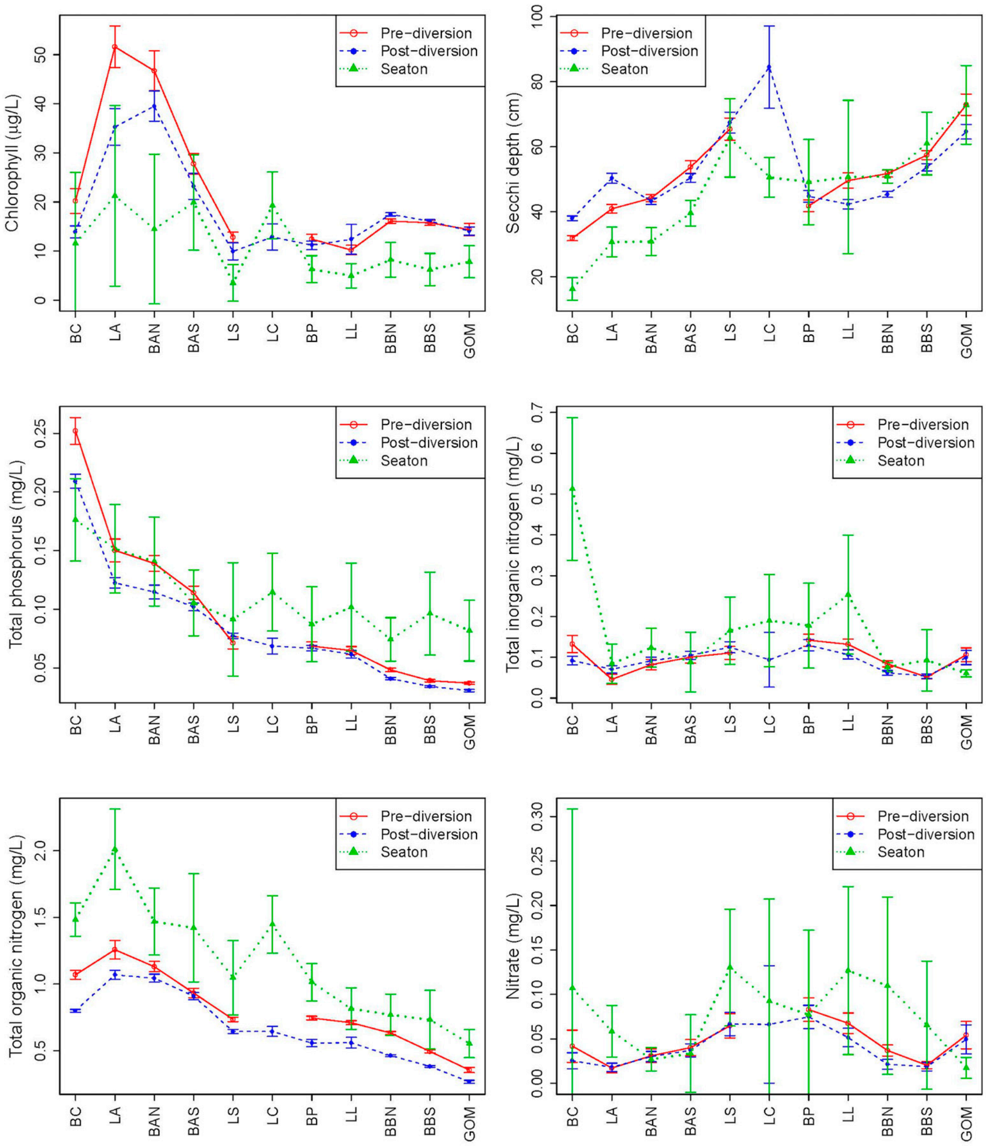

Figure 7. A comparison of water quality parameters from transects of the Barataria Basin from [16,18,45,46]. The means are geometric and standard error bars arithmetic. Station designations are defined in Figure 3. Data collected for pre-diversion (1994–June 2002), post-diversion (July 2002–2016), Seaton (1977–1978). Nitrate concentrations given as mg-N/L.

5.2. Wetland-Nutrient Interactions in Upper Barataria Basin

The water chemistry data from transects from swamp bayous to the Gulf of Mexico are primarily along the central drainage axis of Barataria Basin generally showed very low levels of nitrate (Figure 7), but a number of studies showed that agricultural drainage has high concentrations of nitrate and other nutrients. To capture the effects of episodic events, [48] (see also [49]) measured water quality parameters during rainfall events. They sampled runoff from sugarcane fields, a dredged canal receiving direct runoff from sugarcane fields (St. James Canal), Bayou Chevreuil which is affected by agricultural runoff and drainage from a natural swamp forest (Table 2). Mean concentrations of nutrients and TSS were uniformly low in drainage from the natural swamp. By contrast, concentrations were much higher in waterways receiving agricultural runoff. These data clearly show that peak concentrations in agricultural runoff were much higher than levels measured during the two transect studies, and that TSS and nutrient concentrations decreased rapidly, especially if there was flow through wetlands.

Table 2. Range of mean values from all storm events for total suspended sediment (TSS) and nutrient concentrations (mg/L) in stations receiving agricultural runoff in the upper Barataria Basin (from [48,49]; data collected 2005–2006). Peak values in parentheses.

Parameter	Agricultural Drainage Ditches	St. James Canal	Bayou Chevreuil	Swamp Forest Runoff
TSS	0–(1350)	186–275 (1500)	62–124 (350)	24–29
Total P	0.1–(3.5)	0.5–0.7 (1.0)	0.2 (0.8)	0.1–0.2
TKN	0.2–(16.5)	1.9–2.2 (7.0)	2.1–2.3 (7.0)	1.4
NO_x	0.1–(15.5)	0.5–2.7 (6.0)	0.2–2.2 (6.0)	0.2–0.3
NH_4	0–(2.3)	0.1–0.3	0.1–0.4	0.1

The relative insensitivity of drainage from natural swamps to nutrient loading was demonstrated by [50] who measured the impact of precipitation on the N:P ratio of water draining from a natural swamp compared to Bayou Chevreuil, which receives direct agricultural runoff. The N:P ratio in the natural swamp was unaffected by the weighted 5-day precipitation average prior to sampling (Figure 8 bottom). N:P ratios were always less than 5 and averaged approximately 2, indicating strong potential inorganic nitrogen limitation. By contrast, the N:P ratio in Bayou Chevreuil was significantly and positively related to the 5-day weighted precipitation average (Figure 8 top). At rainfall levels averaging greater than 2 cm, the N:P ratio was >20, indicating strong P limitation. With no rainfall the previous 5 days, the N:P ratio was <5 and was not different from the natural swamp drainage.

A series of studies addressed nutrient dynamics in swamp forest bordering Bayou Chevreuil that received high agricultural runoff. Reference [50] sampled nutrients in water as it flowed through the swamp and developed a simple nutrient accounting model of nutrient uptake and release. Organic nitrogen and phosphorus comprised 77% and 41%, respectively, of TN and TP. Nitrate was generally less than 0.1 mg/L. The model indicated strong uptake of NO_3 (87%) and NH_4 (33%) and release of PO_4, organic N and organic P, indicating that the swamp was removing and transforming inorganic floodwater nutrient concentrations. Reference [51] characterized surface water quality in the Bayou Boeuf Basin, which receives drainage from sugarcane fields, and reported similar results. They reported that nitrate was generally lower than 0.1 mg/L except during high runoff periods when concentration reached 1–3 mg/L. Hydrological modeling indicated that creating breaks in spoil banks along canals would increase N reduction from the current 21.4% to only 29.2% because only a very small fraction of the stormwater carried in channels is exposed to wetlands. References [52,53] studied the impact of redox in laboratory microcosms. There was a negative correlation between dissolved oxygen and PO_4 concentration. They concluded that water quality deterioration in the upper Barataria Basin was strongly related to bypassing forested wetlands by canals and a great reduction in overland flow. Litter decomposition in the field and in laboratory microcosms showed that more aerated conditions led to higher litter decomposition and higher nutrient concentrations in remaining litter.

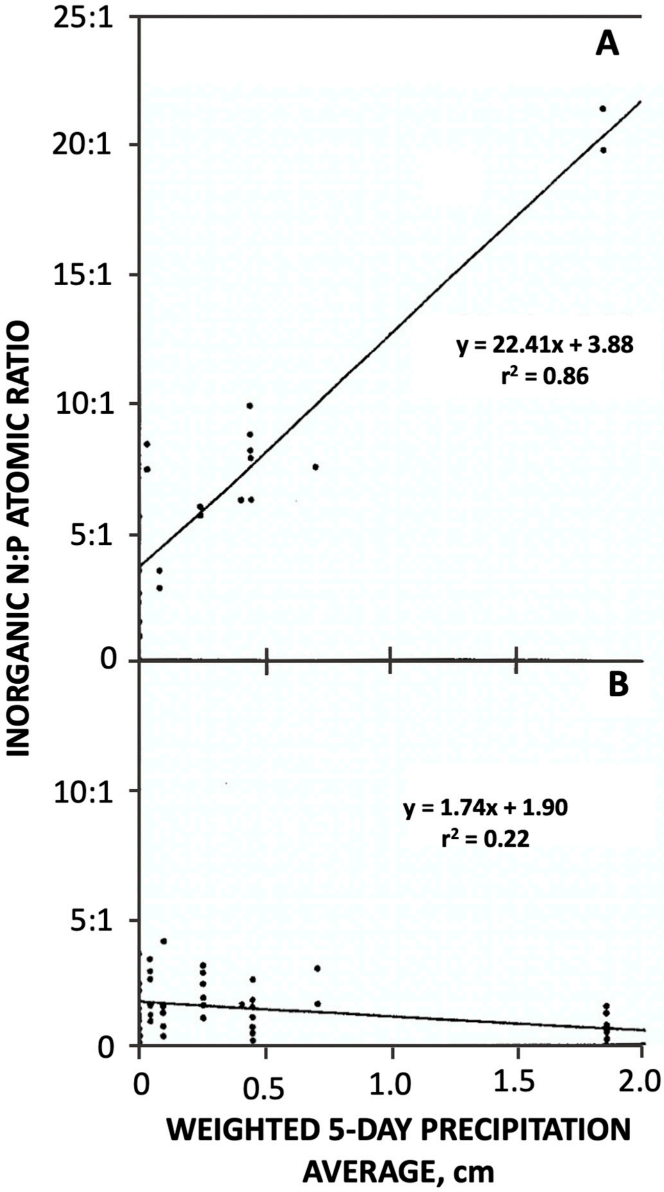

Figure 8. The relationship of weighted 5-day precipitation average prior to sampling of inorganic N/P ratios in (**A**) Bayou Chevreuil and (**B**) natural swamp [50]; data collected 1982–1983.

5.3. Non-Conservative Nutrient Dynamics in Barataria Basin

An important issue in analyzing nutrient biogeochemistry in the basin is whether different parts of the basin are net sources or sinks for different nutrient species. Several approaches have been used to address this question. These include 1) analysis of nutrient dynamics in wetlands (as discussed above), 2) quantification of denitrification as a pathway for nitrate loss and sequestration of nutrients in soil and sediments, and 3) use of mixing diagrams to investigate source/sink behavior of different nutrient species. The results of the studies of nutrient dynamics in wetlands indicated that the deterioration of water quality in most of the upper basin was due to a combination of agricultural runoff and bypassing wetlands via canals that allowed runoff to flow directly into water bodies.

