Restoration and Sustainability of the Biloxi Marsh Complex:
Comments on the 2017 Comprehensive Master Plan

By

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and

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Prepared for the Biloxi March Corporation

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Executive Summary

Overview of Report

We reviewed the current condition of salt marshes in the Biloxi Marsh Complex (BMC), and have examined data from 10 CRMS monitoring sites to predict long-term resilience and sustainability under the future sea level rise scenarios applied in the 2017 draft of the Comprehensive Coastal Master Plan (CMP17). The 20-mile wide BMC platform has been determined to serve residents of metro New Orleans and St. Bernard as a buffer to hurricane surge and waves on the basis of numerous post-Katrina hindcasts. Despite a forecast that the BMC will survive less than 30 years under the "High" sea level rise scenario, CMP17 recommends few restoration measures to extend the lifespan of this important landform. While the modeling conducted for CMP17 is impressive, we suggest that some features of the output that drove project selection may be modeling artifacts that should be critically examined for the next CMP17 draft.

Outstanding Technical and Scientific Issues

We recommend that the Coastal Protection and Restoration Authority explore and resolve the following technical questions:

- Do the models apply the inundation-driven "marsh collapse thresholds" correctly for all marsh types, particularly saline marshes?
- If the persistence and spread of fresh marsh in out-year simulations is attributable to lack of a marsh collapse threshold for this marsh type, should some other limiting threshold be applied?
- Why does it appear that the CMP17 models do not capture the benefits of linear shore protection measures - short of major levees - to slow wave-driven lateral shoreline translation, the major marsh loss mechanism affecting the BMC?

Subsidence Rates and Elevation covering BMC

A review of between 8 and 9 years of CRMS data from the BMC highlighted differences between East and West BMC marshes that should inform the restoration initiative. The East BMC is affected by sediment transported to the marsh from Chandeleur Sound, while Lake Borgne supplies the West BMC. East BMC marshes are up to 10 cm higher than those in the western BMC, but all marshes are accreting at rates of between 0.7 and 1.7 cm/y, and exhibit a positive surface elevation change (SEC) trajectory averaging 0.6 cm/y, the same as the mean value of shallow subsidence (SS). Our findings support those of D.J. Reed (unpublished in King et al. 2006) that "*marsh soil development in the Biloxi Marsh show that marshes there are sustainable now and should be well into the future.,*"

Resilience and Sustainability

The ICM does not appear to capture effects of Lake Borgne shoreline retreat, the primary cause of BMC marsh loss. This problem appears to have led to erroneous conclusions about the sustainability of the BMC as represented in CMP17. A careful analysis of the environmental setting of the BMC shows that the area was strongly impacted by the MRGO but is now on a recovery trajectory. But there is still a need for additional restoration activities that we recommend be incorporated CMP17. If this restoration is done, most of the BMC should be sustainable for the next 50 years and beyond, and continue to provide all-important hurricane flood risk reduction benefits to the New Orleans metro area.

The CMP17 may be overestimating geologic subsidence in the BMC (McLindon 2017). BMC marshes are among the oldest extant in the Mississippi River deltaic plain, dating from the active period of the St. Bernard Delta, 3000 to 4000 y BP. Depth to Pleistocene ranges from 50 to 100 feet. The CMP17 estimates deep subsidence in the BMC at 0.44 cm/y, but we prefer the value of Jankowski et al. (2017), 0.1 cm/y lower. Relative Sea Level Rise (RSLR) in the BMC averages 1.1 cm/y, of which about half is contributed by shallow subsidence that occurs mainly in the upper 10 cm of the marsh. We use a value of 0.2 cm/y for Eustatic or Global SLR acquired through satellite altimetry. Marsh aggradation (SEC) in the BMC ranges from 0.13 to 0.98 cm/y. Highest elevation marshes from the eastern BMC had the lowest SEC. Suffice it to say that no two marsh sites were the same although they are all salt marshes dominated by *Spartina alterniflora*. Trying to model marsh dynamics at all of these very different sites using the same parameterization is likely to be frustrating and produce inaccurate results.

The eastern and western zones of the BMC function differently and restoration approaches proposed should reflect this. Marshes of the eastern BMC are high and positioned at the top of the tidal frame. They are experiencing low, easily sustainable rates of SEC, and are composed of firm, consolidated sediments with a significant shelly sand component. The primary sediment source is Chandeleur Sound and it is sufficient now and will remain so into the future. These marshes are likely to survive the highest projected rates of RSLR over the next 50 years, with a limit of perhaps 2.0 cm/y, twice the current rate. These marshes could benefit from shoreline stabilization measures including the planting of mangroves, which have strong root systems, and artificial nearshore oyster reefs, but little additional is required. This would reduce the shoreline retreat that continues to carve up the myriad of marsh and shell islands that make up the Eastern BMC.

The West BMC marshes are about 10 cm lower than those in the Eastern BMC but experience healthy rates of SEC ranging from 0.4 to 0.9 cm/y. Shoreline retreat along Lake Borgne is highly variable but has been measured at up to 60 m/y when the year includes a major hurricane. The Western BMC marshes experienced the most severe impacts caused by the construction and operation of the Mississippi River Gulf Outlet (MRGO) navigation channel between 1960 and 2009.

Higher salinities introduced by this channel led to loss of *Rangia* clams in Lake Borgne. These clams provided a continuous supply of shell that maintained high berms on the lake shores comparable to the oyster shell beaches armoring the marsh edges of the Eastern BMC. When the living Rangia disappeared, shell supply to the beaches and berms was reduced and the berms degraded. Northwest winds generated during frontal passage are a primary source of high wave energy on the west-facing coast of the Western BMC. In the past, waves re-suspended sediments that fed the berms and led to accretion in the marshes. Currently, locally generated waves are causing high rates of erosion and shoreline retreat both along Lake Borgne and in much smaller interior lakes and ponds.

The MRGO also increased tidal and wind-driven flow between Lake Borgne and Chandeleur Sound leading to erosion and widening of Bayou LaLoutre and other smaller tidal channels of the BMC interior, particularly on the western side. Since the MRGO was closed with a Rock Dam just south of the Bayou LaLoutre crossing, the area is recovering, but further restoration will be needed to lead to long-term sustainability. Another way of stating this is that the BMC is already recovering from the negative impacts of the MRGO, so relatively low-cost restoration measures could be effective in enhance the ongoing recovery, rather than starting from a deteriorating baseline.

Salinities in Lake Borgne and in Western BMC marshes have decreased. After MRGO, salinities in Lake Borgne increased to 8-22 parts per thousand (ppt) but now range from 3 to 10 ppt. The MRGO-induced salinity rise hastened the loss of Rangia clam populations and fresher wetlands in the BMC. Many oaks died along the Bayou LaLoutre ridge, but a number of what appeared to be dead trees are now sprouting new leaves after many years of apparent dormancy. Roseau cane (*Phragmites*) is again spreading in the BMC. *Spartina alterniflora* was recently noted spreading across a low mud platform at the base of the Bayou LaLoutre banks, indicating a reversal of decades of erosion. Although we are not sure how it should be done, it does not appear that CMP17 prioritizes recovering areas for restoration projects even if they might work better and longer because the ecosystem is already in recovery. CMP17 should include additional restoration projects to take advantage of the recovery to leverage a more sustainable system.

Restoration principles, whether explicit or implicit have been a foundation for all existing BMC restoration planning. First, it is important to recognize that sediment supply is sand from Chandeleur Sound on the east, and mud from Lake Borgne on the west. On the east, establishing shoreline fringing artificial oyster reefs will enhance shell production for shoreline armoring while planting mangroves will increase sediment capture and erosion resistance. High winds during fronts are effective in re-suspending fine-grained silts and clays in Lake Borgne. This sediment is delivered to the Western BMC when storms raise lake water level. But the same locally generated waves that suspend sediment from the bottom of Lake Borgne also causes the shoreline erosion that increased dramatically after the Rangia shell berms disappeared.

The USACE MRGO Ecosystem Recovery Plan (ERP) and the proposed Point aux Marchettes PPL 27 Coastal Wetlands Planning Protection and Restoration Act (CWPPRA) project currently awaiting approval both rely on the same small-scale and relatively low-cost marsh restoration measures, namely low rock revetments and artificial oyster reefs to slow shoreline retreat in combination with marsh shoreline wetland nourishment to reinforce marsh edges until both Rangia and Oysters begin producing enough shell to effectively armor BMC once again.

Long-term, another diversion - in addition to the Mid-Breton outlet - will be needed to increase freshwater input to Lake Borgne and the BMC as sea level rises. A moderately large diversion could enhance ecosystems in both the Central Wetlands Unit (CWU) and the BMC. Much of the infrastructure for this diversion is already in place. This includes the Violet Canal, the MRGO channel between the Bayou Dupre flood gate, the Rock Dam, and the Bayou LaLoutre channel. The Laloutre ridge restoration included in CMP17 can be modified to also include channel restoration. One or more additional water control structures will be required to direct some sediment to the CWU while also controlling the rate at which diverted river water is shunted directly to Lake Borgne. The USACE MRGO ERP provides a somewhat vetted menu of small to medium-sized projects like the Point aux Marchettes project that can be implemented gradually as funding becomes available. But a suite of such projects should certainly be included in the final version of CMP17 even if they also appear on the USACE MRGO restoration wish list.

<u>Conclusions</u>

Preservation of the BMC should be a priority for any comprehensive CMP, as was true for CMP12. Given the limitations of the ICM, it would be useful to propose marsh creation and shoreline stabilization measures as part of integrated projects.

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Laloutre ridge that has been included in CMP17. One or more additional water control structures will be required to direct some sediment to the CWU while also controlling the rate at which diverted river water is shunted directly to Lake Borgne. The USACE MRGO ERP provides a somewhat vetted menu of small to medium-sized projects like the Point aux Marchettes project that can be implemented gradually as funding becomes available. But a suite of such projects should certainly be included in the final version of CMP17 even though they also appear on the USACE MRGO restoration wish list.

Additional study must be completed which refines CPRA's subsidence polygon 11 to more accurately quantify subsidence rates covering solely the BMC,

- Running multiple historical and predictive sea level rise scenarios models combined with more accurate subsidence rates observed in the BMC should be considered,
- Based on the data that validates the BMC's near term sustainability, restoration projects such as the Point Aux Marchettes Shoreline Protection and Marsh Creation should be included in CMP17,
- CMP17 should be consistent with the USACE's MRGO Ecosystem Restoration Alternative Plan C as a continuation of the restoration initiative that caused the de-authorization and closure of the MRGO. Simply damming the MRGO below Bayou LaLoutre without any further ecosystem restoration was never contemplated and is insufficient to preserve the valuable resource which is the BMC,
- Due to the clear evidence of the BMC's near term sustainability and partial recovery after the damming of the MRGO, CMP17 should include all projects which were a part of CMP12,
- A realistic storm surge model should be developed to explore how removal of the BMC marsh platform affects storm surge and waves in the MRGO funnel. CRMS and other data shows the BMC is eroding at the edges, not subsiding, thus assuming the existence of a "mudflat" is not realistic.

Contents

INTRODUCTION

This report was prepared at the request of Mr. Louis Buatt, Attorney at Law, on behalf of the Biloxi Marsh Lands Corporation, owners of the Biloxi Marsh Complex (BMC), to be attached with comments on the Draft Plan for 2017 Coastal Master Plan (CMP17). We reviewed available information on the environmental setting and factors that can affect wetland sustainability in the BMC. It might be expected that CMP17 planning would prioritize the bolstering of BMC sustainability given the widely recognized role of these marshes as a storm buffer for eastern New Orleans and St. Bernard Parish, and their recovering habitat value following closure of the Mississippi River Gulf Outlet (MRGO). Because this does not appear to be the case, we urge that the Coastal Protection and Restoration Authority (CPRA) reassess the merits of adding additional restoration measures for the BMC in the final version of CMP17.

We support this recommendation with an analysis of 9 years (2008-2016) of Coastal Reference Monitoring System (CRMS) data from 10 stations. This has allowed us to characterize current marsh elevation, subsidence, accretion, marsh surface aggradation and shoreline transgression, and to predict how these processes might change in the future, with or without additional restoration measures. Finally, we review the CMP17 projects proposed to enhance BMC sustainability and recommend additional measures that will increase long-term effectiveness of hurricane protection and rising habitat productivity over the next 50 years.

CMP17 Modeling

CMP17 provides a sobering view of what the future holds for all of Louisiana's coastal wetlands (Figure 1). Despite a projected expenditure of $25B on restoration projects over 50 years in addition to another $25B on levee and floodwall construction, land loss in the CMP Eastern Region that includes BMC property is slowed only by 16 and 24 percent for the Medium and High sea level rise rates (SLR, Table 1), respectively, when compared to the Future Without Action (FWOA).

At the end of 50 years during which all proposed CMP17 projects have been constructed and operated as proposed, cumulative land loss is projected to total 2352 and 3775 km^2 for the Medium and High SLR scenarios, respectively (Table 1), out of an initial 8927 km^2 of marsh in the Eastern Region in Year 0. Very little brackish or saline marsh remains anywhere in the Eastern Region (Figure 1). The BMC survives beyond 50 years under the Low SLR scenario, but disappears between 40 and 50 years for the Medium SLR, and between 30 and 40 years in the High SLR projection (Figure 2).

These loss numbers are much higher than those forecast in the 2012 CMP for three main reasons. First, and most significantly, the eustatic (global) sea level rise (ESLR) rates used to force the hydro- and eco-models are higher than in the earlier plan. The High, or "less optimistic" SLR rate in the 2012 CMP (0.86 cm/y) is the Low scenario in CMP17, while the Medium and High rates in the new plan are 1.26 and 1.66 cm/y (Table 2), respectively, which correspond to 2100 rises of 1.0, 1.5, and 2.0 m (Figure 3). These new rates bracket the range of values in the climate change literature. Estimates of what is probable have gone up since 2014, so that the Medium and High rates in CMP17 are now considered more likely than the Low scenario.

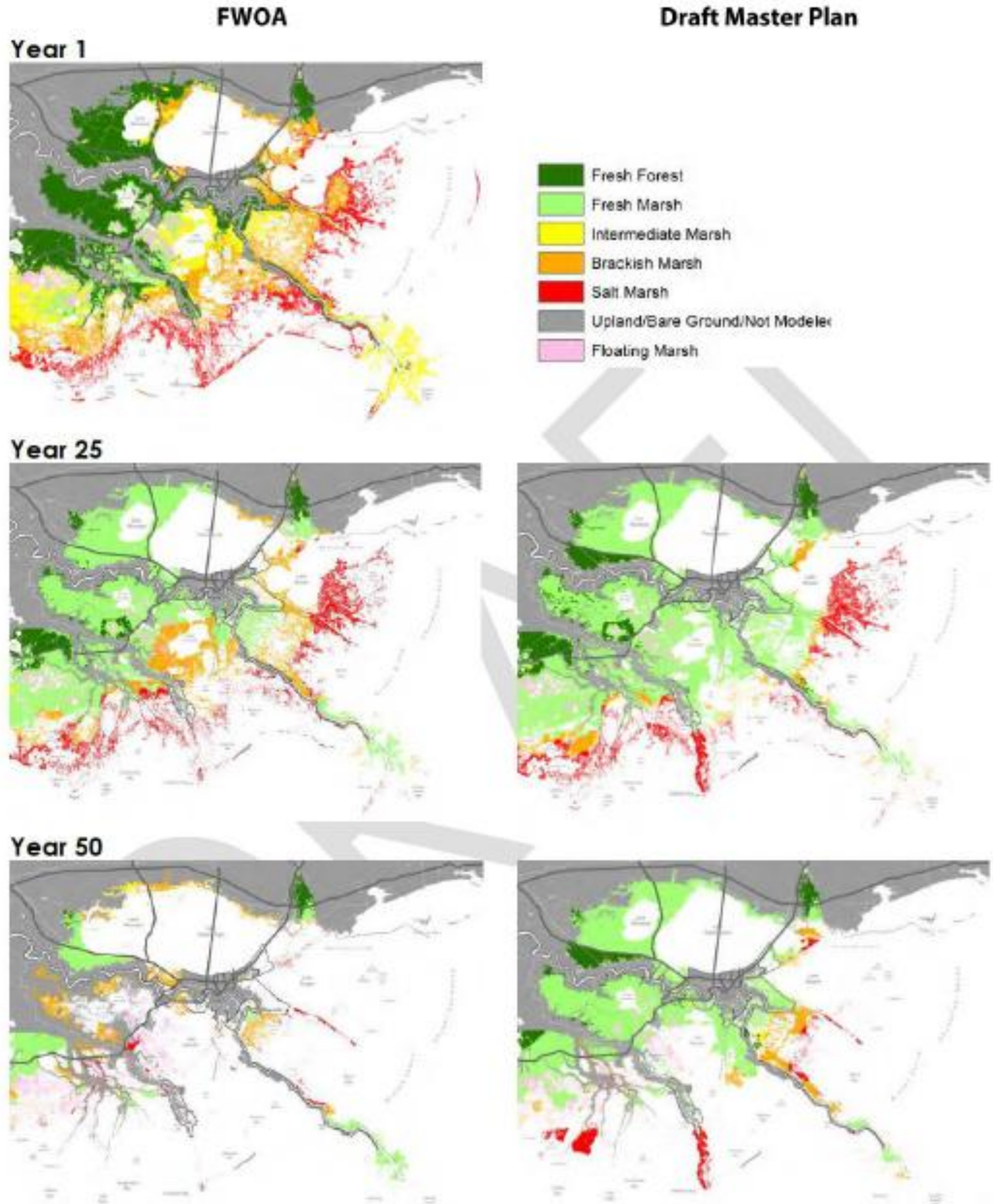


Figure 1. Changes in land area and wetland type in the Eastern Region over 50 years for the "Future Without Action" (FWOA) on left, and with CMP17 on right for the high sea level rise scenario. The Chandeleur and Breton Islands are lost completely before Year 25, while the BMC disappears between Years 25 and 50 in both scenarios. (Figure 383 from the 2017 CPRA Plan, App. C, Chapter 4)

Table 1. Effect of Fully Implemented 2017 CMP (Group 301) on Land Loss at Years 25 and 50 for Medium and High Sea Level Rise Rates. East Region includes Biloxi Marshlands. (Modified from Table 12, 2017 CPRA Plan, App. C, Chapter 4).

Medium ESLR Scenario									
	Year 0	Year 25	Difference Year 25 vs. Year 0	FWOA Year 25	Difference with FWOA at Year 25	Year 50	Difference Year 50 vs. Year 0	FWOA Year 50	Difference with FWOA at Year 50
East	8,927	8,068	-859	7,775	293	6,575	-2,352	5,155	1,420
Central	3,516	3,551	35	3,502	49	3,025	-492	2,830	194
West	3,853	3,978	124	3,798	180	2,856	-997	2,474	382
Total	16,297	15,597	-700	15,075	523	12,455	-3,842	10,460	1,996
High ESLR Scenario									
	Year 0	Year 25	Difference Year 25 vs. Year 0	FWOA Year 25	Difference with FWOA at Year 25	Year 50	Difference Year 50 vs. Year 0	FWOA Year 50	Difference with FWOA at Year 50
East	8,927	7,581	-1,346	7,083	498	5,252	-3,675	3,076	2,176
Central	3,516	3,430	-87	3,358	72	2,115	-1,402	1,779	335
West	3,853	3,633	-221	3,363	269	912	-2,942	760	152
Total	16,297	14,644	-1,653	13,804	840	8,278	-8,019	5,615	2,663

Second, the primary modeled pathway for land loss in CMP17 is triggered by what is termed "marsh collapse," which occurs when the land surface is predicted to fall below a critical elevation in the tidal frame. Low marshes with a soil surface elevation below this threshold are flooded more frequently and for longer periods than the physiology of marsh vegetation can withstand. The reason that collapse occurs is that sediment input and organic matter production in the root zone is insufficient for the marsh surface to aggrade rapidly enough to keep up with relative sea level rise (RSLR), which is the sum of ESLR and local subsidence. When the marsh vegetation dies, the roots that hold the soil together and give it strength decompose rapidly and the surface drops by 10 cm or more (Nyman et al. 1995, Day et al. 2011). Because of the spatial scale of Integrated Compartment Model (ICM) polygons, when salinity rises or falls, large swaths of wetlands can change to open water or to a new habitat type within a year or two, creating steps in the land-loss/habitat change curves (Figure 4).

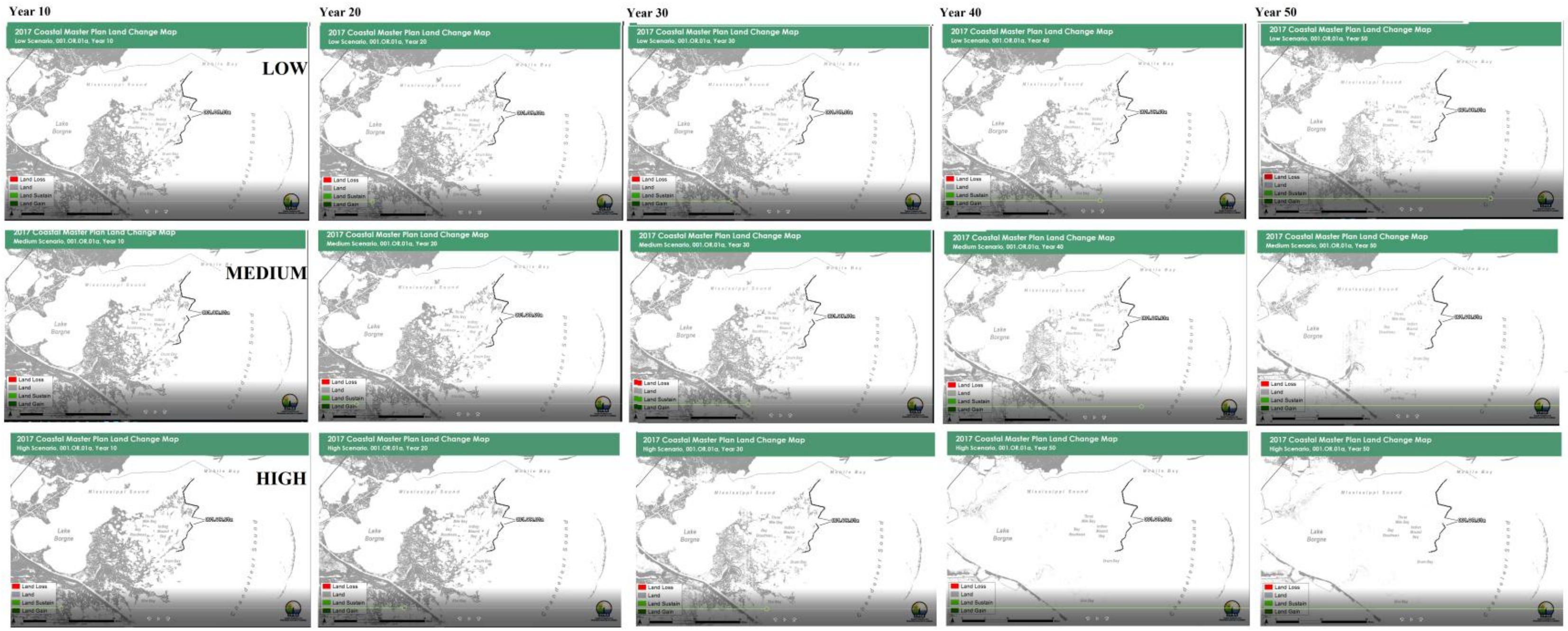


Figure 2. Forecast land loss in the BMC by decades under three Eustatic Sea Level Rise (ESLR) scenarios modeled. Project depicted is the Biloxi Marsh Oyster Reef. Remaining marsh in the BMC is similar in Year 50, Year 40 and Year 30 for the Low, Medium and High ESLR scenarios, respectively.

