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Examination of Deltaic Processes of Mississippi River Outlets—Caernarvon Delta and Bohemia Spillway in Southeastern Louisiana

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ABSTRACT

Deltaic processes of the Mississippi River Delta have been severely limited by artificial river levees, which prevent overbank flows during Spring floods. To counteract the effects of severing the connection between the river and the delta, focus has been placed on reconnecting the river to the delta by the creation of artificial outlets or diversions. The Caernarvon Freshwater Diversion and the Bohemia Spillway are two legacy diversions located on the east bank of the Mississippi River south of New Orleans.

The Caernarvon Freshwater Diversion was designed to deliver up to 8000 cfs from the Mississippi River. The sediment load in the diverted water is carried into the Caernarvon Diversion outfall area known as the Big Mar Pond. Turbidity measurements were taken from December 2009 through 2012 and used to calculate the total suspended solids (sediment load) delivered to the receiving basin. In total, approximately 264,000 yd^3 of sediment was delivered to the receiving basin. Often, the diversion is not operated when sediment spikes are present and therefore does not maximize potential sediment capture. Despite this variability in operation of the diversion, and the fact that the Caernarvon Diversion was built to minimize sediment capture, there has been enough accumulation in some areas to permanently support emergent wetland plant life on a new subdelta. Total wetland growth of the sub-delta in Big Mar Pond from 1998 to 2011 was 600 ac. Of this total, 581 ac were new growth since 2004. This pattern is similar to that documented for other larger diverted flows, such as the Wax Lake Delta, where there is an initial delay in wetland growth as mineral soil platforms vertically accrete to a threshold on which emergent vegetation can survive.

Bohemia Spillway was created in 1926 by the removal of existing artificial river levees, thereby allowing unencumbered flow across the river's natural levee during high river stages. In 2011, the Mississippi River watershed experienced an historic flood similar to the 1927 flood which provided an ideal opportunity to investigate and study the hydrology of the Spillway. Field surveys were conducted to measure the magnitude of the overbank flow into the Spillway and a Mississippi River flow survey was conducted using Acoustic Doppler Current Profiler (ADCP) measurements. These surveys indicate that the Spillway passed 30,000 to 50,000 cfs at peak flow. Current land loss rates in the Bohemia Spillway are negligible, perhaps due to receiving inputs of freshwater, nutrients, and sediment during high river events.

It is instructive to compare the natural processes of overbank flow, sediment delivery, and deltaic land building of the two river outlets, although neither of the outlets was built for these purposes. The first three decades of discharge through the Bohemia Spillway were higher than the long-term average, and probably had greater sediment concentrations than the post-1950 sediment load, which was reduced by dams located upriver. The landscape response for the Bohemia Spillway and the Caernarvon Diversion has similarities and differences. The Bohemia Spillway has not built a delta, but it has in-filled some canals, and more importantly, has prevented the pattern of indirect wetland loss due to canals, or "interior" wetland loss due to relative sea level rise or other more regional processes. In spite of the delta development, the Caernarvon Diversion area has regionally lost wetlands since its operation began with large wetland losses occurring during Hurricane Katrina. Overall, the Bohemia Spillway wetlands are more resilient.

The history of the Bohemia Spillway does suggest sustainability may be achieved by high discharges and high sediment concentrations early in the life history of the outlet followed by years of lower discharge as the diversion becomes a tool for wetland maintenance rather than wetland building. The need for the later phase of maintenance can be also inferred from the Caernarvon Diversion pre-history. Because the Mississippi Riv-

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er levee was intentionally breached at Caernarvon during the 1927 flood, a large sediment pulse was deposited, followed by a 65-yr hiatus in regular sediment input before the Caernarvon Diversion became operational. This hiatus undoubtedly contributed to subsequent regional land loss during Hurricane Katrina in 2005. For both Bohemia Spillway and the Caernarvon Diversion, there are clearly some benefits in reconnecting the river to the marsh.

INTRODUCTION

For more than a century, deltaic processes of the Mississippi River Delta have been severely limited by artificial river levees, which prevent overbank flows during Spring floods. The potential negative effects to the delta of reduced freshwater, sediment, and nutrients have been speculated for equally as long. Historically, the water delivered in overbank flows to the adjacent marsh contained freshwater, nutrients, and sediment that helped to sustain the marsh and counteract the natural subsidence which occurs in Mississippi River Delta wetlands. Severing of the river from the delta prevents the nourishment of the marsh by plant productivity and substrate accretion, indirectly contributing to land loss through sediment and nutrient starvation. Lack of mineral sediment input is one of many contributors to Louisiana's catastrophic wetland loss crisis (Boesch et al., 1994). Continuous river levees along the Mississippi River prevent overbank flow and, therefore, sediment from reaching the adjacent deltaic wetlands. The resulting sediment starvation prevents growth of new land and creation of new wetlands. Existing wetlands may be weaker and more vulnerable to other impacts, such as hydrologic modifications, subsidence, saltwater intrusion, and physical erosion by hurricanes or other storms.