Nitrogen loading to the basin**.** We calculated loading of NO_3 from agricultural fields to wetlands and water bodies in the upper basin above US highway 90 based on area of agricultural land and estimated NO_3 concentration in runoff. Net precipitation runoff from the fields was calculated monthly based on an average water budget of the area.

Although the highest concentration of NO_3 reported in field drainage ditches was 13 mg/L, average values are significantly lower. NO_3 concentrations are highest during the spring when fields are fertilized (Pers. Comm. Herman Waguespack, American Sugarcane League, hlwag@amscl.org). To estimate nutrient loads, we used 3 mg/L NO_3 in agricultural runoff for March-May, 1 mg/L in Feb and June, and 0.5 mg/L for the remaining months of the year.

Nitrate loading to wetlands and water bodies of the upper basin was estimated using the total area of wetlands plus water bodies and the area of Lac des Allemands, the largest water body in the upper basin (see Figure 3). Many canals have been dredged in and across wetlands to accelerate field runoff to bayous and lakes throughout the basin. Although the spoil material along canals reduces overland flow, there are many breaks in the spoil banks. However, when water levels are high in the basin, water flows out of channels and lakes into wetlands. Thus, it is difficult to determine how much upland runoff flows into wetlands where nutrients are very efficiently removed. Loading of NO_3 calculated for wetlands plus water bodies was 0.2 g NO_3-N/m^2/year. When loading was calculated just for Lac des Allemands, the loading was 2.63 g NO_3/m^2/year. The actual value is between these two extremes. Although this loading rate is specific for Lac des Allemands, the largest water body surrounded by extensive agriculture fields, this value is low, indicating that NO_3 would be quickly reduced via uptake by vegetation and/or denitrification.

The role of denitrification. Reference [54] reviewed a number of denitrification studies in coastal Louisiana and reported that sediments of water bodies and wetland soils are capable of high potential denitrification rates when exposed to high NO_3 concentrations (i.e., >100 μM = 1.4 mg/L). Maximum potential denitrification rates in experimental and natural settings can exceed 2500 μmol/m^2/h depending on NO_3 availability and loading rates. Twelve of the studies included in the analysis were from the Barataria Basin. Denitrification rates were significantly higher in the upper basin where agricultural runoff with high NO_3 concentrations is prevalent. For instance, the average denitrification rates in Lac des Allemands freshwater marsh soils exposed to high NO_3 concentration (100–300 μM) is 79 g N/m^2/year ± 10 (range: 0.6–172.4 g N/m^2/year; N = 6, Table 1 in [54]); this rate is higher than the NO_3 loading rate (2.63 g NO_3/m^2/year) estimated for this region (see section above). High rates were also observed in an isolated salt marsh, with values ranging from 1.4 to 20 (g N/m^2/year) while two additional salt marsh sites values were as high as 51 and 10 g N/m^2/year. In a swamp forest in the upper basin, values as high as 205 and 192 g N/m^2/year were reported. In Bayou Chevreuil peak values were from 53 to 115 g N/m^2/year while rate at the Davis Pond diversion ranged from 0 to 88 g N/m^2/year.

Denitrification by both wetland soils and anoxic sediments of open water bodies needs to be considered when assessing N loss from the system at large spatial scales [55]. But currently, there are no denitrification rate estimates for sediments of water bodies in the middle basin. Given the large extent of open water bodies and sediments, it is expected that benthic sediments do contribute to the N loss and/or assimilation in extensive areas such as Lac des Allemands (48 km^2), Lake Cataouatche (37 km^2) and Lake Salvador (181 km^2) in the upper Basin (Figure 3). Recent studies show that denitrification rates in benthic sediments from Lake Cataouatche can range from 3.1 to 6.2 g N/m^2/year [56] and similarly range from 3.9 to 6.8 g N/m^2/year in northern Barataria Bay [57]. Although these rates represent approximately 33% of the wetland soil denitrification rates, the large area of open water can significantly contribute to net N loss. In fact, [57] calculated that the marsh is only flooded 37% of the time while the estuarine bottom is constantly in contact with the water column, increasing the importance of the benthic denitrification. Thus, to evaluate the relative importance of denitrification in controlling high NO_3 inputs from agriculture fields and via hydrological modifications, including freshwater diversions such as Davis Pond (see section 4.4), open water areas need to be considered. This is critical given the local variability in wetland spatial distribution and hydrological connectivity among channels, canals and open water bodies throughout the basin. Connectivity varies by seasonally and tidally controlled hydrological exchange with the adjacent coastal ocean/continental shelf. For example, connectivity is high during the peak spring river discharge when Mississippi River water enters the lower bay bringing NO_3 into the system [58].

Source–sink dynamics. Because sampling in the 1970s [45,46], and between 1994 and 2016 [16] was performed primarily along the central drainage axis of the basin, both studies failed to capture high nutrient levels in agricultural runoff. For [45] transects, only four stations had NO_3 greater than 1 mg/L; there were 3 samples between 1 and 2 mg/L and one value of 3 mg/L. In the case of the transect of [16], the highest NO_3 sampled was 2.5 mg/L and there were three samples higher than 2 mg/L. By contrast, NO_3 resulting from agricultural runoff was regularly greater than 5 mg/L and was as high as 13 mg/L.

Salinity mixing diagrams were plotted to evaluate source–sink nutrient dynamics for nitrate in the basin using three data sets obtained from the transects of [16,45,46] (Figure 9). We also used stations added in 2005 in eastern Lake Salvador and Lake Cataouatche, as well as the Mississippi River, to capture the effect of the David Pond diversion (Figure 9, see [18]). In both the [16,45] data sets, the mixing diagrams show that there is strong non-conservative uptake of NO_3 (Figure 9a,b).

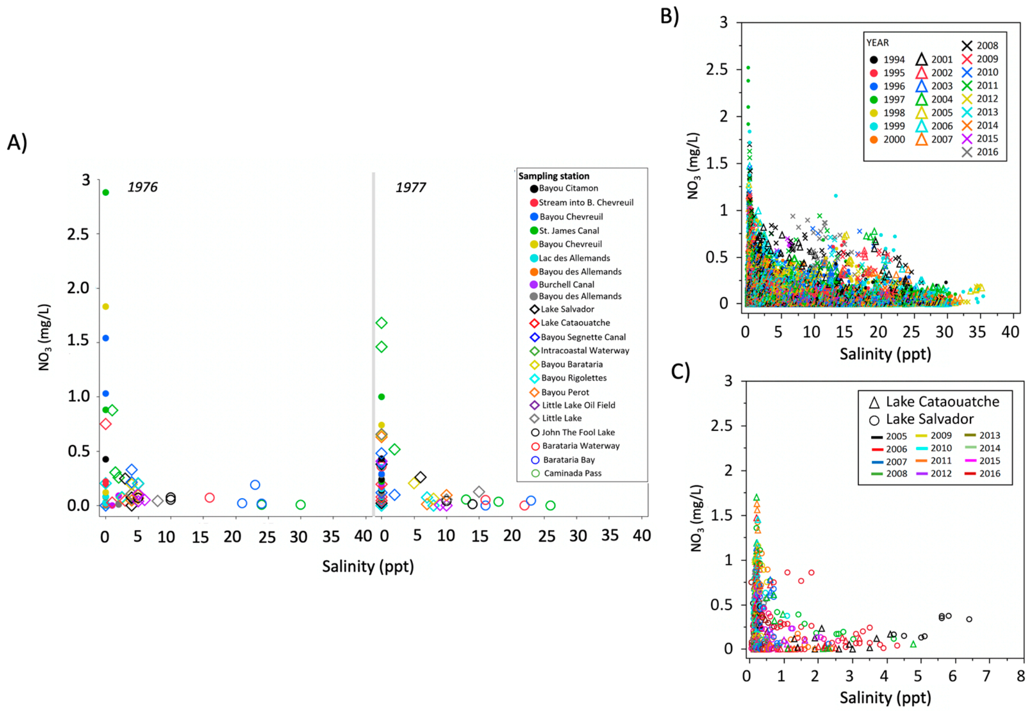

Figure 9. Mixing diagrams for inorganic nitrogen (NO_x) in the Barataria Basin. (**A**) Data from [46]; (**B**) data from [16]; (**C**) mixing diagram for stations added in 2005 in Lake Cataouatche and eastern Lake Salvador by [16] to reflect the impact of the Davis Pond diversion; notice the change in the X-axis range (salinity).

The added stations in Lakes Salvador and Cataouatche (see [16] for station locations) give a better understanding of nutrient source–sink dynamics (Figure 9c). First, a reduced area analysis shows that the main source for nutrients to Lake Cataouatche and eastern Lake Salvador was the Mississippi River, which was directly measured. Second, focusing on this smaller area underscores the reduced influence of nutrient inputs from the upper basin on Lake Cataouatche and eastern Lake Salvador, where NO_3 exhibits strong non-conservative uptake.

Another permanent loss pathway is burial of organic carbon and nutrients, which can be quite high due to high relative sea-level rise rates due both to eustatic sea-level rise and the high rate of subsidence in the Mississippi Delta that can exceed 1.0 cm/year [59].

A bald cypress-water tupelo forested wetland in the upper Barataria Basin receiving secondarily treated municipal effluent had net carbon sequestration of 49,505 mt CO2e/year [60]. By contrast, a study in freshwater floating marshes in the Bayou Boeuf Basin showed net carbon loss and decrease in elevation when wetland death was simulated using herbicides [61].

5.4. Changes in the Trophic Status of the Barataria Basin over Four Decades

Refs. [45,46] based the development of the Barataria Basin trophic state index (TSI) on the work of [43] who used a multivariate analysis to characterize the trophic state of 55 Florida Lakes. Reference [18] followed this approach and re-analyzed the [45] data as well as pre- and post-diversion data from [16]. The results for the [45] re-analysis were very similar to the original analysis (Figure 10).

The results of the TSI scores for the three transects yielded very similar spatial patterns. Positive scores are more eutrophic and negative scores are more mesotrophic. Scores for stations upstream of Lake Salvador (Figure 10) were generally greater than 1. The highest scores were for Bayou des Allemands, Lac des Allemands, and bayous receiving agricultural runoff. These stations had high nutrients and chlorophyll *a* and turbid waters with low Secchi disk depths (see Figure 7). Downstream of Lake Salvador, TSI scores for the three periods were generally less than -1, indicating non-eutrophic waters with greater clarity and lower chlorophyll *a* and nutrient levels. Post-diversion scores in this lower region somewhat elevated compared to pre-diversion scores, suggesting a slight tendency toward more enrichment. Lake Cataouatche scored greater than zero for the [45] transect while the post-diversion score was approximately -1. The shift is likely due to relatively clear river water entering the lake, the sediments having been retained in the Davis Pond wetlands as well as rapid reduction of NO_3 due to high denitrification and uptake rates.