Table 2. Model Parameters used in CMP17 Scenarios

Sea Level Scenario	Precipitation	Evapotranspiration	50 yr rate ESLR (cm/y)	Subsidence (cm/y)	RSLR (cm/y)	Overall Storm Frequency	Average Storm Intensity
	Used in ICM					Used in CLARA	
Low	>Historical	<Historical	**0.86**	20% of range **0.44**	**1.3**	-28%	+10.0%
Medium	>Historical	Historical	**1.26**	20% of range **0.44**	**1.7**	-14%	+12.5%
High	Historical	Historical	**1.66**	50% of range **0.65**	**2.3**	0%	+15.0%

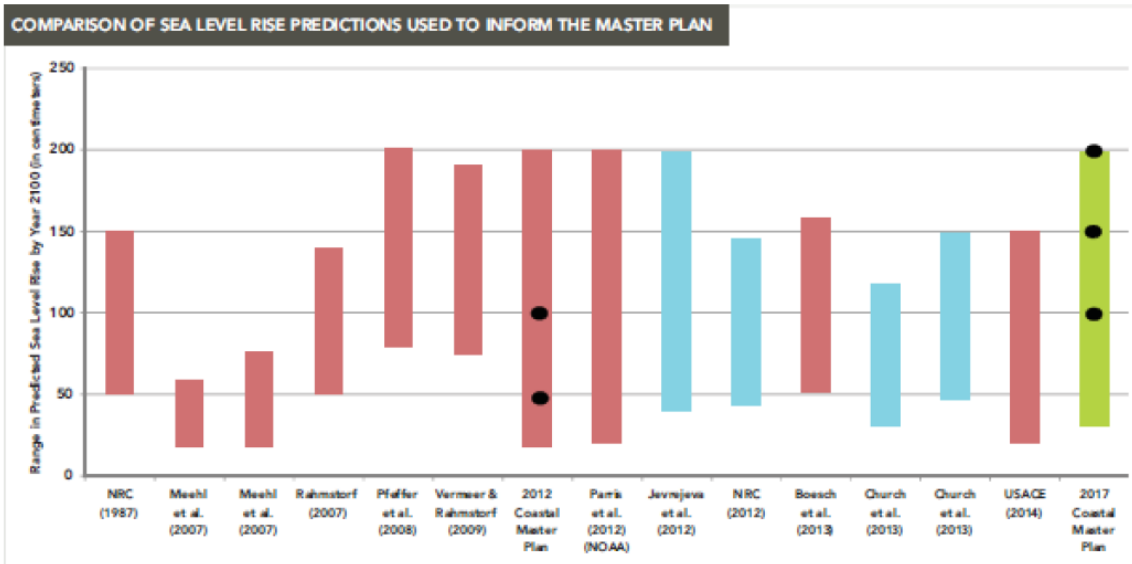


Figure 3. Estimates of sea level rise by 2100 used in the 2017 CMP range from 1 to 2 m, as shown by the black dots in the green bar, while those used for the 2012 CMP ranged from 0.5 to 1 m. (Figure 3.6 in the 2017 CMP main text).

Third, thresholds in the ecosystem models have been changed to reflect additional information on the sensitivity of different wetland types to prolonged flooding (Snedden et al. 2015, Morris et al. 2014). This comes into play when diversions introduce large volumes of river water into adjacent estuarine basins that cause water level to rise locally in the vicinity of the outlet, thus contributing to a potential for wetland submergence (Figure 5). This can stress and kill brackish marshes near the diversion outlet, particularly if the diversion is not delivering much suspended sediment. For this reason, diversions discharging into existing wetlands are forecast to cause a net loss of land in the initial decades of operation (Figure 6). This initial loss period might well be shortened if the diversion were introducing water from the Mississippi with a higher suspended sediment concentration (Kemp et al. 2016). However, Day et al. (2016a) have also proposed that large diversion discharges be rotated so that flooding of any receiving area would be episodic and short-term while land could be built more rapidly. At Caernarvon, for example, Day et al. (2016b) reported that the 1927 artificial crevasse reached discharge levels of nearly 10,000 m^3/sec but only flowed for three months. This crevasse covered an area of about 130 km^2 with as much as 45 cm of sediment.

Another apparent model artifact that needs more investigation is the unrealistic persistance and spread of relatively fragile fresh marsh in the model output. The CMP17 notes that "fresh marsh is not subjected to an inundation collapse criterion; therefore, regardless of the sea level rise and subsidence rates modeled, fresh marsh did not collapse into open water areas" (p. 237, 2017 CPRA Plan, App. C, Chapter 4). So, unless salinity gets high enough to convert fresh marsh to intermediate or brackish marsh, which *are* subject to inundation collapse, fresh marsh tends to dominate what limited wetlands remain after 50 years in model projections (Figure 1).

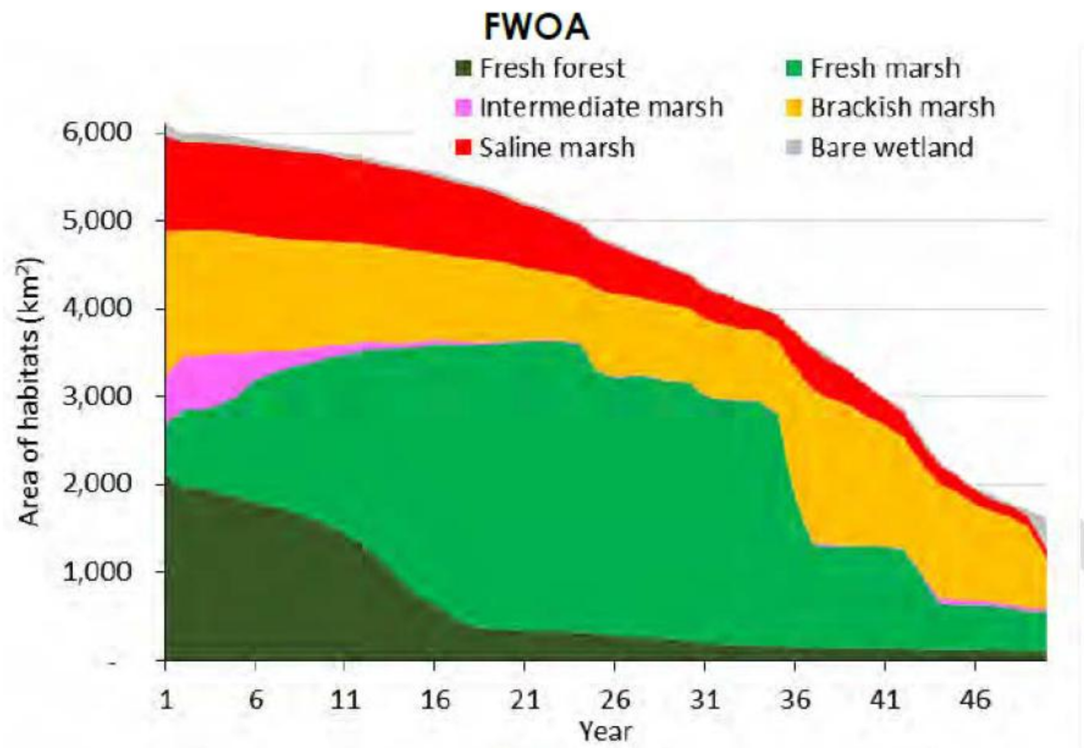


Figure 4. ICM forecasts that marsh loss and habitat changes for the Eastern Region occur in steps. (Figure 312 from the 2017 CPRA Plan, App. C, Chapter 4)

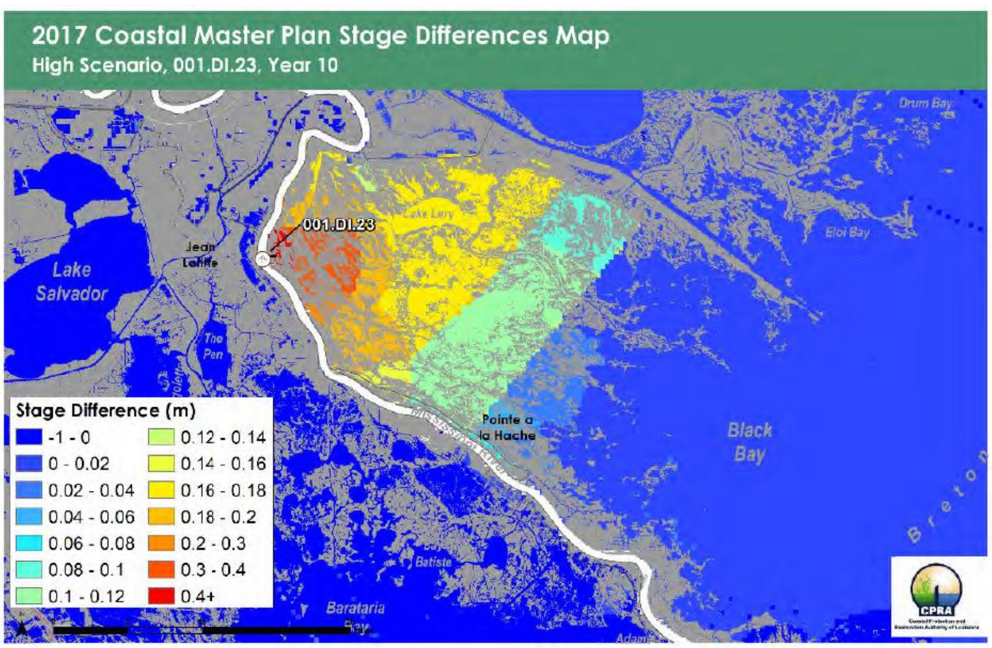


Figure 5. Change in mean annual water level resulting from the Mid-Breton Sound Diversion relative to FWOA (Figure 186, 2017 CPRA Plan, App. C, Chapter 4). This shows that water levels will be raised by up to 0.4 m near the diversion but will not impact the Biloxi Marsh Complex.

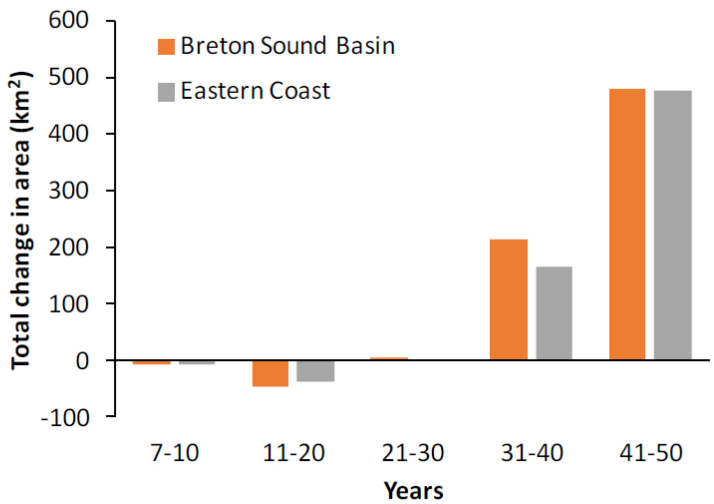


Figure 6. The Mid-Breton Sound Diversion initially is predicted to cause land-loss relative to the FWOA, so that net land-gain begins only after 3 decades of operation. (Figure 197, 2017 CPRA Plan, App. C, Chapter 4)

Low levels of salinity intrusion into fresh, peat dominated marshes can lead to rapid collapse when this soil undergoes anaerobic decomposition as SO_4 (sulfate) introduced with seawater is reduced. Such decomposition process has been documented to varying degrees in most coastal wetlands (Cahoon et al. 2003, Nyman et al. 1995, Day et al, 2011, Voss et al. 2013). Increased sulfate reduction causes S^{2-} (sulfide) to reach concentrations in soil pore water that are toxic to marsh plants. Plants stressed by sulfide produce less root material to bind organic soils, so that rip-up and other physical damage from tropical storm surge and waves can reduce the stability of interior estuarine freshwater systems. It seems unlikely to us that fresh marsh species will outcompete all other types as the ICM predicts after 50 years, right out to the coast of the Gulf of Mexico (Figure 1).

Also, we are not convinced that the ICM is really capable of simulating long-term response of shorelines to armoring with rock berms, or protection by natural or artificial oyster reefs and other linear structures (Figure 2). CMP17 authors state with regard to bank stabilization and shoreline protection that “the overall lack of project effects observed is likely in part due to the spatial resolution of the model” (p. 201, 2017 CPRA Plan, App. C, Chapter 4). CMP17 does not include stand-alone shoreline protection or armoring projects, because they produced no change in land gained or lost when modeled ICM.

On the other hand, shoreline protection projects using rock revetments have been included as necessary components in more complex CMP17 projects that derive modeled land sustainability benefits from other project measures like marsh creation or diversions. CMP17 does not include any of the numerous shoreline protection or oyster reef projects proposed in CMP12, the Mississippi River Gulf Outlet Ecosystem Restoration Plan (MRGOERP, USACE 2012), or the Coastal Wetlands Planning Protection and Restoration Act (CWPPRA, Louisiana Coastal Conservation and Restoration Task Force 2015). But it is interesting that the CWPPRA Task Force continues to propose new shoreline projects in the BMC. The Pt. aux Marchettes Shoreline Protection Project recently received the highest ranking of any project on the CWPPRA 27th Priority List (Figure 7). Shoreline protection and marsh terracing (in lakes) continue to be favored by local natural resources managers for their effectiveness in stopping land loss, at least in the short-term. But in order to be included in CMP17, given the apparent limitations of the ICM, we recommend that such projects be combined with a marsh creation component.

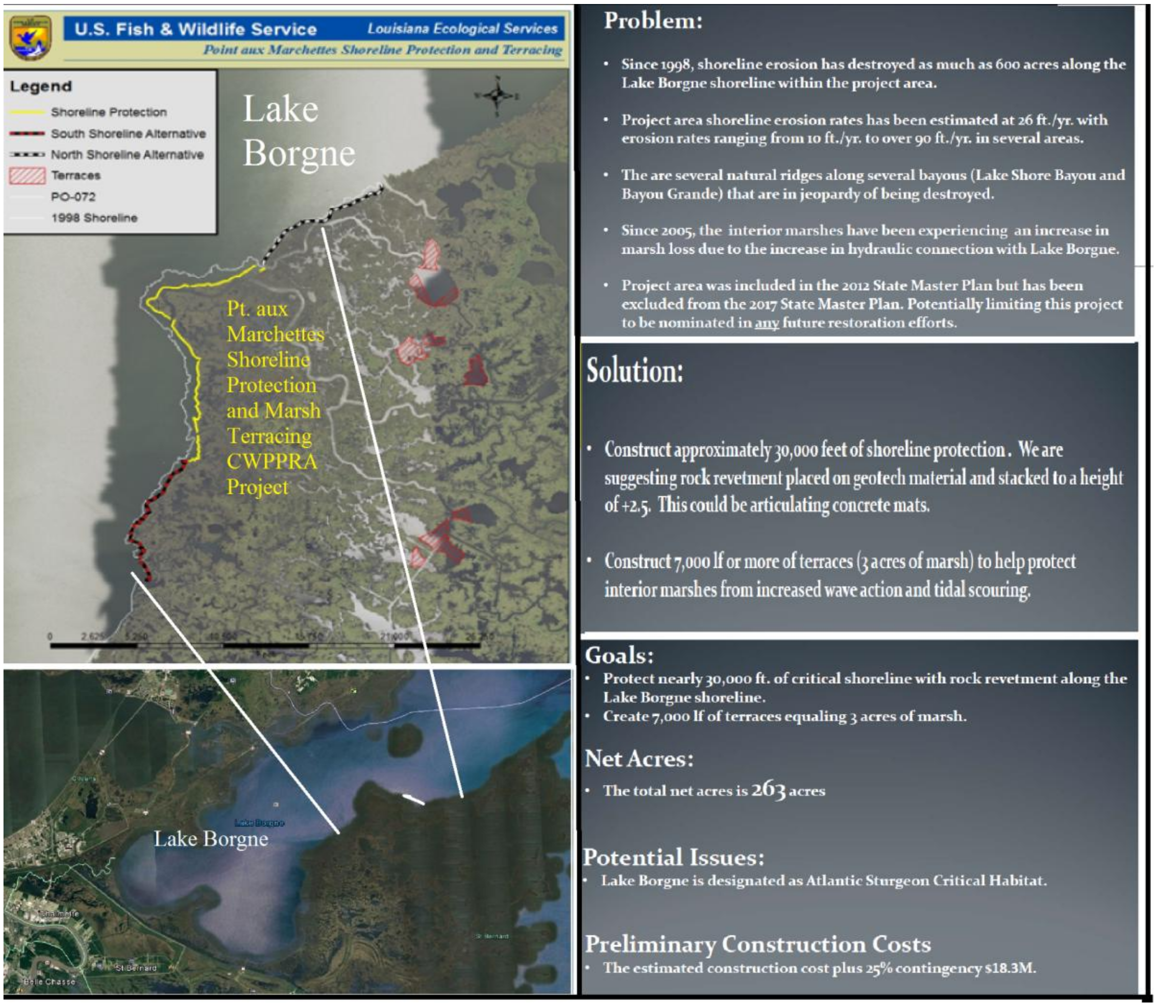


Figure 7. Pt. aux Marchettes CWPPRA project ranked highest of all on the 27th Priority Project List includes both rock revetment on the Lake Borgne shore and marsh terracing of BMC interior lakes.

A large "oyster barrier reef" project was proposed for the east-facing Chandeleur Sound BMC shoreline (Figure 2) that was included in CMP12 is not part of CMP17 possibly because the ICM model was unable to forecast benefits. Stable shell beaches are found in places along the Louisiana coast adjacent to the few places where natural reefs are still extant and producing shell, as in the Southwest Pass of Vermilion Bay. The Chenier ridges of southwestern Louisiana are largely composed of shells that accumulated in the past to form beaches and storm berms on the open Gulf shoreline. Some of this ancient oyster shell is being reintroduced to the modern littoral system at Chenier au Tigre in Vermilion Parish where it forms a steep beach fronted by sandy bars in what would otherwise be a muddy marsh shoreline (Kemp and Wells 1987).

Coarse shell material, like stone cobbles and shingle can play a role in dissipating wave energy and retarding shoreline retreat on muddy coasts (Buscombe and Masselink 2006). Certainly, living shoreline projects that renewably produce shell to armor the marsh edge deserve more consideration from the CMP17 planners, particularly as they are relatively inexpensive and produce other ecosystem benefits.

THE MRGO AND BILOXI MARSH DETERIORATION

MRGO damage to wetlands. Construction of the 40 foot deep MRGO ship channel along the principal axis of the Lower Pontchartrain estuary fundamentally changed hydrodynamics with respect to tides and salinity after 1960 (Figure 8). This led to a cascade of negative environmental impacts throughout the basin, from north of the Bayou LaLoutre ridge to the swamps around Lake Maurepas. When the MRGO was dredged through the Bayou LaLoutre ridge, salinity intrusion into Lake Borgne and the Central Wetlands Unit began immediately(Figure 8). Similarly, Lake Borgne and the Central Wetlands Unit (CWU) went from fresh to oligohaline conditions to a brackish and saline state (Shaffer et al. 2009). Salinity increase was dramatic in some spots. For example, salinity increased in the GIWW (MRGO Reach 1) from a mean of 3 parts per thousand (ppt) to between 8 and 10 ppt after the MRGO opening. In the CWU, salinity generally ranged between 4 and 12 ppt, so that second-growth swamp tree species like bald cypress and water tupelo died, creating “skeleton forests” (Hunter et al. 2016).

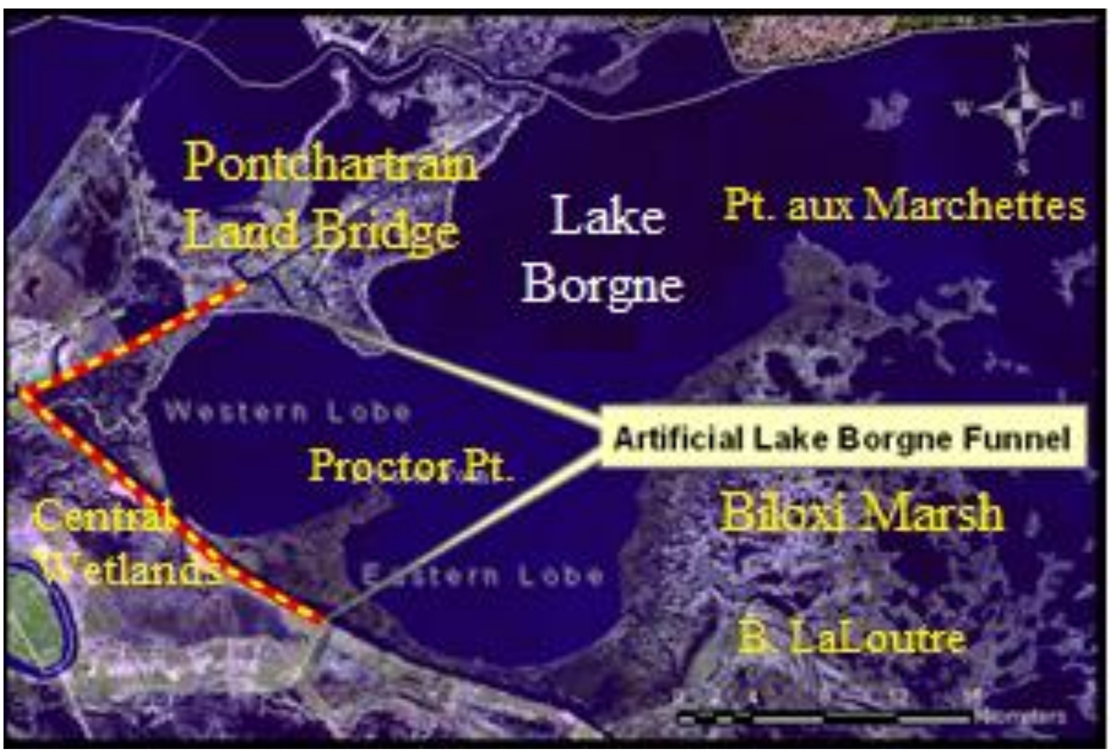


Figure 8. Lake Borgne Funnel, Biloxi Marsh Complex, MRGO and Pontchartrain Land Bridge.

