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Review

Recovery and Restoration of Biloxi Marsh in the Mississippi River Delta

G. Paul Kemp [1,*], Elizabeth C. McDade [2], John W. Day [1,3], Robert R. Lane [3], Nancye H. Dawers [4] and Jason N. Day [3]

[1] Department of Oceanography & Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA; johnday@lsu.edu
[2] Chinn-McDade Associates LLC, 1401 Distributors Row, Suite C, New Orleans, LA 70123, USA; ecmcdade@bellsouth.net
[3] Comite Resources, P.O. Box 66596, Baton Rouge, LA 70896, USA; rlane@comiteres.com (R.R.L.); jnday@comiteres.com (J.N.D.)
[4] Department of Earth & Environmental Sciences, 101 Blessey Hall, Tulane University, New Orleans, LA 70118, USA; ndawers@tulane.edu
* Correspondence: gpkemp@lsu.edu; Tel.: +1-225-772-1426

Abstract: The State of Louisiana is leading an integrated wetland restoration and flood risk reduction program in the Mississippi River Delta. East of New Orleans, Biloxi Marsh, a ~1700 km^2 peninsula jutting 60 km north toward the State of Mississippi is one of few Delta wetland tracts well positioned to dissipate hurricane surge and waves threatening the city's newly rebuilt hurricane flood defenses. Both its location on the eastern margin of the Delta, and its genesis as the geologic core of the shallow water St. Bernard/Terre aux Boeuf sub-delta, which was the primary Mississippi outlet for almost 2000 years, make Biloxi Marsh attractive for restoration, now that the Mississippi River Gulf Outlet deep-draft ship channel has been dammed, and 50 years of impacts from construction and operation have abated. Now, the cascade of ecosystem damage it caused can be reversed or offset by restoration projects that leverage natural recovery and increased access to suspended sediment from the Mississippi River. Biloxi Marsh is (1) geologically stable, (2) benefiting from increased input of river sediment, and (3) could be restored to sustainability earlier and for a longer period than most of the rest of the submerging Mississippi Delta. The focus of this review is on the Biloxi Marsh, but it also provides a template for regional studies, including analysis of 2D and 3D seismic and other energy industry data to explore why existing marshes that look similar on the ground or from the air may respond to restoration measures with different levels of success. Properties of inherent durability and resilience can be exploited in restoration project selection, sequencing and expenditure. Issues encountered and investigative methods applied in the Biloxi Marsh are likely to resonate across initiatives now contemplated to sustain valuable river deltas worldwide.

Keywords: Mississippi River Delta; Biloxi Marsh; marsh submergence; relative sea level rise; delta restoration

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1. Introduction

The Mississippi River Delta (Delta), at 25,000 km^2, is one of the largest coastal wetland ecosystems in the world, with enormous ecological and economic importance [1–5]. It supports an array of linked estuarine habitats ranging from oyster reefs, barrier islands and salt marshes to freshwater forested wetlands hundreds of km inland, as well as shallow water bodies from small ponds to large lakes and bays. Over the past 90 years, about 25 percent of the Delta land mass has disappeared into open water due largely to impacts caused or accelerated by human activity [6–10]. The State of Louisiana through the Coastal Protection and Restoration Authority (CPRA) has budgeted almost USD 1 B-y^{-1} to bend both the natural and built risk-reduction infrastructure in the Delta toward greater sustainability [11] despite some of the highest relative sea level rise rates [RSLR] in the world [5].

Historic wetland loss in the Delta has ranged up to 80 km^2-y^{-1} since the early 1930s, reaching a peak around 1980, and dropping since to 25 km^2-y^{-1} in the 2010s, the lowest decade on record [10]. Similarly, wetland loss rates have varied spatially across the Delta. Two wetland basins, Barataria and Terrebonne, located between the outlets of the Mississippi and Atchafalaya Rivers in the central part of the Delta, accounted for 65% of the cumulative Delta wetland loss between 1932 and 2016 [7,10]. Lower loss rates have been observed in basins on either side of the Delta, where fluvial sediment input still occurs, though at a reduced rate than in the past [2].

Assessing the sustainability of Biloxi Marsh (Figure 1), relative to the value it provides in ecosystem services is inherently multidisciplinary, and a complement to forecasts from numerical hydrodynamic and ecosystem models [1–3]. As part of a mandate received when it was created after the Hurricane Katrina disaster (2005), CPRA has pursued a scientific/engineering planning initiative that delivered over 100 restoration projects, and Louisiana's first Coastal Master Plan (CMP) in 2007, with major revisions in 2012 and 2017 [11,12]. The 2012 plan was the first to apply numerical modeling of deltaic hydrodynamics and landscape evolution to forecast marsh loss or survival. This approach was refined in 2017 [13–15], and continues to be improved, with the next major upgrade to be released in 2023 [16,17].

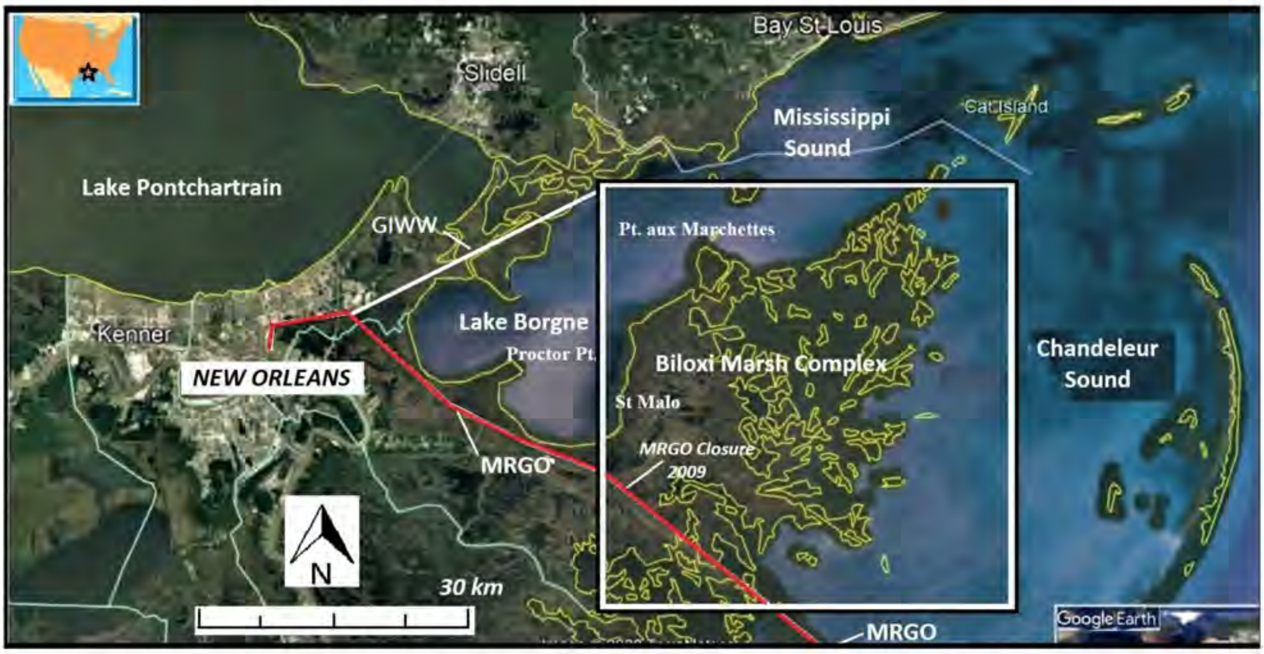

Figure 1. New Orleans and the Biloxi Marsh Study Area showing the Mississippi River-Gulf Outlet in red, and position of the Closure Structure built in 2009. Biloxi Marsh is situated in the triangular "hurricane surge funnel" between the MRGO and Gulf Intracoastal Waterway (GIWW) north of Lake Borgne.

CMP2017 forecasts of deltaic wetland change over the 50-year planning horizon relied on "plausible ranges" of subsidence, sea level rise, marsh aggradation and shoreline translation to characterize polygons covering tens to thousands of km^2 [12–15,17]. Virtually all of Biloxi Marsh—under any of the modeled global sea level rise scenarios—was predicted to become open water within 30 years, along with most of the rest of the saline and brackish marsh in the Delta today [12]. This grim outlook initially led CPRA to scale back proposed wetland restoration work for Biloxi Marsh.

The Biloxi Marsh Lands Corporation (BLMC), a major landowner on the Biloxi Marsh peninsula, sponsored field research conducted by the authors in 2018. Results were released recently [18,19] and are now being used in a CPRA reassessment of Biloxi Marsh subsidence rates [17]. Here, we review this new information and how it fits into the multi-disciplinary tapestry of Biloxi Marsh studies published over nearly a century. The goal is to show how regional information less often tapped in CPRA planning can help guide restoration of Delta marshes.

Our focus is on the Biloxi Marsh, but this review illustrates how antecedent properties such as comparative durability and restoration response potential (resilience) of Delta wetlands can be assessed more generally. This calls for more attention to subsurface geology, including available 2D and 3D seismic data, identifying avenues for salinity and sediment input, and even to patterns of prehistoric human occupation and usage. Such disparate information can then be applied to questions about why existing marshes that appear similar on the ground or from the air respond to restoration measures with an unpredictable range of effectiveness or resilience. Inherent properties that emerge from the geologic history of the marsh can be exploited in restoration project selection and sequencing, as well as to prioritize expenditure. Issues encountered, and investigative methods applied, in the Biloxi Marsh are likely to resonate across the many delta initiatives now contemplated or in progress around the globe [20].

2. Biloxi Marsh

The Biloxi Marsh peninsula that divides Lake Borgne from Chandeleur Sound covers 1700 km^2, and is about equally divided between land and water (Figure 1). The peninsula partially occludes the entrance to Lakes Borgne and Pontchartrain from the Gulf of Mexico. Regionally, it is part of a natural deltaic infrastructure of salt and brackish marshes that—when added to built flood defenses—provides "multiple lines of defense" [21]. Biloxi Marsh is positioned to reduce surge and wave stresses on levees and floodwalls produced by hurricanes tracking east of metro New Orleans [22–25] (Figure S1). These man-made structures have been rebuilt since they failed in 2005 [26,27], and earthen levee crowns have been raised and capped with a "soft armor" designed to prevent breaching even during overtopping [28].

Biloxi Marsh is one of the most productive estuarine areas on the northern U.S. Gulf Coast for both commercial and recreational fishing, including oyster cultivation and harvesting, and for muskrat, alligators and overwintering waterfowl [29,30]. Because of this productivity so close to New Orleans, a portion of Biloxi Marsh (144 km^2) has been leased for decades to the Louisiana Department of Wildlife and Fisheries which manages it for public use as the Biloxi Wildlife Management Area [30].

An early post-Katrina step toward Delta restoration was taken in 2009 when the 76 km long Mississippi River-Gulf Outlet (MRGO) ship channel was decommissioned and physically closed—after 50 years of operation—with a rock dam where it crossed Bayou La Loutre (Figure 1). The free-flowing MRGO was a 15 m-deep conduit dredged in the early 1960s from the Gulf of Mexico through Biloxi Marsh into the heart of New Orleans [31]. Otherwise, Biloxi Marsh has changed less than the rest of the Delta based on surveys made in the 1840s by the U.S. Surveyors General Office [18], with few canals, or oil/gas structures.

Before it was dammed, the MRGO increased conveyance of saline Gulf waters from Chandeleur Sound into Lake Borgne, and helped carry surge into New Orleans and its eastern suburbs during hurricanes Betsy (1965), Camille (1969), Katrina (2005), Rita (2005) and Gustav (2008) [27,31]. Ship wakes eroded the unprotected marsh edges, causing the channel to widen from 200 to more than 600 m wide in places [32]. However, one of the most detrimental effects of the MRGO on Biloxi Marsh was indirect. Naturally protective beaches composed of *Rangia* clam shells disappeared from the Lake Borgne coast as the composition of the benthic community shifted when salinity increased [33,34]. Other MRGO impacts to Biloxi Marsh and to the flooding of New Orleans during Hurricane Katrina have been reported elsewhere [31]. However, observed recovery of marsh in parts of the study area near the MRGO and on Bayou La Loutre natural levees suggests a potential for recovery and resilience [18].

In addition to MRGO closure, the CPRA constructed two phases of detached rock breakwaters in 2009 and 2013 designed to stabilize 13 km of the southern Lake Borgne shoreline [35]. Addressing poor foundation conditions drove up construction costs to more than USD 2M-km^{-1}, but almost a decade later the breakwaters are performing well, and have largely arrested or reversed shoreline retreat on this stretch of Lake Borgne coast. Day et al. [18] recently reported 1 m-y^{-1} marsh advance in sites behind the breakwaters (Figure S2), compared with 1 to 2 m-y^{-1} of retreat at unprotected sites to the north.

3. Methods

CPRA has acknowledged that Biloxi Marsh is data-poor compared to the rest of the Delta [12,17]. In response, major Biloxi Marsh landowners (BLMC), and Lake Eugenie Land & Development, Inc., LKEU) have augmented an existing field research program to acquire post-MRGO data on local salinity, shoreline erosion, sediment supply and subsidence. The authors have participated in this work since 2017 [18,19], and seek here to integrate recent results with those acquired through more than 70 years of earlier Biloxi Marsh studies. Geological information reaching back to the 1930s is combined with a recent 3D seismic interpretation to provide a more complete picture of the inherent durability of the Biloxi Marsh. Here, we focus on Biloxi Marsh itself, rather than on the role of these wetlands in slowing, diminishing and redirecting hurricane surge and waves away from New Orleans [24,25], (Figure S1). Couvillion et al. [10] provide the most recent assessment of land-loss patterns in Biloxi Marsh, as they do for the rest of the Delta through 2015.