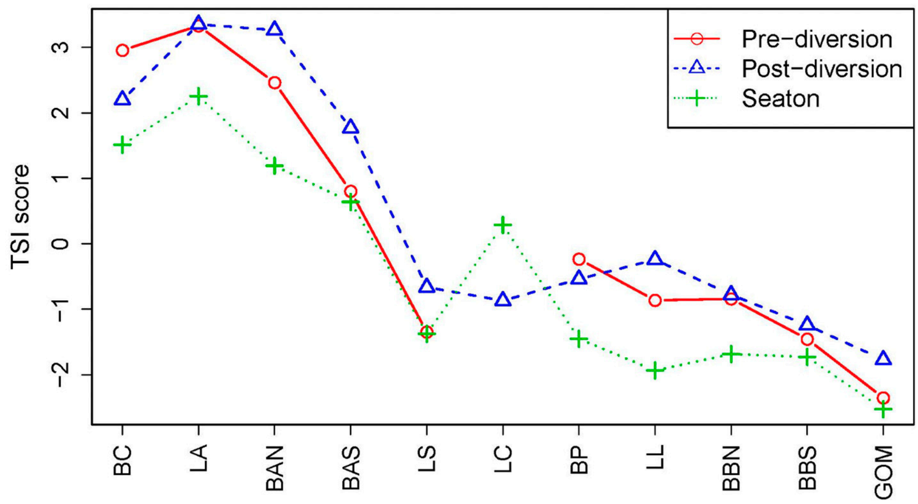

Figure 10. Trophic state index scores for station groupings for the Seaton (1977–1978), pre-diversion (1994–2002 June) and post-diversion (July 2002–2016) transects (from [18]). Locations on the horizontal axis are defined in Figure 3.

6. Aquatic Metabolism and Materials Export in Barataria Basin

A series of studies in the 1970s and 1980s reported on aquatic metabolism and water and materials export (Figure 5a and b) prior to the Davis Pond diversion thus documenting functioning of the system with minimum input of water from the Mississippi River.

Gross aquatic primary production (GAPP) was highest in the upper basin, lowest in the mid basin, and intermediate in the lower basin (Table 3, [44]). GAPP was 3286 g O_2/m^2/year in Lac des Allemands, 2222 in Lake Cataouatche, 1058 in Lake Salvador, 1307 in Little Lake, and 1850 in lower saline waters (Table 3). Net community production was -450, -350, -198, -117, and 0 to +54 g $O_2/m^2/year$, respectively, in these water bodies. The degree of heterotrophy was highest in the upper basin and decreased down basin. The water column was slightly autotrophic in the most saline part of the basin. P/R ratios were 0.76 in Lac des Allemands, 0.72 in Lake Cataouatche, 0.67 in Lake Salvador, 0.85 in Little Lake, and 1.03 in saline waters of the lower basin and nearshore Gulf of Mexico. Chlorophyll *a* (Chl *a*) was much higher in Lac des Allemands and Lake Cataouatche than in either bayous or Lake Salvador, Little Lake, and saline bays. The lower GAPP in upper basin bayous was likely due to light limitation due to both shading by swamp forests bordering these narrow streams and turbid waters from agricultural runoff. The high heterotrophy in upper basin waters is supported by organic matter exported from wetlands and upland runoff. The strong seasonal signal of aquatic metabolism is characteristic of all water bodies measured, with generally higher metabolism in the warmer months (Figure 11).

Table 3. Comparative aquatic productivity (g $O_2/m^2/year$) and mean annual chlorophyll *a* (mg/m^3) in Barataria Basin from freshwater bayous to offshore areas. NDP = net daytime photosynthesis; NR = nighttime respiration; GP = gross production; NCP = net community production (modified from [44]; data collected 1973–1981).

	Chl *a*	**NDP**	**NR**	**GP**	**NCP**
Bayous	25	316	446	762.	−130
Lac des Allemands	65	1418	1868	3286	−450
Lake Cataouatche	50	876	1205	2222	−350
Lake Salvador	12	402	602	1058	−198
Little Lake	10	639	753	1307	−117
Brackish-Saline	10	940	910	1850	0 to 54
Offshore	7.6	732	.	.	.

In summary, the waters of the upper basin are strongly heterotrophic due to high TOC input from wetlands and upland drainage. There is a strong seasonality of aquatic metabolism in Lac des Allemands as a result of high nutrient input and lack of strong light limitation in this shallow lake (Figure 12). Similar findings were reported for Fourleague Bay [62], which receives high input of Atchafalaya River water. This bay has a mean depth of approximately 1 m, the same as Lac des Allemands. In Fourleague Bay, as in Lac des Allemands, APP is high despite highly turbid waters because the shallow water column is well mixed and phytoplankton are, on average, exposed to higher light than if they were stationary in the water column [62–65]. Despite high nutrient concentrations, bayou metabolism is much lower due to shading by swamp forests that border these narrow streams and generally high turbidity from upland runoff.

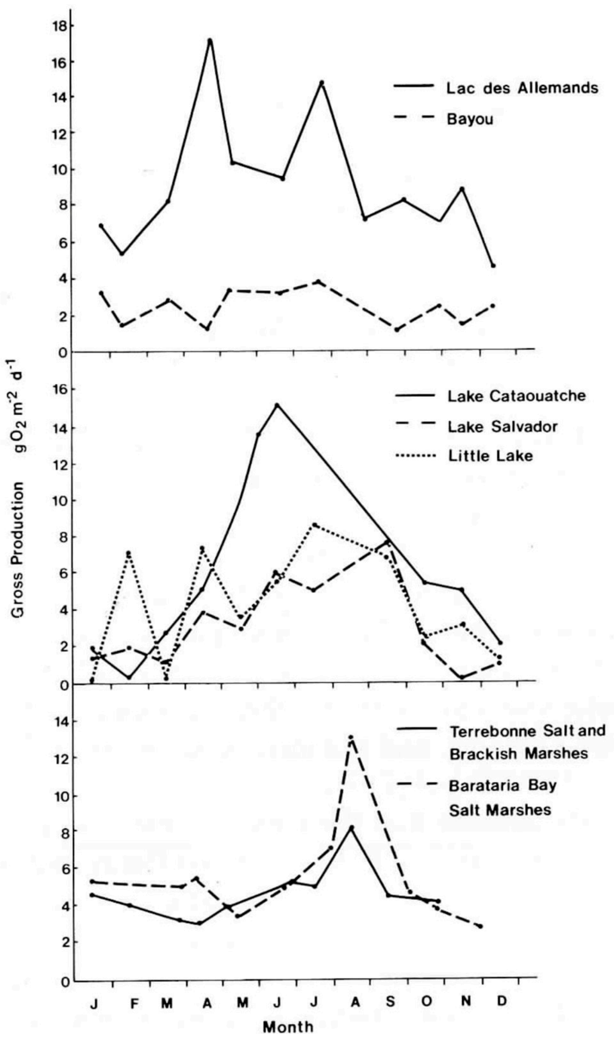

Figure 11. Gross production of major lakes and bayous in Barataria Bay going from fresh (upper), low salinity (middle), to salt water conditions (lower; from [44]; data collected 1973–1981).

Reference [66] measured seasonal TOC, DOC, and Chl *a* concentrations in Barataria and Caminada Bays and in the nearshore Gulf of Mexico. Concentrations of all three constituents generally decreased from the upper bay stations that were directly influenced by marsh drainage to the lower bays to offshore (Table 4). Based on concentration gradients and estimates of flushing times, they calculated that export of TOC to the coastal ocean was approximately 150 g C/m^2 of estuary per year (Table 5). Reference [66] used a flushing time reported of 23 days (equivalent to a renewal rate of 4.4% per day) for the whole estuary, which includes Barataria and Caminada Bays and associated smaller water bodies. Reference [16] report that the pulse residence time, defined as e^{-1} (63% removal), is 50 to 70 days in the middle of Lac des Allemands, 100 days in Lake Salvador, 20–30 days in Little Lake, and 1–4 days in Barataria Bay close to the tidal inlets [67,68]. Reference [66] summarized metabolic measurements for the lower basin waters and wetlands (Table 5). Based on these measurements, the estimate for export to the Gulf or burial) was 260 g C/m^2/year, which is in the range estimated by [6].

Table 4. Mean values (±s.e.) of dissolved organic carbon (DOC), total organic carbon (TOC), and chlorophyll *a* (CHL a) for the year in Caminada and Barataria bays (modified from [66]; data collected November 1971 to November 1972).

Group	DOC (mg/L)	TOC (mg/L)	Chl a (mg/m^3)
Marsh	6.7±0.2	8.5±0.2	10.2±0.6
Upper Bay	6.2±0.3	7.6±0.3	10.3±0.8
Lower Bay	4.3±0.3	4.5±0.3	8.1±0.8
Offshore	2.4±0.1	2.8±0.1	7.6±0.8

Overall, the information summarized in this section indicates that in the 1970s and early 1980s, the Barataria Basin was a productive estuarine system with strong export of water and materials from the upper basin to the nearshore Gulf of Mexico. The system was strongly heterotrophic in the upper basin and becoming slightly autotrophic in the lower basin.

Table 5. Metabolic measurements and estimates for Barataria Bay (modified from [66]; data collected November 1971 to November 1972).

	g C/m^2/year
(1) Net marsh production	590
(2) Marsh consumption	300
(3) Flushed from marsh	290
(4) Flushed from bay	240
(5) Phytoplankton and benthic algae production	450
(6) Total organic carbon available to water (4) + (5)	690
(7) Consumption in water	430
(8) Net estuary production available for export or sedimentation	260

(1) and (3) are per m^2 of marsh, (4) and (8) are, per m^2 of water surface.

7. Structure and Productivity of Wetlands in Barataria Basin

Wetlands in the basin range from freshwater forested and emergent wetlands to brackish and saline marshes in the lower basin. Because of their size, in contrast to many coastal systems, deltas often have very large areas of freshwater ecosystems that are important for their ecological functioning. This is true of the Barataria Basin as is discussed in this section.

7.1. Forested Wetlands

The swamp forests in the upper Barataria Basin are part of once, vast old growth stands of bald cypress (*Taxodium distichum* [L.] Rich.) that covered the coastal region of Louisiana. These stands were mostly clear-cut between 1880 and 1925 [69,70]. After logging, water tupelo (*Nyssa aquatica* L.) and swamp red maple (*Acer rubrum* var. *drummondii* {Hook. and Arn. ex Nutt.} Sarg.) increased in importance because the rotting bald cypress stumps and fallen logs provided habitat for germination of the maple seeds, and there was little competition for growing space and light [71]. Along the bayous in the basin, small natural levees are only slightly higher (15–30 cm) than adjacent bald cypress-water tupelo areas and still have small areas of bottomland hardwood forests [72].

In the first forested wetland study within the basin, [72] compared the growth rates of trees in typical bottomland and bald cypress-water tupelo swamp forests during 1974. Although there were more trees in the bottomland plot, they found that the standing biomass of trees in the swamp was more than twice that in the bottomland hardwood plot (367 versus 157 MT/ha, respectively). Trees in the bald cypress-water tupelo forest were between 50 and 95 years old and had large diameters, while the majority of trees in the bottomland forest were estimated to be less than 30 years old and of smaller size. Tree stem biomass growth in the bottomland site was 800 g/m²/year while stem biomass growth in the bald cypress-water tupelo site was 500 g/m²/year. Leaf litter-fall in the two forests was similar (574 g/m²/year in the bottomland site and 620 g/m²/year in the bald cypress—water tupelo site yielding aboveground net primary production values of 1374 and 1120 g/m²/year for bottomland hardwood and bald cypress-water tupelo sites, respectively.