The BMC north of the Bayou LaLoutre ridge was a semi-enclosed system with restricted water circulation through small tidal channels prior to construction of the MRGO. Tidal and wind-driven water level fluctuations within small marsh channels were reduced compared to those in the lakess and bays. Water exchange between Chandeleur Sound and Lake Borgne was limited, and was largely blocked by the BMC. This was especially true of hurricane-induced water exchange. After the opening of MRGO, the massive channel led to much greater exchange between the Sound and the Lake. Hurricane surge could enter the area directly via the MRGO channel without having to flow over the Biloxi marshlands or through the much longer route through Mississippi Sound. This artificial connectivity was to prove disastrous during Katrina when surge and waves destroyed levees adjacent to the Lake Bourgne funnel (Figure 8) and led to disastrous flooding.

Especially important were the losses of cypress trees (*Taxodium distichum*) and Roseau cane stands (*Phragmites*) that extended out to the shore of Lake Borgne prior to MRGO. These two species confer a greater drag on hurricane surge than the low-lying *Spartina alterniflora* marshes that replaced them (Van Heerden et al. 2009, Shaffer et al. 2009). Other fresh to intermediate marshes became open water where the substrate would not support higher salinity marsh. Increased tidal flows between the two large water bodies that were conveyed by the MRGO led to extensive erosion and scour within the Bayou LaLoutre channel and other waterways in the BMC, while the MRGO ship channel widened rapidly, primarily due to erosion caused by ship wakes. This expansion led to multiple breeches between the MRGO channel and southern Lake Borgne (Figure 9).

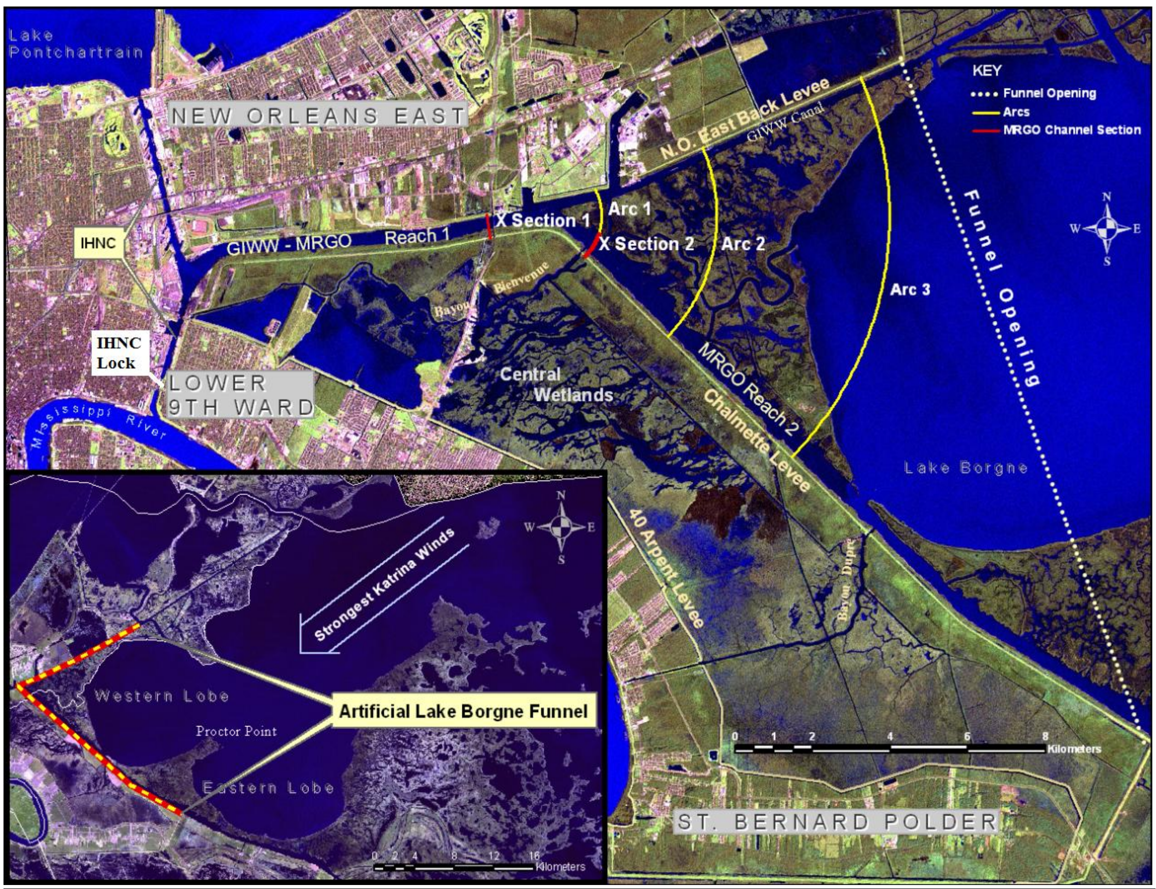


Figure 9. Juxtaposition of hurricane protection levees, marshes, polders, MRGO Reaches 1 and 2 and southern Lake Borgne where surge and waves were generated during passage of Hurricane Katrina (August 29, 2005).

Widespread wetland loss occurred initially as dredging took place within the canal footprint and adjacent wetlands were buried under up to 2 m of spoil along the south or west bank. Post-construction mortality of wetlands in the BMC and throughout the Pontchartrain Basin was dramatic (Shaffer et al. 2009). Especially pronounced was the loss of over 10,000 acres of cypress forests, and almost all freshwater and low salinity marsh in the CWU. Live oaks (*Quercus virginiana*) long the Bayou LaLoutre canal banks east of the MRGO appeared to die (Figure 10). This was evidenced by stark, bleached skeletal trunks and branches without any leaves, and was consistent with the salinity increase caused by the MRGO (Figure 10). Where fresh marshes and swamp were replaced by brackish and saline marshes, the bulk density (dry weight/unit volume) of surficial marsh soils taken from shallow cores is low over much of the CWU (< 0.2 grams per cubic centimeter, g/cm^3). Above- and below-ground vegetation biomass remains low compared to healthy marshes elsewhere in the BMC (Hunter et al. 2016).

Figure 10. Formerly "dead" live oak on the bank of B. LaLoutre with new growth on December 20, 2016.

Shoreline Erosion. Britsch and Dunbar (2016) showed that long-term retreat of western BMC shorelines accelerated after construction of the MRGO. Habitat mapping over time also indicated that ponds formed and expanded in the BMC during this period. Thomason (2016) found retreat rates of 2.8 and 6.7 m/y, respectively, at sites in the Eastern BMC while Martinez et al. (2009) reported 2.90 m/y (Figure 11). Wind speed and direction determined which shorelines experienced most erosion, but susceptibility was also affected by shoreline geology. Translation was reduced where more sand and shell was present in the soil profile. Trosclair (2013), however, measured up to 62 m of retreat on the Lake Borgne shoreline after Hurricane Isaac.

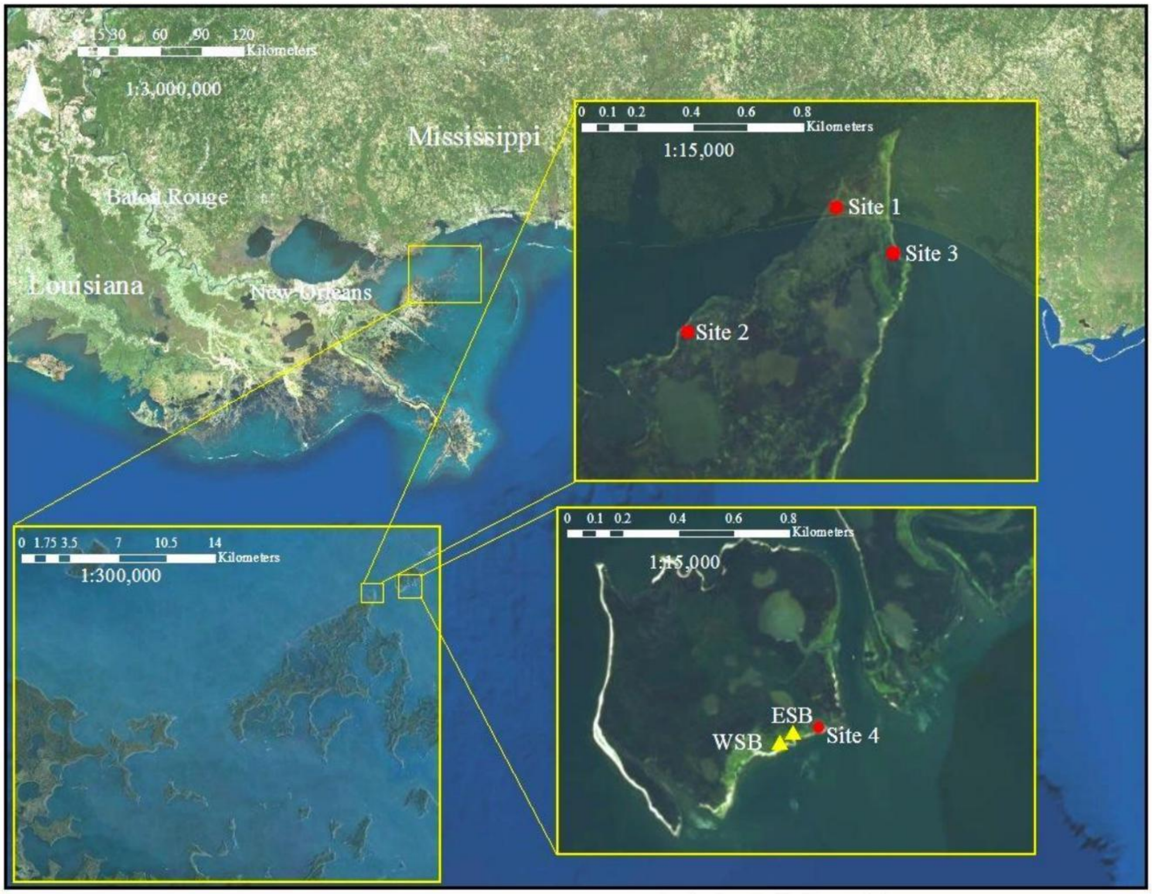


Figure 11. Study sites in the eastern Biloxi marshes used by Thomason 2016.

Shoreline marsh properties that contribute to erodability include marsh type, soil composition (% sand, organic matter) and depth of rooting. The presence or absence of sand or shell beaches is also important. A shell berm can reduce shoreline retreat as it grows higher and wider, and begins to transform the typical marsh scarp into a sloping beach face (Schwimmer 2001; Wilson and Allison, 2008; Trenhaile, 2009; Trosclair, 2013; Karimpour et al., 2015). Marsh edge vegetation captures sediment put into suspension by waves in Lake Borgne or Chandeleur Sound so that lake-margin marshes tend to be higher and more consolidated that those farther inland. This hardens the marsh edge, making it less vulnerable to erosion during storms (Howes et al., 2010; Anderson et al., 2011). Vegetated marsh platforms also attenuate wave energy more effectively than non-vegetated flats (Moller and Spencer, 2002). Cold fronts during the winter months build wave energy in the larger water bodies that can mobilize bottom sediments and produce both high sediment concentrations and wind tides high enough to ensure that lake-rim marshes aggrade at a higher rate than those in the interior (Turner et al., 2006; Baumann 1980; Reed 1989). This tends to preferentially increase elevation and consolidation at the lake rim if edge erosion is not too rapid, and especially where shell or sand has accumulated into berms and beaches. Waves that approach the shoreline of a shallow bay are both depth- and fetch limited. Depth-limited waves are steeper and fetch-limited waves have a shorter period than swell incident on Gulf beaches. Though generally small in amplitude, such locally-generated seas readily erode shoreline marsh scarps that rarely exceed 0.5 m in elevation (Fagherazzi, 2007; Trosclair, 2013). On the other hand, hurricane-driven waves riding on several meters of storm surge may not even break at the marsh edge but on man-made features like spoil banks and levees (Bendoni et al., 2016).

Shell beaches backed by berms more than a meter high once characterized both the Chandeleur Sound and Lake Borgne facing shorelines of the BMC, with oyster shell on the Sound side and Rangia clam shell deposits on the Lake Borgne side (Figure 12). Wave-induced winnowing of modern and paleo oyster reefs and beds, when coupled with wave run-up onto marsh platforms, concentrates shells on marsh edges, producing a sloping beach profile that absorbs wave energy. These shells armor shorelines and can reduce erosion, depending upon the shell abundance and consolidation of the marsh substrate (Piazza et al., 2005; Rodriguez et al., 2014). Once shells are deposited, it is more difficult for them to become re-entrained and removed due to the way in which shells are stacked or imbricated on the beach face (Allen, 1984).

The Rangia clam (*Rangia cuneata*) is plentiful in low salinity bays of Atlantic and Gulf Coast estuaries. It generally occurs at salinities less than18 ppt, but is most abundant in oligohaline waters below 5 ppt, as it experiences less competition and predation at these levels. Rangia is an important component of estuarine food webs, providing forage for fishes, crabs, shrimp, and waterfowl. It was also a favored menu item for native Americans during the 3000 years that they visited BMC marshes prior to European colonization, as is indicated by the numerous shell piles or middens they left in the BMC (Figure 12).

Rangia grew in densely populated beds distributed across the muddy bottom of Lake Borgne prior to the salinity increase caused by the MRGO. Like the oyster, the clam also filters large volumes of water, clearing it of turbidity when winds are calm. Loss of the clam population cut off the source of new shell to berms on the Lake Borgne shoreline of the Western BMC and this undoubtedly accelerated shoreline retreat. Studies conducted in 1969-1972 (Tarver and Dugas 1973), 1978-1980 (Sikora and Sikora 1982) and 1982-1983 (Poirrier et al. 1984) indicated declines in large clams (> 20 mm) in Lake Pontchartrain from 1954 baseline densities (Figure 13). This drop was attributed to intensive commercial shell dredging that removed the clams but also fluidized the bottom of the lake, limiting recruitment (USACE 1987). Densities increased to 1954 levels after dredging was stopped in 1990, but large clams were still absent from a 250 km^2 area of Lake Pontchartrain subject to regular stratification caused by saltwater intrusion from the MRGO (Abadie and Poirrier 2000).

The post-dredging increase in large clam density from 1996 through 2000 was regarded as a return to normal conditions. However, this recovery was abruptly reversed by a 96% population decrease between 2000 and 2001, after the extreme drought of 1998-2000 gave rise to more extensive stratification and spread of high salinity bottom water (Figure 13). *Rangia* can survive at high salinities so Poirrier and Caputo (2015) determined that the precipitous population decline was not a direct result of high salinity but, instead, to overgrowth by, and competition from the hooked mussel, *Ischadium recurvum*. Sustained periods of higher salinity in Lakes Borgne and Pontchartrain appear to favor establishment of a different benthic community. Salinities have fallen in both lakes since 2009 when the MRGO was dammed, and Rangia clam populations in Lake Pontchartrain and Lake Borgne are rebounding.

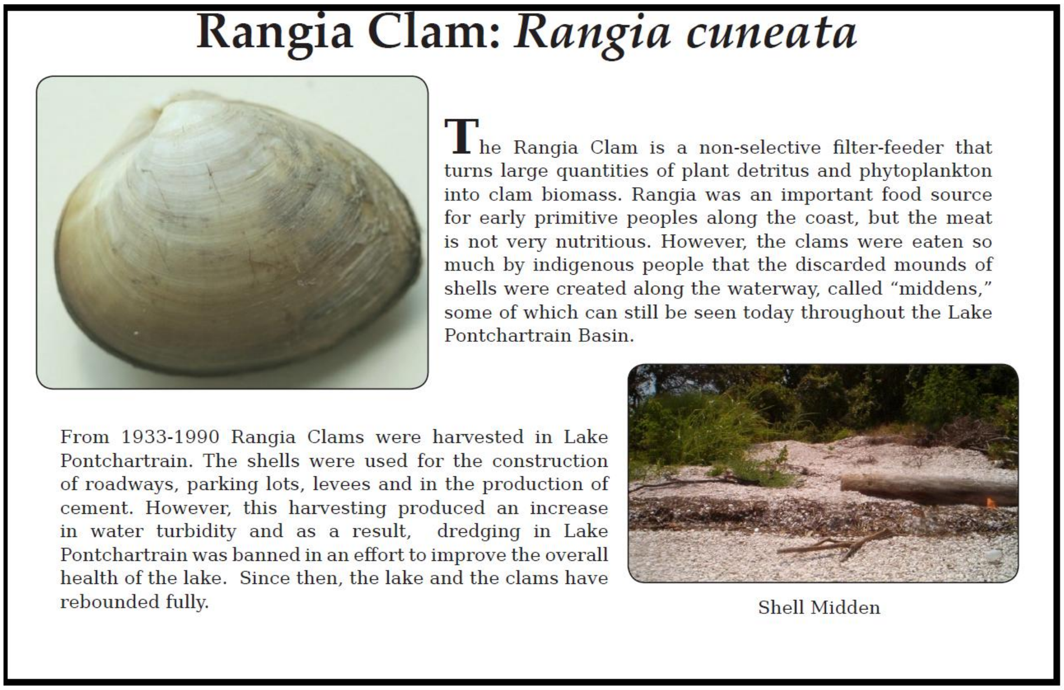


Figure 12. Rangia clams are typically no more than 3 cm wide and live in muddy bottoms of oligohaline estuarine lakes and bays.

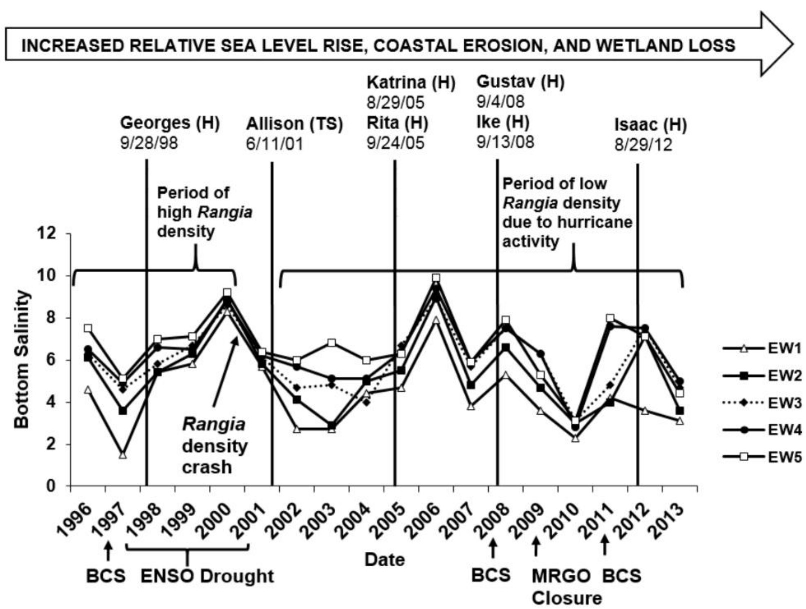


Figure 13. Bottom water salinity and *Rangia cuneata* density in Lake Pontchartrain over time (Poirrier and Caputo 2015).

Poirrier (2015) produced a conceptual diagram showing how a number of factors have affected *Rangia* populations in the Lake Pontchartrain Basin since shell dredging stopped (Figure 14). Hurricane waves fluidize bottom mud and bury clams. Low dissolved oxygen on the bottom also impacts *Rangia* populations following openings of the Bonnet Carre

Spillway, which convey river water with high nutrient concentrations into the lakes, reducing salinity, but also causing the algal blooms that are associated with oxygen depletion in bottom waters (Figure 14).

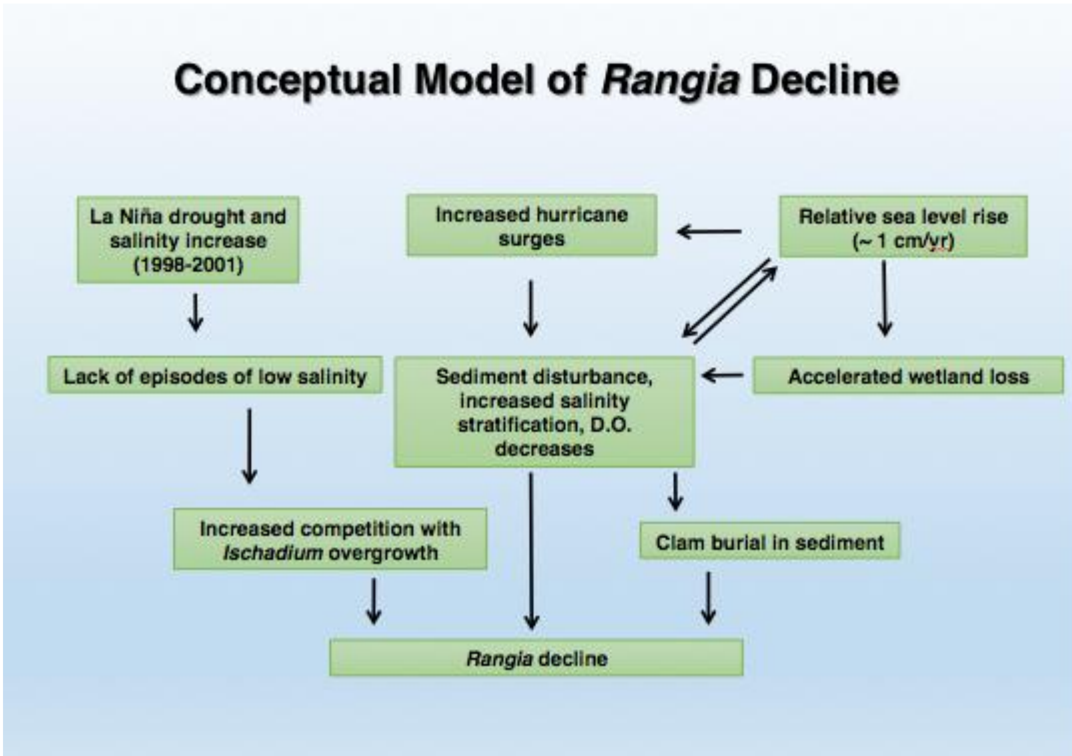


Figure 14. Factors affecting Rangia decline in Lake Pontchartrain and adjacent low salinity areas from Porrier 2015.