3.1. Review of Geological and Archaeological Data

Biloxi Marsh is featured in geological and archaeological literature from the 1930s [36–38], 1940s [39], 1950s [40–42], and 1960s [43,44]. The period between 1970 and 1995 saw progress in isotopic and luminescence technique for dating prehistoric archaeological sites [45–47], and global positioning technology (GPS) that made shallow seismic and high-resolution sub-bottom (CHIRP), as well as side-scan sonar more accessible. These tools were used more widely and improved by development of networks of Continuously Operating Reference Stations (CORS) to improve accuracy of GPS locating, particularly in the vertical, as the digital revolution drove down the cost of data storage and manipulation [48–56]. This trend continues today as 3D seismic has become the standard [57–61]. Since 2007, the investment in Delta restoration, which grew from USD 10M-y^{-1} in 1990 to USD 1B-y^{-1} in 2020 [62], has led to acquisition of new types of measurements over more than a decade at hundreds of instrumented monitoring stations in the swamp and marsh [63]. CPRA has made data from Coastwide Reference Monitoring System (CRMS) stations public [64]. This has promoted new collaborations with the academic science community to extract information in support of the coastal restoration mission [65–67].

BLMC, LKEU, and their geophysical consultants have supplemented public data with 2D and 3D seismic from Seitel, Inc., that is specific to Biloxi Marsh. Some was shown to two of the authors (ECM and NHD) by the BLMC geophysical consultant [68]. Additional 2D seismic in Lakes Borgne and Pontchartrain has been acquired under contract to the U.S. Geological Survey (USGS), and a 3D survey that was made available to researchers from the University of New Orleans (UNO) by Western Geophysical was also reviewed [57–61]. This subsurface information provides valuable context for the detailed measurements of marsh aggradation and subsidence that are being used to parameterize CPRA marsh ecosystem models.

3.2. Data Collected at Marsh and Water Quality Study Sites

Historical marsh vegetation and water quality data were first acquired by Wright et al. [69] and Rounsefell [70], respectively, between 1959 and 1961, prior to dredging of the MRGO (Figure 2). Salinity and other water quality data have also been collected in the Biloxi Marsh study area by the Louisiana Department of Wildlife and Fisheries (LDWF) beginning in 2004, and by the USGS beginning in 2008 for intervals that spanned the 2009 U.S. Army

Corps of Engineers (USACE) dam installation at Bayou La Loutre [71,72]. The Lake Pontchartrain Basin Foundation (LPBF) has provided monthly synoptic salinity data at the Rounsefell stations since 2012 [73]. Measurements were also made using fixed water level and salinity sensors adjacent to marsh study sites established in 2018 (Figure 2), while discrete measurements were made monthly at the Rounsefell stations [18].

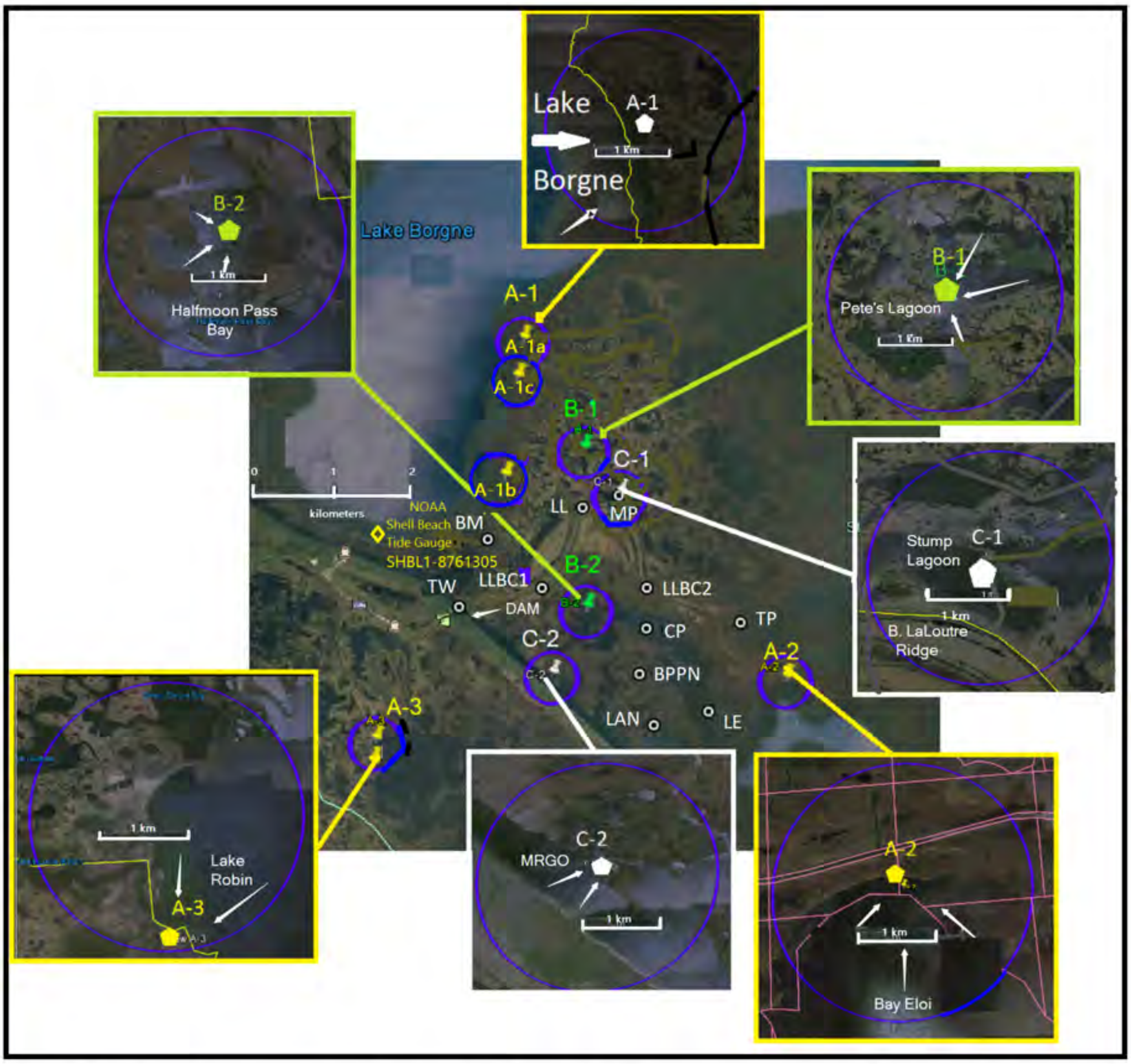

Figure 2. 2018 Marsh and Shoreline Study sites on BLMC and LKEU properties (hexagons) in Biloxi Marsh. Arrows indicate principal wave directions. White labeled sites are Rounsefell [70] water quality stations. NOAA Shell Beach Tide Gauge and Meteorology Station SHBL1-8761305 is marked by yellow diamond in southern Lake Borgne.

In 2003 and 2004, researchers from the University of New Orleans (UNO) established multiple Sediment-Erosion Table (SET) field stations (Figure S3) in Stump and Blind "lagoons", two interior marshes in Bayou La Loutre levee flank depressions [19]. Similar stations were set up in early 2018 by the authors on the higher energy shorelines of Lake Borgne, Lake Robin, and Chandeleur Sound [18]. The 2018 Marsh Study sites were selected for a diversity of wave exposure and fetch on lake and bay shorelines, as well as proximity to active tidal channels (Figure 2). Each marsh site was set up to track shoreline change and marsh surface elevation change (SEC), in addition to sediment supply using the SET and Marker Horizon (MH) techniques (Figure S4) at positions located along shore-normal transects [18,74–77].

3.3. Coastwide Reference Monitoring System (CRMS) Data

Between 2006 and 2009, CPRA established the CRMS network of more than 200 marsh sites across the Delta, where data have now been collected regularly for more than a decade and stored online [63,64]. CRMS elevation data are all tied to the same vertical datum, which means it can be compared across the delta, or when translated into mean sea level (MSL) can be cross-referenced to tidal marshes everywhere. Parameters reported from CRMS sites include marsh elevation, water level, salinity (SAL) and tide range (TR). Bulk density (BD) and percent organic matter (%OM) values used here are an average from the upper 12 cm of the marsh at each CRMS site. Data were downloaded from 15 CRMS sites in the CPRA Coastal Information Management System (CIMS) database [64]. The CRMS stations are arrayed along an 80 km northeast to southwest transect indexed by latitude (Figure 3). Time-series were analyzed to extract decadal trends (2008–2018) of factors affecting the sustainability of Biloxi Marsh wetlands, and then to contrast them with the trajectory of the Breton marshes south of Biloxi Marsh, an area of wetlands that is disappearing more quickly.

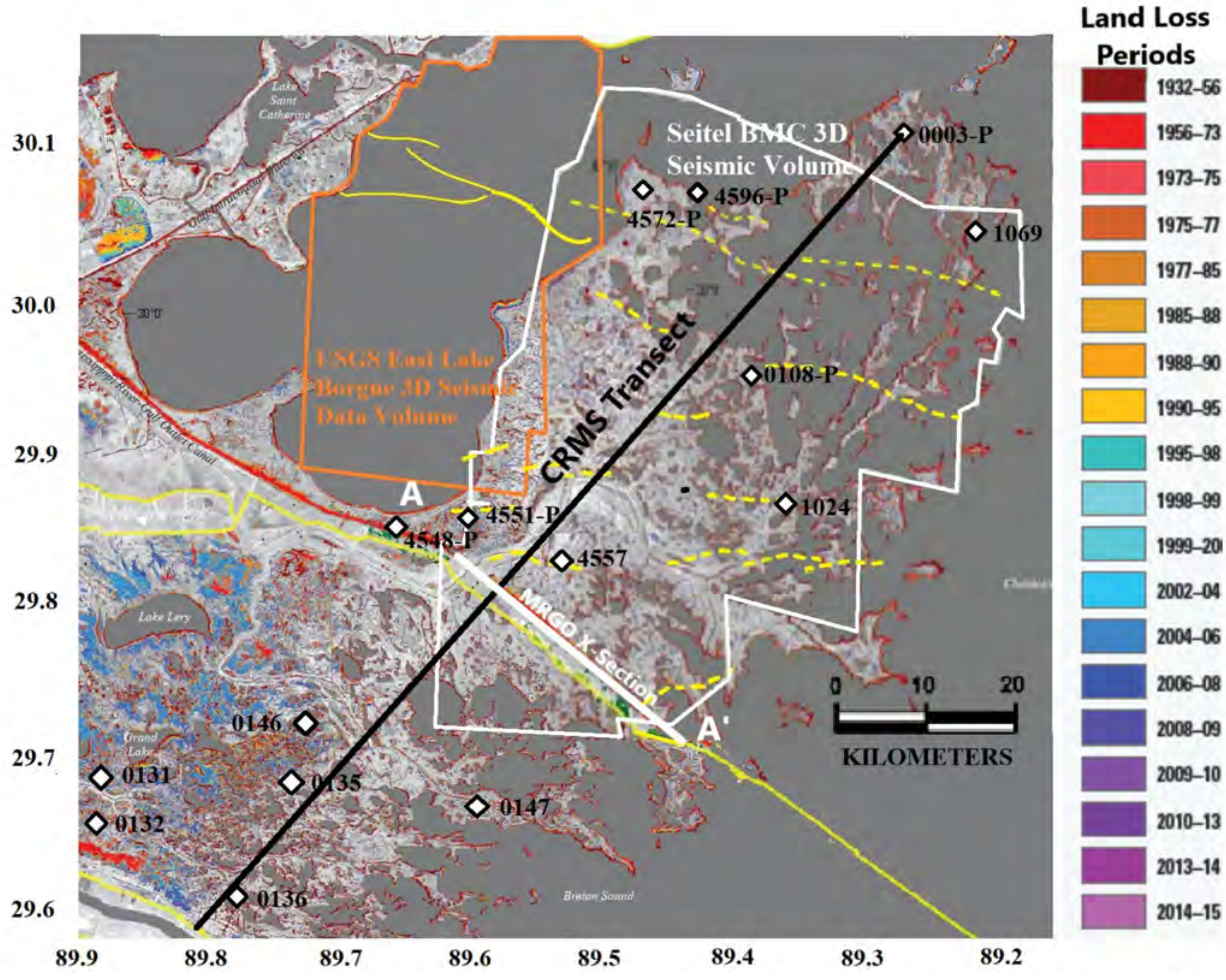

Figure 3. Dashed yellow lines on Biloxi Marsh peninsula are traces of growth faults projected from 1200 m onto the 2016 map of persistent land loss colored by loss interval [10]. Projected Biloxi Marsh faults (dashed yellow) are on trend with those of similar character (solid yellow) projected from 3D seismic and CHIRP data acquired in Lake Borgne by Western Geophysical, USGS and UNO [57–61]. Numbered CRMS stations (diamonds) along transect from northern tip of Biloxi Marsh to the east bank of the Mississippi River near Bohemia. A 'P' following the CRMS station number indicates that the SET is anchored in the Pleistocene Prairie terrace. (Figure S4). A to A′ marks a geologic cross-section in the MRGO right-of-way (Figure 4).