In a subsequent study during 1978, the natural bald cypress-water tupelo site used in the [72] study was compared to a permanently flooded site and a managed site [73]. The permanently flooded site was impounded by road and drainage projects while the managed site was surrounded by levees and was flooded in the winter and spring and drained in the summer for crawfish farming purposes. As described in [72], bald cypress and water tupelo were the dominant trees, making up more than 70% of the total number and 94% of the basal area. Overall tree density was 1,303 trees/ha. In the crawfish farm, the annual drawdown of water allowed seeds to germinate and seedlings to establish. Swamp red maple and ash (*Fraxinus profunda* and *F. caroliniana)* were the most common tree species even though they constituted only 39% of the basal area. Baldcypress and water tupelo were the largest trees in this area, making up nearly 50% of the BA. The permanently flooded area contained the fewest number of trees (943 trees/ha) and the lowest BA. Baldcypress and water tupelo made up 63% of the BA but buttonbush and swamp red maple had the highest stem density. Although the density and BA of ash indicated that it was a major component of this area, the majority of the trees had dead or dying crowns. In addition, the site contained a number of species not found in the other two areas including diamond-leaf oak (*Quercus laurifolia*), hawthorn (*Cratageus* sp.), and wax myrtle (*Morella cerifera* (L.) Small).

In the naturally flooded site, the combined stem productivities and litterfall of bald cypress and water tupelo represented nearly the entire production of that area (1,166 g/m²/year) and was almost identical to the site's productivity in 1974 [72]. Net primary productivity in the permanently flooded area was 886 g/m²/year. Despite the high rate of stem growth of individual bald cypress and water tupelo trees in the permanently flooded site, their low densities resulted in lower overall areal productivity with a significant portion of the total productivity due to buttonbush (*Cephalanthus occidentalis* L.), swamp red maple, and snowbell (*Styrax americana*), which were becoming the dominant species in the area. In the crawfish farm, seasonal flooding and the constant flow of water enriched with nutrients through the area when it is flooded were conducive to high productivity levels. Estimated net productivity of trees in the crawfish farm was 1779.9 g/m²/year.

From 1977 to 1981, [74] found that net productivity was greatest in the crawfish pond (579 g/m²/year), intermediate in the naturally flooded site (405 g/m²/year), and least in the permanently flooded site (293 g/m²/year). They found a progressive decline in litterfall productivity through the first 4 years of study and suggested this was due to continuous flooding leading to mortality of trees. An increase in litterfall was observed in 1981 in all areas and was probably related to drought conditions that year which for the first time in many years allowed the sites to dry out, thus improving growing conditions. Between 1979 and 1985, [74] monitored growth rates of bald cypress and water tupelo in the three sites.

In an examination of community structure and changes between 1987 and 1989, [75] found that tree density decreased significantly ($p = 0.003$) in the impounded (declined from 480 trees/ha to 160) and crawfish farm (declined from 1030 trees/ha to 620) sites but not so dramatically in the naturally flooded (declined from 990 trees/ha to 880) site. There were decreases in all size classes, especially the 10 and 20 cm diameter classes. The majority of the trees dying were swamp red maple and ash. A follow-up survey of these sites in 2009 (Conner, unpublished data) found tree density increases in the impounded and crawfish farm sites (670 and 260 trees/ha, respectively). These increases were due to swamp red maple, ash, and buttonbush recruitment. In the naturally flooded site, tree density declined to 830 trees/ha.

The results of these studies highlight the developing problem within wetland forests in coastal Louisiana. Long periods of flooding lead to greater mortality and lower productivity. The whole Louisiana coastal area is subsiding at a rate of approximately 9 ± 1 mm/year [76], and these forests are becoming flooded, on average, for longer periods of time with deeper water [77]. Mortality rates in Louisiana are typically low (around 2%/year) in areas that have not been altered hydrologically [75]. In Louisiana, a major concern is the severe alteration of hydrology due to subsidence, relative sea-level rise, and hydrologic alteration such as dredging and levee construction). Reference [75] found annual mortality in South Carolina and Louisiana plots with increased water levels rose from 4% in 1987 to 16% in 1997. All of the less flood-tolerant trees died, leaving only bald cypress, water tupelo, and swamp red maple, and all of the surviving swamp red maple trees were stressed, as evidenced by dying canopies. They concluded it would only be a matter of time before they died. With limited natural regeneration in these sites due to increased flooding, the areas will become marsh or open water when the existing bald cypress and water tupelo eventually die [78]. However, there is also evidence that bald cypress trees relieved of competition by rising floodwaters grow better and may persist as open forest [79,80]. Another concern is that exotic, invasive species such as Chinese tallow have the potential to become established as the dominant canopy tree in these disturbed areas as was seen in the adjacent Pontchartrain and Verret basins after hurricanes [81,82].

In an effort to improve permanently flooded conditions in the impounded area described in the above studies, eight wide gaps were made in the spoil bank along Bayou Chevreuil in 2017 to allow for better drainage and water circulation into and out of the impounded area. Eight sites (seven in the impounded area and one in a nearby naturally flooded site) were established by [83] to monitor the impacts of the hydrologic restoration. While the reference site showed no change in diameter difference between 2017, 2018, and 2019, all seven sites in the newly opened impounded area experienced a dramatic increase in diameter in 2018. During 2018 and 2019 canopy closure increased by 20%, and litterfall production was also greater. In addition, extensive natural regeneration of bald cypress and water tupelo has occurred for the first time in 60 years. They attributed these increases to the hydrologic restoration [84].

At least two forested wetland sites within or adjacent to the Barataria Basin (Thibodaux and Luling) have been used as receiving bodies for treated municipal effluent. Both sites are impounded wetlands. In each site, soils have been shown to be an important sink for atmospheric CO_2 [60,85]. Trees can also sequester carbon. Baldcypress trees in other coastal Louisiana sites have been documented to generally have slightly higher to significantly higher growth when exposed to nutrient rich waters [86–89]. At the Hammond Assimilation Wetland near Ponchatoula, Louisiana, bald cypress increased in diameter growth from 2 to 3 mm/year to 15 mm/year [89].

7.2. Herbaceous Wetlands

Herbaceous wetland patterns of the Barataria Basin landscape include extensive bands of zones that parallel the coast with the species distribution reflecting the decreasing salinity gradient northward through the basin. Saline and brackish marshes dominated by smooth cordgrass (*Sporobolus alterniflorus*) and saltmeadow cordgrass (*Sporobolus pumilus*) occupy the lower basin adjacent to the coast, with lower salinity intermediate and freshwater wetlands occupying the uppermost areas of the basin [90].

Freshwater marshes fringe the wetland forest boundaries and extend southward merging into intermediate salinity marshes [90]. One of the most interesting and historically important freshwater marsh community types in the Barataria Basin and all of coastal Louisiana is the maidencane (*Panicum hemitomon*) dominated floating freshwater marsh (flotant). The flotant marsh historically thrived in the freshwater zones of Barataria

Basin as well as other coastal Louisiana basins, and covered much of the freshwater marshes in coastal Louisiana through the middle of the last century [91,92]. The areas covered by this marsh type are now reduced from historic coverage. However, it remains one of the important wetland types in coastal Louisiana. The maidencane-dominated freshwater flotant marshes around Lake Boeuf in the Bayou Boeuf watershed of the upper basin are among the best examples of this important marsh community type.

These freshwater maidencane marshes have remained productive for at least a century [93,94]. The plant community is dominated by maidencane, while eastern marsh ferns (*Thelypteris palustrus*) and royal ferns (*Osmunda regalis*) and the perennial vines hairypod cowpea (*Vigna luteola*) and arrowleaf tearthumb (*Polygonum sagittatum*) are also important species. This is a very diverse plant community with 71 plant species recorded on the floating marsh, adjacent lake, canal banks, and swamp forest. Of these, 32 species were within one-meter square study plots in the maidencane flotant marsh. Maidencane is the dominant species, comprising approximately 70% of the total live biomass. The eastern marsh and royal ferns account for an additional 10% of biomass, and the hairypod cowpea and arrowleaf tearthumb vines produce another 5% of the total dry mass of the plant community. Other plant species that occur frequently are broadleaf arrowhead (*Sagittaria latifolia*), swamp loosestrife (*Decodon verticillatus*), rice cutgrass (*Leersia oryzoides*), and seaside goldenrod (*Solidago sempervirens*) [92,95]. Net primary production was 1960 g dry wgt/m^2/year, with the measured turnover rate based on tagged maidencane culms of 1.21 crops per year [96].

The freshwater flotant marsh classification as described by [92] is typified by the buoyant marshes around Lake Boeuf. The maidencane-dominated marsh there is a thick mat of organic material densely bound by root material that is free-floating continuously except during very low water level periods when the marsh mat rests on the underlying substrate.

Saline marshes in the Barataria Basin have undergone dramatic change since the middle of the last century, resulting in extensive wetland loss (4). However, during the same period, the freshwater marsh in the upper basin around Lake Boeuf has been much more resilient. Local residents familiar with the area have described the flotant marsh condition as remaining about the same over the past century. Information from local references and the recollections of nearby residents point out these wetlands have not changed much in structure and appearance in the past 100 or more years. These upper reaches of the Barataria Basin have remained freshwater dominated, enabling the true freshwater vegetation assemblages to thrive and remain productive in the Lake Boeuf marsh.

Further evidence of the stability of this marsh is reported from the [93,94] long-term vegetation dynamics study at Lake Boeuf which shows that the vegetation community structure changed very little over the 1979–1990 period. Maidencane was dominant over the 12-year study, with peak end-of-season-live biomass averaging 636 g dry wgt/m^2, or 76% of the total of all species. Total mean live end-of-season biomass varied from 602 to 1173 g dry wgt/m^2. There was a total of 45 plant species found within the study plots. Analyses showed that community structure changed little from 1979 to 1990, with most of the interannual variation in biomass due to weather factors, particularly temperature (mean of daily maximum temperature during summer—positive; maximum temperature during growing season—negative) [93,94].

The areal extent of the Lake Boeuf marsh has remained fairly stable during the period of observations reported by [93,94]. Some edge erosion along water bodies occurred during high water events. However, historical mapping of the flotant marsh at Lake Boeuf indicated a net marsh loss of only approximately 4% for the years 1945, 1952, 1981, and 1992 [93,94].

Data from [97] indicated a nutrient gradient with depth for TKN through the marsh porewater in the freshwater marsh in the upper Barataria Basin around Lake Boeuf, with concentrations increasing with depth from the marsh mat to peat layer to underlying water. Inorganic N (primarily ammonium) accounted for a large part of the trend. TP was also highest in the free-water zone and lower in underlying peat and mat layers. In below ground solid samples, a TKN gradient with depth also existed and higher concentrations were in the organic sludge below the free-water layer, decreasing upward in the peat, mat, and roots.

In the Lake Boeuf marsh landscape system, N and P were higher in the marsh mat water samples than in the adjacent lake and swamp [97]. Water from the lake and swamp moving under the mat during rising water levels was more dilute than water moving out from under the mat during falling stages, indicating a likely net export of N and P, which may be important to the nutrient budget of the regional ecosystem.

8. Synthesis of System Functioning and Change

8.1. Source–Sink Model of Nutrient Dynamics and Trophic Status

Reference [46] developed a conceptual source–sink model of nutrient dynamics and trophic status for the Barataria Basin (Figure 12). They characterized the upper basin as an active source and saturated sink. Practically all freshwater areas are highly eutrophic and are sources of nutrients. Only streams draining natural wetlands are not eutrophic. Under natural conditions, Lac des Allemands was likely able to retain most nutrients from upland and wetland runoff because of low nutrients in upland runoff and high nutrient uptake in wetlands. There are elevated nutrients and organic matter derived from agricultural and wetland runoff as well as in situ phytoplankton production and high export of organic matter and nutrients down basin. Reference [46] characterized the middle part of the basin as intermediate filtration. These areas have higher loading from the upper basin than the lower basin, which has low levels of nutrients and chlorophyll *a* and clear water. These areas are relatively unaffected by input from the upper basin and have a high capacity to act as nutrient sinks. This is especially true for NO_3, which is rapidly reduced via denitrification in anaerobic wetland soils and submerged sediments [98]. Reference [42] showed that drainage density was related to the trophic state index (Figure 6). Drainage density included both natural channels and dredged canals in wetlands and drainage canals in agricultural fields.