Low salinity conditions in Lake Borgne prior to the construction of the MRGO provided optimal habitat conditions for *Rangia* populations in the Lake (Michael Porrier, personal communication). Lake Borgne shores had a nearly continuous berm composed of *Rangia* shells along its margins prior to MRGO. That shoreline berm protected the western Biloxi marshes as long as a healthy and abundant clam population existed that could continually supply shells for the berm. Loss of the *Rangia* population led to the degradation of the berms and the rapid shoreline retreat that now characterizes the Lake Borgne shore, and is the target of the Pt. aux Marchettes CWPPRA Project (Figure 7). We recommend stabilizing this shoreline with a rock revetment until the Rangia population can fully rebound and resume the supply of shell to natural berms. This linkage illustrates how the post-MRGO recovery sets the stage for other beneficial projects that might be proposed in a revised CMP17.

SUSTAINABILITY OF THE BILOXI MARSHES FROM CRMS DATA

In 2003, the Louisiana Office of Coastal Protection and Restoration (OCPR) and the U.S. Geological Survey (USGS) began to build the ambitious Coastwide Reference Monitoring System (CRMS) as a systematic way to monitor and evaluate effectiveness of coastal restoration projects. The CRMS network today provides hourly hydrology readings (salinity, water level and water temperature), and less frequent data on species composition, soil properties (% organic, bulk density, accretion), as well as surface elevation changes at 390 stations across the Louisiana coast.

Ten CRMS sites were established in the Biloxi marshes in 2007 and 2008 (Figure 15). CRMS 4551 to the north, and CRMS 4557 to the south are on either side of Bayou LaLoutre near the MRGO rock dam. Similarly, CRMS 4548 and CRMS 3800 are located inland of the rock dam on the north and south sides of the MRGO, respectively. CRMS4572 and CRMS4596 are situated at the northern tip of the contiguous, Western BMC while stations CRMS0108 and CRMS1024 are on the line between the Eastern and Western Biloxi marshes. The northeastern extent of the non-contiguous Eastern BMC, are monitored at sites CRMS0003 and CRMS1069 (Figure 15).

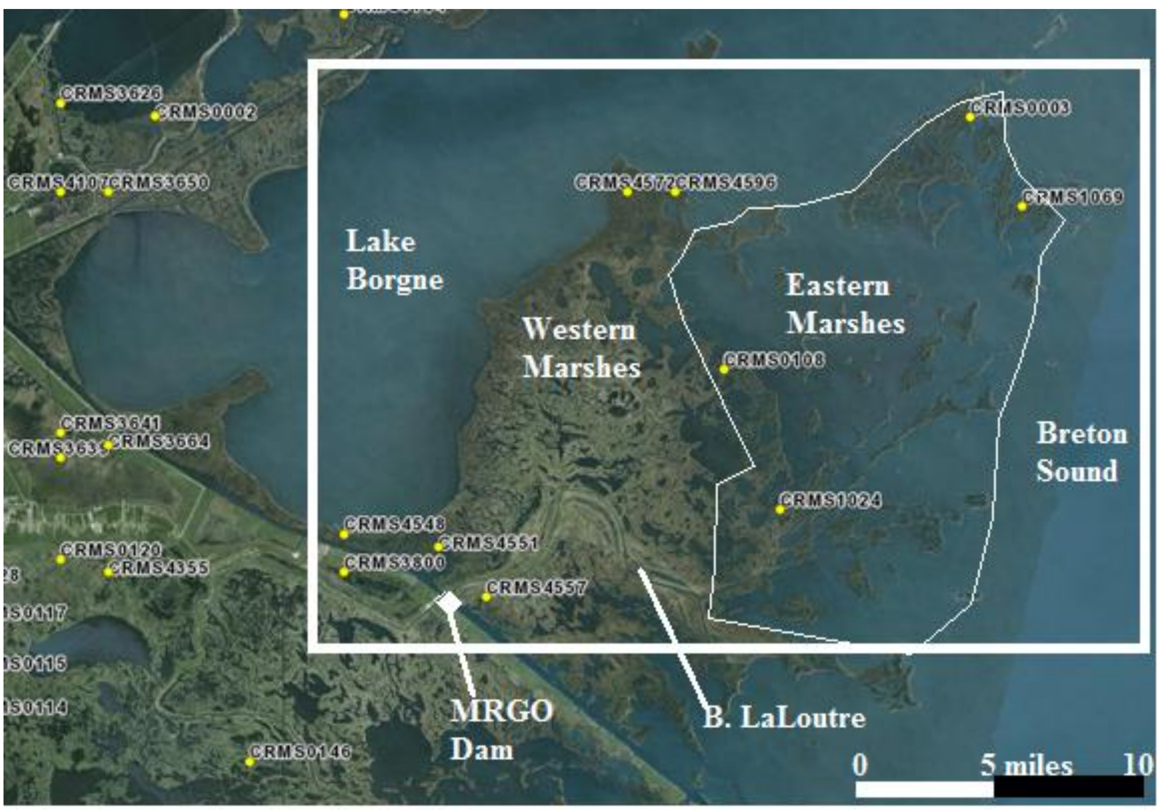
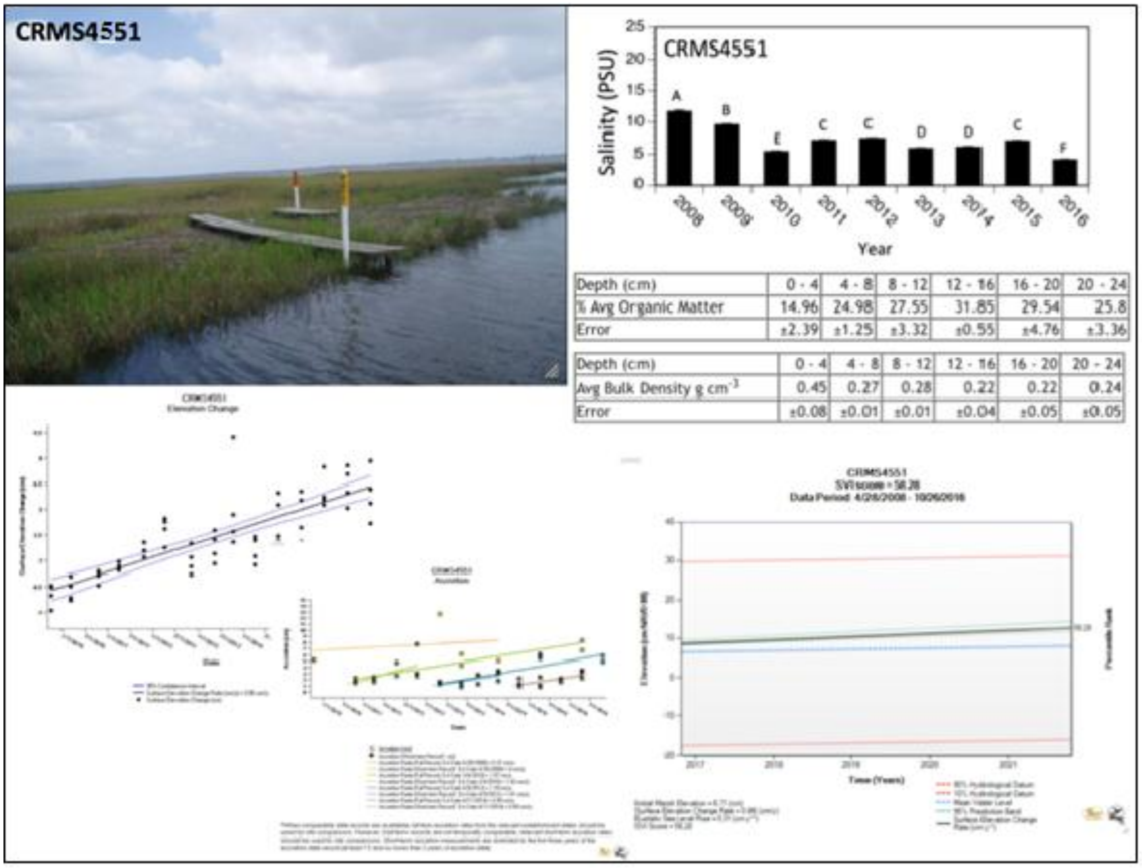


Figure 15. Biloxi Marsh showing eastern and western marshes, MRGO, MRGO Rock Dam, Bayou LaLoutre ridge and 10 CRMS stations, each with about 9 years of data.

*CRMS 4551***.** The CRMS4451 site is located approximately 1.9 miles north of the intersection of Bayou La Loutre and the MRGO (Figure 15). The surrounding region is composed of 33% wetlands and 67% open water as of 2012. Salinity at CRMS4551 was highest during 2008 and 2009 before the MRGO closure, and significantly lower thereafter (Figure 16, upper right panel).

Recent salinity at the sight ranged from 2.2-12.4 PSU with a mean of 5.6 PSU from October 2015 to October 2016, during which time water levels ranged from -1.5 to 3.6 ft NAVD88 with a mean of 0.76 ft NAVD88. Flooding at the site ranged from 35.9% to 79.1% with a mean of 55.2% for all years combined (Table 3). The site has a marsh vegetation type of Polyhaline Oystergrass dominated by *Spartina alterniflora* Loisel with 69.5% coverage (Visser et al. 1998, 1999, 2000). Bulk density of the soils was 0.45 g/cm^3 in the top 4 cm, but then dropped to range from 0.22-0.28 g/cm^3 for the rest of the 24 cm soil profile (Figure 16). Percent organic matter was 15.0% in the top 4 cm, then increased to range from 25.0 to 31.8% for the remaining soil profile. Accretion was taken over four time periods and ranged from 0.37-1.18 cm/y, with the highest rate following Hurricane Katrina, and a long-term average of 0.9 ± 0.18 cm/y. Wetland surface elevation at the site, as measured by the RSET rod technique (Cahoon et al. 2002), was increasing by 0.86 cm/y (Figure 16).

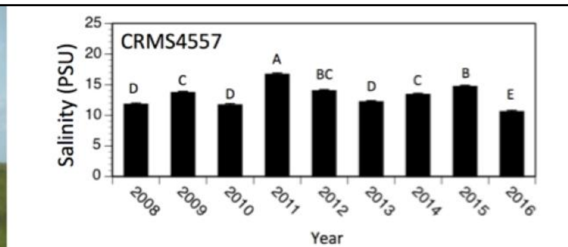


Depth (cm)	0 - 4	4 - 8	8 - 12	12 - 16	16 - 20	20 - 24
% Avg Organic Matter	14.96	24.98	27.55	31.85	29.54	25.8
Error	±2.39	±1.25	±3.32	±0.55	±4.76	±3.36

Depth (cm)	0 - 4	4 - 8	8 - 12	12 - 16	16 - 20	20 - 24
Avg Bulk Density g cm^{-3}	0.45	0.27	0.28	0.22	0.22	0.24
Error	±0.08	±0.01	±0.01	±0.04	±0.05	±0.05

Figure 16. Data from CRMS 4551.

CRMS 4557. The CRMS 4557 site is located approximately 1.7 miles east-southeast of the point of intersection of Bayou LaLoutre and the MRGO (Figure 15). In contrast to CRMS 4551, CRMS 4557 is located south of the MRGO Rock Dam. Mean annual salinity was greater than 10 ppt before the 2009 closure, and did not change significantly after the closure (Figure 17, upper right panel). From October 2015 to October 2016, salinity ranged from 3.9 to 26.6 ppt with a mean of 12.1 ppt, and water levels ranged from -1.02 to 3.86 ft NAVD88 with a mean of 0.66 ft NAVD88. Flooding at the site ranged from 18.2% to 59.9% with a mean of 36.6% for all years combined (Table 3). The site is dominated by *Spartina alterniflora* Loisel with 69.5% coverage and a marsh vegetation type of Polyhaline Oystergrass (Visser et al. 1998, 1999, 2000). Bulk density steadily decreased through the soil profile with 0.26 g/cm^3 in the top 4 cm and decreasing to 0.14 g/cm^3 by the bottom 20-24 cm segment (Figure 17). Percent organic matter increased through the soil profile, with 24.3% in the top 4 cm increasing to 49.8% by the 16-20 cm segment. Accretion, measured over four intervals, increased from 0.62 to 1.78 cm/y, with a mean of 1.27±0.28 cm/y. Surface elevation increased at a mean rate of 0.98 cm/y (Figure 17).



Depth (cm)	0 - 4	4 - 8	8 - 12	12 - 16	16 - 20	20 - 24
% Avg Organic Matter	24.28	32.44	38.1	36.12	49.82	47.46
Error	±6.7	±5.24	±11.68	±8.55	±17.38	±16.6

Depth (cm)	0 - 4	4 - 8	8 - 12	12 - 16	16 - 20	20 - 24
Avg Bulk Density g cm^{-3}	0.26	0.22	0.21	0.18	0.15	0.14
Error	±0.1	±0.02	±0.03	±0.05	±0.04	±0.08

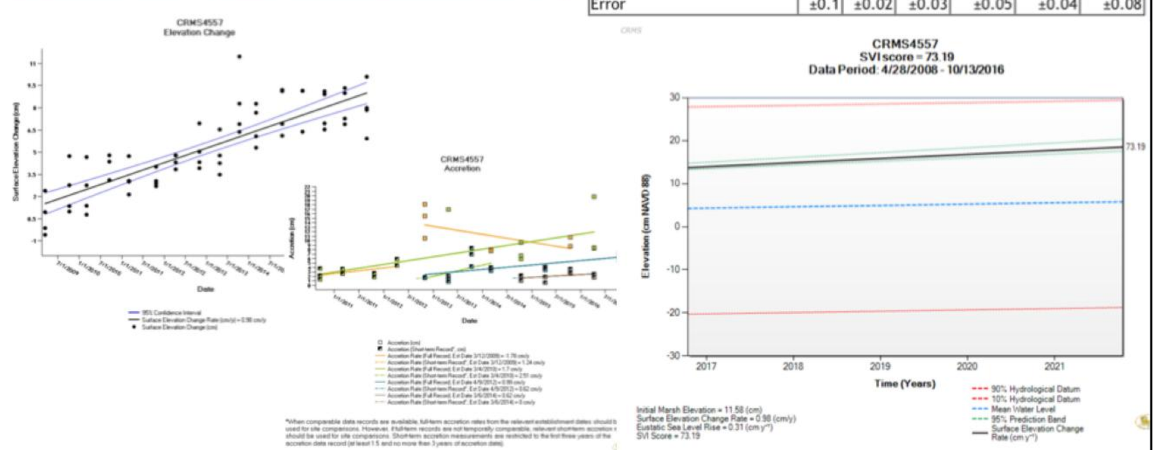


Figure 17. Data from CRMS 4557.

CRMS 4572. The CRMS4572 site is located approximately 1.0 miles northeast of the point of entry of Bayou La Fee into Lake Borgne (Figure 15). Wetlands comprise 87% of the area as of 2008, with the balance as open water. Salinities were significantly lower for most years compared to 2009, but only for 2010 and 2013 when compared to 2008 (Figure 18, upper right panel). It should be noted that the 2016 data set is incomplete and does not include the fourth quarter of the year. Recent Salinity from September 2015 to September 2016 had a mean of 8.2 ppt and ranged from 1.5 to 27.2 ppt. Water levels during that time ranged from -1.88 to 2.78 ft NAVD88 with a mean of 0.73 ft NAVD88. Flooding ranged from 23.6% to 55.9% with a mean of 42.2% for all years combined at this site (Table 3). The site has a marsh vegetation type of Polyhaline Oystergrass dominated by *Spartina alterniflora* Loisel with 62.0% coverage (Visser et al. 1998, 1999, 2000). Bulk density was 0.46 g/cm^3 at the 1-4 cm segment, 0.51 g/cm^3 at the 4-8 cm segment, and then decreased to 0.23-0.24 g/cm^3 for the next three lower segments (Figure 18). Percent organic matter was 15.7% in the top segment, followed by 9.8%, 27.7%, 33.0%, 33.2% and then 23.2% for the last 20-24 cm segment. Accretion ranged from 0.50 cm/y to 0.98 cm/y during the time intervals measured, with a mean of 0.73±0.13 cm/y. Marsh surface elevation has increased by 0.74 cm/y since measurements began in 2009 (Figure 18).

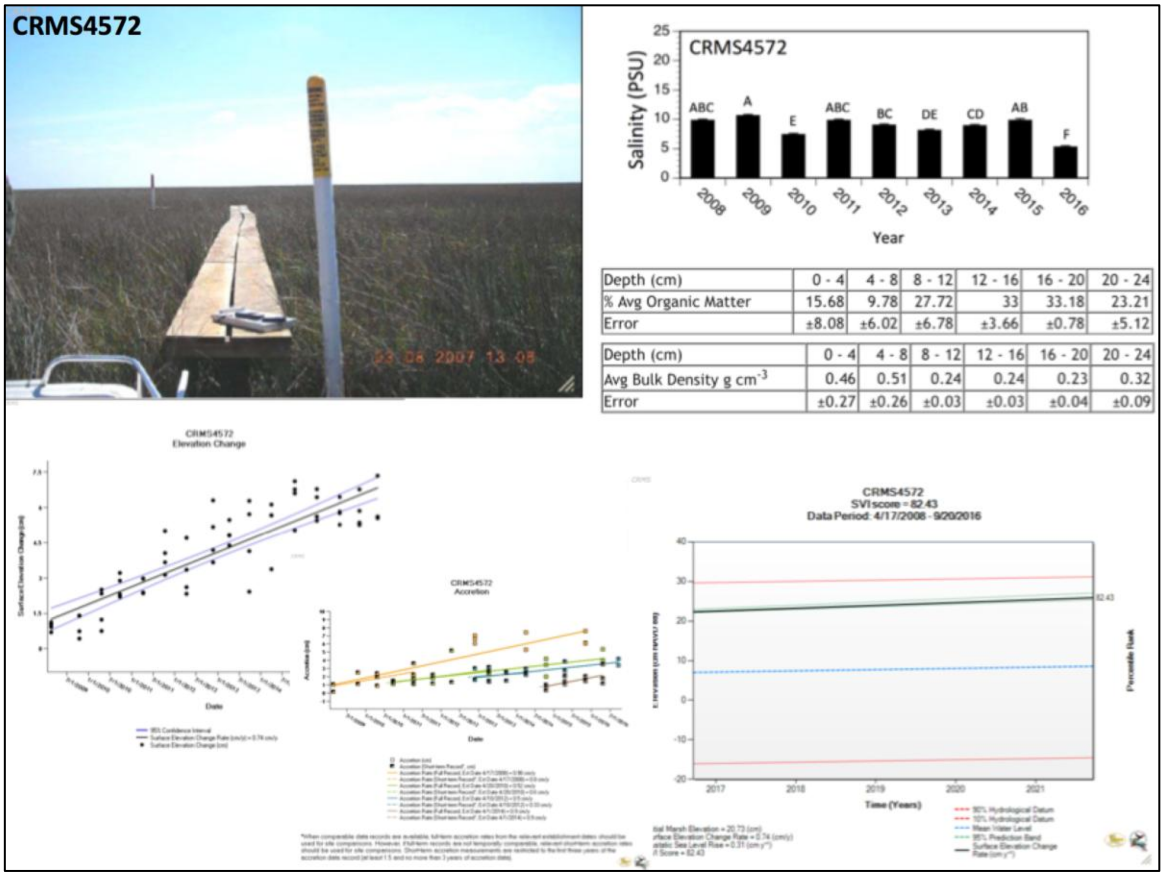
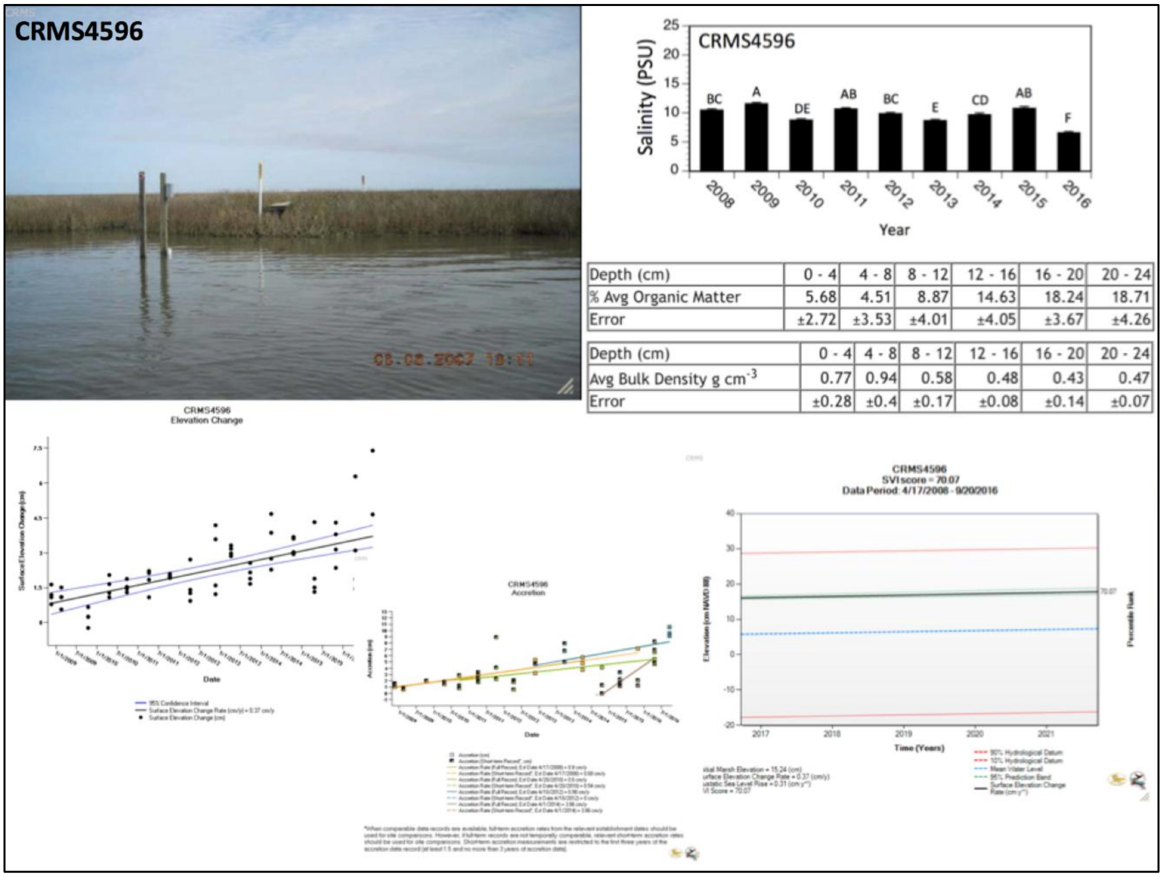


Figure 18. Data from CRMS 4572.