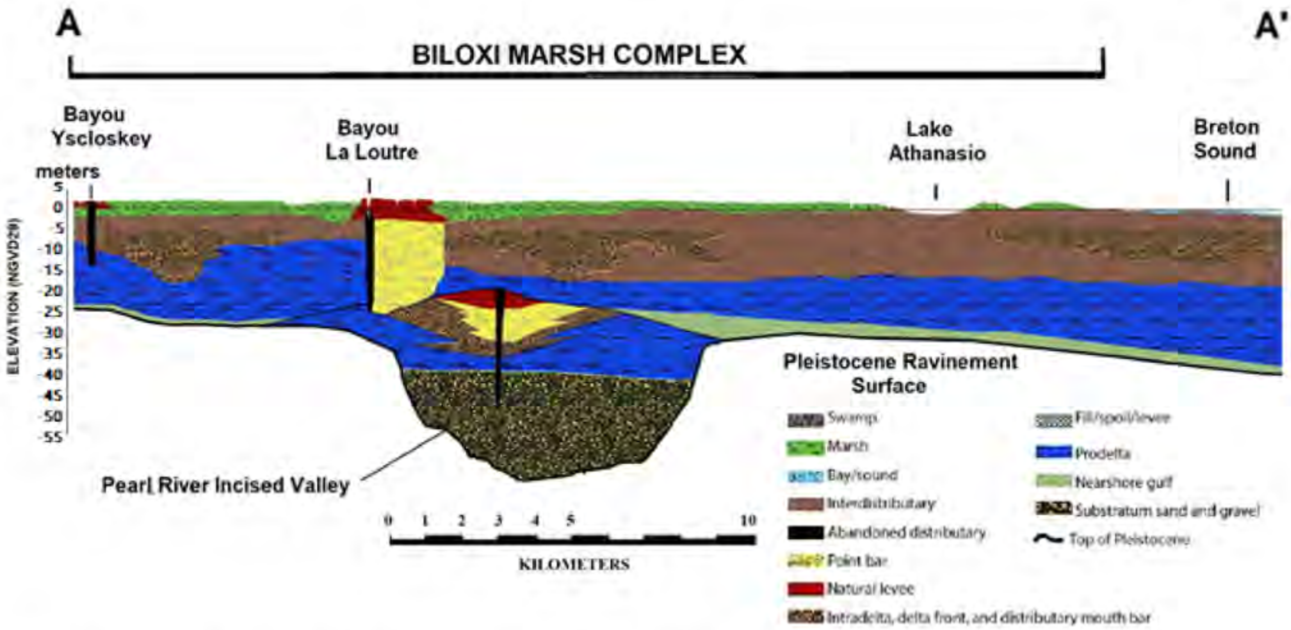

Figure 4. Biloxi Marsh portion of cross-section drawn by Fitzgerald et al. [32] from USACE boring logs made along the MRGO right of way prior to dredging [42]. Section A—A′ location is shown on Figure 3.

4. Results and Discussion

All Delta marsh is subject to submergence stress caused by a combination of subsidence and sea level rise, as well as by any reduction in suspended sediment input [78]. To this list for Biloxi Marsh must be added the environmental stresses and consequences caused by 50 years of MRGO operations. Now that the MRGO is blocked, it is necessary to re-evaluate suitability of Biloxi Marsh for priority restoration. This fresh look includes new appraisals of geological stability, shoreline processes, and what is happening at the marsh surface.

Vegetation of the Biloxi Marsh today is either brackish or salt marsh. Less salt-tolerant plants, including clumps of Roseau Cane (*Phragmites australis*) and Cattails (*Typha latifolia*), are now found near Bayou La Loutre, reflecting a freshening since MRGO closure [71,72]. These species were more widespread in Biloxi Marshes before construction of the MRGO [69]. Now, "live" oak trees (*Quercus virginiana*) along Bayou La Loutre that have appeared dead for years are sprouting new leaves, and living up to the name [18].

4.1. Geology, Geophysics and Archaeology

Geophysical and well data reveal the Biloxi Marsh subsurface to be a model of stability compared to the geologic dynamism apparent in the subsurface of much of the rest of the Delta [79–85]. Biloxi Marsh is near the northern edge of the rift that opened into the Gulf of Mexico about 180 Ma [79,80]. The early Cretaceous (100 Ma) buried shelf edge passes under Biloxi Marsh at the shallow depth of about 5000 m, providing a stable base for the comparatively thin accumulation of Cenozoic strata above [79]. South of shelf edge carbonate deposits are the thick salt layers [82–85] that have contributed to instability since the ancestral Mississippi River began building its northern Gulf sedimentary wedge 70 Ma [86]. The buoyant salt has responded to loading by deforming and flowing upward and laterally while creating basin center evacuation zones and persistent highs in ridges, diapirs and above relict buried plugs [84,85].

Geophysical data from Biloxi Marsh were processed—as is customary in the oil industry—for evaluation of subsurface structure below a depth of about 450 m [68]. Relatively few faults appear to reach this high in the section. Growth faults are observed in the middle Miocene to Pliocene section (13.5 to 2.5 Ma), where bed thickness increases slightly but progressively to the south across each buried fault segment. There is little evidence of salt mobilization that could affect the surface of Biloxi Marsh, and bedding is largely horizontal since the middle Miocene, with a slight tilt to the south.

Clear fault planes to the surface were not visible on the seismic due to acoustic interference, however, geologists on our team (ECM and NHD) worked with an interpretation prepared by geophysical consultants for the landowners [68], and projected the 3D traces of apparent growth faults to the modern marsh surface by extrapolating them into the Holocene at the same dip angle. The projections highlighted areas in the marsh where effects of recent fault movement, such as land-loss or stream deflection might be expected [37,54,59]. These fault traces, as well as some in Lake Borgne seismic acquired by the U.S. Geological Survey [58–61], were projected in the same way onto the Couvillion et al. [10] persistent land loss map (Figure 3).

It is not confirmed whether faults mapped at depth actually extend to Biloxi Marsh surface, or whether slippage has occurred in the Holocene. All fault traces are *en echelon*, down-to-the-basin. Fault segments projected in the northern part of Biloxi Marsh are tens of kilometers long and may be continuous with traces identified in Lake Borgne (Figure 3). Fault traces farther south in Biloxi Marsh are shorter, appear in groups of 2 or 3 and do not have counterparts in 3D seismic data to the west from southern Lake Borgne. While surface displacements across elements of the Baton Rouge—Denham Springs fault trend have been detected in northern Lake Pontchartrain [52], displacements are subtler in Lake Borgne [58,59]. No land loss patterns in Biloxi Marsh are positively tied to Holocene movement along fault alignments, as have been mapped elsewhere in the Delta [61]. While the course of Bayou La Loutre may have been influenced by fault position, movement at the Biloxi Marsh surface appears to be either dormant now, or too slow to leave signs that an experienced observer would recognize [41], and is unlikely to account for much modern land-loss.

Russell et al. [36] described Biloxi Marsh as an "abandoned portion of the Mississippi River delta . . . [where] land is retreating before attack of the sea aided by compaction of Recent unconsolidated sediments, an eastward tilt of the area, and regional subsidence of the Gulf Coast geosyncline" (Italics added). Treadwell [41], Russell's student who spent nearly two years in the field studying Biloxi Marsh geomorphology, also noted the "eastward tilt" of the underlying geology on the Chandeleur Sound side of the Biloxi Marsh peninsula. He described a downwarping that caused the seaward end of exposed natural levees to become submerged under marsh or water as they approached Chandeleur Sound.

Rather than a "tilt", Kulp et al. [53] have shown that the Holocene sedimentary wedge under Biloxi Marsh thickens to the southeast, filling accommodation space created by the dip of the Pleistocene surface. This thickening of the unconsolidated sediment column has led to more compaction and subsidence on the eastern side of the peninsula [51,57]. Marsh is largely missing there, with portions of natural levees surviving as islands that are substrates for oyster reef and oyster shell beach development on the margin of Chandeleur Sound (Figure 3).

Fitzgerald et al. [32] produced a cross-section (A—A') based on USACE borings [42] made along the MRGO right-of-way prior to construction (Figure 4). It shows the southeastward thickening Holocene deltaic wedge, with the Holocene-Pleistocene (H-P) discontinuity at 25 m near Bayou Yscloskey and 35 m at Breton Sound. It also depicts another major feature incised into the weathered Pleistocene Prairie ravinement surface. This is an 8-km wide, 50-m deep U-Shaped valley carved by the ancestral Pearl River during the last sea level low-stand that ended about 18 ka [86–88]. The width of this valley is similar to that of the alluvial meander belt of the Pearl River today where it crosses the modern Mississippi Sound shoreline. The filled Pearl River valley follows a southeasterly path across what is now northern Lake Borgne between the current river mouth and the shelf edge. It is filled with a heterogeneous mix of gravel and sand under a mud cap deposited as sea level approached its current elevation 7 to 5 ka [88].

It appears from the MRGO cross-section that the drape of fine-grained nearshore Gulf bottom sediments and pro-delta clays is locally thicker over the buried channel feature (Figure 4). This may have contributed to the greater subsidence rate that "tilted" the eastern side of Biloxi Marsh peninsula. The presence of this channel fill or the completely buried distributary channel above it may also have influenced the odd loop that Bayou La Loutre takes to the north and east of the A—A′ section, or perhaps the presence of both younger features was influenced by an older fault trend [37,44].

Returning to the Russell et al. [36] observation that Biloxi Marsh is "an abandoned portion of the Mississippi River delta", we can add that Biloxi Marsh is also a "marginal" deltaic feature. The Mississippi River shifted to the eastern side of its alluvial valley about 4.5 ka. With this move, the River abandoned nearly 4.0 ka of inner-shelf delta building west of where the Mississippi River alluvial valley entered the Gulf [39,40,44]. It then created, for the first time in the Holocene since sea level stabilized, an east-facing deltaic discharge in the vicinity of what is now New Orleans (Figure 5).

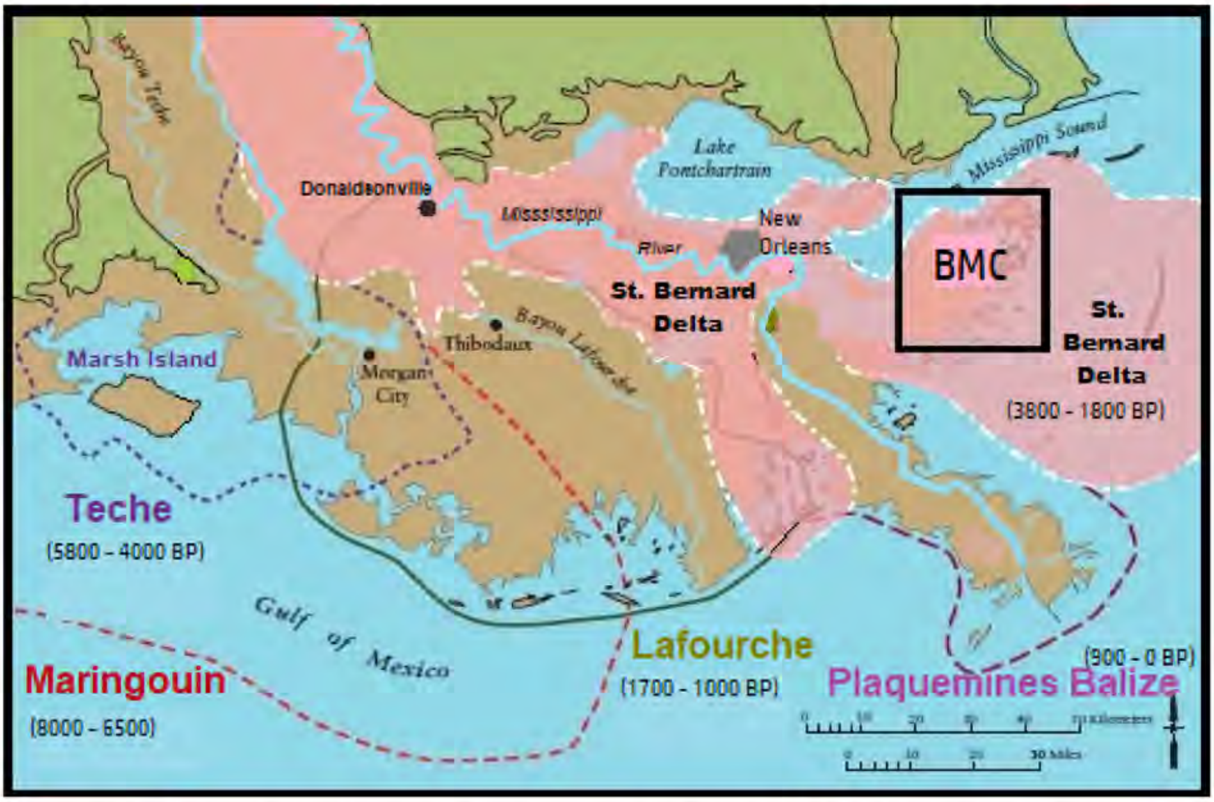

Figure 5. St. Bernard sub-delta at its maximum extent about 1.8 ka with outlines of other Holocene delta lobes and approximate times of advancement (modified from Heinrich et al. [88]).

This avulsion grew to become the St. Bernard sub-delta, which initially debouched into the shallow nearshore Gulf on the seaward side of the shore-parallel barrier island chain that lies under much of New Orleans and its suburbs [43,55]. These islands enclosed the coastal lagoon that is now Lake Pontchartrain and followed the western side of Lake Borgne, restricting deltaic sedimentation north of the main river channel to the seaward side of this island arc [43,51,55]. A large beach ridge complex at the south end of what is now Lake Borgne further constrained St. Bernard delta development as the mouth advanced eastward, parallel to the mainland coast [86]. The main Mississippi River outlet then turned north into even shallower water to build Biloxi Marsh. The marsh on the west side of the peninsula, north of the MRGO right-of-way (Figure 4), tops a Holocene stratum less than 25 m thick [49,53]. The crowns of Bayou La Loutre natural levees are all that is visible at the surface today to mark the banks of that once large mainstem Mississippi channel.

Biloxi Marsh has no roads, bridges or buildings, and therefore few deep borings outside the MRGO, but its prehistoric cultural heritage is among the best studied anywhere on the Gulf coast [45–47]. Holocene chronologies, since calibrated with radiocarbon and luminescence dates [54,55,65], were first established on the basis of pottery finds in archaeological sites [45,47]. Hunter-gatherers made extensive use of two coastal molluscan food species that are still found in the area today. The small, relatively low-salinity clam, *Rangia cuneata*, populates muddy inner-estuary bay bottoms, and the oyster, *Crassostrea virginica*, forms reefs in the saltier, seaward parts. Prior to the MRGO, Lake Borgne was *Rangia* territory while Chandeleur Sound was, and still is for oysters. The edible meat of these bivalves had to be extracted from thick shells, which were then heaped over generations into voluminous, readily preserved waste piles or middens. When built on the natural levees of distributaries, such mounds might grow high enough with use to support oak trees and habitations safe from storm tides [43,45–47].