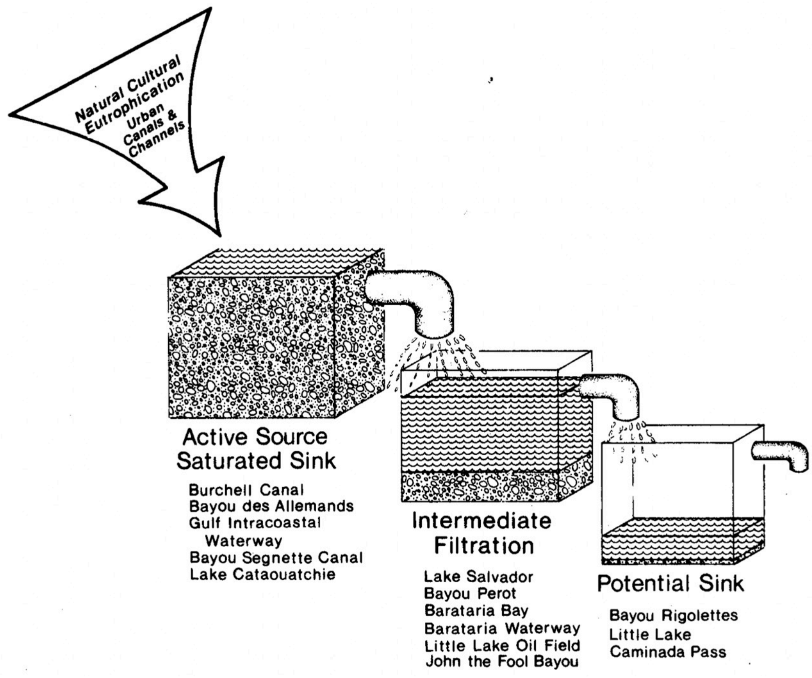

Figure 12. Conceptual model of nutrient uptake dynamics and trophic status of water bodies in the Barataria Basin (From [46]).

8.2. Freshwater Residence Time and Nitrogen Export

Several studies have reported that freshwater residence time is a good predictor of the percentage of total nitrogen exported to the coastal ocean. References [99,100] reported that the percentage of annual-scale TN inputs that were exported was inversely related to the log of the water residence time (Figure 13, black circles). Reference [100] added systems with shallow, open water areas and large areas of emergent vegetation such as those in the Mississippi Delta. They reported that such systems remove considerably more N for a given water residence time. We plotted this relationship for Lac des Allemands and found that it fits the pattern of other areas in the Mississippi Delta and similar shallow water systems with extensive intertidal wetlands. Organic matter burial is also an important pathway for N removal in the Mississippi Delta due to the high subsidence rate. Due to these factors, nitrogen sinks such as denitrification, burial, and wetland plant uptake can remove more nitrogen than in systems not having these important characteristics [101,102].

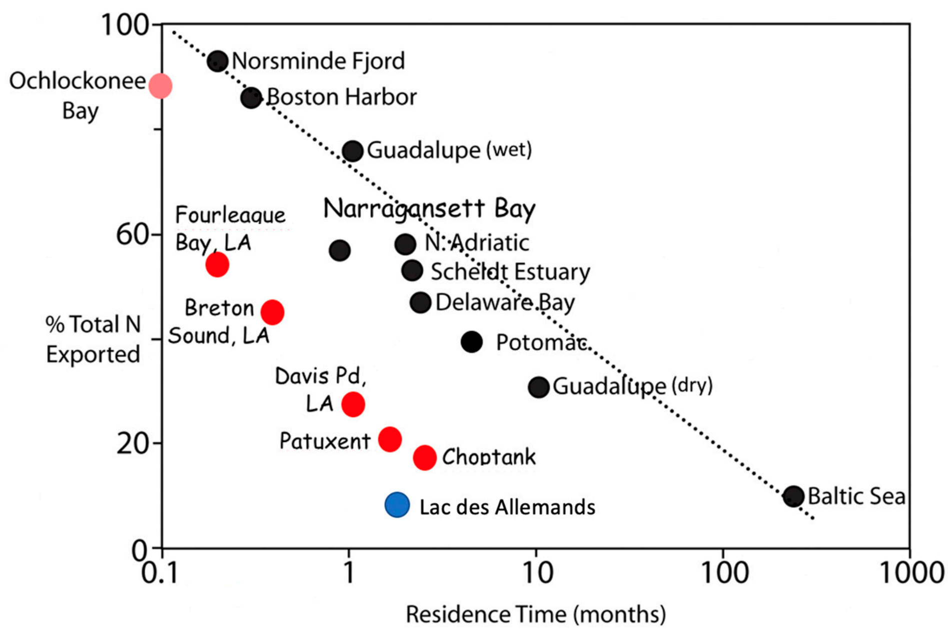

Figure 13. Percent of total N inputs that are exported from different estuarine systems versus freshwater residence time. The black circles are from [99,100]. Red circles are from more recent analyses by [103–105] and unpublished data (see [106]). Modified from [107]. Residence time of Lac des Allemands is approximately 2.6 months [44].

8.3. The Impact of the Davis Pond Diversion on Wetlands and Waters of Mid Barataria Basin

The Davis Pond diversion is the first substantial direct input of river water into the basin in over a century. The GIWW inputs, while originating as Atchafalaya River water, at least partially mix with estuarine water in the Terrebonne Basin. The Davis Pond diversion is one of the first diversions in a program of planned introductions of river water from the Mississippi and Atchafalaya rivers to combat salinity intrusion and reverse land loss in the Mississippi Delta. There have been a series of studies on the impacts of the Davis Pond diversion on water quality and wetlands. These studies demonstrate wetland gain in the receiving area of the diversion and water quality changes in Lakes Cataouatche and Salvador [16,108–112]. Mixing diagrams (discussed above) show rapid, non-conservative uptake of nitrate to background levels within Lake Cataouatche and eastern Lake Salvador. There was a minor enrichment in the mid basin [18]. The impact of a much larger planned diversion to Barataria Bay needs further study. Reference [113] measured the impact of Atchafalaya River discharge on nutrient dynamics in Atchafalaya Bay and adjacent areas. There was non-conservative reduction of nitrate of 41–47% as river water flowed to the Gulf of Mexico.

9. Summary and Conclusions

The Barataria Basin is one of the interdistributary basins in the Mississippi Delta. Human activities have strongly impacted the basin and include a dramatic reduction in river water into the basin, high rates of relative sea-level rise, pervasive changes in hydrology, wetland loss, and water quality deterioration.

The hydrology of the basin has been pervasively altered with elimination of riverine input via small distributary complexes, crevasses and overbank flow. The original forests of the natural levees have been cleared and drainage has been altered by excavation of a dense network of drainage canals in agricultural fields and extensive channelization in wetlands. This results in nutrient-laden upland runoff largely bypassing wetlands and flows directly to open water bodies. Spoil banks associated with canal dredging have resulted in semi-impoundment of large areas of forested wetlands in the upper basin.

When the system was natural, most upland runoff in the upper basin flowed through wetlands where nutrient uptake occurred and nutrient stoichiometry in water flowing from wetlands was relatively constant. Nutrient processing has changed dramatically with fertilizer application and rapid nutrient runoff, especially nitrate, that is discharged directly to open water bodies. Therefore, wetlands no longer significantly buffer nutrient concentrations and stoichiometry. Nitrate flowing from uplands and from the Davis Pond diversion is rapidly reduced in wetlands and water bodies, primarily via denitrification.

Because stormwater runoff from agricultural lands with high nutrient concentrations is discharge directly to water bodies in the upper basin, the water bodies have become very productive, heterotrophic due to high organic input from wetlands and uplands, and eutrophic to hyper-eutrophic. Water bodies in the lower basin with low agricultural input are less productive and slightly autotrophic, and more mesotrophic. Thus, water quality in the upper basin is highly degraded, while there is good water quality in terms of nutrients in the lower basin.

Another aspect of water quality in the basin is salinity. The general future trends in salinity will likely be a gradual increase up basin with subsidence and more Gulf water entering the basin, but episodic droughts (and surge events in impounded areas) will result in salinity spikes, which is exacerbated by lack of riverine influence. A cycle of periodic salinization followed by slow freshening of wetlands [38] has important implications for these ecosystems, with salinity peaks serving as bottlenecks that limit coastward extent of swamp forests and fresh marshes.

The Davis Pond diversion introduces Mississippi River water directly into receiving wetlands and Lake Cataouatche. There has been wetland gain in the Davis Pond receiving area and strong non-conservative uptake of nitrate, with denitrification being a major pathway. There is evidence of a slight enrichment in the middle basin due to the diversion.

Wetlands in the basin have become degraded and there has been extensive wetland loss in the lower Basin. The upper basin is dominated by bald cypress-water tupelo swamps, and freshwater floating marshes in the Lake Boeuf Basin and around Lac des Allemands and Bayou des Allemands, but there has been relatively little loss of wetland area. However, forested wetlands are now mostly permanently flooded so that productivity is declining and recruitment is essentially absent so that there is a slow deterioration of these wetlands. Locally, a reduction in impoundment has proven effective at restoring fluctuating water levels and natural seedling recruitment. However, long-term trends in water level due to RSLR will ultimately lead to permanent flooding and lack of seedling recruitment. Without restoration, the surviving bald cypress-water tupelo forests will slowly disappear due to lack of recruitment and mortality of adult trees. Coastward swamp forests are more vulnerable than more inland swamp forests because of the influence of salinity intrusion. In the lower basin, there has been massive coastal marsh loss due to increasing water levels, lack of riverine input, and pervasive alteration of hydrology. Marsh productivity has declined due to these human impacts [114]. Oil and gas activity have contributed significantly to marsh loss [115].

Restoration approaches for the upper and lower basins differ both in the scale required and the potential for success. The upper basin is characterized by pervasive alterations of hydrology and eutrophic to hyper-eutrophic water quality but minimal wetland loss. In the lower basin, there is also severe hydrologic alteration, extensive wetland loss, and increased influence of salinity, but minimal water quality deterioration [16–18,114]. There is potential for dramatic water quality improvement in the upper basin that is conceptually rather straight forward but practically more complicated. In essence, the hydrologic plumbing needs to be re-naturalized [83]. The pervasive short circuiting of upland runoff to open water bodies needs to be reversed. Water flow from agricultural fields should be routed through wetlands and impediments to overland flow through wetlands need to be removed. Studies from the upper basin clearly show that wetlands lead to a dramatic reduction in nutrients entering water bodies. References [116,117] modeled hydrology and eutrophication in forested wetlands of the upper basin. Simulation showed that removal of spoil banks so that more water flowed through wetlands led to lowered stages in Bayou Chevreuil, increased swamp productivity [84] and decreased eutrophication.