CRMS 4596. The CRMS4596 site is located approximately 0.5 miles southeast of the point of entry of the Mosquito Inlet into Mississippi Sound (Figure 15). As of 2012, wetlands comprised 86% of the area with the rest as open water. Mean annual salinity was lower for most years compared to 2009, but as with CRMS 4572, only salinity during 2010 and 2013 were significantly lower than during 2008 (Figure 19, upper right panel). Salinity from September 2015 to September 2016 ranged from 1.4 to 32.4 ppt with a mean of 9.7 ppt, and water levels ranged from -1.71 to 3.57 ft NAVD88 with a mean of 0.86 ft NAVD88. Mean annual flooding ranged from 19.7% to 66.4% with a mean of 35.6% for all years combined (Table 3). The site is dominated by *Spartina alterniflora* Loisel with 44.5% coverage and a marsh vegetation type of Polyhaline Oystergrass (Visser et al. 1998, 1999, 2000). Bulk density was high, with 0.77 and 0.94 g/cm^3 in the top two 4 cm segments, decreasing to 0.43 g/cm^3 by the 16-20 cm segment (Figure 19). Percent organic matter was only 5.7% and 4.5% in the top two segments, increasing to 18.7% by the last segment (20-24 cm). Accretion ranged from 0.60 to 0.98 cm/y during the first three measurement intervals, but was 3.86 cm/y during the most recent interval starting April 2014, with an overall mean of 1.56±0.77 cm/y. The elevation of the wetland surface increased at a rate of 0.37 cm/y (Figure 19).

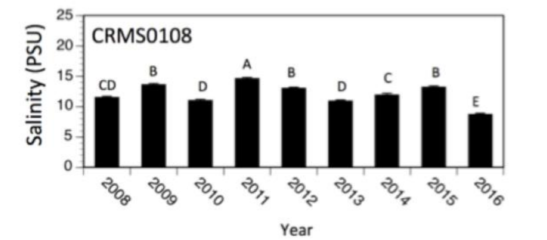


Depth (cm)	0 - 4	4 - 8	8 - 12	12 - 16	16 - 20	20 - 24
% Avg Organic Matter	5.68	4.51	8.87	14.63	18.24	18.71
Error	±2.72	±3.53	±4.01	±4.05	±3.67	±4.26

Depth (cm)	0 - 4	4 - 8	8 - 12	12 - 16	16 - 20	20 - 24
Avg Bulk Density g cm^{-3}	0.77	0.94	0.58	0.48	0.43	0.47
Error	±0.28	±0.4	±0.17	±0.08	±0.14	±0.07

Figure 19. Data from CRMS 4596.

CRMS 0108. Site CRMS0108 is located approximately 0.8 miles southwest of the entrance of Redfish Bayou into Bay Boudreau (Figure 15). Wetlands comprise 58% of the land and water 42% as of 2012. There was not a significant impact on salinities at this site from the MRGO closure in 2009 (Figure 20, upper right panel). Salinity from September 2015 to September 2016 ranged from 4.6 to 27.8 ppt with a mean of 11.6 ppt, and water levels ranged from -1.43 to 3.55 ft NAVD88 with a mean of 0.66 ft NAVD88. Annual flooding ranged from 7.0% to 41.6% with a mean of 25.5% for all years combined (Table 3). The site has a marsh vegetation type of Polyhaline Oystergrass dominated by *Spartina alterniflora* Loisel with 62.0% coverage (Visser et al. 1998, 1999, 2000). Bulk density was 0.23 g/cm^3 at the surface segment, increased to 0.33 and 0.31 g/cm in the lower segments before steadily decreasing to 0.20 g/cm^3 by the last segment (20-24 cm). Percent organic matter was lowest (19.3%) at the 4-8 cm segment and increased to 32.7% by the last 20-24 cm segment. Accretion over the four time intervals ranged from 0.45 to 1.96 cm/y, with the highest accretion following hurricane Katrina, and an overall mean of 1.04±0.33 cm/y. Surface elevation increase at the site was 0.66 cm/y (Figure 20)



Depth (cm)	0 - 4	4 - 8	8 - 12	12 - 16	16 - 20	20 - 24
% Avg Organic Matter	23.14	19.33	23.29	28.39	31.41	32.73
Error	±3.92	±4.03	±3.8	±3.32	±3.79	±0.95

Depth (cm)	0 - 4	4 - 8	8 - 12	12 - 16	16 - 20	20 - 24
Avg Bulk Density g cm^{-3}	0.23	0.33	0.31	0.27	0.21	0.2
Error	±0.04	±0.02	±0.01	±0.03	±0.02	±0.04

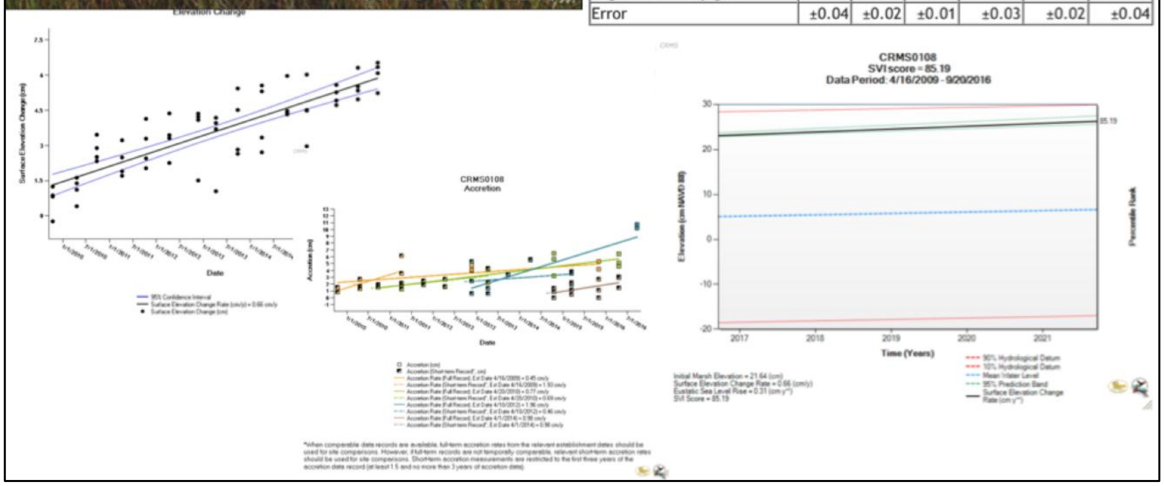


Figure 20. Data from CRMS0108.

CRMS 1024. The CRMS1024 site is located approximately 4.6 miles northeast of the intersection of Bayou Petre and Bayou la Loutre (Figure 16). The region consists of 60% wetlands as of 2012. Though there was significantly lower mean annual salinity during 2010 compared to 2008 and 2009, however, salinities rose significantly the following years (Figure 21, upper right panel). Recent mean salinity was 13.6 ppt and ranged from 4.7 to 12.3 ppt, and water levels during the same period from September 2015 to September 2016 had a mean height of 0.73 ft NAVD88 and ranged from -1.63 to 2.91 ft NAVD88. Flooding at the site ranged from 18.6% to 46.7% with a mean of 30.0% (Table 3). The site is dominated by *Spartina alterniflora* Loisel with 80.0% coverage and a marsh vegetation type of Polyhaline Oystergrass (Visser et al. 1998, 1999, 2000). Bulk density generally decreased with depth, ranging from 0.41 and 0.45 g/cm^3 at the first two segments to 0.31 g/cm^3 at the last segment (20-24 cm). Percent organic matter ranged from 16.5% to 19.0%. Accretion increase ranged from 0.76 to 1.56 cm/y over the four measurement periods, with a mean of 1.11±0.17 cm/y, and surface elevation increased by 0.80 cm/y (Figure 21).

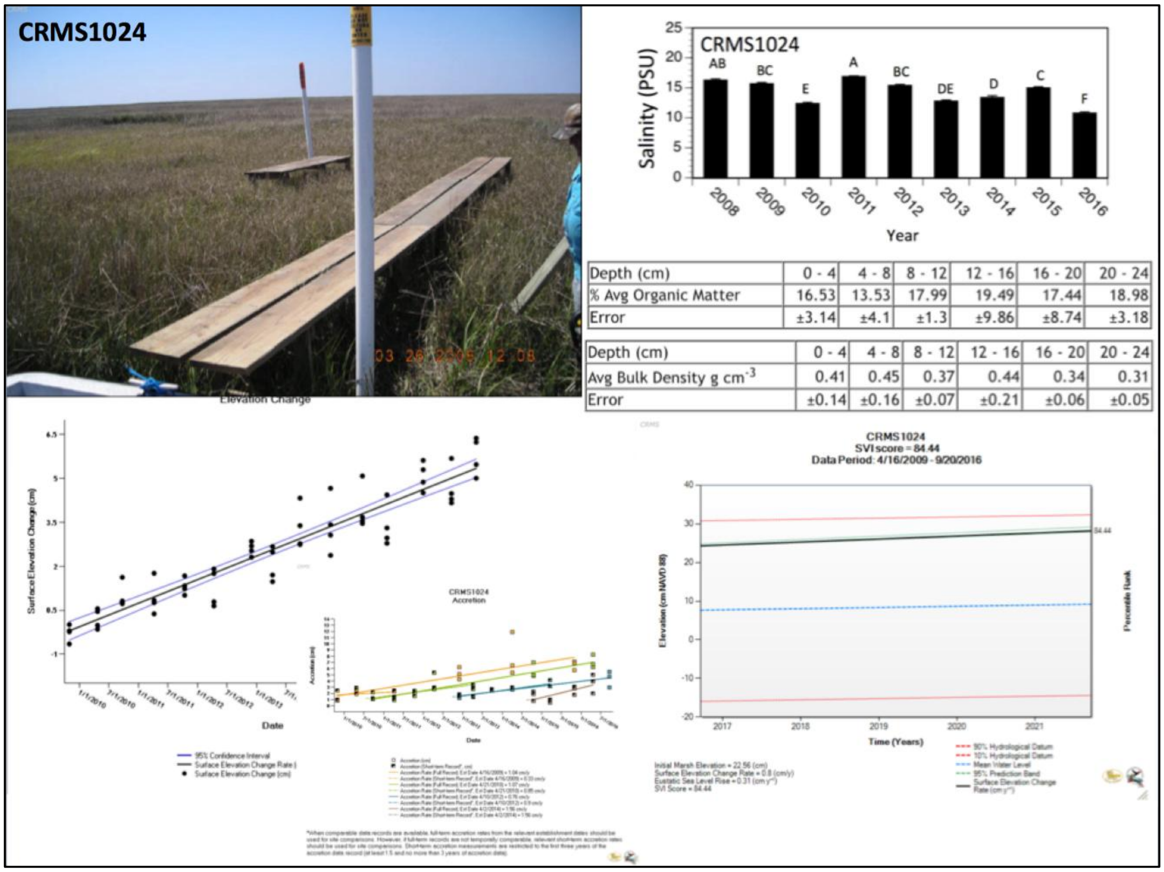


Figure 21. Data from CRMS 1024.

CRMS 0003. CRMS0003 site is located approximately 2.7 miles northeast of the entrance of Turkey Bayou into the Mississippi Sound in the most northeastern extent of the Biloxi marshes (Figure 15). The surrounding area consists of 33% wetlands and 67% open water. As at CRMS 1024, there was significantly lower mean annual salinity during 2010 compared to 2008 and 2009, but salinities rose significantly the following years (Figure 22, upper right panel). Salinity from September 2015 to September 2016 ranged from 2.4 to 33.4 PSU with a mean of 15.7 PSU, and water levels during the same period ranged from -2.2 to 3.3 ft NAVD88 with a mean of 0.67 ft NAVD88. Flooding ranged from 5.5% to 28.4% with a mean of 15.6% for all years combined at this site (Table 3). The site has a marsh vegetation type of Polyhaline Oystergrass dominated by *Spartina alterniflora* Loisel with 62.5% coverage (Visser et al. 1998, 1999, 2000). Bulk density was highest at the surface segment (0.71 g/cm^3) decreasing to 0.54 g/cm^3 by the second to last segment (Figure 22). Organic matter content was lowest at the surface segment (5.2%), but ranged from 10.2 to 13.6% for the remaining segments. Accretion increase ranged from 0.46 cm/y to 1.21 cm/y during the four measurement periods, and had a mean of 0.86±0.15 cm/y. Surface elevation increased at the relatively low rate of 0.14 cm/y (Figure 22).

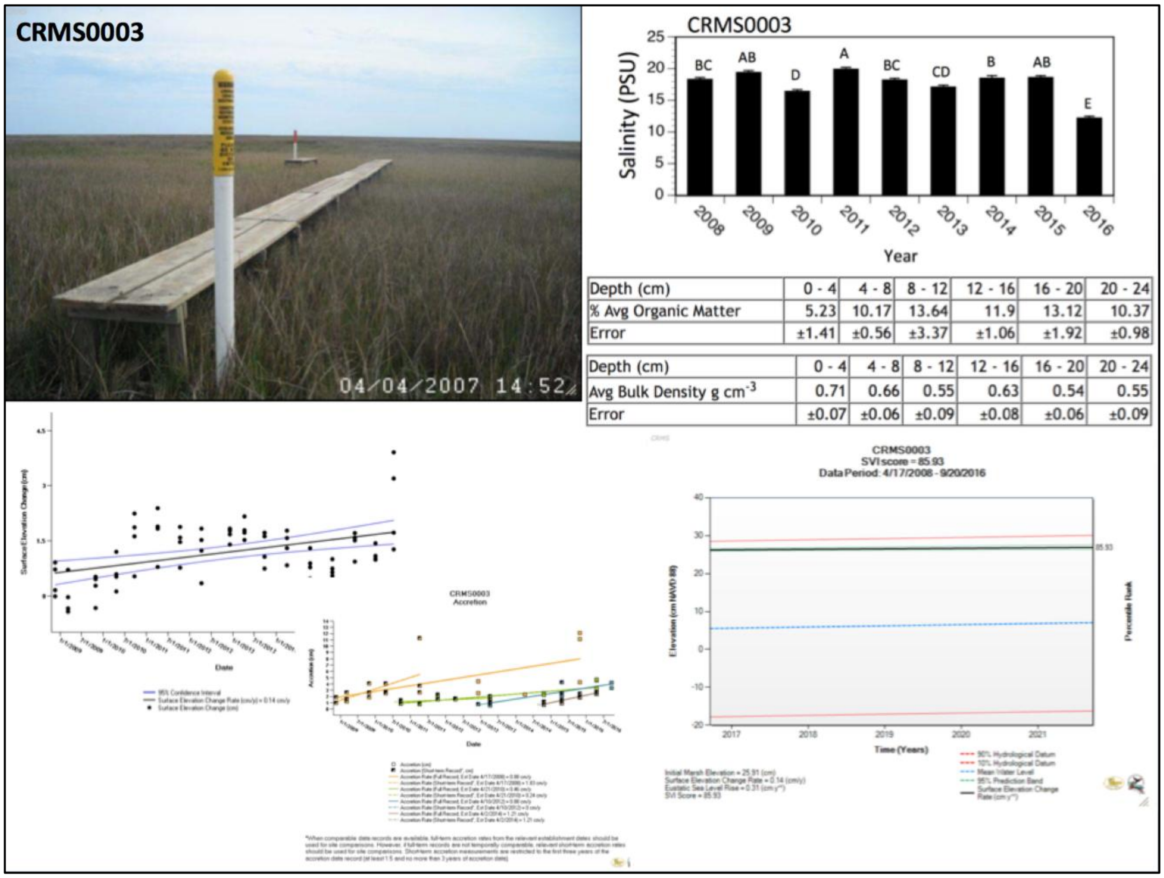


Figure 22. Data from CRMS0003.

CRMS 1069. The CRMS1069 site is located approximately 3.5 miles east of where Picnic Bayou enters into Northwest Jack Williams Bay in the most northeastern extent of the Biloxi marshes (Figure 15). The region consists of 61% wetlands with the balance as open water. Mean annual salinity was significantly lower during 2010 and 2013 compared to 2008 and 2009, but there was not a significant difference for the other years. Note that the 2016 data set is incomplete and does not include the fourth quarter of the year, and thus shouldn't be included in this analysis (Figure 23, upper right panel). Salinity ranged from 3.0 to 34.5 ppt with a mean of 16.9 ppt from September 2015 to September 2016. Water levels during the same period ranged from -1.17 to 3.22 ft NAVD88 with a mean of 0.73 ft NAVD88. Flooding ranged from 9.3% to 27.7% with a mean of 17.3% for all years combined (Table 3). The site is dominated by *Spartina alterniflora* Loisel with 70.0% coverage and a marsh vegetation type of Polyhaline Oystergrass (Visser et al. 1998, 1999, 2000). Bulk density ranged from 0.90 to 1.32 g/cm^3 in the top four segments, and then dropped to 0.60 g/cm^3 by the last segment (Figure 23). Percent organic matter content was very low, with 3.5 and 2.9% in the first two segments followed by increasing bulk density with depth with 11.4% by the last segment. Accretion was very high, ranging from 0.53 cm/y to 3.46 cm/y with a mean of 1.68±0.63 cm/y, however, surface elevation only increased at a rate of 0.13 cm/y (Figure 23).

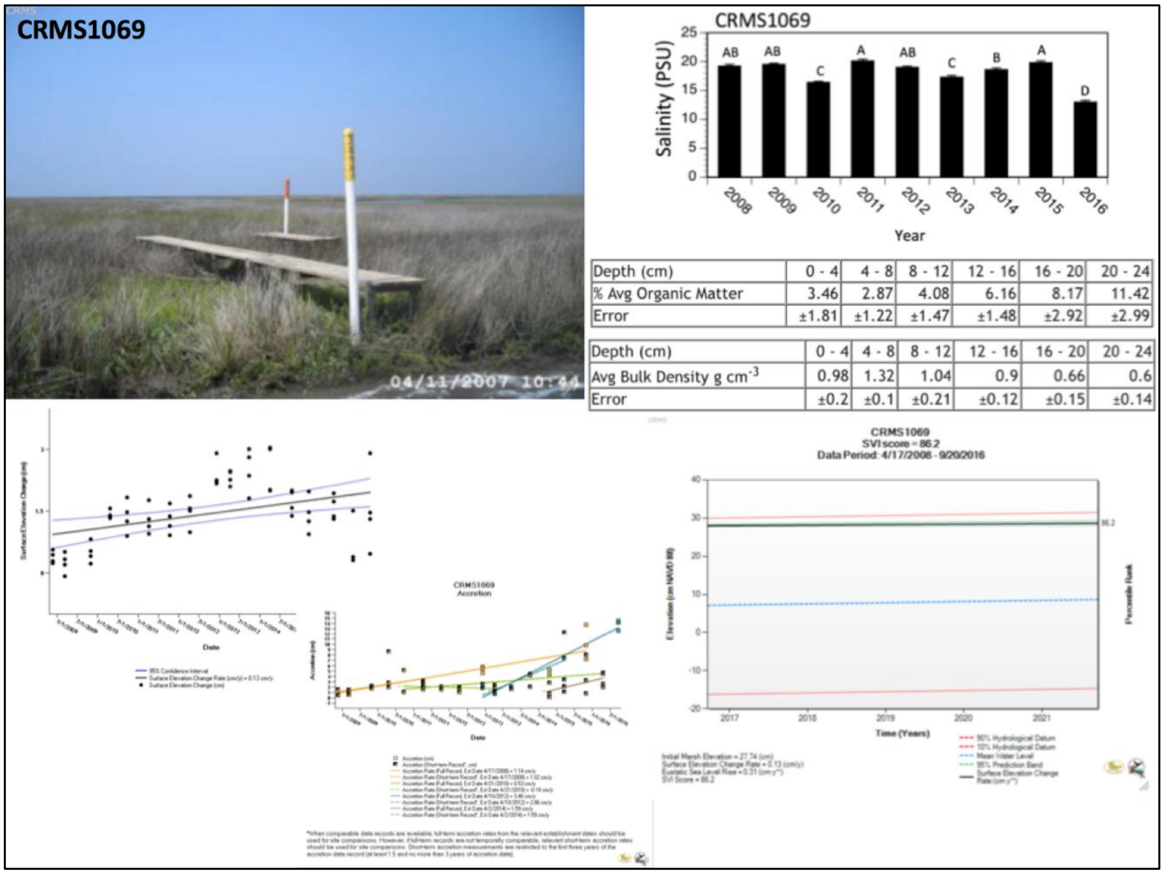


Figure 23. Data from CRMS 1069.

Table 3. Percent flooding at the CRMS sites in the Biloxi marshes.

Year	CRMS4551	CRMS4557	CRMS4572	CRMS4596	CRMS0108	CRMS1024	CRMS0003	CRMS1069
2008	39.2%	25.9%	40.1%	23.0%	7.0%	26.0%	12.0%	11.0%
2009	55.5%	36.0%	52.3%	29.8%	27.9%	31.5%	17.3%	21.7%
2010	45.5%	27.8%	50.7%	34.4%	24.1%	26.0%	13.4%	15.9%
2011	35.9%	18.2%	30.4%	19.7%	15.6%	18.6%	5.5%	9.3%
2012	57.0%	34.0%	55.9%	40.8%	33.6%	32.5%	12.6%	20.8%
2013	66.6%	49.0%	54.7%	52.1%	41.6%	46.7%	21.6%	25.9%
2014	49.2%	32.1%	23.6%	28.2%	16.4%	20.5%	12.1%	10.7%
2015	67.7%	48.2%	31.0%	49.6%	28.5%	29.9%	23.0%	18.9%
2016	79.1%	59.9%	46.6%	66.4%	33.3%	40.9%	28.4%	27.7%
All	55.2%	36.6%	42.2%	35.6%	25.5%	30.0%	15.6%	17.3%

CRMS 3800 & CRMS 4548. To focus on the effect of MRGO closure on salinity, salinity data from CRMS 3800 and CRMS 4548 sites on opposite sides of the MRGO north of the Rock Dam, and on nearby CRMS 4551 (Figure 15) were compared (Figure 24). Mean annual salinities at all three of these sites decreased significantly between 2008 and 2016.