Today, scrubby vegetation and dead trees mark the tops of a few middens built on Bayou La Loutre distributaries. These are the only visible signs of the buried channels, as the natural levees are now covered by marsh. A number of Biloxi Marsh "Indian Mounds" are identified on the 1893 U.S. Coast and Geodetic Survey 15-min Shell Beach Quadrangle (1890 survey), but few are noted on the next edition of the series (1939). The crown of the largest mound in Biloxi Marsh in 1890, one on the south Lake Borgne shore at the entrance to Bayou St. Malo (Figure 1), was noted as 25 feet (7.6 m) above MSL. In 1939, the top of the same mound was measured at only 15.3 feet (4.6 m), showing a 3 m loss in the 50 years between surveys. This mound no longer exists, as the shoreline has retreated through it.

Sherds of pottery invariably accompanied human use and habitation and were also incorporated into the middens. These have been used to classify the time of their manufacture by comparing vessel configuration, clay type and markings across sites [46,47,55]. The sequence of formation of the St. Bernard delta lobe on the eastern margin of the Mississippi River delta was initially worked out in this way, extending from about 4.0 ka to western contact (Figure 6).

People using the emerging St. Bernard delta lobe first left evidence of their presence at sites on the western and southern shores of Lake Borgne during the Archaic (Poverty Point) and Tchula periods (Figure 6). The Biloxi Marsh peninsula quickly emerged in the Tchula period when the Bayou La Loutre channel became the Mississippi River mainstem, and turned north into shallow water protected from Gulf waves [43–45]. The river bifurcated multiple times into distributaries that radiated north over a 180° arc from the vicinity of the current Bayou La Loutre loop, creating a shallow-water version of the "Head-of-Passes" central "core" feature of the modern Balize delta (Figure 5). This "core" has persisted to become Biloxi Marsh (Figure 6).

The St. Bernard sub-delta built rapidly during the 400 years of the Marksville period. The Bayou La Loutre course of the Mississippi River mainstem and its distributaries extended across the inner shelf 20 to 30 km east of the current position of the Chandeleur Islands [48–51,57]. The sub-delta achieved its greatest subaerial extent about 1.8 ka, when the oldest, north trending distributaries in Biloxi Marsh began to lose flow to a southerly sub-delta channel in the Bayou Terre aux Boeufs course (Figure 6). Marksville people established sites on the oldest and highest natural levees of distributaries on the west side of Biloxi Marsh, and along the eastern shore of Lake Borgne.

Human population and use of the St. Bernard delta increased greatly as the St. Bernard sub-delta was gradually abandoned and the Mississippi River depo-center shifted west to the central deltaic plain (Figure 5). At its greatest extent, the St. Bernard/Terre au Boeuf sub-delta covered almost 5000 km^2 of what is now Chandeleur Sound and the nearshore Gulf, in addition to 2000 km^2 in the Biloxi Marsh peninsula [43,44].

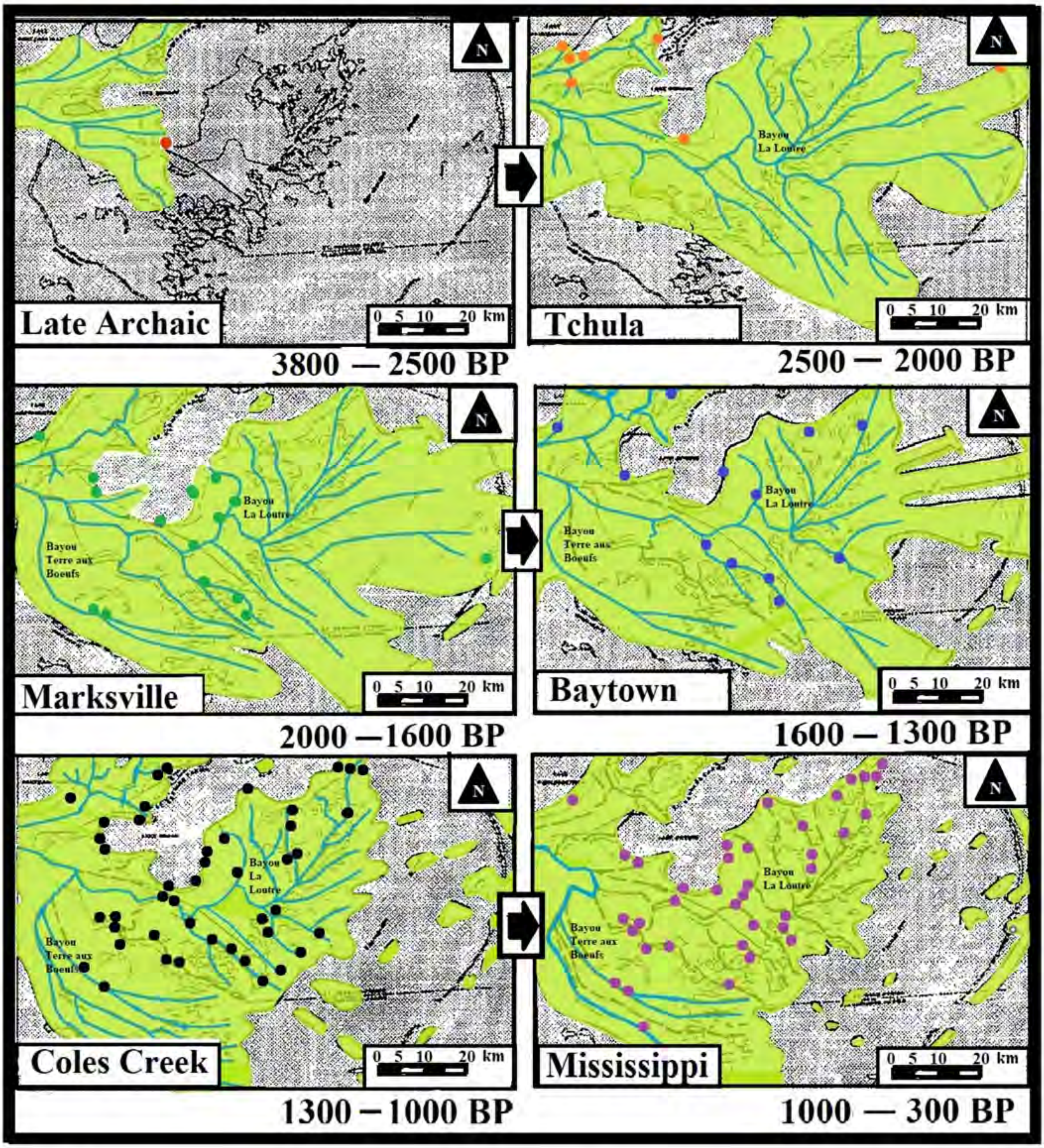

Figure 6. Sequence of St. Bernard sub-delta lobe development beginning 3.8 ka, and deterioration following abandonment about 1.8 ka, showing midden sites of usage by indigenous peoples during successive cultural phases prior to western contact. Adapted from Braud et al. [47].

Bayou La Loutre and Bayou Terre aux Boeufs bar and channel sands were reworked into delta front barrier beaches [50]. Subsequently, the Chandeleur and Breton Island arcs detached from the more rapidly retreating mainland marshes, and rolled back to the rhythm of storm strikes toward the St. Bernard sub-delta core, breaching and reforming as they do today, and leaving behind a thin sheet of sand on the shelf [55,57].

Eastern marshes in what are now Chandeleur and Breton Sounds formed in about 400 years, and disappeared just as quickly when they were no longer nourished by river sediments or protected from waves (Figure 6). The Biloxi Marsh peninsula, in contrast, has survived for more than 2.5 ka to become one of the oldest marshes in the Mississippi Delta, exceeded only by Marsh Island, a feature of comparable size 250 km to the west. Marsh Island shares with Biloxi Marsh a marginal deltaic position, a shallow Pleistocene sub-stratum, as well as a nexus with protective oyster reefs on the seaward side, expansive shallow bays inland, and a revived source of river sediments (Figure 5).

The most rapid loss of St. Bernard wetlands took place immediately after abandonment by the Mississippi, at rates that must have exceeded 10 km^2-y^{-1} at times [44,86,87], despite a more stable global sea level than that of today [87,89]. Subsidence would have been the major driver at this time as 40 to 60 m of unconsolidated Holocene pro-delta clays expelled water and compacted, but wave erosion must also have been important.

More than 25 occupation sites have been identified in Biloxi Marsh that date to the 2 ka since the Mississippi River abandoned the La Loutre and Terre aux Boeufs courses [57], when the Coles Creek and Mississippian cultures were ascendant (Figure 6). The composition of middens shifted from clams to oysters as isohalines moved inland [45–47], but apparently enough fresh drinking water was still available, though perhaps only seasonally, from senescent distributary channels [45]. Waves have built oyster shell beaches with storm berms 2 to 3 m high that exist today along the western margins of Chandeleur Sound on island and mainland shores [41]. In contrast, virtually none of the once more extensive *Rangia* shell beaches facing Lake Borgne survive, except where coastal midden accumulations have come under wave attack [36,41,43].

Mississippi River deposition into or through the Biloxi Marsh "Head-of-Passes" core was active over a 2000-year period, far longer than for any subsequent Holocene sub-delta. Persistent river deposition into the limited accommodation space available, explains the high mineral content of sediments deposited there, at the expense of finer-grained sediment and organic matter. A profusion of abandoned distributary channels radiating from Bayou La Loutre (Figure 6) provides a skeletal framework of partially overlapping silty prodelta bar and natural levee facies, along with sandier point-bar deposits (Figure 4). These fill much of the 10 to 30 m thick Holocene section [36,45–47]. As sub-aerial portions of the natural levees have sunk, they have loaded underlying pro-delta clays, contributing to the unusually high bearing strength of Biloxi Marsh soils compared to those of other Mississippi River Delta brackish and salt marshes. However, this skeletal channel network also introduces local variability into Biloxi Marsh subsidence rates as Lane et al. [19] found at Stump and Blind Lagoons on a buried flank of the Bayou La Loutre natural levee (Figure S3).

4.2. Historical Biloxi Marsh Land-Loss

Wave erosion on the perimeter of the peninsula along its Lake Borgne and Chandeleur Sound shores has historically caused most land-loss in Biloxi Marsh (Figure 7). Dredging to maintain the 15 m deep MRGO and cyclic disturbance of the unprotected banks by large ship wakes caused it to widen throughout its 50 years of operation until 2005, after which no further deep-draft ship traffic or dredging was permitted. Fitzgerald et al. [34] studied land-loss in Biloxi Marsh study area, using both high-resolution imagery and data published by Britsch and Dunbar [7] for land-loss in three intervals between (1) 1932 and 1958, (2) 1958 and 1974, and (3) 1974 to 2001. The first period is before MRGO construction, while the next two cover most of the operational life of the seaway. We have updated Biloxi Marsh loss rates for two additional increments, (4) 2001 to 2011 and (5) 2011 to 2015, based on Couvillion et al. [10]. The fourth period covers the last years of ship channel operation and installation of the rock dam in 2009, while the fifth interval documents post-MRGO recovery.

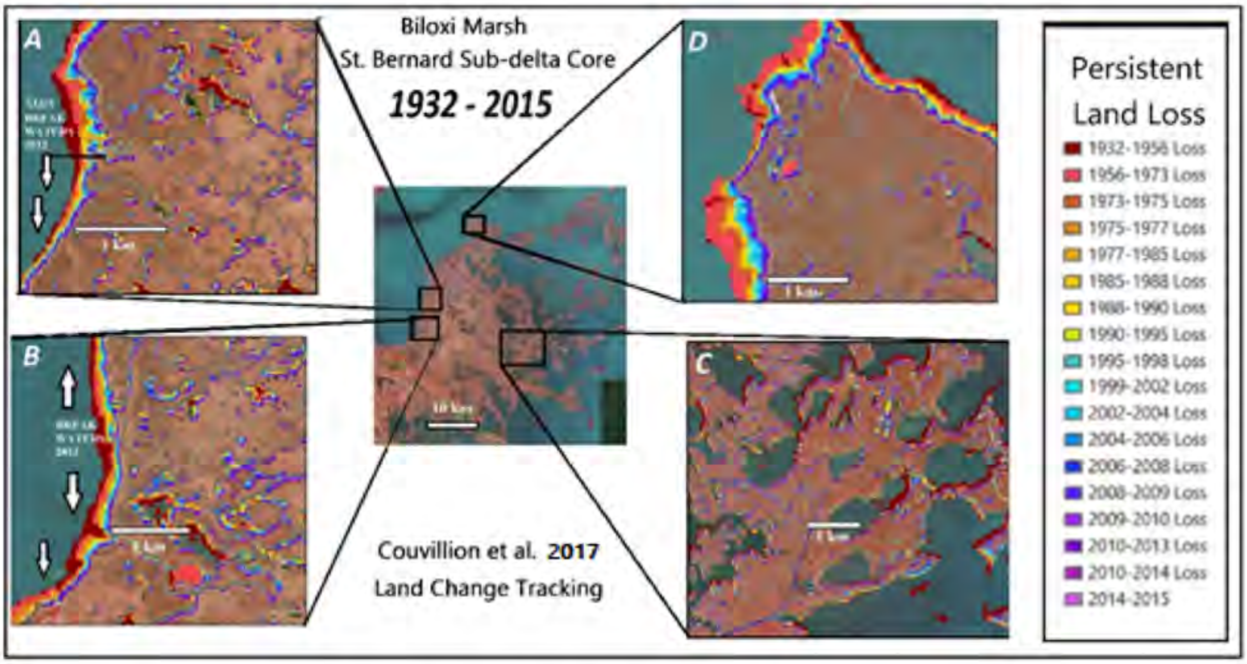

Figure 7. Biloxi Marsh historical land-loss adapted from Couvillion et al. [10]. Land-loss has varied over time and space. Loss that occurred in the 1950s through 1980s is depicted in brown, red and yellow, while more recent loss is shown in blues and violets. Shoreline retreat on the Lake Borgne coast has always been the principal cause of land-loss (**A**,**B**,**D**). New breakwaters in southern Lake Borgne are slowing or reversing shoreline retreat (**A**,**B**). More recently, cumulative interior marsh loss has increased as abandoned tidal channels have enlarged into lakes (**A**,**B**). Most interior land-loss occurred earlier in the southeast (**C**) to form stable rounded lakes. Shoreline retreat is most rapid at the northern tip of Biloxi Marsh but interior marsh loss is lower than elsewhere on the peninsula (**D**).