Sustaining productive wetlands in the upper basin is dependent on preventing saltwater intrusion and lowering long-term flooding in swamp forests. The upper basin is almost completely fresh but saline spikes can occur during prolonged south winds and during drought periods. Because there is only one outlet from the upper basin via Bayou des Allemands, controlling salinity intrusion is less complicated than where intrusion occurs over a broad area, as in the lower basin. The combination of a control structure at Highway 90 and introductions of river water could maintain a fresh upper basin.

Maintaining sustainable forested wetlands in the upper basin will require a coordinated plan of restoration of hydrology, planting of bald cypress and water tupelo, protection from nutria (*Myocastor coypus*) herbivory, and small targeted sediment diversions from the River that deliver to swamp areas to reduce permanent flooding. The work of [84,116,117] show that restoring sheet flow hydrology can lead to enhanced accretion, recruitment and forest productivity. Since bald cypress and water tupelo trees can live for centuries, the restoration plan will lead to long-term sustainability of forested wetlands.

Wetland restoration in the lower basin is an integral part of the Coastal Master Plan [118]. Major activities include river sediment diversions, marsh creation using dredged sediments and Barrier Island restoration. The mid Barataria sediment diversion at Myrtle Grove will deliver up approximately 2200 m^3/sec to the eastern part of the lower basin. Reference [118] projects that the diversion will result in the creation of thousands of ha of new land over 50 years. A number of marsh creation projects using dredged sediments are planned for the lower basin, especially in the “land bridge” where saline marshes are still relatively healthy. Several barrier island and coastal ridge restoration projects are also planned. Reference [114] used modeling results to examine spatial and temporal patterns in future wetland loss due to future changes in precipitation evapotranspiration, subsidence and eustatic sea-level rise. Inundation and salinity were important contributors to wetland loss, with salt marsh being most susceptible. These results suggest that maximum use of riverine sediments, with increased fine sediment supply from the Missouri Basin, should be integral parts of coastal restoration [24,119]. As noted above, the upper basin is more resistant to sea-level rise because floating marshes are not impacted directly by sea-level rise and adult swamp forest trees can live for centuries in continuously flooded conditions. The upper basin, however, needs to be protected from salinity intrusion. This can be accomplished by a combination of targeted moderate river diversions combined by control of salinity intrusion via Bayou des Allemands at Highway 90 with a water control structure.

The findings of this review have implications for the restoration and management of deltas globally. These broader issues include how hydrological alterations lead to poor water quality, the impact of agricultural runoff on water quality, the importance of wetlands to improving water quality, the role of denitrification in reducing nitrogen levels, the importance of appropriate hydrology to wetland health, approaches to identifying spatial and temporal trends in the health and functioning of coastal and especially deltaic systems, and the important ecological roles of coastal freshwater areas in deltas.

Author Contributions: Conceptualization, J.W.D.; methodology, all authors; writing—original draft preparation, J.W.D.; writing—review and editing, all authors; supervision, J.W.D. All authors have read and agreed to the published version of the manuscript.

Funding: Contribution by W.H.C. to this manuscript was supported by NIFA/USDA, under project number SC-1700590. V.H.R-M and I.A.V-L. were funded by the NASA-EPSCoR (Grant# 80NSSC18M002) and the US Department of the Interior–South Central Climate Adaptation Science Center (SC-CASC), Cooperative Agreement#G12 AC00002. There was no funding specifically for the preparation of this manuscript.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: This review is based on the work of many students who completed studies in the basin, including Ann Seaton Witzig, Thomas Butler, Michael Tritico, Fred Sklar, and Georgeanne Happ. This paper represents Technical Contribution No. 6938 of the Clemson University Experiment Station.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kemp, P. Mud Deposition at the Shoreface: Wave and Sediment Dynamics on the Chenier Plain of Louisiana. Ph.D. Dissertation, Louisiana State University, Baton Rouge, LA, USA, May 1987.
2. Roberts, H.H. Dynamic changes of the holocene Mississippi River delta plain: The delta cycle. *J. Coast. Res.* **1997**, *13*, 605–627.
3. Hijma, M.; Shen, Z.; Törnqvist, T.; Mauz, B. Late Holocene evolution of a coupled, mud-dominated delta plain-chenier plain systems, coastal Louisiana, USA. *Earth Surf. Dynam.* **2018**, *5*, 689–710.
4. Couvillion, B.R.; Fischer, M.R.; Beck, H.J.; Sleavin, W.J. Spatial Configuration Trends in Coastal Louisiana from 1985 to 2010. *Wetlands* **2016**, *36*, 347–359.
5. Stagg, C.L.; Osland, M.J.; Moon, J.A.; Hall, C.T.; Feher, L.C.; Jones, W.R.; Couvillion, B.R.; Hartley, S.B.; Vervaeke, W.C. Quantifying hydrologic controls on local- and landscape-scale indicators of coastal wetland loss. *Ann. Bot.* **2020**, *125*, 365–376.
6. Day, J.W.; Smith, W.; Stowe, W.; Wagner, P. *Community Structure and Carbon Budget of a Salt Marsh and Shallow Bay Estuarine System in Louisiana;* Publ. No. LSU-SG-72-04; Center for Wetland Resources, Louisiana State University: Baton Rouge, LA, USA, 1973; p. 79.
7. Conner, W.H.; Day, J.W. (Eds.) *The Ecology of Barataria Basin, Louisiana: An Estuarine Profile*; Biological Report; National Wetlands Research Center, U.S. Fish and Wildlife Service: Washington, DC, USA, 1987; Volume 85, 165p.
8. Blum, M.D.; Roberts, H.H. The Mississippi delta region: Past, present, and future. *Annu. Rev. Earth Planet. Sci.* **2012**, *40*, 655–683.
9. Condrey, R.E.; Hoffman, P.E.; Evers, D.E. The last naturally active delta complexes of the Mississippi River (LNDM): Discovery and implications. In *Perspectives on the Restoration of the Mississippi Delta*; Day, J.W., Kemp, G.P., Freemen, A.M., Muth, D.P., Eds.; Springer: Dordrecht, The Netherlands, 2014, pp. 33–50.
10. Swarzenski, C.M. *Surface-Water Hydrology of the Gulf Intracoastal Waterway in South-Central Louisiana, 1996-99*; Professional Paper 1672; U.S. Geological Survey, Reston, VA; 2003; p. 51.
11. USACOE (U.S. Army Corps of Engineers). *Freshwater Diversions*; USACE: New Orleans, LA, USA, 2006.
12. Coleman, D.J.; Kolker, A.S.; Johannesson, K.H. Submarine groundwater discharge and alkaline earth element dynamics in a deltaic coastal setting. *Hydrol. Res.* **2017**, *48*, 1169–1176.
13. Hopkinson, C.S., Jr.; Day, J.W.Jr.; Kjerfve, B. Ecological significance of summer storms on shallow coastal lake and estuarine systems. *Cont. Mar. Sci.* **1985**, *28*, 69–77.
14. Wiseman, W.J.; Swenson, E.M.; Power, J. Salinity trends in Louisiana estuaries. *Estuaries* **1990**, *13*, 265–271.
15. Wissel, B.; Gaçe, A.; Fry, B. Tracing river influences on phytoplankton dynamics in two Louisiana estuaries. *Ecology* **2005**, *86*, 2751–2762.

16. Turner, R.E.; Swenson, E.M.; Milan, C.S.; Lee, J.M. Spatial variations in Chlorophyll a, C, N, and P in a Louisiana estuary from 1994 to 2016. *Hydrobiologia* **2019**, *834*, 131–144.
17. Couvillion, B.R.; Beck, H.; Schoolmaster, D.; Fischer, M. *Land Area Change in Coastal Louisiana 1932 to 2016*; Scientific Investigations Map 3381; U.S. Geological Survey, Reston, VA; 2017; p. 16.
18. Day, J.W.; Li, B.; Marx, B.D.; Zhao, D.; Lane, R.R. Multivariate analyses of water quality dynamics over four decades in the Barataria Basin, Mississippi Delta. *Water* **2020**, *12*, 3143.
19. Britsch, L.D.; Dunbar, J.B. Land loss rates: Louisiana Coastal Plain. *J. Coast. Res.* **1993**, *9*, 324–338.
20. Britsch, L.D.; Dunbar, J.B. Land Loss in Coastal Louisiana 1932 to 2001. In *A Series of 7 Large Format Maps*; Technical Report ERDC/GSL TR-05-13; Engineer Research and Development Center: Vicksburg, MS, USA, 2006.
21. Couvillion, B.R.; Barras, J.A.; Steyer, G.D.; Sleavin, W.; Fischer, M.; Beck, H.; Trahan, N.; Griffin, B.; Heckman, D. *Land area change in coastal Louisiana from 1932 to 2010*; Scientific Investigations, Map 3164, Scale 1:265,000; U.S. Geological Survey, Reston, VA; 2011; p. 12.
22. Day, J.W.; Britsch, L.D.; Hawes, S.R.; Shaffer, G.P.; Reed, D.J.; Cahoon, D. Pattern and process of land loss in the Mississippi delta: A spatial and temporal analysis of wetland habitat change. *Estuaries* **2000**, *23*, 425–438.
23. Day, J.W.; Boesch, D.F.; Clairain, E.J.; Kemp, G.P.; Laska, S.B.; Mitsch, W.J.; Orth, K.; Mashriqui, H.; Reed, D.J.; Shabman, L.; et al. Restoration of the Mississippi Delta: Lessons from hurricanes Katrina and Rita. *Science* **2007**, *315*, 1679–1684.
24. Day, J.W.; Shaffer, G.P.; Cahoon, D.R.; DeLaune, R.D. Canals, backfilling and wetland loss in the Mississippi Delta. *Estuar. Coast. Shelf Sci.* **2019**, *227*, 106325.
25. Day, J.W.; Kemp, G.P.; Reed, D.J.; Cahoon, D.R.; Boumans, R.M.; Suhayda, J.M.; Gambrell, R. Vegetation death and rapid loss of surface elevation in two contrasting Mississippi delta salt marshes: The role of sedimentation, autocompaction and sea-level rise. *Ecol. Eng.* **2011**, *37*, 229–240.
26. Elsey-Quirk, T.; Graham, S.A.; Mendelssohn, I.A.; Snedden, G.; Day, J.W.; Twilley, R.R.; Shaffer, G.; Sharp, L.A.; Pahl, J.; Lane, R.R. Mississippi river sediment diversions and coastal wetland sustainability: Synthesis of responses to freshwater, sediment, and nutrient inputs. *Estuar. Coast. Shelf Sci.* **2019**, *221*, 170–183.
27. Fisk, H.N. *Geological Investigation of the Alluvial Valley of the Lower Mississippi River. Illus;* U.S. Army Corps of Engineers, Washington, DC, USA, 1944; p. 78.
28. Davis, D.W. Crevasses on the lower course of the Mississippi River. Coastal Zone'93. In *Proceedings of the Eighth Symposium on Coastal and Ocean Management, New Orleans, LA, USA, 19–23 July 1993*; American Society of Civil Engineers: Reston, VA, USA, 1993; pp. 360–378.
29. Davis, D.W. Historical perspective on crevasses, levees, and the Mississippi River. In *Transforming New Orleans and Its Environs: Centuries of Change*; Colten, C.E., Ed.; University of Pittsburgh Press: Pittsburgh, PA, USA, 2000; pp. 84–106.
30. Day, J.W.; Cable, J.E.; Lane, R.R.; Kemp, G.P. Sediment deposition at the Caernarvon crevasse during the great Mississippi flood of 1927: Implications for coastal restoration. *Water* **2016**, *8*, 38.
31. Day, J.W.; Agboola, J.; Chen, Z.; D'Elia, C.; Forbes, D.L.; Giosan, L.; Kemp, P.; Kuenzer, C.; Lane, R.R.; Ramachandran, R.; et al. Approaches to defining deltaic sustainability in the 21st century. *Estuar. Coast. Shelf Sci.* **2016**, *183*, 275–291.
32. Day, J.W., Jr.; Butler, T.J.; Conner, W.H. Productivity and nutrient export studies in a cypress swamp and lake system in Louisiana. In *Estuarine Processes: Circulation, Sediments, and Transfer of Material in the Estuary*; Academic Press: New York, NY, USA, 1977; Volume 2, pp. 255–269.
33. Rosenzweig, J. Reinventing the Mississippi River Delta: A Flood of Creativity. Master's Thesis, Tulane University School of Architecture, New Orleans, LA, USA, 2007.
34. Lane, R.R.; Kemp, G.P.; Day, J.W. A Brief History of Delta Formation and Deterioration. In *Multifunctional Wetlands*; Nagabhatla, N., Metcalfe, C.D., Eds.; Springer: Cham, Switzerland, 2018; pp. 11–27.
35. Visser, J.M.; Sasser, C.E.; Chabreck, R.H.; Linscombe, R.G. The impact of a severe drought on the vegetation of a subtropical estuary. *Estuaries* **2002**, *25*, 1184–1195.
36. Day, J.; Hunter, R.; Keim, R.F.; DeLaune, R.; Shaffer, G.; Evers, E.; Reed, D.; Brantley, C.; Kemp, P.; Day, J.; et al. Ecological response of forested wetlands with and without large-scale Mississippi River input: Implications for management. *Ecol. Eng.* **2012**, *46*, 57–67.
37. Edwards, B.L.; Allen, S.T.; Braud, D.H.; Keim, R.F. Stand density and carbon storage in cypress-tupelo wetland forests of the Mississippi River delta. *For. Ecol. Manag.* **2019**, *441*, 106–114.
38. Hsueh, Y.H.; Chambers, J.L.; Krauss, K.W.; Allen, S.T.; Keim, R.F. Hydrologic exchanges and baldcypress water use on deltaic hummocks, Louisiana, USA. *Ecohydrology* **2016**, *9*, 1452–1463.
39. Needham, H.F.; Keim, B.D.; Sathiaraj, D. A review of tropical cyclone-generated storm surges: Global data sources, observations, and impacts. *Rev. Geophys.* **2015**, *53*, 545–591.
40. Doyle, T.W.; Conner, W.H.; Day, R.H.; Krauss, K.W.; Swarzenski, C.M. Wind damage and salinity effects of Hurricanes Katrina and Rita on coastal baldcypress forests of Louisiana. *Plant Environ. Sci.* **2007**, *12*, 163–168.
41. Keim, R.F.; Lemon, M.G.T.; Oakman, E.C. Post hurricane salinity in an impounded coastal wetland (Bayou Sauvage, Louisiana, USA). *J. Coast. Res.* **2019**, *35*, 1003–1009.
42. Gael, B.T.; Hopkinson, C.S. Drainage density, land-use and eutrophication in Barataria Basin, Louisiana. In *Proceedings of the Third Marsh and Estuary Management Symposium, Baton Rouge, LA, USA, 6–7 March 1978*; Day, J., Culley, D., Turner, R., Mumphrey, A., Eds.; Louisiana State University Division of Continuing Education: Baton Rouge, LA, USA, 1979; pp. 147–163.