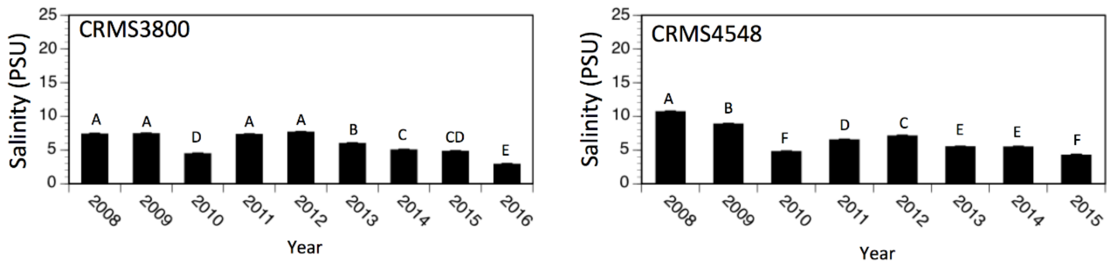


Figure 24. Mean annual salinity at CRMS3800 and CRMS4548 sites.

CRMS Synthesis

The frequency and duration of flooding of the BMC CRMS sites vary as much at a single site between years as do the 8-year means of different sites (Table 2). The range for all years, all sites, is that BMC marshes flooded between 7 and 79 percent of the time, with multi-year site means averaging 16 to 55 percent between site means. There is no long-term trend in flooding percentage. The continuity of wetland cover in the areas around the CRMS sites ranged from 33 to 87% with a mean of 62.5±7.7%. Salinity exhibited a spatial gradient. Lower salinities occurred in the Western BMC around Lake Borgne (CRMS 4572, 4596, 4557, 4551, 4548) while Eastern BMC marshes were saltier (CRMS 0108, 1024, 0003, 1069) (Table 3). The closure of MRGO lowered the mean salinity of CRMS 4551 (7.2 ppt) relative to CRMS 4557 (13.3 ppt) by about 50%. These sites are close to each other (Figure 15), but on opposite sides of the MRGO Rock Dam (Table 3).

Bulk densities at the CRMS sites are indicative of stable and robust wetland soils responding successfully to RSLR. Bulk density in the upper 4 cm of the soil column were reflective of wetland soil accretion and shallow consolidation dynamics, as will be discussed. High bulk density has been shown to increase plant recovery and productivity (DeLaune and Pezeshki 1988). Mean bulk density at the top of the marsh soil profile is generally greatest in salt marshes and averages 0.24±0.11 g/cm^3 for all Louisiana salt marshes, with progressively lower values from brackish (0.16±0.07 g/cm^3) to fresh (0.08±0.05 g/cm^3; Nyman et al. 1990) marshes. *Spartina alterniflora* marsh requires a soil with a minimum bulk density of approximately 0.20 g/cm^3 for vegetation to thrive (DeLaune et al. 1990; Delaune and Pezeshki 2003).

Bulk densities in the upper 4 cm of BMC marsh soils range from 0.23 to 0.98 g/cm^3. The lowest values (CRMS 4557 and 0108) are still average when compared to all healthy Louisiana salt marshes. The mean at all BMC sites is 0.5 g/cm^3, however, more than twice the average (Table 3). Values of 0.40 g/cm^3 or greater occur elsewhere in coastal Louisiana only on the bay side of barrier islands and where recently introduced river sediment is available (Perez et al. 2000; Day et al. 2011). These are firm, walkable marshes nourished by regular sediment inputs from Lake Borgne and Breton Sound.

Highest bulk densities are found at CRMS 0003 and 1069 on the northernmost island of the fragmented Eastern BMC (Figure 15). These are the highest marshes in the BMC, averaging about 36 cm high relative to the NAVD88 datum, and more than 12 cm above mean sea level (MSL) for the 2008 to 2016 interval (Table 3). They also have the highest salinities, with a mean around 18 ppt. The remainder of the BMC marshes range from 16 to 27 cm high relative to the NAVD88 datum, and are subject to mean annual salinities from 7 to 14 ppt. CRMS 4557 and 0108, the sites with the lowest bulk densities, flood less than other sites at similar elevations, 37 and 26 percent, respectively (Figure 24), and have the highest organic matter percentages of all BMC marsh soils (Table 3), These sites appear to lack local tidal connectivity for mineral sediment input, but are maintaining elevation within the tidal frame by retaining organic matter, and are aggrading at above average rates, 0.66 and 0.98 cm/y, for CRMS 4557 and 0108, respectively.

Salt marshes that lack adequate sediment supply and are dropping through the tidal frame typically have bulk densities lower than 0.2 g/cm^3. They are candidates for early conversion to open water as salt marshes do not exhibit the floating adaptation found in submerging intermediate and fresh marshes. But all marshes are capable of maintaining elevation in the face of subsidence and ESLR by capturing sediment, primarily silt and clay, but also by amending the soil column with living and dead roots and other organic plant material.

Marsh soil accretion rates in the BMC ranged from 0.7 to 1.7 cm/y, averaging 1.2 cm/y (Table 3). The mean change in soil surface elevation was lower though positive in all cases, ranging from 0.13 to 0.98 cm/y, and averaging 0.6 cm/y. The highest accretion rate, 1.7 cm/y, was measured at CRMS 1069, which was both the highest marsh and the one with the lowest change in surface elevation. Tidal marshes cannot build up beyond the upper bound of the tidal frame. In sediment-rich marshes, high marshes that flood infrequently may still capture sediment efficiently that enters from the bays during storms. On the other hand, such marshes also experience greater loading, drainage, and drying on low tides. All of these factors drive shallow consolidation, also called shallow subsidence (SS). So, substantial accretion of mineral sediment occurs at site 1069, but consolidation, estimated at 1.6 cm/y, is also enhanced so that marsh aggradation, which is the difference between accretion and surface elevation change, averages only 0.13 cm/y. It may be an indication of the resilience and sustainability of such marshes that nearby CRMS 0003, which is as high as CRMS 1069 (Table 3), the same surface elevation increase was achieved with only half the accretion, 0.9 cm/y, and still has a high bulk density (0.7 g/cm^3).

Increasing eustatic sea level rise is critical to restoration planning for deltaic wetlands worldwide, because it may be augmented by even higher rates of subsidence, as is true in the BMC. Current ESLR is between 2-3 mm/y (Miller & Douglas 2004; FitzGerald et al. 2008; Rahmstorf 2007; Williams 2013; Karegar et al. 2015; Jankowski et al 2017), and there is a strong scientific consensus that the rate of ESLR will accelerate in the future (Meehl et al. 2007; McCarthy et al. 2009). The USGS estimates ESLR in the Gulf, as determined from satellite altimetry, is currently about 0.2 cm/y.

Other factors contribute to the RSLR experienced by the BMC marsh, notably deep subsidence (DS), a combination of glacial isostatic bulge relaxation (0.1 cm/y) and other compaction processes happening below the bottom of the CRMS Sediment-Erosion Table (SET) benchmark rod. Jankowski et al. (2017) estimate a total for deep subsidence of 0.3 cm/y for the BMC. It is necessary to add DS and SS to estimate total subsidence at any point.

Table 3. Water, soil properties and marsh elevation dynamics for CRMS sites located in the western (yellow) and eastern Biloxi marshes between 2008 and 2016.

				Top 4 cm of marsh soil	
CRMS Site	**Mean Marsh Elevation in cm (NAVD88)**	**Mean Water Elevation in cm (NAVD88)**	**Salinity ppt**	**% Organic Dry Weight**	**Bulk Density g/cm^3**
4548	20.02	18.69	6.80	10.98	0.61
4551	18.65	22.39	7.20	14.96	0.45
4572	15.68	13.52	8.93	15.68	0.46
4596	18.46	13.85	10.01	5.68	0.77
0108	26.53	17.51	12.21	23.14	0.23
4557	23.21	19.28	13.27	24.28	0.26
1024	23.00	15.59	14.37	16.53	0.41
3	36.33	20.59	17.95	5.23	0.71
1069	35.59	22.88	18.45	3.46	0.98
MEAN	*24.16*	*18.26*	*12.13*	*15.33*	*0.50*

				Marsh Surface Elevation Dynamics	
CRMS Site	**Mean Marsh Elevation in cm (NAVD88)**	**Mean Water Elevation in cm (NAVD88)**	**Marsh Accretion in cm/y**	**Marsh Surface Elevation Change cm/y**	**Shallow Subsidence cm/y**
4548	20.02	18.69	1.60	0.69	0.91
4551	18.65	22.39	0.90	0.86	0.04
4572	15.68	13.52	0.73	0.74	-0.01
4596	18.46	13.85	1.56	0.37	1.19
0108	26.53	17.51	1.04	0.66	0.38
4557	23.21	19.28	1.27	0.98	0.29
1024	23.00	15.59	1.11	0.80	0.31
3	36.33	20.59	0.86	0.14	0.72
1069	35.59	22.88	1.68	0.13	1.55
MEAN	*24.16*	*18.26*	*1.19*	*0.60*	*0.60*

Following Jankowski et al. (2017), we calculate:

RSLR = ESLR + DS + SS;

where

SS = A – SEC; and

where ESLR is the eustatic sea level rise, DS is deep subsidence, and SS is shallow subsidence, the difference between Accretion (A) and surface elevation change (SEC), all in cm/y. SS is the only unknown as ESLR and DS are specified from the literature. When RSLR is calculated in this way for each of the CRMS sites, it ranges from 0.5 to 2.1 cm/y, with an average of 1.1 cm/y. This mean value is less than the 1.3 (+/- 0.9) cm/y that Jankowski et al. (2017) found for all Mississippi River delta wetlands, but higher than in Chenier Plain marshes (9.5 +/- 0.6 cm/y). The broad range of RSLR rates at CRMS stations provides an indication of the resilience of the BMC to RSLR to respond to sea level. The high end of the range from BMC stations, which may indicate a limit, is about twice current RSLR, or 2.1 cm/y.

D. J. Reed (unpublished in King et al. 2008) reached similar conclusions with respect to the sustainability of the Biloxi Marshes when she notes that *"soils are building up and maintaining their elevation in the face of subsidence and sea-level rise through a combination of organic matter accumulation (mostly plant roots) and periodic inputs of sediment."* Reed was reporting results of a two-year study during which the MRGO remained open, from 2003 to 2005. She observed that over 0.2 cm of material was deposited on the wetland surface near Blind Lagoon (see Figure 2 in King et al. 2008). This accretion was attributed principally to sediment mobilized by Hurricane Ivan. Marsh elevation registered a more dramatic gain between August and October as a result of Hurricanes Katrina and Rita. Reed stated that *"measurements of both subsidence and marsh soil development in the Biloxi Marsh show that marshes there are sustainable now and should be well into the future*."

Low elevation gains on the eastern side of the Biloxi Marsh reflect the high position of these sites within the tidal frame, and the low percent time flooded; 15 to 17% for the eastern most sites. Percent time flooded for the 3 sites on the eastern edges of the contiguous Biloxi Marshes and for the site on the Gulf side of the rock weir ranged from 30 to 45% (Figure 25). The two sites on the western side of the Biloxi Marshes were 42% and 55%. This pattern of an inverse relationship between % time flooded and elevation gain was reported for marshes at Old Oyster Bayou (OB) near lower Fourleague Bay affected by the Atchafalaya River and marshes at Bayou Chitigue that is isolated from the river (Day et al. 2011).

Day et al. developed a conceptual model of marsh deterioration based on studies of the response of Oyster Bayou (OB) and Bayou Chitigue (BC) salt marshes to RSLR. The BC marsh was at the lower end of the tidal frame elevation range, and flooded about 85% of the time, more than any BMC site (Figure 25). Despite high sediment input, sediment capture was low and surface soils did not drain and consolidate. OB sediment input was lower but had a higher mineral content than at BC reflecting the proximity of OB to the mouth of the Atchafalaya River. Drainage of the higher elevation marsh allowed the soil surface to dry so that recently deposited sediments were retained. Thus, sediment capture, consolidation and soil strength, and organic matter content are dependent on position in the tidal frame while the mineral content is related to the proximity of a fluvial source. Because BC elevation was low at the initiation of the study, marsh collapse was observed within a few years as the plants were overwhelmed by the metabolic impacts of prolonged inundation.

The collapse observed at BC is not the same as erosive soil removal by waves and currents. Once collapse occurs, low elevation and fluidized soils prevent revegetation. The accretion deficit at BC is representative of deltaic interior marshes (2–3 mm $year^{-1}$, Baumann et al., 1984; Hatton et al., 1983; DeLaune et al., 1994). But the Eastern BMC is more like the OB marshes in that they sit high in the tidal frame, and are inundated for only 30 to 40 percent of the time. The Western

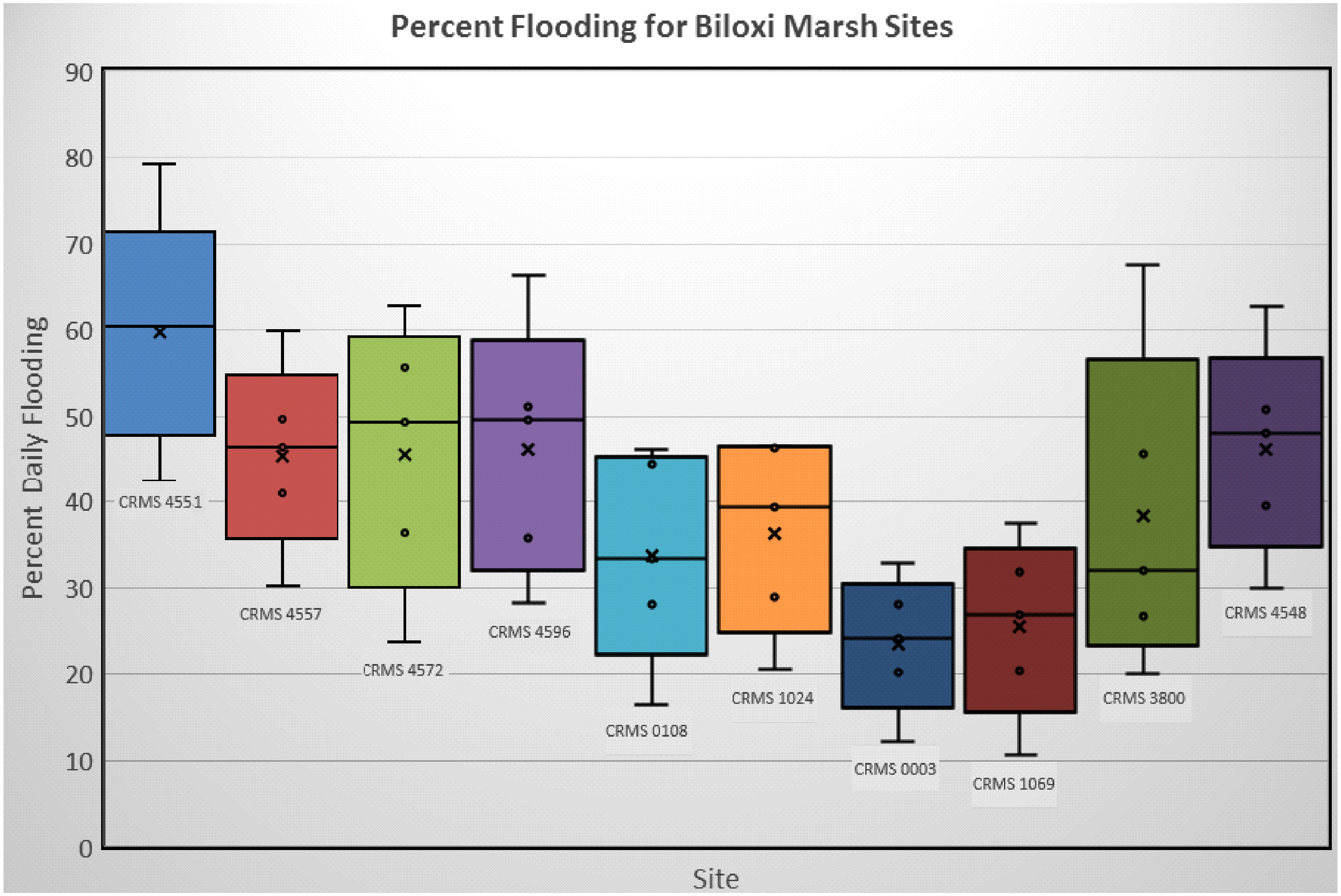


Figure 25. Flooding at BMC CRMS stations ranges from less than 20 percent to more than 60 percent.

BMC is more similar to the BC marshes, though, though at 50 to 60 percent flooding, they are not currently in danger of submergence. A modest amount of marsh nourishment behind rock revetments on the Lake Borgne shoreline might well be the key to sustaining the BMC.

An overall impression gained from working with the remarkable CRMS data sets is that marshes one might assume are alike, actually are not. They fall at different places on a spectrum for any attribute like elevation, organic matter content, accretion, shallow subsidence and salinity. This is because the marsh ecosystem responds in a variety of ways to the varying stimuli caused by natural and man-made factors. Feedback between accretion and consolidation, for example, may confer flexibility in how different salt marshes successfully respond to RSLR than has been commonly understood. But it is not clear what length of record would be necessary to support higher resolution forecasting of long-term sustainability that can accommodate such variability, beyond what was attempted in the CMP17 modeling program.

BMC Management Perspectives in a Deltaic Context

The BMC platform originally formed near Mississippi River distributaries of the St. Bernard delta between 4500 and 3000 years BP. The Bayou LaLoutre distributary was the most recent to supply sediment to the BMC. After Bayou LaLoutre was detached from the Mississippi in early colonial times, the Eastern BMC has been sustained solely by re-suspended coarse-grained sediment input from Chandeleur Sound. The Western BMC received finer grained sediments from Lake Borgne, and never attained the elevation of the western marshes (Table 3). Under a regime of greater flood duration and decreased drying and consolidation, sediment capture and retention efficiency is lower in the Western BMC . With the loss of the marsh edge berm due to the decline of Rangia caused by the MRGO, shoreline retreat has become the principal driver for land loss in the all of the BMC. Loss of surface elevation relative to the tidal frame has not been as big a problem in the BMC as in other parts of the Mississippi Delta that are experiencing higher rates of RSLR, though this could become a significant factor in the future as the CMP17 seems to show (Figure 2).

Increasing input of mineral sediment to the Western BMC would extend the lifespan of these marshes, as is found in streamside salt marshes (Hatton et al., 1983). From a planning perspective, it makes sense to protect and nourish swaths of the healthiest shoreline marshes first with relatively minor amendments of sediment to assure their long-term survival (Mendelssohn and Kuhn, 2003). The volume requirement and cost of thin-layer applications will be much lower than the more substantial quantities required for other, more fragmented and lower deltaic marshes. These short-term measures can be effective in retaining marsh while more expensive river diversions and large-scale marsh creation projects are brought on-line. It will not be necessary for river sediments to be directly delivered to marsh surfaces, but only to the adjacent bays and lakes where existing processes are sufficient to deliver it where needed.

These findings have important implications for wetland management in the BMC. Although these findings support the long-term use of one or more river diversions (Boesch et al., 1994; Day et al., 2007, 2009; Roberts, 1997; Tornqvist et al., 2008; Blum and Roberts, 2009), limited marsh nourishment through relatively thin layer applications is likely to be quite effective in the near-term (Mendelssohn and Kuhn, 2003). Since wave-driven shoreline retreat is currently the process responsible for most BMC marsh loss, however, artificial shoreline armoring will also be necessary on the Lake Borgne side until the natural supply of Rangia shell recovers.

System Recovery and Restoration Planning After MRGO Closure

With the closure of the MRGO, a number of scientific studies and observations show that the system is recovering towards pre-MRGO conditions. But additional restoration is needed to counter deterioration and extend marsh sustainability that will augment hurricane protection for the New Orleans area. The USACE MRGO Ecosystem Restoration Plan provides a blueprint and menu of measures for a sustainable system. This plan should be implemented and updated as additional restoration needs are identified (USACE 2012).

Flux of water throughout the BMC is lower since closure of MRGO. This is apparent in the Bayou LaLoutre channel, and smaller tidal creeks north of the MRGO Rock Dam closure and Bayou LaLoutre ridge. *Spartina alterniflora* is now colonizing low depositional terraces that have formed at the base of the exposed bank along the LaLoutre canal, reversing erosion and retreat that occurred when the MRGO was open.

Salinity levels in much of the BMC, especially north of the LaLoutre Ridge, and in the CWU have dropped significantly towards pre-MRGO levels. Hunter et al. (2016) reported that surface water salinity in the CWU averaged between 2 and 3 ppt in 2012, and that ground water salinity had decreased to the point that cypress could be successfully planted and grown in some areas by 2014 (Figure 26). Input from the Pearl River helps to maintain low salinities in Lake Borgne now that the MRGO has been closed. Lower salinity in Lake Borgne will allow recovery of *Rangia* populations and provide a shell supply for the berms on the eastern shore of Lake Borgne.

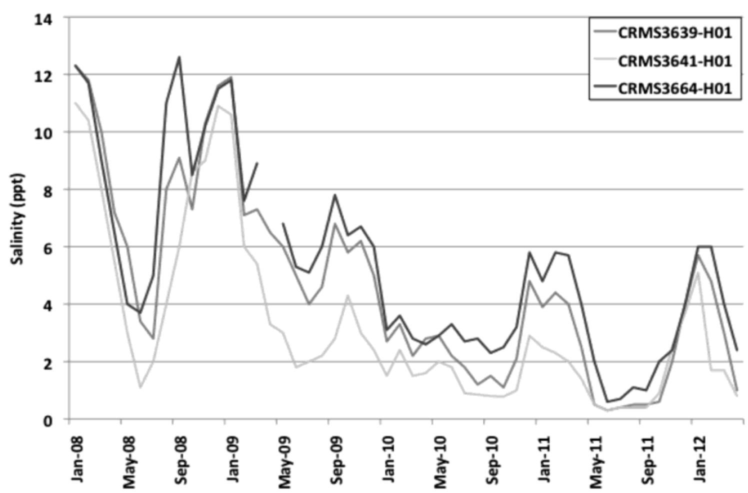


Figure 26. Surface water salinities measured at three CRMS stations in the CWU showing that the areas is reverting to a pre-MRGO salinity regime. (see also Hunter et al. 2016).