Building and operating the MRGO directly caused 18 km^2 of land-loss in and adjacent to the dredged cut where it crosses the study area [32]. Excluding this footprint, average annual land-loss estimates for the Biloxi Marsh study area increased from 1.3 km^2-y^{-1} (1932–1958) to 1.7 km^2-y^{-1} (1958–1974) to 2.6 km^2-y^{-1} (1974–2001). The 2.6 km^2-y^{-1} rate also applied for the fourth period which included Hurricanes Katrina, Rita, Gustav and Ike (2001–2010), before dropping back to 1.0 km^2-y^{-1} over the last 5 years (2011–2015), since MRGO closure. The post-MRGO value is similar to that from the 1932 to 1958 interval, before MRGO construction. Recent diminished land-loss also reflects lower shoreline retreat where CPRA has built detached rock breakwaters along 13 km of the southeastern shore of Lake Borgne [35] (Figure 7A,B).

The fourth land-loss interval (2001 to 2010) includes the impacts of Hurricane Katrina (2005) which tracked directly over Biloxi Marsh (Figure S1). Barras [90] showed that this powerful storm caused an anomalously high one-year land-loss of 100 km^2 in the Breton Sound marshes just south of Biloxi Marsh (Figure 3). Biloxi Marsh endured a 5.5 m storm surge, but emerged comparatively unscathed (Figure S1). The most recent Biloxi Marsh loss rates are not particularly high by historical (1–3 km^2-y^{-1}), or certainly by mid-Holocene standards (10 km^2-y^{-1}), even with the recent increase in global sea level rise [89].

Wave erosion has always caused shoreline retreat along the Lake Borgne and Chandeleur Sound coasts [35,90,91]. Shell-rich berms and beaches still provide some erosion resistance on the Chandeleur Sound side, but *Rangia* beaches are gone from Lake Borgne, along with the less reflective, sloping foreshore that developed on the seaward side. Today, small, discontinuous clam shell storm berms sit on top of the marsh, rather than forming actual beaches in front of the marsh. At the northern end of Biloxi Marsh peninsula, shoreline retreat is active but interior marsh fragmentation is less than on the rest of the peninsula, suggesting that mineral sediment supply to the marsh surface is higher than elsewhere (Figure 7D).

4.3. Salinity and Suspended Sediment

Rounsefell [70] measured salinity at a number of stations across Biloxi Marsh in 1959 and 1960, prior to dredging of the MRGO. Since MRGO has been dammed, salinity has also been monitored at these stations by a number of researchers [18,71–73]. Results show that salinity levels in Lake Borgne and Biloxi Marsh have returned to pre-MRGO levels since closure (Figure S5). Mean annual salinity at the south end of Lake Borgne was 12.5 ppt prior to closure, and has dropped since by 60%, to average 5 ppt. [71]. Biloxi Marsh salinities in 2018 ranged from 1.4 to 23.0 ppt in synoptic surveys made at all Marsh and Rounsefell stations [18]. Mean salinity for the whole study area in 2018 was 10.5 ± 4.4 ppt (Table S1). Salinity was lower during spring when Mississippi River discharge was higher, especially after the Bonnet Carré Spillway was opened (Figure 8), as it was again, twice, in 2019 (Figure 9).

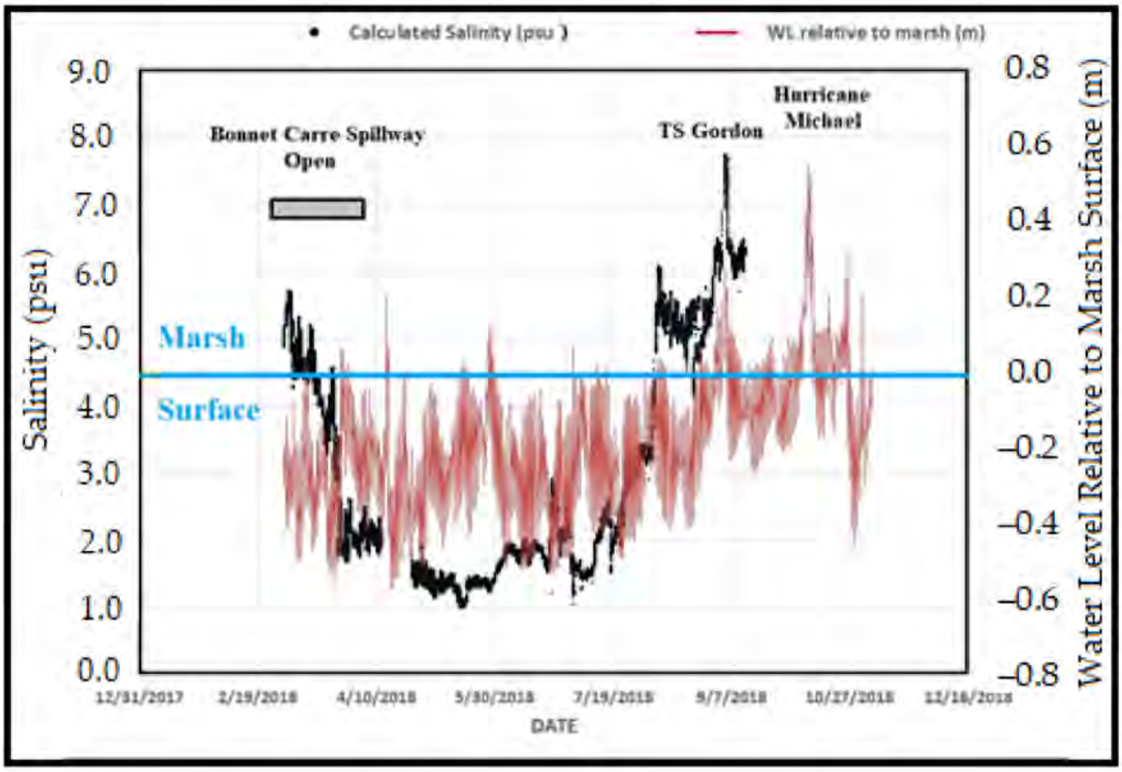

Figure 8. Continuous salinity (black) and water level (red) relative to marsh elevation at Site A1b (Figure 2) on the shore of Lake Borgne from 2 March to 4 November 2018. The one-month Bonnet Carré Spillway opening (gray bar) in March lowered salinity in southern Lake Borgne almost 6 psu to between 1 and 2 psu through early July. Salinity rose with water level in the fall despite a modest increase in Mississippi River discharge. Tropical cyclones coming ashore in Mississippi (T.S. Gordon 9/4) and on the Florida panhandle (H. Michael 10/13) briefly pushed 0.3 and 0.5 m, respectively, of saltier water into Lake Borgne.

Salinity at Marsh Station A1b (Figure 2) near the entrance of Bayou St. Malo on Lake Borgne dropped from 6 to 2 ppt after the Spillway opened in early March 2018, attained a maximum discharge of 5500 m^3-s^{-1}, and closed by the end of the month. Salinity then decreased slowly to 1 ppt through the beginning of July (Figure 8). As Gulf coast sea level followed its seasonal rise through the summer and fall, salinity also increased in Lake Borgne, reaching 7 ppt briefly during the 0.3 m surge generated by Tropical Storm Gordon on 4 September 2018. TS Gordon went ashore about 100 km away, just east of Pascagoula on the Mississippi coast. Lake Borgne salinity continued to rise through September, reaching 10 ppt as Mississippi River discharge remained low, but the salinity sensor failed in late September. Hurricane Michael hit the Florida coast 400 km away on October 10 as a

Saffir-Simpson Cat 5 storm, and caused a 0.5 m surge in Lake Borgne, and presumably a second salinity spike (Figure 8). Synoptic data indicate that salinity decreased after October (Table S1).

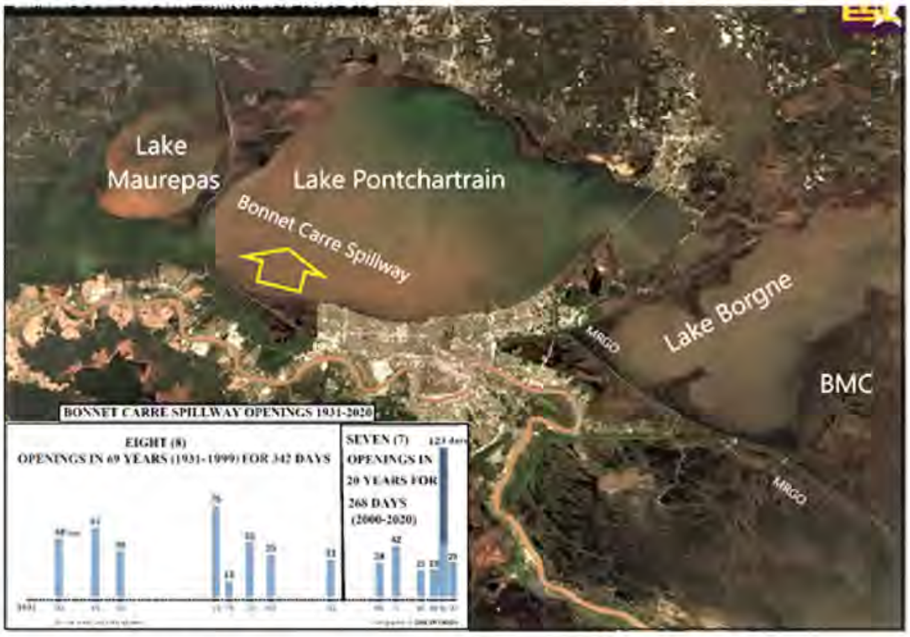

Figure 9. Landsat-8 30 m true-color image showing suspended sediment plume from the Bonnet Carré Spillway in Lakes Pontchartrain and Borgne on 6 March 2019, after the second opening of that year. INSET: Increased usage of Spillway; 8 times in first 70 years; 7 times since 2000 (20 years). Satellite image adapted from LSU Earth Scan Laboratory [92]. Bonnet Carré Spillway openings graphic modified from The Advocate [93].

Closure of the MRGO removed a significant source of salt water to Lake Borgne, so salinity there is once more controlled by freshwater discharges of the Pearl River and smaller streams emptying into Lakes Maurepas and Pontchartrain. On the other hand, the Mississippi River is gaining as a direct contributor of freshwater and sediment to the Pontchartrain-Borgne estuary. Although the Mississippi River stage and discharge triggers for opening the Bonnet Carré Spillway have changed little since 1931 (Figure 9), the USACE has had to open it three times as often in the last 20 years (average 13 d-y^{-1}) as was required in the previous 70 (average 5 d-y^{-1}).

Two of the post-MRGO closure synoptic salinity datasets include a year or years when the spillway was opened. Data from 2011 when the structure was open for 42 days show that Lake Borgne salinity dropped to 0 ppt during that record high Mississippi discharge. Mean salinity for Lake Borgne ranged from 4 to 6 ppt in the pre-MRGO Rounsefell study [70], and has returned to this range [Figure S5]. The salinity gradient from southern Lake Borgne across Biloxi Marsh to Chandeleur Sound averages 0.5 ppt-km^{-1} with the dam in place [18].

Poirrier [33] has found that the benthos of Lake Borgne is currently undergoing a return to the original *Rangia*-dominated community, as it replaces the higher salinity species that became established during the five decades that the MRGO was open. A resurgence of *Rangia* in what is once more an oligohaline Lake Borgne had previously been predicted as a restoration consequence of MRGO closure [94]. This shift is potentially important to slowing Lake Borgne coastal retreat, as *Rangia* shell historically provided most of the coarse beach material that once paved the Biloxi Marsh shoreline.

The Bonnet Carré Spillway is increasingly important as a source of suspended sediments, in addition to freshwater, that reach Lake Borgne and Biloxi Marsh (Figure 9). More frequent openings introduce vast quantities of fine-grained sediments that reach the outer estuary. The Biloxi Marsh is in an excellent position to capture silt and flocculating clay particles introduced by the River and remobilized by waves in the shallow lakes and bays that surround the peninsula. Some climate change forecasts for the Mississippi River valley suggest that the higher frequency of extreme floods experienced in the past two decades will likely continue or go up [95]. If so, this will increase suspended sediment supply to Lake Borgne, reconnecting Biloxi Marsh to a more regular source of river sediment that has been largely missing since 1927, when the USACE began building sturdier levees along the lower river [96].

Biloxi Marsh sites are similar to those studied by Day et al. [78] for marshes in the western Terrebonne and eastern Atchafalaya basins that, like Biloxi Marsh, capture re-suspended river sediment on the marsh surface during winter cold fronts and tropical storms in the warmer months [97,98]. They found that these salt marshes received regular inputs of Atchafalaya River sediments. The marsh surface was situated high enough in the tidal frame to flood only 15% of the time. These marshes have remained stable for over a half century of observation [78]. In contrast, similar marshes monitored outside of the zone of river sediment influence, lost 10 cm of elevation relative to sea level so that they flooded 85% of the time. These sites experienced marsh collapse and conversion to open water within less than a decade [78,99].