43. Brezonik, P.; Shannon, E. Trophic state of lakes in north central Florida. In *Florida Water Resources Research Center*; Publ. No. 13; University of Florida: Gainesville, FL, USA, 1971.
44. Day, J.W.; Hopkinson, C.S.; Conner, W.H. An analysis of environmental factors regulating community metabolism and fisheries production in a Louisiana estuary. In *Estuarine Comparisons*; Kennedy, V., Ed.; Academic Press: New York, NY, USA, 1982; pp. 121–136.
45. Seaton, A. Nutrient Chemistry in the Barataria Basin—A Multivariant Approach. Master's Thesis, Louisiana State University, Baton Rouge, LA, USA, 1979; 123p.
46. Seaton, A.; Day, J. The development of a trophic state index for the quantification of eutrophication in the Barataria Basin. In *Proceedings of the Third Marsh and Estuary Management Symposium, Baton Rouge, LA, USA, 6–7 March 1978*; Day, J., Culley, D., Turner, R., Mumphrey, A., Eds.; Louisiana State University Division of Continuing Education, Baton Rouge, LA, USA, 1979; pp. 113–125.
47. Witzig, A.; Day, J. *A Tropic State Index for the Louisiana Coastal Zone*; Technical Completion Report to the LA; Water Resources Research Institute, Louisiana State University: Baton Rouge, LA, USA, 1983; 35p.
48. Yu, K.; DeLaune, R.D.; Tao, R.; Beine, R.L. Nonpoint source of nutrients and herbicides associated with sugarcane production and its impact on Louisiana coastal water quality. *J. Environ. Qual.* **2008**, *37*, 2275–2283.
49. DeLaune, R.; Yu, K.; Devai, I.; Tao, R. *Water Quality of Upper Barataria Basin: Impact of Nonpoint Source Pollution Associated with Sugarcane Production (St. James Sugarcane Run-off Project)*; Final Report DEQ Contract No. CFMS597, Grant number C9-996102-08; Louisiana State University: Baton Rouge, LA, USA, 2007; 104p.
50. Kemp, P.; Day, J. Nutrient dynamics in a swamp receiving agricultural runoff. In *Cypress Swamps*; Ewel, K., Odum, H.T., Eds.; University of Florida Press: Gainesville, FL, USA, 1984; pp. 286–293.
51. Lane, R.R.; Huang, H.; Day, J.W.; Justic, D.; DeLaune, R.D. Water quality of a coastal Louisiana swamp and how dredging is undermining restoration efforts. *Estuar. Coast. Shelf Sci.* **2015**, *152*, 23–32.
52. Day, J.W.; Kemp, P. Long term impacts of agricultural runoff in a Louisiana swamp forest. In *Ecological Considerations in Wetlands Treatment of Municipal Waste Water*; Godfrey, P., Ed.; Van Norstrand Reinhold Co.: New York, NY, USA, 1985; pp. 317–326.
53. Kemp, G.P.; Conner, W.H.; Day, J.W. Effects of flooding on decomposition and nutrient cycling in a Louisiana swamp forest. *Wetlands* **1985**, *5*, 35–51.
54. Rivera-Monroy, V.H.; Lenaker, P.; Twilley, R.R.; Delaune, R.D.; Lindau, C.W.; Nuttle, W.; Habib, E.; Fulweiler, R.W.; Castañeda-Moya, E. Denitrification in coastal Louisiana: A spatial assessment and research needs. *J. Sea Res.* **2010**, *63*, 157–172.
55. Rivera-Monroy, V.H.; Branoff, B.; Meselhe, E.; McCorquodale, A.; Dortch, M.; Steyer, G.D.; Visser, J.; Wang, H. Landscape-level estimation of nitrogen removal in coastal Louisiana wetlands: Potential sinks under different restoration scenarios. *J. Coast. Res.* **2013**, *67*, 75–87.
56. Upreti, K.; Rivera-Monroy, V.H.; Maiti, K.; Giblin, A.; Geaghan, J.P. Emerging wetlands from river diversions can sustain high denitrification rates in a coastal delta. *JBR Biogeosciences* **2021**, in review.
57. Vaccare, J.; Meselhe, E.; White, J.R. The denitrification potential of eroding wetlands in Barataria Bay, LA, USA: Implications for river reconnection. *Sci. Total Environ.* **2019**, *686*, 529–537.
58. Vargas-Lopez, I.A.; Rivera-Monroy, V.H.; Day, J.W.; Whitbeck, J.; Maiti, K.; Madden, C.J.; Castro, A.T. Assessing chlorophyll a spatiotemporal patterns combining in situ continuous fluorometry measurements and Landsat 8/OLI data across the Barataria Basin (Louisiana, USA). *Water* **2021**, in review.
59. Day, J.W., Jr.; Templet, P.H. Consequences of sea level rise: Implications from the Mississippi Delta. *Coast. Manag.* **1989**, *17*, 241–257.
60. Lane, R.R.; Mack, S.K.; Day, J.W.; Kempka, R.; Brady, L.J. Carbon sequestration at a forested wetland receiving treated municipal effluent. *Wetlands* **2017**, *37*, 861–873.
61. Lane, R.R.; Mack, S.K.; Day, J.W.; DeLaune, R.D.; Madison, M.J.; Precht, P.R. Fate of soil organic carbon during wetland loss. *Wetlands* **2016**, *36*, 1167–1181.
62. Lane, R.R.; Madden, C.J.; Day, J.W.; Solet, D.J. Hydrologic and nutrient dynamics of a coastal bay and wetland receiving discharge from the Atchafalaya River. *Hydrobiologia* **2011**, *658*, 55–66.
63. Randall, J.M.; Day, J.W. Effects of river discharge and vertical circulation on aquatic primary production in a turbid Louisiana (USA) estuary. *Neth. J. Sea Res.* **1987**, *21*, 231–242.
64. Madden, C.J. Control of Phytoplankton Production in a Shallow, Turbid Estuary. Ph.D. Dissertation, Louisiana State University, Baton Rouge, LA, USA, 1992.
65. Madden, C.J.; Day, J.W., Jr.; Randall, J.M. Freshwater and marine coupling in estuaries of the Mississippi River deltaic plain 1. *Limnol. Oceanogr.* **1988**, *33*, 982–1004.
66. Happ, G.; Gosselink, J.G.; Day, J.W., Jr. The seasonal distribution of organic carbon in a Louisiana estuary. *Estuar. Coast. Mar. Sci.* **1977**, *5*, 695–705.
67. Das, A. Modeling the Impacts of Pulsed Riverine Inflows on Hydrodynamics and Water Quality in the Barataria Bay Estuary. Ph.D. Dissertation, Louisiana State University, Baton Rouge, LA, USA, 2010.
68. Das, A.; Justić, D.; Swenson, E. Modeling estuarine-shelf exchanges in a deltaic estuary: Implications for coastal carbon budgets and hypoxia. *Ecol. Model.* **2010**, *221*, 978–985.
69. Norgress, R.E. The History of the Cypress Lumber Industry in Louisiana. Master's Thesis, Louisiana State University, Baton Rouge, LA, USA, 1936.