Lowered salinity is reflected in a transition towards freshwater and lower salinity vegetation in the region. Oak trees which appeared to be dead on the La Loutre ridge have re-sprouted over a large area (Figure 10). Intermediate marsh has become established in the CWU in areas with freshwater input. As the area freshens, more cypress should be planted in the highest areas to restore the swamp forests that existed there prior to MRGO. This would enhance the storm buffer capacity of the area. In lower marshes of the western BMC, the tall reed, *Phragmites,* has returned to the Biloxi Marshes along the LaLoutre canal and is spreading throughout the western BMC. Re-establishment of cypress and *Phragmites* in the area between Lake Borgne and the

Central Wetlands Unit will further enhance storm buffering capacity. Storm buffer benefits could also be achieved by plantings of mangroves in the Eastern BMC.

HURRICANE RISK REDUCTION FOR NEW ORLEANS

Those of us who have studied and modeled hurricane surge and waves in coastal Louisiana are aware of a controversy that once existed between coastal engineers and scientists from other disciplines. In a pre-Katrina world, it was common to hear coastal engineers and modelers say that the frictional effects of wetlands on slowing surge and attenuating waves was the same as that of a bare mud bottom once the vegetation was submerged. With the arrival of ADCIRC+SWAN SL6 and Katrina observations by a host of forensics experts (Figure 27), it is no longer plausible to make this assumption (van Heerden et al. 2007; Dietrich et al. 2010). It is true is that every storm is different and that wetlands are generally more effective at diminishing waves than surge. Swamp forests and 3 m high Roseau cane colonies offer more resistance than 1 m high Spartina marshes, but this is as much caused by the separation of the wind boundary layer from the water surface, as with the penetration of the vegetative resistance elements (stems, trunks) through much or all of the water column.

Wetlands offer areas that surge water can be harmlessly stored without directly contributing to increased surge, and where large waves generated in lakes and bays can be broken and reduced in amplitude and period. Waves now get much more attention from engineers designing levees and floodwalls than in the past because they generally initiate overtopping and cause erosion of earthen structures on both protected and unprotected sides that can, and have, led to breaching (Shaffer et al. 2009; van Heerden et al. 2007).

The voluminous hindcasting literature from Hurricane Katrina provides much useful information on buffering effects of the BMC on storm surge and waves. Specific storms like Katrina and Rita are preferable to an amalgam of maximum water levels and wave heights derived from multiple storm simulations. A primary consideration is the track azimuth and forward speed of the storm system. Hurricane Katrina followed a track that took it almost directly over the BMC at a relatively slow speed that allowed time for surge and wave development in the Lake Borgne funnel (Figures 8, 9). Smaller or faster storms following the same track would produce different surge and wave combinations that would be affected to a different degree by the BMC.

BMC wetlands are modeled as projecting 3 to 5 feet upward from an older deltaic platform (Figure 27). The effect of the BMC wetlands and platform on maximum storm surge elevation is to limit the rise. While surge elevation gradients occur to the east and west of the BMC, the maximum water level surface flattens across the entire marsh platform (Figure 28). Much smaller marsh creation projects are justified in CMP17 by very limited effects on reducing surge and waves moving across them. But none of these artificial marshes is the 20-miles wide like the BMC. It is not clear, however, if the muddy BMC platform would continue to exist after the marsh dies. Barrier islands transition to sand shoals but this is not necessarily true for marsh platforms. Without a vegetated cap, it is possible that the platform could quickly deepen by a meter or more.

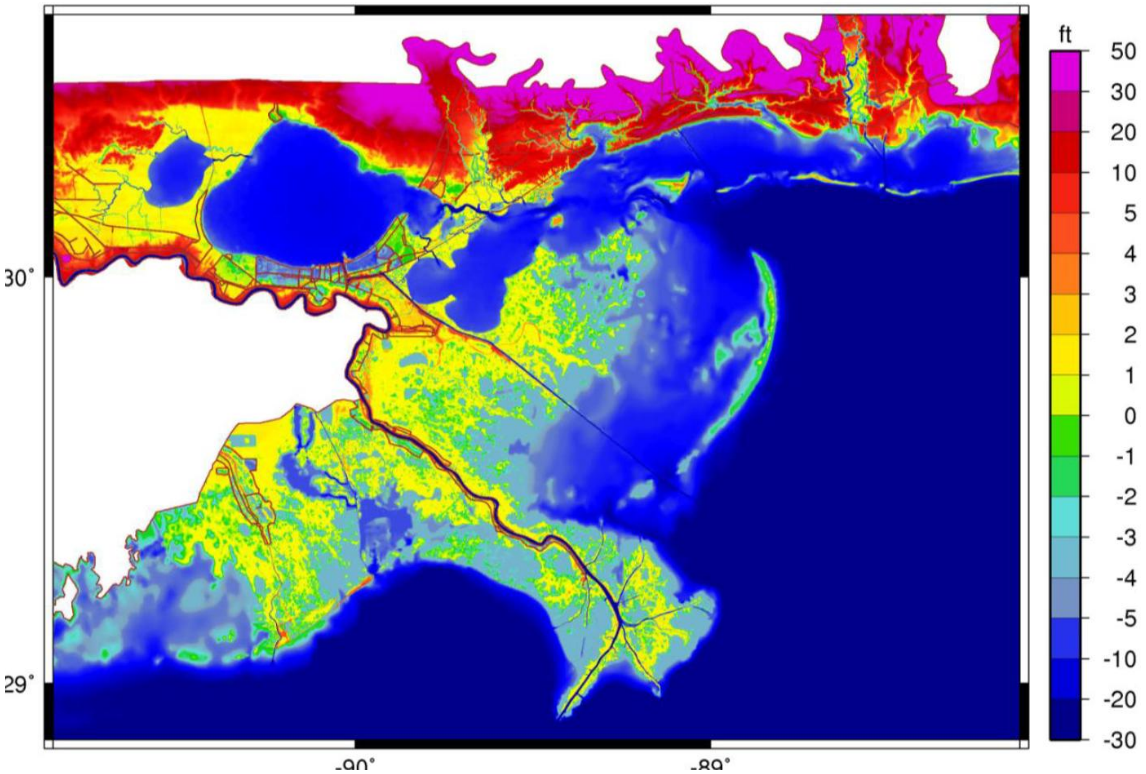


Figure 27. Bathymetry and topography of southeast Louisiana as incorporated in the ADCIRC + SWAN SL16 model. Elevations are in feet (NAVD88). The BMC is shown as having marsh elevations between +1 and -1 foot, while the unvegetated portion of the marsh platform is shown with elevations of -3 to -5 feet.

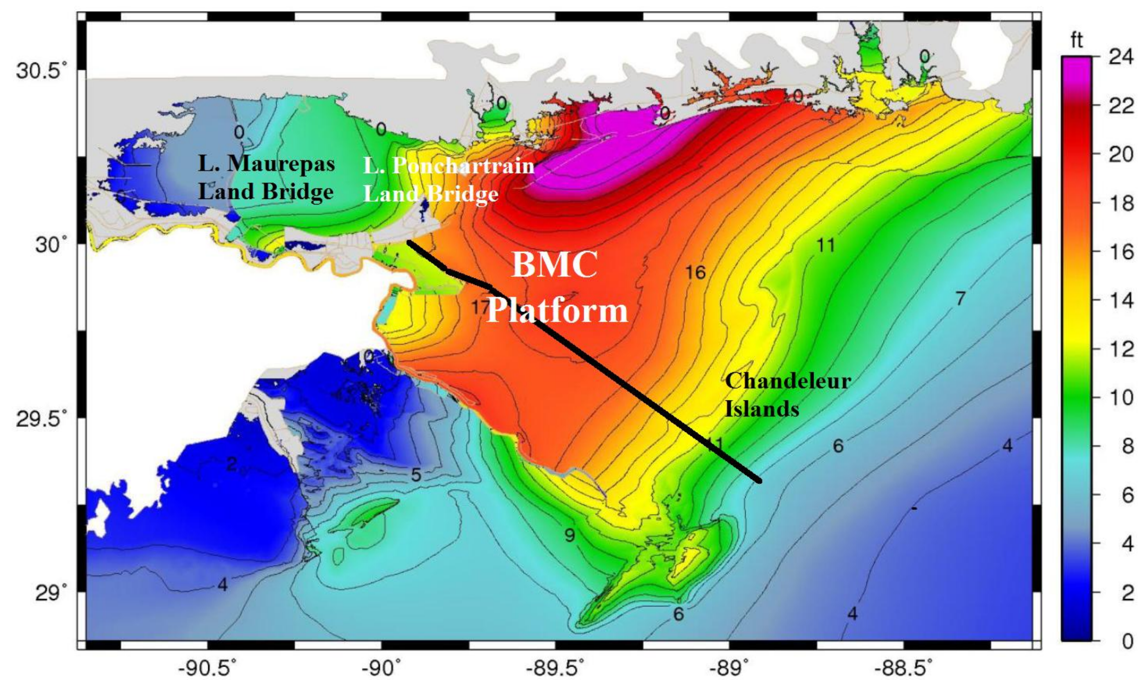


Figure 28. Maximum of the actual Katrina surge elevation (ft, NAVD88) hind as modeled using ADCIRC+SWAN SL 16 and incorporating levee and floodwall breaches.

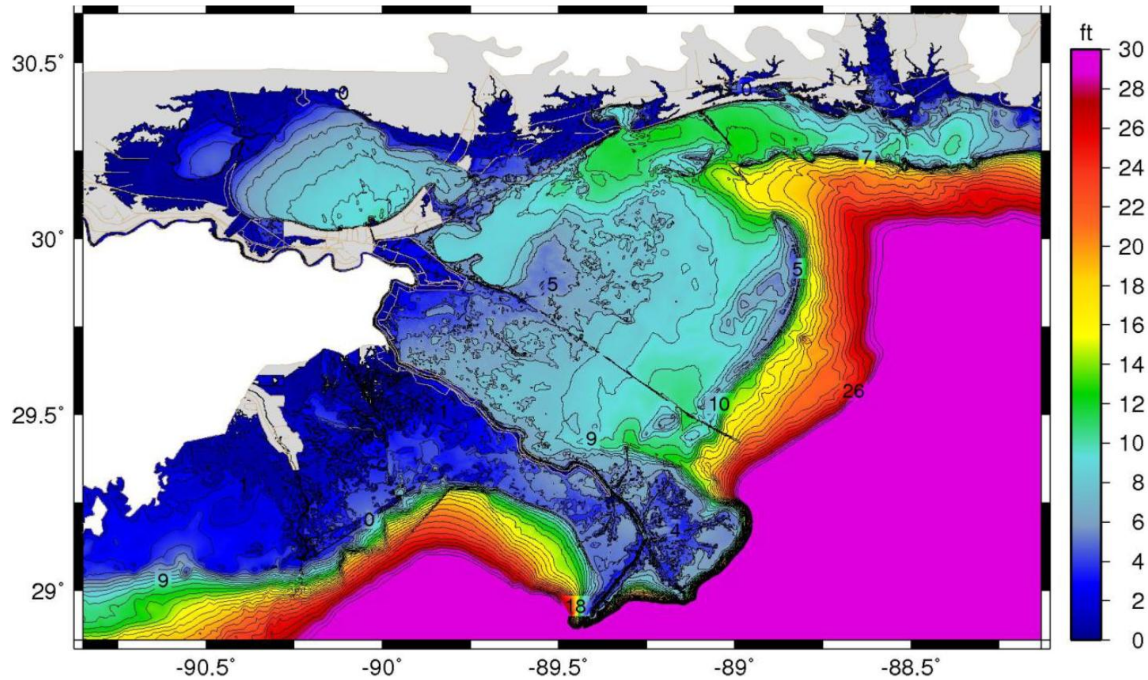


Figure 29. Maximum significant wave heights (ft) for Katrina as modeled using ADCIRC+SWAN SL 16. Waves which approach the BMC through Breton Sound decrease from 14 feet behind the Chandeleurs to 5 feet in the western BMC, though they increase again to 9 feet in Lake Borgne.

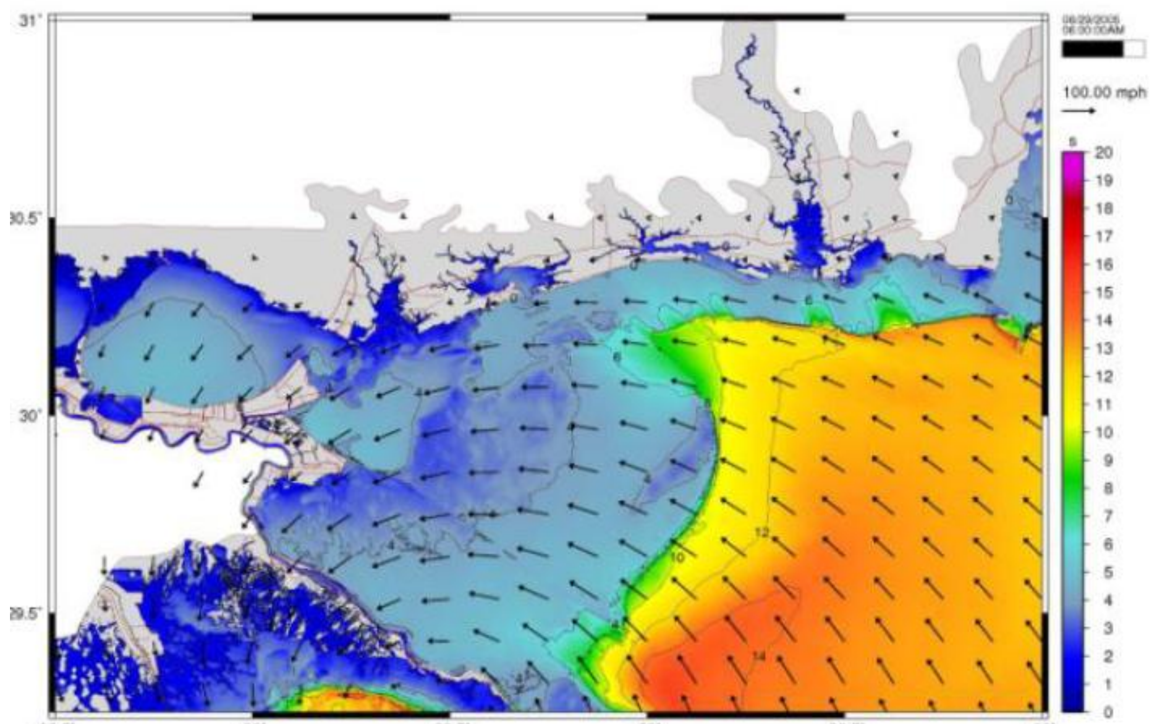


Figure 30. Wave periods at full surge development in Lake Borgne Funnel. Wave period was up to 14 seconds on the Gulf side of the Chandeleurs but was diminished by the islands to 6 seconds. Wave period in the western BMC never was greater than 3 seconds.

The effect of wetlands on hurricane waves is easier to predict. While the barrier islands do even more, the BMC does reduce wave amplitude and period. The reduction in significant wave height from 8 feet in Breton Sound to the western marshes of the BMC is about 3 feet, even though there is some regeneration in Lake Borgne (Figure 29). The big, 10 to 15 second swell waves generated by the storm in the Gulf break and completely disappear before reaching the BMC (Figure 30). Instead, waves behind the Chandeleur Islands reform as smaller, locally generated seas that almost disappear when passing over the marsh. We did not have the time to run ADCIRC+SWAN SL16 to test the importance of the BMC by experimentally removing it from the grid, but this would be an instructive analysis.

EXISTING BMC RESTORATION PLANS

The Mississippi Gulf Outlet Ecosystem Restoration Plan (USACE 2012)

The USACE (2012) project report outlines the management options, cost benefit analysis, and final recommendations for restoration of the region surrounding the decommissioned MRGO navigation channel. Dredging and spoil placement during the construction of MRGO destroyed thousands of acres of wetlands, as has been discussed, and interrupted local circulation through natural waterways, and breached an important hydrologic boundary when the Bayou LaLoutre ridge was cut. Prior to construction of the MRGO, tidal movement into Lake Borgne was dominated by flow from the north, out of Mississippi Sound. Flow through BMC tidal creeks from Chandeleur Sound was reduced as it moved northwest across the marshes and wetlands toward Lake Borgne. Following construction of the MRGO, the circulation pattern reversed. Dominant tidal flow into Lake Borgne came via the MRGO. This drastically altered salinities on the Lake Borgne side of the LaLoutre ridge. After the MRGO was completed, significant habitat shifts occurred as Lake Borgne and its surrounding wetlands transitioned to a higher salinity condition.

Operation of the MRGO cause high rates of bank erosion from ship wakes, while destroying wetlands and threatening the integrity of the Lake Borgne shoreline and adjacent communities, infrastructure, and cultural resources. Erosion of the MRGO channel banks and the daily influx of saltwater with tides and storms ensured the transition of the estuary toward the more saline end point that wildlife managers predicted before the MRGO was built. Although the impacts of the MRGO to the habitat of the Bayou LaLoutre Ridge are not quantified, the MRGO passed through a 150 m dredged cut, destroying upland habitat and a natural salinity barrier. Undoing this MRGO damage was a central focus of the 2012 Ecosystem Restoration Plan (ERP) and has led to a CMP17 project to restore BMC ridge habitat.

While Lake Borgne and the Western BMC is slowly recovering from MRGO impacts, it is still in need of additional restoration measures to reverse shoreline retreat on the Lake Borgne side caused by removal of the *Rangia* shell beaches and berms. Rapid action is required to protect the integrity of the southern Lake Borgne shoreline and prevent continued erosion of MRGO channel banks, and the CMP17 calls for some marsh creation in this area.

Protection and restoration of the south Lake Borgne/MRGO land bridge is technically feasible and has been approved by the CPRA. These wetlands were first targeted for protection and restoration in WRDA 2007 Section 7006 and 7013. A 2005 post-Katrina Louisiana House Concurrent Resolution directed the USACE not to pursue dredging to return the MRGO to service at its authorized dimensions, and to begin a process to de-authorize the ship channel and return the waterway, as close as possible to the marsh that it destroyed. The channel was de-authorized in 2008, and dammed in 2009. The USACE Ecosystem Restoration Program (ERP) was completed in 2012 but has not yet led to any new federal restoration efforts in the BMC.

The area surrounding the MRGO was divided in the ERP into 51 subunits based on geomorphology and hydrological characteristics (Figure 32). Of those 51 subunits, Biloxi marshes comprised four (07, 06, 18 and 40), however, only sections 07, 18 and 40 were considered impacted by the MRGO and thus included in the restoration plans. The evidence in this report shows that subunit 06 should have been included.

Subunit 07 - Biloxi Marshes Interior, and 18 - Eloi Bay - compose a unique geomorphologic feature that has been identified as a critical landscape feature for storm surge damage risk reduction and is technically significant, in terms of scarcity and connectivity, as a geologic barrier for storm surge reduction (USGS 1994; USACE 2009; Walmsley et al. 2009; Howes et al. 2010; Shepard et al. 2011). The only remaining natural ridge in the immediate vicinity of the MRGO is the Bayou La Loutre ridge. This habitat is technically significant because of its scarcity, biodiversity, and function as a limiting habitat on which species of concern depend (Conner and Day 1988; Twedt and Portwood 1997; Barrow et al. 2000).

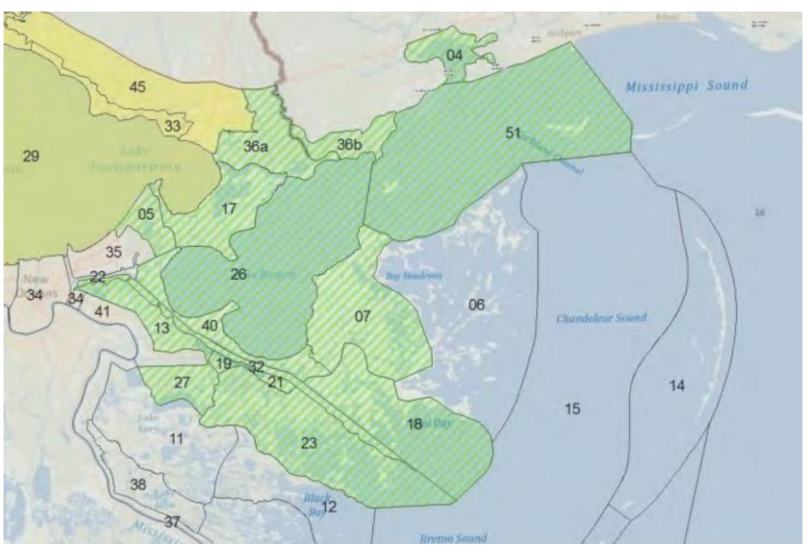


Figure 31. Ecosystem Subunits for areas determined to have been affected by the MRGO in the 2012 USACE ERP.

The Biloxi Marsh also supports oyster reef habitat, which is arguably one of the most imperiled types of marine habitat on earth (Beck et al. 2011). This area is also significant because of its recreational value and importance as an area that can potentially reduce the loss of life and property due to hurricane flooding, as has been discussed (Burkett et al. 2002). A primary barrier to extending BMC sustainability is a lack of freshwater and sediment to increase Rangia clam production and marsh soil aggradation to stabilize the Lake Borgne shoreline from wind driven waves.

Subunit 40 - South Lake Borgne - covers the MRGO/Lake Borgne Landbridge, the narrow strip of marsh separating the MRGO from the lake. South Lake Borgne marsh is considered a critical landscape feature that contributes to the integrity of the estuary. These subunits were grouped together because the areas are contiguous and create a structural framework for the estuary. The BMC landscape feature is among the most important to the public anywhere in the deltaic plain because of its proximity to New Orleans, hurricane surge reduction and recreational value. The number of state, local, and NGO plans that have been written for BMC restoration underscore this significance (LPBF 2006; Lopez 2006; Day et al. 2006; Lopez et al. 2010).

The Biloxi marshes in conjunction with the Pontchartrain Landbridge and the Lake Maurepas Landbridge (Figure 8), as well as forested habitats within the Lake Borgne ecosystem, have also been identified as critical landscape features for providing hurricane and storm damage risk reduction in the region. The connection between these features and storm surge is based on the geographic structure of the estuary, as has been discussed. The Biloxi Marsh separates Lake Borgne from the Chandeleur Sound. If the Biloxi Marsh did not exist, Lake Borgne would merge with Chandeleur Sound as CMP17 predicts for year 50 and 30, under the Medium and High SLR scenarios, respectively (Figure 2). As was discussed above, the degree of protection that would be provided for the New Orleans metro area after the marsh is gone is not known. Similarly, if the Pontchartrain Landbridge disappeared, Lakes Pontchartrain and Borgne would merge to form one large lake and with enough fetch could develop much larger waves against the New Orleans hurricane protection structures. The effect would be compounded if the Pontchartrain Landbridge and the BMC were to disappear at about the same time. CMP17 forecasts this happening by year 40 under the High SLR scenario, despite significant expenditures on the Pontchartrain Landbridge and very little on the BMC.