A consequence of the relative antiquity of Biloxi Marsh wetlands compared to other Delta marshes is that tidal channels last longer but change function. Biloxi Marsh is littered with abandoned tidal channel segments—many still with a meandering form—that appear dark in aerial views. These former channels are now disconnected from turbid bays or active tidal channels transporting suspended sediment from surrounding lakes and bays (Figure 10). Unlike active tidal channels, abandoned stream segments in Biloxi Marsh do not naturally maintain elevated banks or revegetate, but instead enlarge into shallow, dendritic lakes with irregular edges. Such abandoned channels tend to disappear relatively quickly in other parts of the sinking Delta, but persist as lakes in Biloxi Marsh [41].

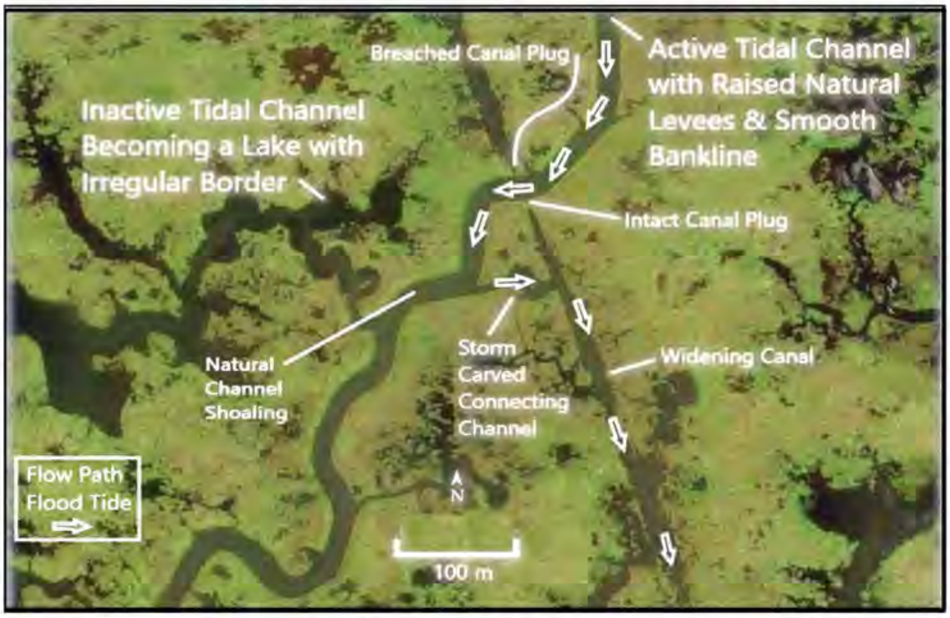

Figure 10. Close-up of western Biloxi Marsh 2 km east of Lake Borgne where a turbid natural tidal channel crosses a canal dredged 15 years earlier. Arrows indicate the flow path on a flood tide. The straight canal captured the discharge of the natural channel when hurricane surge runoff scoured a connecting channel around a canal plug. Abandoned channels/lakes that are cut off from sediment supply appear dark compared to the turbid active tidal channel.

Treadwell [41] described three types of tidal channels in Biloxi Marsh. First are those that formed in mudflats between active deltaic distributaries. A second type invaded partially infilled channels of abandoned distributaries. These came into existence at the time of initial colonization by marsh vegetation, or as part of distributary channel senescence. The third type still forms today when hurricane winds shift direction causing meters of surge water to run off the marsh at high velocity [Figure S1]. Then, abandoned tidal channels may be reopened, and new connections created to other bayous or bays and sounds surrounding Biloxi Marsh. Treadwell [41] noted that this "last process is more important in causing alterations in existing channels than in opening new ones." It is also the process that a modern observer is most likely to witness.

In fact, we observed this third process where a small pipeline canal (12-m wide) had been dredged 2 km straight through the marsh between two loops of the same meandering tidal bayou. The bayou crossed the canal about midway between the loops, roughly forming a "Figure 8" (Figure 10). Two hurricanes struck in the year after the canal was dredged in the mid-1990s, before the ditch could be refilled. A decade later, the canal had widened by an average of 5 m downstream of the natural channel crossing. There, a canal plug on the south bank of the Bayou remained intact, but had been bypassed by a newly scoured 100-m long, 3-m deep channel segment that now connects the natural channel with the pipeline canal. At the same time, the adjacent, much longer loop of the natural channel has largely filled with sediment downstream of the bypass, as it has lost most tidal flow to the more hydraulically efficient canal.

Tidal streams maintain tidal marshes, bringing in sediment, nutrients and oxygen, and carrying out toxins and other products of decomposition [100–102]. As the channels form, enlarge and meander, they rework marsh sediments down to a depth of 3 m, introducing new mineral sediments including silt, clay and shell fragments, and removing or oxidizing organic matter. The high degree of tidal channel dissection of Biloxi Marsh is another indication of both the age and durability of that surface relative to other Delta marshes, and of a storm tide reworking process that may be important in other deltas worldwide. However, it is also a process that causes interior marsh land-loss.

4.4. Shoreline Processes

Shoreline erosion and retreat is the most significant mode of land-loss in Biloxi Marsh, particularly on the Lake Borgne coast, which has lost any resistance once afforded by *Rangia* shell beaches. CPRA estimated an average rate of retreat for the southern Lake Borgne shoreline at 2.7 m-y^{-1} prior to installation of the detached breakwaters [35]. The only shoreline in Biloxi Marsh with a higher rate of erosion was along the north bank of the MRGO (7.3 m-y^{-1}) before Hurricane Katrina [32,91]. All of the nine marsh sites established in 2018 (Figure 2) are shoreline stations, with six (A1a, b, c; A2, A3, C2) facing large lakes or bays, and the remaining three (B1, B2, C1) on the edges of small ponds or lagoons (Table S2). Marsh site C2 is on the north bank in a wide part of the abandoned MRGO channel. All but one of these marsh shorelines retreated over the 10 months they were monitored in 2018 [18]. Annual retreat for unprotected Lake Borgne marshes ranged from 1 to 2 m per year, with continued expansion of the abandoned MRGO on the low end of this range. Rate of retreat of pond margins was 10% of that bayside, from 0.1 to 0.3 m-y^{-1} (Table S2). The marsh shore at Station A1b, sheltered behind the Lake Borgne breakwaters, however, advanced into the Lake at an average annual rate estimated at 1.2 m-y^{-1} (Figure S2).

At each 2018 marsh site, VA was measured at 3 points along a 50-m transect oriented normal to the shoreline. Tracking sediment deposition inland across the marsh is a good measure of both sediment supply and the effectiveness of the overwash process that delivers it to interior marshes [18,103,104]. At the 5 m station closest to the shoreline, the Bay and Pond marshes both got about the same amount of suspended sediment input, resulting in mean VAs of 22 and 24 mm, respectively (Table S2). It is apparent, however, that the suspended sediment being captured on high tides by marshes at the edge of large lakes and bays is more mineral than what is reaching marshes bordering interior ponds. Mean BD for the bayside marshes averaged 0.33 g-cm^{-3}, more than three times the BD mean (0.10 g-cm^{-3}) for the pond-side marshes. VA in the A1b marsh (behind breakwaters) was the same as in other bay-side marshes at all three distances from the shore. Clearly, the presence of the rock breakwaters did not reduce suspended sediment supply to the protected marsh. Conversely, VA diminished markedly with distance inland for the pond-side marshes (Table S2).

4.5. Biloxi Marsh Subsidence and Sediment Supply on a Regional Scale

The ten to twelve years of data acquired at almost 200 Delta marsh sites under the Coastwide Reference Monitoring System (CRMS) protocol allow for robust comparisons of Biloxi Marsh hydrology, sediment supply and subsidence with data from marshes elsewhere in this Delta and worldwide [18–20,78]. Having a mature (>10-year time-series) and spatially distributed network of marsh stations where data are collected in a standardized format at regular intervals is critical input for the ecological models that CPRA applies when considering sites for restoration projects and forecasting land-loss [13–17]. This potential is demonstrated by data from CRMS stations along the 80 km transect running northeast to southwest across Biloxi Marsh and Breton Sound marshes to the Mississippi River (Figure 3). Results are referenced by latitude for nine CRMS stations in Biloxi Marsh and six in the Breton Sound marshes (Table S3). The Biloxi Marsh zone is extended far enough south from the peninsula to include points along Bayou Terre aux Boeufs, as this marsh is genetically part of the St. Bernard sub-delta (Figure 6). The Breton marshes south of Bayou Terre aux Boeufs are much younger, dating from the Plaquemines/Balize sub-delta phase, which did not begin until 0.9 ka, 1 ka after the St. Bernard sub-delta was abandoned by the Mississippi River (Figure 5).

Decadal mean salinity increased linearly with latitude along the CRMS Transect, from close to zero near Bohemia, where the USACE Mississippi River east bank levee ends, to 15 ppt in Mississippi Sound at the north end of the Biloxi Marsh peninsula (Figure 3). CRMS sites in Biloxi Marsh averaged 9 ± 4 ppt during the growing season, compared to 2 ± 2 ppt in the Breton Sound marshes (Table S3). Marsh elevation relative to NAVD88 or MSL datums, which are equivalent in this area, did not differ significantly along the CRMS Transect, averaging 214 ± 56 mm and 239 ± 55 mm, for Biloxi Marsh and Breton marshes, respectively.

Two important marsh soil properties, soil bulk density (BD) and percent organic matter (%OM), both from the upper 12 cm, exhibited divergent spatial trends with latitude (Figure 11). BD averaged 0.3 g-cm^{-3} in the Breton marsh and almost double that, (0.5 g-cm^{-3}), in Biloxi Marsh, following a quadratic curve (r^2 = 0.47) north from 0.25 to 0.80 g-cm^{-3}. Percent organic matter (%OM) averaged 32% in Breton marsh soils and 16% in Biloxi Marsh (Table S3) and decreased linearly (r^2 = 0.61) with latitude (Figure 11). In summary, Biloxi Marsh soils had less voids, more mineral sediment (silt and clay), and half the organic matter found in Breton soils. These trends in surface soil properties between the younger Breton and older Biloxi Marsh are consistent with the difference in bearing strength noted by all who have walked both marshes. Biloxi Marsh is far firmer and supportive while the Breton marshes are less tractable.

All other measurements made at CRMS sites are in units of marsh surface elevation change ($\pm$mm-y^{-1}) [18,19,68,69,100]. VA is the rate at which sediment, both inorganic and organic, accumulates on the marsh surface above a marker horizon (Figure S4). Shallow Subsidence (SS) is not directly measured, but is calculated as:

$$SS = VA - SEC \quad (1)$$

where SEC is the soil Surface Elevation Change, determined using the SET, so that

$$SEC = VA - SS \quad (2)$$

Deep Subsidence (DS) is derived from regression of vertical velocity time-series from continuously operating GPS stations (CORS) with more than a decade of data [56,66,67]. These receivers are scattered throughout the Delta on stable structures (Figure S4). Karegar et al. [66]

worked with data from the CORS network first established by Dokka [56], and found a significant negative linear correlation between down-dip subsidence (DS) and latitude, as well as the thickness of the Holocene section. This relationship has been adopted by Jankowski et al. [67] and by Day et al. [18] to estimate DS. Where the rSET reached or penetrated the top of the Pleistocene formation (<20 m deep), these authors applied a DS of 1 mm-y^{-1} to account for Glacial Isostatic Rebound (GIA) [56,66,67]. The only additional direct measurements required from the CRMS marsh stations to assess sustainability are SEC from SET, and VA from the MH technique (Figure S4).

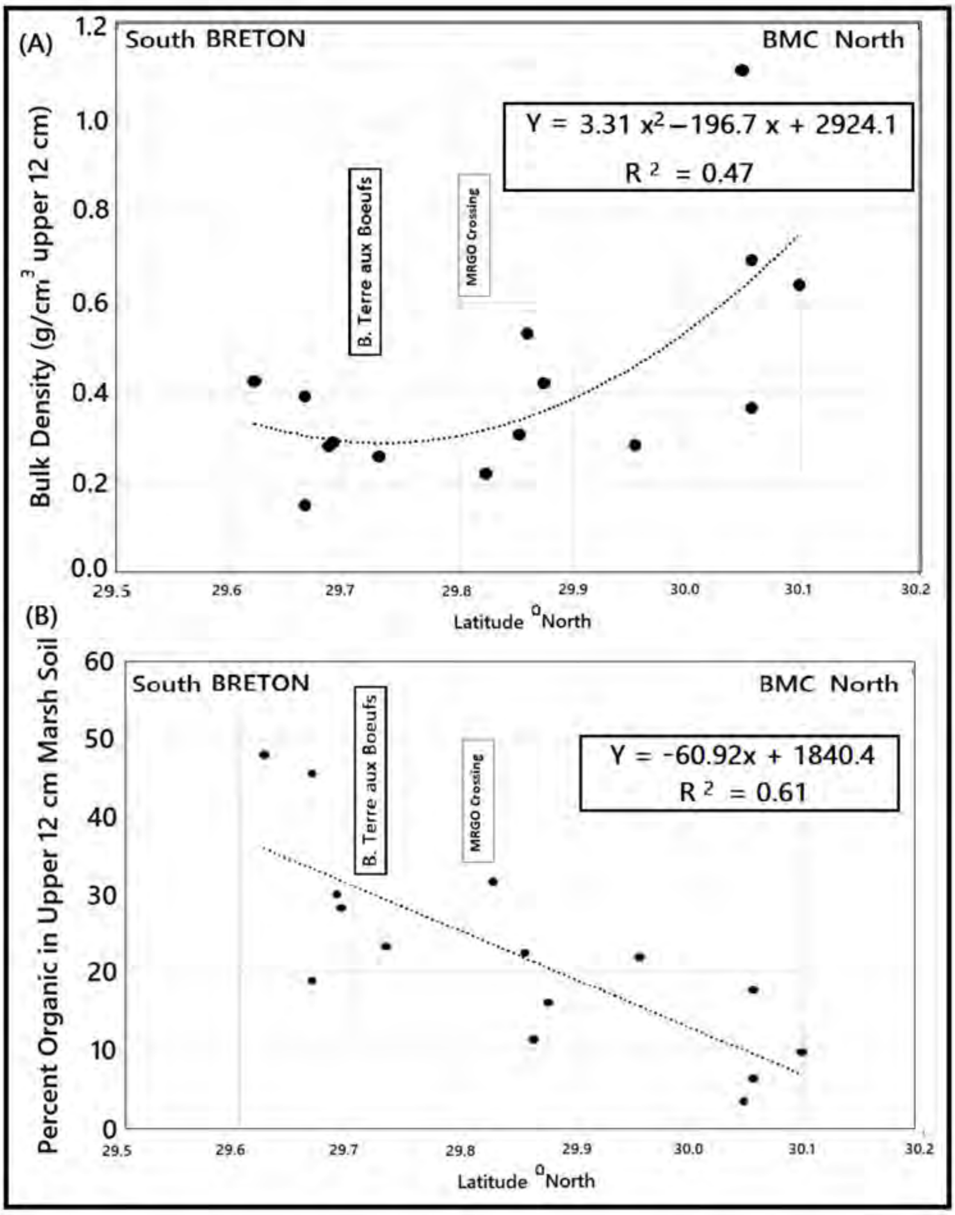

Figure 11. Latitudinal distribution of (**A**) Bulk Density, and (**B**) % Organic Matter on CRMS Transect (Figure 3, Table S3).