70. Mancil, E.M. An Historical Geography of Industrial Cypress Lumbering. Ph.D. Dissertation, Louisiana State University, Baton Rouge, LA, USA, 1972.
71. Anderson, R.C.; White, J. A cypress swamp outlier in southern Illinois. *Ill. State Acad. Sci*. **1970**, *63*, 6–13.
72. Conner, W.H.; Day, J.W. Productivity and composition of a baldcypress-water tupelo site and a bottomland hardwood site in a Louisiana swamp. *Am. J. Bot.* **1976**, *63*, 1354–1364.
73. Conner, W.H.; Gosselink, J.G.; Parrondo, R.T. Comparison of the vegetation of three Louisiana swamp sites with different flooding regimes. *Am. J. Bot.* **1981**, *68*, 320–331.
74. Conner, W.H.; Day, J.W. Water level variability and litterfall productivity of forested freshwater wetlands in Louisiana. *Am. Midl. Nat.* **1992**, *128*, 237–245.
75. Conner, W.H.; Mihalia, I.; Wolfe, J. Tree community structure and changes from 1987 to 1999 in three Louisiana and three South Carolina forested wetlands. *Wetlands* **2002**, *22*, 58–70.
76. Nienhuis, J.H.; Törnqvist, T.E.; Jankowski, K.L.; Fernandes, A.M.; Keogh, M.E. A new subsidence map for coastal Louisiana. *GSA Today* **2017**, *27*, 58–59.
77. Conner, W.H.; Day, J.W. Rising water levels in coastal Louisiana: Implications for two coastal forested wetland areas in Louisiana. *J. Coast. Res.* **1988**, *4*, 589–596.
78. Conner, W.H.; Brody, M. Rising water levels and the future of southeastern Louisiana swamp forests. *Estuaries* **1989**, *12*, 318–323.
79. Keim, R.F.; Izdepski, C.W.; Day, J.W. Growth responses of baldcypress to wastewater nutrient additions and changing hydrologic regime. *Wetlands* **2012**, *32*, 95–103.
80. Allen, S.T.; Keim, R.F.; Dean, T.J. Contrasting effects of flooding on tree growth and stand density determine aboveground production, in baldcypress forests. *For. Ecol. Manag.* **2019**, *432*, 345–355.
81. Howard, J.J. Hurricane Katrina impact on a leveed bottomland hardwood forest in Louisiana. *Am. Midl. Nat.* **2012**, *168*, 56–69.
82. Conner, W.H.; Duberstein, J.A.; Day, J.W.; Hutchinson, S. Impacts of changing hydrology and hurricanes on forest structure and growth along a flooding/elevation gradient in a south Louisiana forested wetland from 1986 to 2009. *Wetlands* **2014**, *34*, 803–814.
83. Shaffer, G.P.; Kandalepas, D. *Monitoring of the Lac des Allemands Swamp (BA-34-2) Hydrologic Restoration Project*; Annual Report; Wetland Resources, LLC: Ponchatoula, LA, USA, 2016.
84. Shaffer, G.P.; Kandalepas, D. *Monitoring of the Lac des Allemands Swamp (BA-34-2) Hydrologic Restoration Project*; Final Report; Wetland Resources, LLC: Ponchatoula, LA, USA, 2019.
85. Day, J.W.; Ko, J.Y.; Rybczyk, J.; Sabins, D.; Bean, R.; Berthelot, G.; Brantley, C.; Cardoch, L.; Conner, W.; Day, J.N.; et al. The use of wetlands in the Mississippi Delta for wastewater assimilation: A review. *Ocean Coast. Manag.* **2004**, *47*, 671–691.
86. Hesse, I.D.; Day, J.W.; Doyle, T.W. Long-term growth enhancement of baldcypress (Taxodium distichum) from municipal wastewater application. *Environ. Manag.* **1998**, *22*, 119–127.
87. Brantley, C.G.; Day, J.W., Jr.; Lane, R.R.; Hyfield, E.; Day, J.N.; Ko, J.Y. Primary production, nutrient dynamics, and accretion of a coastal freshwater forested wetland assimilation system in Louisiana. *Ecol. Eng.* **2008**, *34*, 7–22.
88. Hunter, R.G.; Day, J.W.; Lane, R.R.; Lindsey, J.; Day, J.N.; Hunter, M.G. Impacts of secondarily treated municipal effluent on a freshwater forested wetland after 60 years of discharge. *Wetlands* **2009**, *29*, 363–371.
89. Shaffer, G.P.; Day, J.W.; Hunter, R.G.; Lane, R.R.; Lundberg, C.J.; Wood, W.B.; Hillmann, E.R.; Day, J.N.; Strickland, E.; Kandalepas, D. System response, nutria herbivory, and vegetation recovery of a wetland receiving secondarily-treated effluent in coastal Louisiana. *Ecol. Eng.* **2015**, *79*, 120–131.
90. Sasser, C.E.; Visser, J.M.; Mouton, E.; Linscombe, J.; Hartley, S.B. *Vegetation Types in Coastal Louisiana in 2013*; Open-File Report; U.S. Geological Survey, Reston, VA; 2014.
91. O'Neil, T. *The Muskrat in the Louisiana Marshes*; Louisiana Wildlife and Fisheries Commission: New Orleans, LA, USA, 1949.
92. Sasser, C.E.; Gosselink, J.G.; Swenson, E.M.; Swarzenski, C.M.; Leibowitz, N.C. Vegetation, substrate and hydrology in floating marshes in the Mississippi river delta plain wetlands, USA. *Vegetatio* **1996**, *122*, 129–142.
93. Sasser, C.E.; Visser, J.M.; Evers, D.E.; Gosselink, J.G. The role of environmental variables on interannual variation in species composition and biomass in a subtropical minerotrophic floating marsh. *Can. J. Bot.* **1995**, *73*, 413–424.
94. Sasser, C.E.; Gosselink, J.G.; Swenson, E.M.; Evers, D.E. Hydrologic, vegetation, and substrate characteristics of floating marshes in sediment-rich wetlands of the Mississippi river delta plain, Louisiana, USA. *Wetl. Ecol. Manag.* **1995**, *3*, 71–187.
95. Sasser, C.E.S.; Swenson, E.; Evers, D.E.; Visser, J.M.; Holm, G.O.; Gosselink, J.G. *Floating Marshes in the Barataria and Terrebonne Basins, Louisiana*; LSU-CEI-94-02; Coastal Ecology Institute, Louisiana State University: Baton Rouge, LA, USA, 1994.
96. Sasser, C.E.; Gosselink, J.G. Vegetation and primary production in a floating freshwater marsh in Louisiana. *Aquat. Bot.* **1984**, *20*, 245–255.
97. Sasser, C.E.; Gosselink, J.G.; Shaffer, G.P. Distribution of nitrogen and phosphorus in a Louisiana freshwater floating marsh. *Aquat. Bot.* **1991**, *41*, 317–331.
98. Reddy, K.R.; DeLaune, R.D. *Biogeochemistry of Wetlands: Science and Applications*; CRC Press: Boca Raton, FL, USA, 2008.
99. Nixon, S.W.; Ammerman, J.W.; Atkinson, L.P.; Berounsky, V.M.; Billen, G.; Boicourt, W.C.; Boynton, W.R.; Church, T.M.; Ditoro, D.M.; Elmgren, R.; et al. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. *Biogeochemistry* **1996**, *35*, 141–180.

100. Dettmann, E.H. Effect of water residence time on annual export and denitrification of nitrogen in estuaries: A model analysis. *Estuaries* **2001**, *24*, 481–490.
101. Smith, C.J.; DeLaune, R.D.; Patrick, W.H. Fate of riverine nitrate entering an estuary: I. Denitrification and nitrogen burial. *Estuaries* **1985**, *8*, 15–21.
102. Penland, S.; Ramsey, K.E. Relative sea-level rise in Louisiana and the Gulf of Mexico: 1908-1988. *J. Coast. Res.* **1990**, *6*, 323–342.
103. Lane, R.R.; Day, J.W.; Justic, D.; Reyes, E.; Marx, B.; Day, J.N.; Hyfield, E. Changes in stoichiometric Si, N and P ratios of Mississippi River water diverted through coastal wetlands to the Gulf of Mexico. *Estuar. Coast. Shelf Sci.* **2004**, *60*, 1–10.
104. Boynton, W.R.; Hagy, J.D.; Cornwell, J.C.; Kemp, W.M.; Greene, S.M.; Owens, M.S.; Baker, J.E.; Larsen, R.K. Nutrient budgets and management actions in the Patuxent River estuary, Maryland. *Estuaries Coasts* **2008**, *31*, 623–651.
105. Perez, B.C.; Day, J.W.; Justic, D.; Lane, R.R.; Twilley, R.R. Nutrient stoichiometry, freshwater residence time, and nutrient retention in a river-dominated estuary in the Mississippi Delta. *Hydrobiologia* **2011**, *658*, 41–54.
106. Bargu, S.; Justic, D.; White, J.R.; Lane, R.; Day, J.; Paerl, H.; Raynie, R. Mississippi River diversions and phytoplankton dynamics in deltaic Gulf of Mexico estuaries: A review. *Estuar. Coast. Shelf Sci.* **2019**, *221*, 39–52.
107. White, J.R.; DeLaune, R.D.; Justic, D.; Day, J.W.; Pahl, J.; Lane, R.R.; Boynton, W.R.; Twilley, R.R. Consequences of Mississippi River diversions on nutrient dynamics of coastal wetland soils and estuarine sediments: A review. *Estuar. Coast. Shelf Sci.* **2019**, *224*, 209–216.
108. Kral, F.; Corstanje, R.; White, J.R.; Veronesi, F. A geostatistical analysis of soil properties in the Davis Pond Mississippi freshwater diversion. *Soil Sci. Soc. Am. J.* **2012**, *76*, 1107–1118.
109. Spera, A.C.; White, J.R.; Corstanje, R. Influence of a freshwater river diversion on sedimentation and phosphorus status in a wetland receiving basin. *Estuar. Coast. Shelf Sci.* **2020**, *238*, 106728.
110. McAlpin, T.O.; Letter, J.V.; Martin, S.K. *A Hydrodynamic Study of Davis Pond, Near New Orleans, LA*; ERDC/CHL TR-08-11; Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, Visksburg, MS; 2008.
111. Gardner, L.M.; White, J. Denitrification enzyme activity as an indicator of nitrate movement through a diversion wetland. *Soil Sci. Soc. Am. J.* **2010**, *74*, 1037–1047.
112. Keogh, M.E.; Kolker, A.S.; Snedden, G.A.; Renfro, A.A. Hydrodynamic controls on sediment retention in an emerging diversion-fed delta. *Geomorphology* **2019**, *332*, 100–111.
113. Lane, R.R.; Day, J.W.; Marx, B.; Reves, E.; Kemp, G.P. Seasonal and spatial water quality changes in the outflow plume of the Atchafalaya River, Louisiana, USA. *Estuaries* **2002**, *25*, 30–42.
114. Reed, D.; Wang, Y.; Meselhe, E.; White, E. Modeling wetland transitions and loss in coastal Louisiana under scenarios of future relative sea-level rise. *Geomorphology* **2020**, *352*, 106991.
115. Day, J.W.; Clark, H.C.; Chang, C.; Hunter, R.; Norman, C.R. Life Cycle of Oil and Gas Fields in the Mississippi River Delta: A Review. *Water* **2020**, *12*, 1492.
116. Hopkinson, C.S.; Day, J.W. Modeling the relationship between development and storm water and nutrient runoff. *Environ. Manag.* **1980**, *4*, 315–324.
117. Hopkinson, C.S.; Day, J.W. Modeling hydrology and eutrophication in a Louisiana swamp forest ecosystem. *Environ. Manag.* **1980**, *4*, 325–335.
118. CPRA (Coastal Protection and Restoration Authority of Louisiana). *Louisiana's Comprehensive Master Plan for a Sustainable Coast—2017 Draft Plan Release*; CPRA: Baton Rouge, LA, USA, 2017; 169p.
119. Kemp, G.P.; Day, J.W.; Rogers, J.D.; Giosan, L.; Peyronnin, N. Enhancing mud supply from the Lower Missouri River to the Mississippi River Delta USA: Dam bypassing and coastal restoration. *Estuar. Coast. Shelf Sci.* **2016**, *183*, 304–313.