The first objective of the MRGO restoration effort is to bring back the historic salinity gradient identified by Chatry et al. (1983) to re-establish and maintain a healthy mix of estuarine habitat types, optimize ecosystem services and decrease stress to vegetation as measured against the monthly salinity targets in the Biloxi Marsh. The salinity targets were originally developed and adopted by an ad hoc group consisting of representatives from the USACE, Louisiana Department of Wildlife and Fisheries (LDWF), National Marine Fisheries Service (NMFS), St. Bernard Parish (SBP), Louisiana Department of Natural Resources (LDNR) and the Mississippi Bureau of Marine Resources (MBMR) with a goal to enhancing fish and wildlife resources in the Pontchartrain basin and *re-establish a desirable salinity regime for the historic oyster reefs on the seaward fringe of the Biloxi Marsh* (USACE 1984). The group determined that salinity should mimic conditions in 4 out of 10 years when the Mississippi River would have naturally over-flowed its banks in the spring. The targets were developed using ten years of data (1971-1981) from the most productive oyster seed grounds.

Oysters are an important commercial species but are also the best indicator species to determine the optimum salinity range for the Louisiana commercial fishery (LPBF 2006b). Oysters directly contribute to the larger ecosystem by filtering water and providing reef surface habitat for other organisms. And, of course, these reefs produce shell that armors the shorelines of islands in the Eastern BMC marshes.

Four restoration plans ranging were developed by the USACE, ranging from no action (Plan A) to a Plan D that included all feasible restoration measures (Figure 32). Plan C is the Federally Identified Plan (FIP) determined by evaluating a large number of criteria. It called for the most ambitious marsh restoration project ever considered before 2012, apart from that of CMP12. It called for restoring and protecting more than 57,000 acres of habitat, including 10,000 acres of cypress swamp, 14,000 acres of fresh and intermediate marsh, 33,000 acres of brackish marsh, 500 acres of saline marsh, and 54 acres of ridge habitat. Approximately 9,000 acres of restoration features would be located in the BMC, which is not surprising because the BMC has been identified in many plans as a critical landscape feature with respect to storm surge. Interestingly, Plan C differs from CMP17 in including 71 miles of shoreline protection (including 5.8 miles of artificial oyster reef). Additionally, the cypress swamp and forested ridge restoration elements were included, in part, because they were identified as having storm surge damage risk reduction benefits (Figure 33). *The USACE team clearly understood that installing the Rock Dam to close the MRGO is not a substitute for a full restoration program, and is clearly inadequate for protecting, restoring, and sustaining the Biloxi Marsh Complex*.

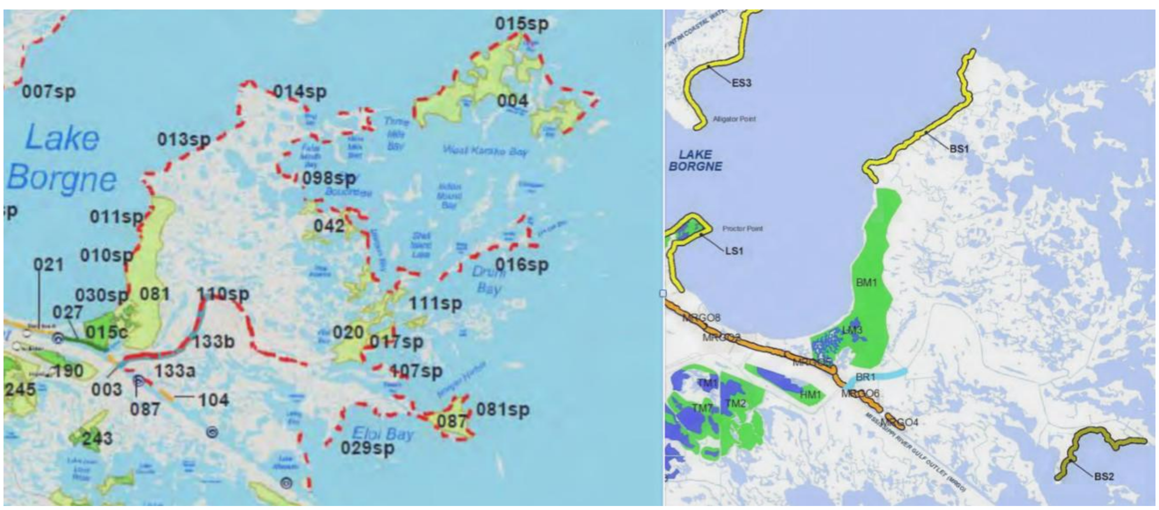


Figure 32. All potential restoration measures proposed in USACE MRGO Ecosystem Restoration Plan for the Biloxi marshes (left), and those accepted (Plan C; right).

River diversions were not considered in the initial development of MRGO ERP alternatives, and were ultimately eliminated from further study as inconsistent with the study goals and objectives. Preliminary analysis and experience with the Violet diversion into Bayou Dupre indicated that a small freshwater diversion would not fully re-establish historic salinity gradients, habitat types, and system resilience and was outperformed by shoreline protection and marsh creation projects.

A more costly, larger freshwater diversion into the BMC could restore the Mississippi River connection and increase marsh productivity and vertical accretion (DeLaune et al. 2003). The Violet Freshwater Diversion is institutionally significant because it has been included in federal, state and local plans for several decades (CMP12, CIAP, and CWPPRA) and has received considerable support from national and regional NGOs (LPBF 2006b, Day et al. 2006, Lopez et al. 2010).

The USACE divided ERP recommendations into tiers by considering the level of ecological uncertainty and long-term potential to extend sustainability given the need for additional study. Restoration measures proposed by the USACE in the BMC are given below.

Tier 1 includes features that have been developed to a feasibility level of detail and are not dependent on a freshwater diversion. Tier 1 features are recommended for construction through the WRDA 2007 Section 7013 authority upon the identification of a non-Federal sponsor and include:

• ***BS1*****:** Approximately 50,600 linear feet (9.5 miles) of protection along the southeast shore of Lake Borgne from the existing CWPPRA Biloxi Marsh Shoreline Protection Project (PO-72) south of Point aux Marchettes extending north to Malheureax Point (Figure 33).

• ***BS2*****:** Approximately 30,700 linear feet (5.8 miles) of artificial oyster reef development between Eloi Point and the mouth of Bayou LaLoutre (Figure 33).

• ***BR1*****:** Approximately 54 acres of ridge restoration on the south bank of Bayou LaLoutre requiring the addition of 400,000 cubic yards of silty sand material (Figure 33).

Tier 2 includes features with feasibility level detail that are dependent upon salinity conditions, but may be sustainable without construction of a freshwater diversion. There are no projects in the Biloxi marshes in the Tier 2 category.

Tier 3A includes further study of the Violet, Louisiana Freshwater Diversion under the WRDA 2007 Section 3083 authority. as well as:

• ***BM1*****:** Approximately 8,000 acres of marsh nourishment along the south shore of Lake Borgne using 11 million cubic yards of material mined from the Lake (Figure 33).

The Biloxi Marsh Stabilization and Restoration Plan

King et al. (2006) developed the Biloxi Marsh Stabilization and Restoration Plan (BMSRP) with funding from the Biloxi Marsh Lands Corporation to increase restoration synergy by proposing a number of different projects that would work well in concert to restore the topography of the BMC. The BMSRP has since been modified to add regional benefits beyond the BMC tract, ranging from protecting New Orleans and surrounding parishes from storm surge, to preventing saltwater intrusion and facilitating the introduction of additional sources of fresh water.

Coastal geologist, Dr. Denise Reed, then a University of New Orleans professor, was a participant in the BMSRP. Reed (p. 13-16) wrote that "*marsh soil development in the Biloxi Marsh show that marshes there are sustainable now and should be well into the future,"* but that additional restoration was needed to achieve the best outcome. The plan addressed six specific goals that, if achieved, would result in stabilizing and restoring the BMC.

* (1) Enhancement of the effectiveness of the BMC as a hurricane buffer for populated areas;
* (2) Reduction in wetland loss;
* (3) Enhancement of existing high-quality habitats;
* (4) Restoration of deteriorated wetlands and habitats;

* (5) Creation of a sustainable ecosystem; and

* (6) Rebuilding of a naturally functioning ecosystem capable of recovering from the engineering projects and economic activities that caused degradation, specifically the MRGO and the leveeing of the Mississippi River.

The BMSRP recognizes that the start of the degradation of the BMC was caused by levee-building along the banks of the Mississippi River that spread upstream and downstream from New Orleans. Early levees could prevent only the routine overbank flooding events but this had an effect on the Biloxi Marsh as the high-water connection of Bayou LaLoutre with the Mississippi was blocked. The BMC also suffered as the Chandeleur Islands lost their integrity and some of the capability to protect southeastern Louisiana from hurricane waves and storm surge, as well as from strong southeasterly winds. *Restoration of river water input is essential to the sustainable restoration of the BMC even if recovery of the Chandeleur Islands is not.*

The BMSRP proposes the use of the MRGO as a conduit for fresh water and sediment to the Biloxi marshes through two alternative conduits (Figure 34). The preferred diversion channel location would be south of, and parallel to, the Violet Canal at a location that would least affect existing infrastructure. A less preferred diversion channel location would be a widened and straightened version of the existing Violet Canal connecting the Mississippi River and the MRGO. Building a water control structures at the junction of the Mississippi River with the Violet Canal (or the alternative channel) and on the MRGO immediately below Bayou LaLoutre were also proposed. The Rock Dam blocking the MRGO at Bayou LaLoutre was constructed by the USACE in 2009, as has been discussed. The size of the diversion channel and its flow rate would be based on designs sufficient to carry a sediment load capable of restoring and sustaining the Biloxi Marsh and surrounding area, with an anticipated discharge of 1100-3100 m^3s (40,000-110,000 cfs).

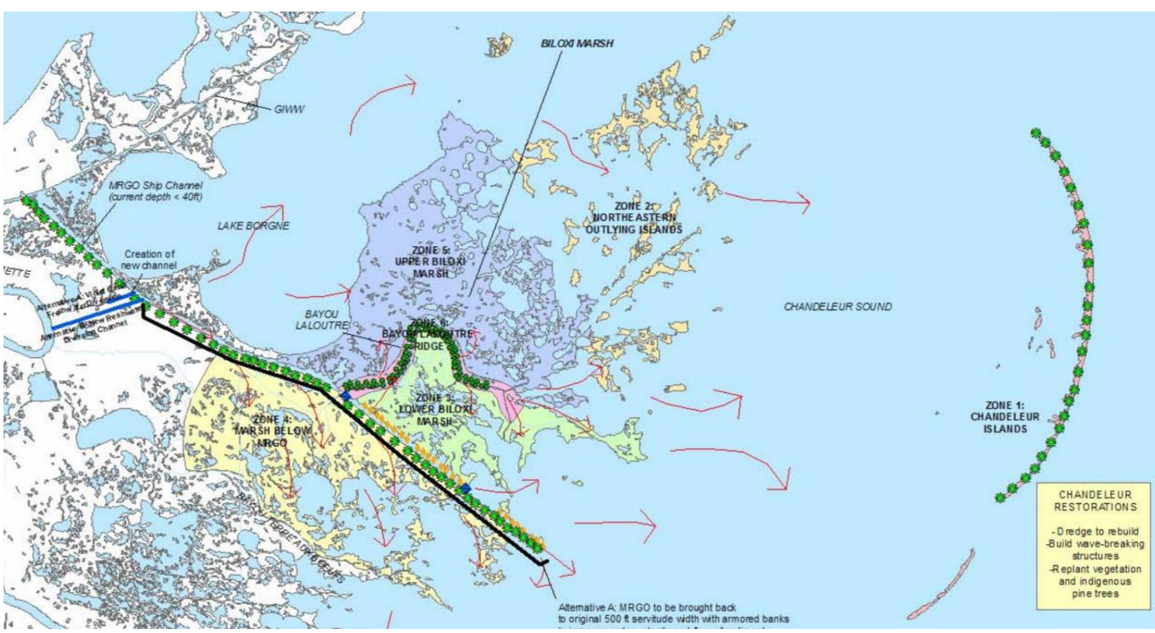


Figure 34. River diversion plan for the Biloxi marshes.

The major concept being advocated in this plan is to manage the river diversion by focusing on the re-design of the MRGO to disperse diverted water into the Biloxi Marsh area and wetlands southwest of the MRGO. The BMSRP proposes construction of two large water control structures in the MRGO, with one at the intersection of Bayou LaLoutre, and the other near Lake Athanasio. These structures would allow for the allocation of river water into Bayou LaLoutre, and then into marshlands north and south of the Bayou La Loutre ridge, as well as serve as barriers to salt water intrusion events.

The BMSRP calls for narrowing the MRGO to its original legal servitude width of 150 m and filling the intervening space with pipeline conveyed sediments from existing water bottoms. Trees would be planted on existing dredged spoil banks and on newly created ridges behind the armored MRGO banks to improve wildlife habitat and serve as a protective buffer for inland infrastructure.

Another major aspect of the Plan is restoration of the Bayou LaLoutre ridges, currently elevated eight to ten feet high, and lined with small live oaks and box elders that has a unique habitat value on its own. Bayou La Loutre runs between the two ridge banks which were then (2006) prone to erosive scour caused by the MRGO, and wake erosion from heavy boat traffic traveling through the bayou. These problems occur on a daily basis and have created cut banks on both sides of the bayou. The ridge provides seven linear miles of natural protection for areas further inland by damping storm surge energy. The existing trees and shrubs on the ridge were devastated by erosion of the banks and exacerbated by storm surges from Hurricanes George, Ivan, Katrina, and Rita.

CONCLUSIONS AND RECOMMENDATIONS

We reviewed the current condition of salt marshes in the Biloxi Marsh Complex (BMC), and have examined data from 10 CRMS monitoring sites to predict long-term resilience and sustainability under future sea level rise scenarios in the context of the 2017 draft of the Comprehensive Coastal Master Plan (CMP17). The 20-mile wide BMC platform has been determined to serve residents of metro New Orleans and St. Bernard as a buffer to hurricane surge and waves on the basis of numerous Katrina hindcasts. But CMP17 recommends few restoration measures to extend the lifespan of the BMC despite a forecast that the BMC will survive less than 30 years under the "High" sea level rise scenario. While the modeling conducted for CMP17 is impressive, we suggest that some features of the output that drove project selection may be modeling artifacts that should be critically examined for the next CMP17 draft. We recommend that the Coastal Protection and Restoration Authority explore and resolve the following technical questions:

- Do the models apply the inundation-driven "marsh collapse thresholds" correctly for all marsh types, particularly saline marshes?
- If the persistence and spread of fresh marsh in out-year simulations is attributable to lack of a marsh collapse threshold for this marsh type, should some other limiting threshold be applied?
- Why does it appear that the CMP17 models do not capture the benefits of linear shore protection measures - short of major levees - to slow wave-driven

lateral shoreline translation, the major marsh loss mechanism affecting the BMC?

A review of between 8 and 9 years of CRMS data from the BMC highlighted differences between East and West BMC marshes that are most affected by sediment transported to the marsh from Chandeleur Sound and Lake Borgne, respectively. East BMC marshes are up to 10 cm higher than those in the western BMC, but all marshes are accreting at rates of between 0.7 and 1.7 cm/y, and exhibit a positive surface elevation change (SEC) trajectory averaging 0.6 cm/y, the same as the mean value of shallow subsidence (SS). Our findings support those of D.J. Reed (unpublished in King et al. 2006) that that "*marsh soil development in the Biloxi Marsh show that marshes there are sustainable now and should be well into the future.,"*

These inadequately and incorrectly addresses issues related to the BMC and draws erroneous conclusions about the sustainability of the area. A careful analysis of the environmental setting of the BMC shows that the area was strongly impacted by the MRGO but with closure of the MRGO, the area has been on a trajectory of recovery. There is a need for restoration activities as part of the CMP. If this restoration is done, most of the area should be sustainable for the next 50 years.

The CMP17 may be overestimating geologic subsidence in the BMC (McLindon 2017). BMC marshes are among the oldest extant in the Mississippi River deltaic plain, dating from the active period of the St. Bernard Delta, 3000 to 4000 y BP. Depth to Pleistocene ranges from 50 to 100 feet under the BMC. The CMP17 estimates deep subsidence in the BMC at 0.44 cm/y, but we prefer the value of Jankowski et al. (2017), which is about 0.1 cm/y lower. Relative Sea Level Rise (RSLR) in the BMC averages 1.1 cm/y, of which about half is contributed by shallow subsidence that occurs mainly in the upper 10 cm of the marsh. We use a value of 0.2 cm/y for Eustatic or Global SLR acquired through satellite altimetry. Marsh aggradation (SEC) in the BMC range from 0.13 to 0.98 cm/y, The highest elevation marshes from the eastern BMC had the lowest SEC. Suffice it to say that no two marsh sites were the same although they are all salt marshes dominated by *Spartina alterniflora*. Trying to model marsh dynamics at all of these very different sites using the same parameterization is likely to be frustrating.

The eastern and western zones of the BMC function differently and restoration should reflect this. Marshes of the eastern BMC are high and positioned at the top of the tidal frame. They are experiencing low, easily sustainable rates of SEC, and are composed of firm, consolidated sediments with a significant shelly sand component. The primary sediment source is Chandeleur Sound and is renewable. These marshes are likely to survive the highest projected rates of RSLR over the next 50 years, with a limit of perhaps 2.0 cm/y, twice the current rate. These marshes could benefit from shoreline stabilization measures including the planting of mangroves, which have strong root systems, and artificial nearshore oyster reefs. This would reduce the shoreline retreat that continues to carve up the myriad of marsh and shell islands that make up the Eastern BMC.

The Western BMC marshes are about 10 cm lower than those in the Eastern BMC but experience healthy rates of SEC ranging from 0.4 to 0.9 cm/y. Shoreline retreat along Lake Borgne is highly variable but has been measured at up to 60 m/y when the year includes a major hurricane. The Western BMC marshes experienced the most severe impacts caused by the construction and operation of the Mississippi River Gulf Outlet (MRGO) navigation channel between 1960 and 2009.

Higher salinities introduced by this channel led to loss of *Rangia* clams in Lake Borgne. These clams provided a continuous supply of shell that maintained high berms on the lake shores comparable to the oyster shell beaches armoring the marsh edges of the Eastern BMC. When the living Rangia disappeared, shell supply to the beaches and berms was reduced and the berms degraded. Northwest winds generated during frontal passage are a primary source of high wave energy on the west-facing coast of the Western BMC. In the past, waves resuspended sediments that fed the berms and led to accretion in the marshes. Currently, locally generated waves are causing high rates of erosion and shoreline retreat both along Lake Borgne and in much smaller interior lakes and ponds.

The MRGO also increased tidal and wind-driven flow between Lake Borgne and Chandeleur Sound leading to erosion and widening of Bayou LaLoutre and other smaller channels of the BMC interior, particularly in the Western BMC. Since the MRGO was closed with a Rock Dam just south of the Bayou LaLoutre crossing, the area is recovering, but further restoration will be needed to lead to long-term sustainability. Another way of stating this is that the BMC is already recovering from the negative impacts of the MRGO, so further restoration measures have a potential to work synergistically.

Salinities in Lake Borgne and in Western BMC marshes have decreased. After MRGO, salinities in Lake Borgne increased to 8-22 parts per thousand (ppt) but now range from 3 to 10 ppt. The MRGO-induced salinity rise hastened the loss of Rangia populations and fresher wetlands in the BMC. Many oaks died along the Bayou LaLoutre ridge, but a number of what appeared to be dead trees are now sprouting new leaves after many years of apparent dormancy. Roseau cane (*Phragmites*) is again spreading in the BMC. Spartina alterniflora was recently noted spreading across a low mud platform at the base of the Bayou LaLoutre banks, indicating a reversal of decades of erosion. Although we are not sure how it should be done, it does not appear that CMP17 does not appear to prioritize recovering areas for restoration projects even if they might function for a longer life-span because the ecosystem is already in recovery. CMP17 should include additional restoration projects to take advantage of the recovery to leverage a more sustainable system.

Restoration principles, whether explicit or implicit have been a foundation for all existing BMC restoration planning. First, it is important to recognize that sediment supply is sand from Chandeleur Sound on the east, and mud from Lake Borgne on the west. On the east, establishing shoreline fringing artificial oyster reefs will enhance shell production for shoreline armoring while planting mangroves will increase sediment capture and erosion resistance. High winds during fronts are effective in re-suspending fine-grained silts and clays in Lake Borgne. This sediment is delivered to the Western BMC when storms raise lake water level. But the same locally generated waves that suspend sediment from the bottom of Lake Borgne also causes the shoreline erosion that has increased dramatically after the Rangia shell berms disappeared.

The USACE MRGO Ecosystem Recovery Plan (ERP) and the proposed Point aux Marchettes PPL 27 Coastal Wetlands Planning Protection and Restoration Act (CWPPRA) project that is currently awaiting approval both rely on the same small-scale and relatively low-cost marsh restoration measures, namely rock revetments and artificial oyster reefs to slow shoreline retreat in combination with marsh shoreline wetland creation projects to reinforce marsh edges until both Rangia and Oysters begin producing enough shell to effectively armor BMC once again.

Long- term, another diversion in addition to the Mid-Breton outlet will be needed to increase freshwater input to Lake Borgne and the BMC as sea level rises. A moderately large diversion could enhance ecosystems in both the Central Wetlands Unit (CWU) and the BMC. Much of the infrastructure for this diversion is already in place. This includes the Violet Canal, the MRGO channel between the Bayou Dupre flood gate, the Rock Dam, and the Bayou LaLoutre channel. This will complement the restoration of the Laloutre ridge that has been included in CMP17. One or more additional water control structures will be required to direct some sediment to the CWU while also controlling the rate at which diverted river water is shunted directly to Lake Borgne. The USACE MRGO ERP provides a somewhat vetted menu of small to medium-sized projects like the Point aux Marchettes project that can be implemented gradually as funding becomes available. But a suite of such projects should certainly be included in the final version of CMP17 even though they also appear on the USACE MRGO restoration wish list.

Preservation of the BMC should be a priority for any comprehensive CMP, as was true for CMP12. The following measures have all been proposed in the past, and in some cases have received preliminary feasibility study. Given the limitations of the ICM, it would be useful to propose marsh creation and shoreline stabilization measures as part of integrated projects.

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