VA did not differ significantly between the two zones, with Biloxi and Breton marshes averaging 12.6 and 11.0 mm-y^{-1}, respectively (Table S3). SEC and SS are inversely related components of VA (Figure 12). SEC measured at Biloxi Marsh CRMS stations averaged 6.4 $\pm$ 2.5 mm-y^{-1} compared to 2.4 $\pm$ 3.4 mm-y^{-1} at the Breton sites, indicating that, despite the scatter, aggradation, the upward vertical displacement of the marsh surface, was almost three times greater in Biloxi Marsh (Table S3). Given that VA is essentially the same along the CRMS Transect, it seems that loading at the marsh surface has caused the underlying soil to compact 30% faster in the Breton than in Biloxi Marsh marshes (Figure 12). This is consistent with observed trends in %OM and BD (Figure 11) indicating that consolidation occurs at the marsh surface during deposition in Biloxi Marsh, rather than over more time, and in a thicker slice of the organic-rich Breton marsh soil [78].

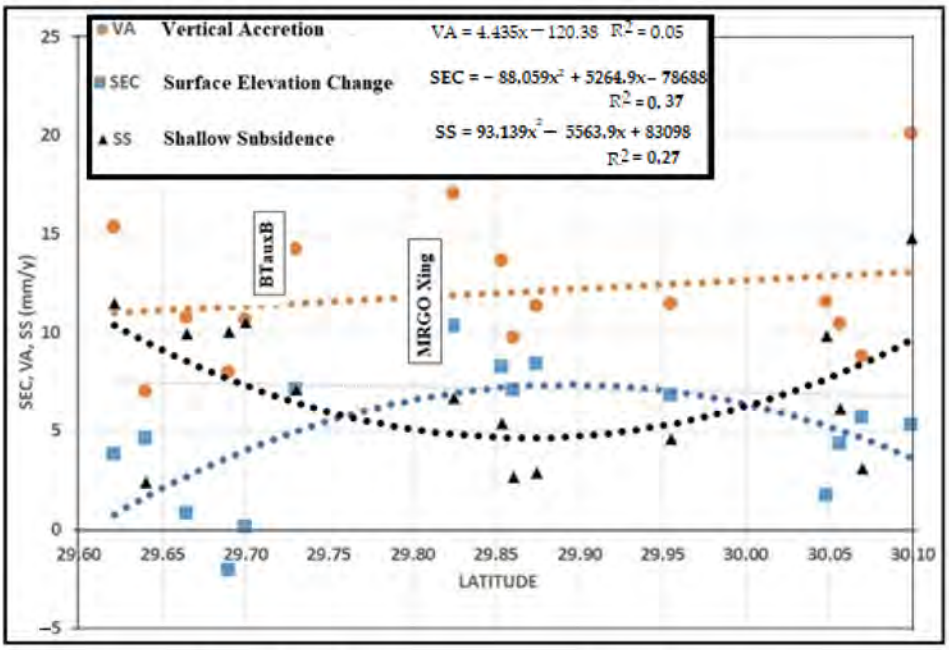

Figure 12. Spatial distribution with Latitude of decadal mean rates (2008–2018) of Vertical Accretion (VA), Surface Elevation Change (SEC) and Shallow Subsidence (SS) on the CRMS Transect (Figure 3, Table S3).

RSLR is ultimately the trajectory that the marsh surface must emulate to survive (Figure 13). It ranges from 5 to 20 mm-y^{-1} on the CRMS Transect (Table S3), averaging 9.8 $\pm$ 3.9 mm-y^{-1} in Biloxi Marsh and 14.6 $\pm$ 3.4 mm-y^{-1} in Breton. If global sea level rise has averaged 2 mm-y^{-1} over the last 2 decades at Pensacola [68], it is apparent that it has not been the largest contributor to RSLR over this period, accounting for only 20% and 14% in the Biloxi and Breton marshes, respectively. The final comparison is for VA—RSLR, which is a proxy for long-term sustainability (Figure 14). All but one of the marshes in the St. Bernard sub-delta footprint are positive in this measure, ranging up to 6 mm-y^{-1} greater than RSLR and exhibiting an 'Accretion Surplus', while all of the much younger Breton marshes plot negative, down to -8 mm-y^{-1} in an 'Accretion Deficit'.

In 2003 and 2004, as was discussed earlier, 15 SET stations were established in the vicinity of Stump and Blind Lagoons [19], in separate levee flank depressions north of the Bayou La Loutre channel (Figure S2). Although five sites were reoccupied in 2018 at Stump Lagoon, only two marker layer horizons could be located there to permit VA measurements [19]. As expected, SEC at Stump Lagoon was negative where any marsh remained, while it was positive at Blind Lagoon where the marsh was still intact (Table S4). Despite the proximity of these two geologically similar features, the Blind Lagoon marsh is much more sustainable than the marsh at Stump Lagoon. Sustainability clearly has local components that can vary widely over short distances.

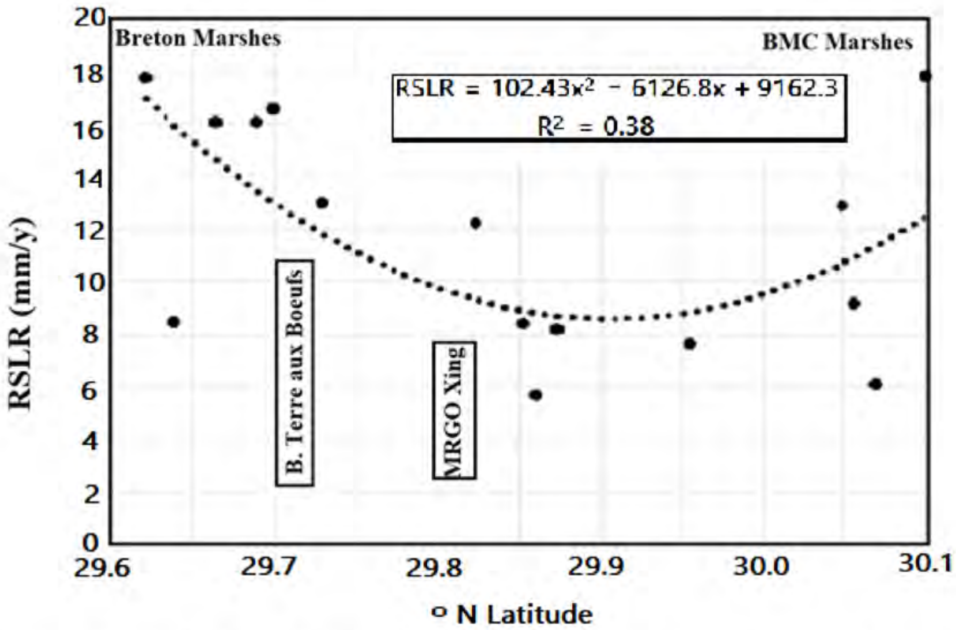

Figure 13. Spatial distribution with latitude of decadal mean rates (2008–2018) of Relative Sea Level Rise (RSLR) at CRMS sites along CRMS Transect (Figure 3, Table S3).

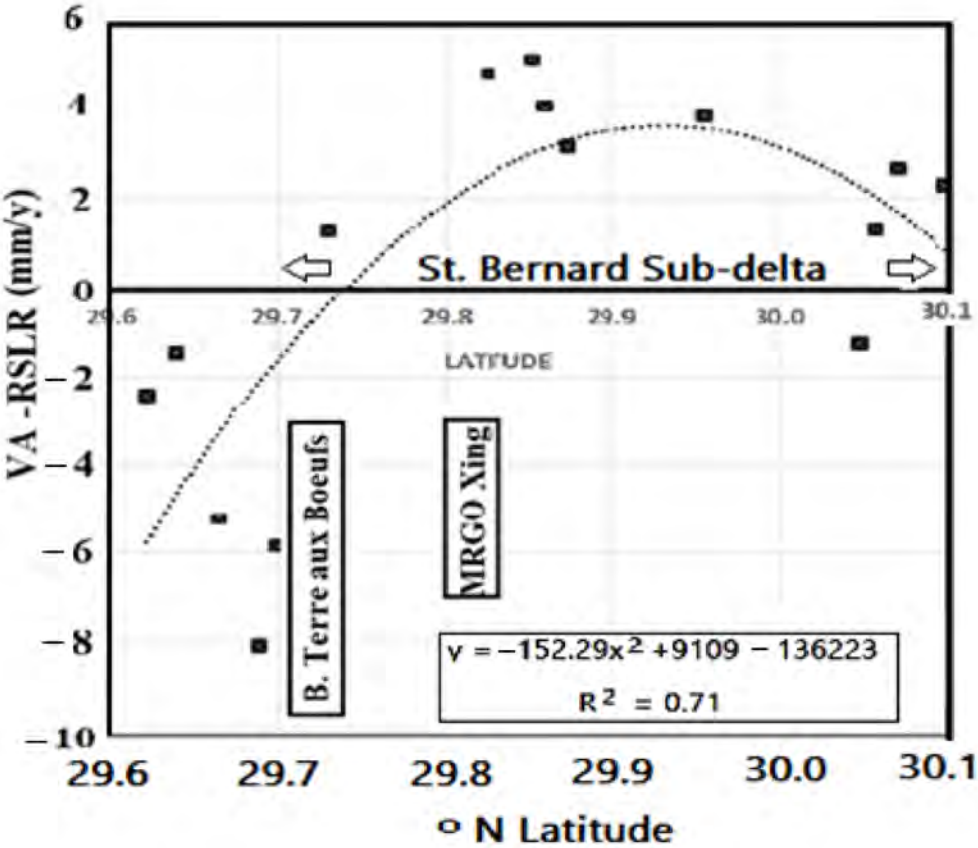

Figure 14. Relative Marsh Sustainability (VA—RSLR) averaged over the 2008–2018 decade with Latitude on CRMS Transect (Figure 3, Table S3). Points north of 29.7° are within the St. Bernard/Terre aux Boeufs sub-delta footprint while those south are from the younger Plaquemines/Balize sub-delta.

Jankowski et al. [69] introduced use of a marsh vulnerability chart with VA plotted against RSLR (Figure 15). Delta marshes fall into one of two fields divided by the 1:1 line, with a 2 mm buffer zone. All Biloxi Marsh CRMS sites plot in the 'Accretion Surplus' area of the "Jankowski Diagram" while most Breton CRMS sites fall into the 'Accretion Deficit' zone. The two remaining Stump Lagoon sites (SL9 and SL11) are also in the deficit region, while interior marsh sites at Blind Lagoon plot on or just below the 1:1 'vulnerability line,' but in the buffer zone where VA essentially equals RSLR.

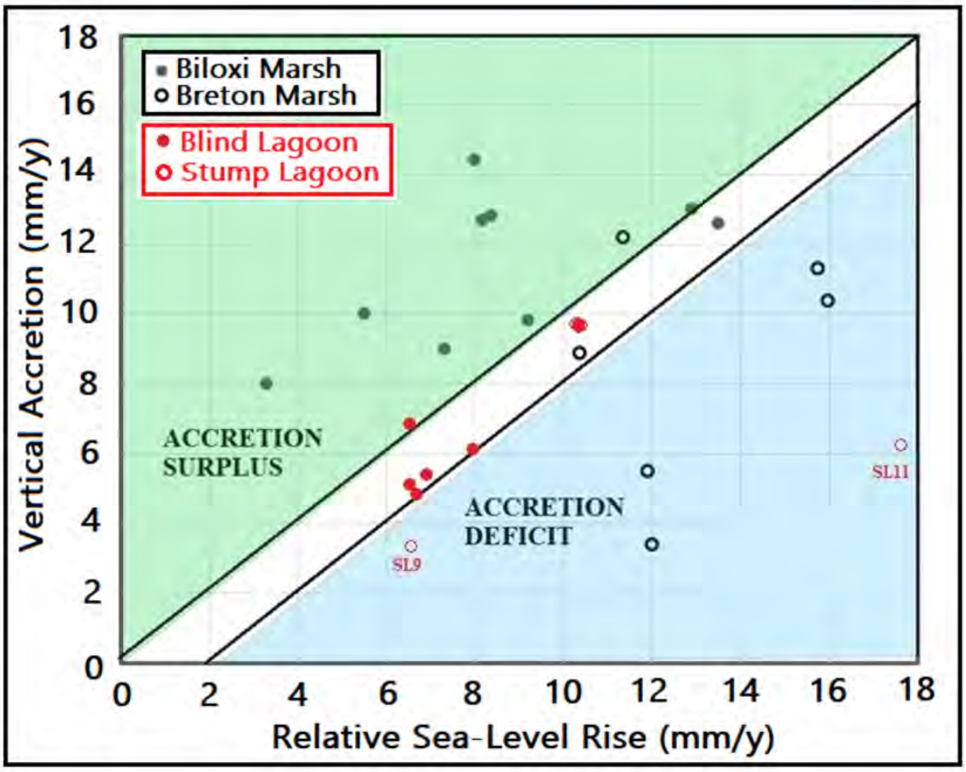

Figure 15. Jankowski marsh vulnerability (to submergence) diagram [67] for CRMS stations in Biloxi and Breton marshes averaged over the 2008 to 2018 decade (Table S3), and in red at UNO interior marsh sites (Table S4) over 1.5 decades at Stump and Blind Lagoons (Figure S3). Sites plotted above the 1:1 line in the green zone are sustainable, while those in the blue are not. Sites in the white "buffer" zone are maintaining elevation relative to RSLR but may not be able to sustain a higher rate in the future.

5. Conclusions

Biloxi Marsh wetlands are transformed into open water in two ways, one related to submergence and inundation [78], and the other as a result of wave action and lateral erosion [103,104]. Prolonged inundation results in plant death and subsequent marsh collapse [99]. Marsh edges exposed to wave erosion and channel scour in a micro-tidal setting are undercut and then subject to progressive failure of the over-steepened scarp, while coarse-grained shell beaches slow erosion by creating a less reflective sloping foreshore [103,104].

The 2023 CMP modelers have proposed new SS rates for use in the western Biloxi Marsh study area (2.5–3.6 mm-y^{-1}) that are the same as those in the Lake Pontchartrain (LPO) polygon (Figure 16). The eastern half of Biloxi Marsh, however, is included in the CHS ecoregion and assigned an SS rate twice that (>6.1 mm-y^{-1}). CHS is the largest ecoregion mapped in the Delta, but has only two CRMS stations (0108 and 1024) within its boundaries to supply SS estimates (Figure 3). These two averaged about 4 mm-y^{-1} for SS over the last decade (Table S3). The MRGO right-of-way separates the low SS LBO polygon from the higher SS Breton Marshes ecoregion (UBR). However, existing data on SS rates along the CRMS Transect do not show a clear shift at the MRGO crossing (Figure 13).

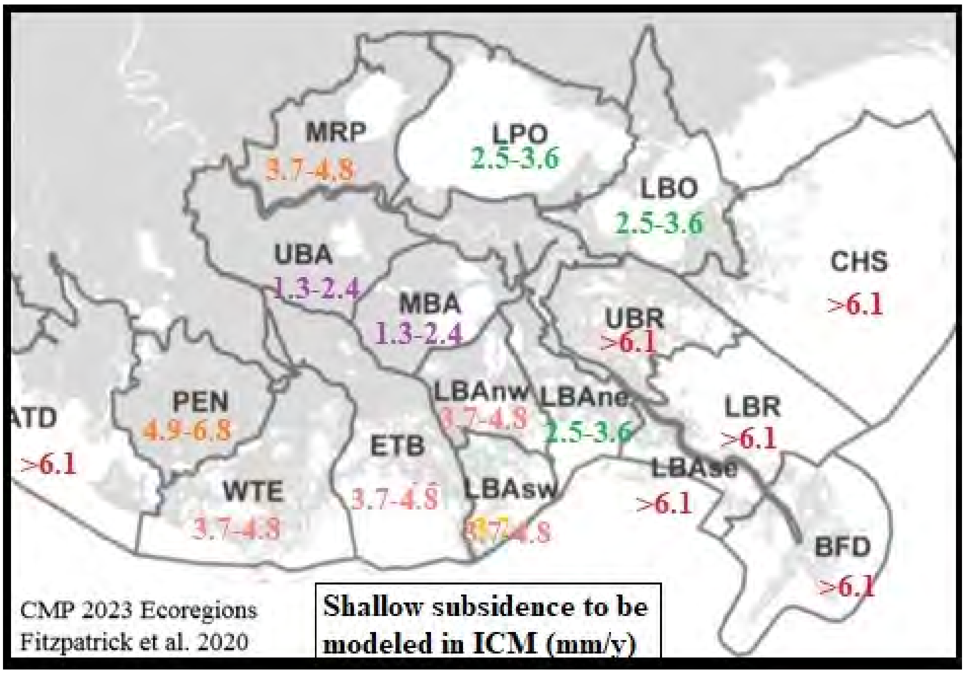

Figure 16. Ecoregion polygons for the 2023 CMP with shallow subsidence (SS) ranges in each for modeling marsh sustainability [17]. Newly proposed ecoregion boundaries partition Biloxi Marsh study area four ways, including portions of Lake Borgne (LBO), Chandeleur Sound (CHS), Upper Breton (UBR) and Lower Breton (LBR) polygons.

Polygon boundaries are coincident with "ecoregions" developed on the basis of hydrology and vegetation types, rather than deltaic geology [17]. We recommend that all of the Biloxi Marsh core be included in a single ecoregion that includes unique habitat associations, between oyster reefs and ancient marshes, for example, that occur on stable Delta margins like Marsh Island and the Biloxi Marsh peninsula.

Subsidence and faulting processes are driven by sediment loading on compressible strata, whether shallow, unconsolidated Holocene deposits or salt flowing at depth. Ample subsurface data have been acquired throughout the Delta, including seismic and well data, as well as archaeological information, to bring the geological context into a clearer focus for coastal planning. We have shown for Biloxi Marsh how this knowledge, combined with data now provided by a mature CRMS network, can provide insights to restoration planning and project sequencing in this and other deltas around the world.

We have also suggested that restoration efforts should build on natural marsh recovery, such as that associated with the damming of the MRGO. Recovery is occurring in different places throughout the Delta as a result of enforcement of Coastal Zone Management permitting guidelines, and requirements for mitigation stemming from unavoidable damage, that have largely stopped canal dredging in the marsh.

MRGO caused salinity intrusion in the 1960s that triggered a destructive sequence along the western Biloxi Marsh coast. It appears that replacement of the *Rangia* dominated benthic community in Lake Borgne caused an almost complete loss of natural shell beaches [33,34]. This is believed to have precipitated an increase in the rate of shoreline retreat that continues today, except where the coast is protected by detached breakwaters (Figure 7). As the shoreline retreats, it intercepts and truncates existing tidal channels and initiates a cascade of changes to internal marsh hydrology. Small existing channel segments expand and deepen as they capture tidal flow, but then are abandoned and trap sediment [41]. This stored sediment is no longer available to nourish the existing marsh, but is disturbed just enough by small waves to prevent revegetation of the former channel footprint (Figure 10).

A brief summary of other findings is given below.

- Biloxi Marsh is the most consequential Delta wetland with respect to reducing hurricane risk to populated areas, and the man-made structures that protect them;
- Stabilizing the marsh shoreline of Lake Borgne using detached rock breakwaters has been tested and proven to be effective and feasible;
- Closure of the MRGO has reduced salinity in the Lake Borgne and returned the salinity gradient across Biloxi Marsh to pre-MRGO conditions, setting the stage for a resurgence of the *Rangia* clam benthic community in Lake Borgne;
- Biloxi Marsh geology and ecology favor marsh restoration and long-term sustainability because the marsh peninsula is inherently durable, relatively unaffected by fault-induced subsidence, and has already lasted longer than any other extant marsh in the Delta;
- Durability of the Biloxi Marsh peninsula is derived from its position as a stable marginal deltaic feature close to the northern boundary of the Gulf Coast continental rift;
- Marsh soils in Biloxi Marsh have less organic matter and more silt, clay and shell (contributing to higher BD) than younger parts of the Delta such as the Breton marshes. This is due to the unusually long 2 ka period of fluvial sediment supply to the St. Bernard sub-delta core;
- Actively meandering tidal channels appear to play an important role in reworking the upper 3 m of Biloxi Marsh before transitioning to lakes upon abandonment;
- Deep subsidence rates (DS) in Biloxi Marsh are lower than in the rest of the Delta because the compressible Holocene section is less than 40 m thick;
- Restoration techniques such as marsh refurbishing with thin-layer dredged sediment, and channel training will likely work better in Biloxi Marsh than in younger marshes due to the greater density and strength of Biloxi Marsh soils.

6. Recommendations

We now know more about why Biloxi Marsh is so durable relative to other Mississippi Delta tidal wetlands. An opportunity exists to create restoration projects that take advantage of the post-MRGO salinity recovery, and of more river sediment coming from the Bonnet Carré Spillway, to prioritize restoration of the Lake Borgne marsh edge. On this coast, some of the healthiest and highest tidal marshes of the Delta are those on the lake edge, that are experiencing the most rapid loss. The CPRA has proven that detached rock breakwaters are effective over a decade or more to stop and even reverse shoreline translation on the Lake Borgne coast of Biloxi Marsh.

Deposition of sediment between the breakwaters and marsh edge is resulting in marsh advance into the quiescent zone created by the structures [Figure S1]. Martin et al. [105] recently reported similar results from Mobile Bay marsh shorelines. More specifically, they conclude:

> While this study shows that large-scale breakwaters in high wave energy environments do not promote the growth of shoreline plantings, *they do effectively reduce wave impacts on the shoreline and enhance natural fringing vegetation. By reducing wave energy, breakwaters mitigate the pressure on vegetation . . . and allow for seaward expansion* [105].

Hot spots of submerging marsh that are temporarily or permanently isolated from sediment supply can be reached using small hydraulic dredges to transfer sediment stored in adjacent abandoned channels, either by flowing or spraying, to raise nearby marsh surface elevation in thin enough layers to promote natural revegetation [106–110]. This has been done recently in the Paul J. Rainey Sanctuary owned by the National Audubon Society in Vermilion Parish [110].

Without more breakwaters, however, shoreline retreat will continue to open new connections between surrounding bays and the marsh interior as the coast invades former active or abandoned tidal channels. Closing shoreline gaps as they form will slow the onset and migration of erosive scour in new parts of active and reactivated tidal channel segments. While more study is needed, blocking some enlarging internal tidal channels may reduce the velocity and volume of tidal exchange across Biloxi Marsh between Lake Borgne and Chandeleur Sound. For these reasons, slowing retreat of the Lake Borgne coast is the single most critical step required to sustain Biloxi Marsh.

These recommendations are specific to Biloxi Marsh. They would be quite different for other parts of the Delta, and certainly for other deltas at the ends of other rivers on other coasts. Understanding what makes a particular part of a delta inherently more durable and resilient, and likely more suited for long-term recovery, is important to prioritizing scarce delta restoration funding. Additionally, to choose among proposed restoration projects and sites, it is critical to have the kind of site-specific information that can be gleaned from seismic surveys, a delta-wide CORS GPS network, and, very importantly, a mature marsh data collection system such as the CRMS.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13223179/s1, Figure S1. Effect on surge and waves in the Lake Borgne-MRGO "Funnel" at 0900 CDT, 29 August 2005. South to north rack of Hurricane Katrina overlaid in light blue on simulation of a tightly coupled SWAN+ADCIRC (wave+surge) model hindcast (ADCIRC SL16). (A) The steepest rise in surge elevation is on eastern margin of Biloxi Marsh study area (black box). Surge is lower in Lake Borgne and Lake Pontchartrain. (B) Bottom friction and wave breaking on the Chandeleur Islands and shoals, and similar interactions on the Biloxi Marsh reduce significant wave height in the Funnel. Modified from [23]. Figure S2. Lake Borgne Marsh Site A1b behind detached breakwaters built in 2013. Bottom panel shows monitoring poles placed along base of marsh edge scarp on 20 February 2018. Top panel shows positions of the marsh edge relative to the same witness poles on 16 November 2018, demonstrating advance of vegetated shoreline over 9 months into Lake Borgne (86 cm +/− 10 cm) behind the CPRA breakwaters [35]. Figure S3. Location of interior marsh sites established by University of New Orleans researchers in 2003 and 2004, and reoccupied in 2018 by Lane et al. [19]. Figure S4. Using the Sediment Erosion Table (SET) and Marker Horizon (MH) techniques in tandem to determine Surface Elevation Change (SEC), Vertical Accretion (VA), Shallow Subsidence (SS = VA-SEC), Deep Subsidence (DS), and Total Subsidence (TS = SS + DS), Local Sea Level Rise (LSLR), and Relative Sea Level Rise (RSLR = TS + LSLR). Modified from [67]. Figure S5. Comparing salinity at sites established by Rounsefell [70] from 1959–1961 (Figure 2), Pontchartrain Conservancy from 2013-18, and from this 2018 sampling [18]. Stations are ranked by distance from the NOAA Shell Beach Gauge at the south end of Lake Borgne. No significant differences between the three datasets were found. Table S1. Salinity (psu from Conductivity) at 2018 Marsh Sites and Rounsefell Stations from March to November 2018; See Figure 2 for locations. Table S2. Shoreline erosion and accretion at the 2018 marsh study sites. See Figure 2 for location. Table S3. Soil Properties and Processes at CRMS stations active for more than a decade in the BMC and Breton Marshes (See Figure 3 for locations). Table S4. Subsidence and accretion data from Stump and Blind Lagoon SET Sites established in 2003, last monitored in 2008, and reoccupied 10 years later in 2018.

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