To counteract the effects of severing the connection between the river and the delta, focus has been placed on reconnecting the river to the delta, mostly through the creation of artificial outlets along the river. Historically, these artificial outlets were built along the Mississippi River to manage flood stage and basin-side salinity. Just before and after the Great Flood of 1927, three large outlets were constructed to alleviate flood stage of the Mississippi River and provide additional flood protection to cities, such as New Orleans. These outlets included the Bohemia Spillway in 1926, the Bonnet Carré Spillway in 1932, and the Morganza Floodway in 1954. In addition, approximately nine small river outlets along the river were constructed in south Louisiana, between 1955 and 2003, primarily to manage basin-side salinity. Although these artificial outlets were built for purposes other than re-establishing the land-building processes of the delta through sediment delivery, they provide insights into deltaic processes and, more importantly, into the potential to re-establish these processes on a large scale via river diversions.

Considering that Louisiana has proposed spending $4.5 billion on new river sediment diversions to help restore coastal Louisiana (Coastal Protection and Restoration Authority [CPRA], 2012), study of these "legacy diversions" has added significance. This paper reviews two legacy diversions located on the east bank of the Mississippi River south of New Orleans: the Caernarvon Freshwater Diversion and the Bohemia Spillway.

CAERNARVON FRESHWATER DIVERSION

Location and Description

The Caernarvon Freshwater Diversion is located 15 mi downriver from New Orleans in Plaquemines Parish near the Plaquemines/St. Bernard Parish line (Fig. 1), and was constructed in 1991. The Caernarvon structure was designed to divert up to 8000 cfs from the Mississippi River into the local estuary through five 15-ft gated box culverts using gravity flow that can only generally flow when the Mississippi River stage at the Carrollton Gauge exceeds 4 ft (Snedden, 2006). Big Mar Pond, a failed agricultural impoundment, is part of the receiving area for waters diverted 1.5 mi from the Mississippi River through a conveyance canal. Although the conveyance canal is directly connected to Big Mar Pond, it is estimated to receive less than half of the Caernarvon Diversion discharge due to the hydrologic efficiency of flow toward Bayou Mandeville and Lake Lery when discharge from the diversion is below 2500 cfs (Cable et al., 2007). This lower-flow condition occurs most of the time. Overland flow onto the marsh platform in the receiving basin occurs, generally, when discharge from the diversion exceeds 4000 cfs (Snedden, 2006; Snedden et al., 2007). Below this discharge the flow in channelized in Bayou Mandeville and the Delacroix Canal, which then flows into Oak River.

Discharge and Operation

The average annual discharge since 1992 is approximately 2500 cfs representing just 0.2% of the Mississippi discharge during a flood. From 2001 to the present, the diversion structure has occasionally been operated under a pulsing regimen to mimic historical Spring floods. From 1993 to 2001, the average discharge through the diversion has been 2200 cfs. During this period, the diversion was closed 55% of the time and flowed above 4000 cfs (inducing overland flow) 9% of the time (averages and percentages calculated from discharge data available at U.S. Geological Survey (USGS) (2014). The maximum percent of time that discharge was above 4000 cfs occurred in 1994 at 16%, followed closely by 1996 and 1997 at 14% and 13%, respectively (Fig. 2). Between 2001 and 2012, the diversion was closed 40% of the time, however, under the pulsing regime, the average discharge was 2700 cfs, and flowed above 4000 cfs 12% of the time. The maximum time the discharge was above 4000 cfs in this time period was in 2007 at 31%, followed closely by 2010 at 27% and 2008 at 21%. Also, during this time period, in 2010, the diversion was opened to maximum discharge during the BP oil spill in an attempt to prevent oil from moving inland. In Spring 2011, during the historic flood that occurred on the Mississippi River, the average discharge was 2000 cfs but was closed 33% of the time and above 3000 cfs only 9% of the time.

The sediment load in the diverted water is carried in to the Caernarvon Diversion outfall area known as the Breton Basin. The sediment load has been found to be variable but generally increases when the sediment load in the Mississippi River increases, which usually occurs during floods (Snedden, 2006; Snedden et al., 2007). However, the timing and magnitude of sediment pulses in the Mississippi River are not completely understood. Additionally, the timing and magnitude of the sediment load that is carried through the Caernarvon Diversion to the receiving basin is also not clear. Therefore, since 2009, Lake Pontchartrain Basin Foundation (LPBF) has been monitoring turbidity of the discharge entering the Caernarvon Diversion. Using our turbidity measurements and an equation relating turbidity to total suspended solids (TSS) or sediment load (developed by Snedden et al., 2007), as well as collecting actual discharge data from the Caernarvon Gauge, we were able to calculate the total sediment load entering the Caernarvon Basin from December 9, 2009, through 2012. In addition, by calculating potential discharge, based on river stage, we also predicted the potential sediment load that could have been delivered, based on potential discharge. In total, it was calculated that the Caernarvon Diversion delivered approximately 264,000 yd^3 of sediment to the receiving basin, including Big Mar. In addition, calculations were made to determine how much sediment could be delivered if the diversion were opened to maximum capacity (depending on river stage) to capture as much riverine sediment as possible. Calculations were based on measured turbidity and potential discharge in relation to river stage at Carrollton (potential discharge was capped at 8000 cfs, the reported maxi-

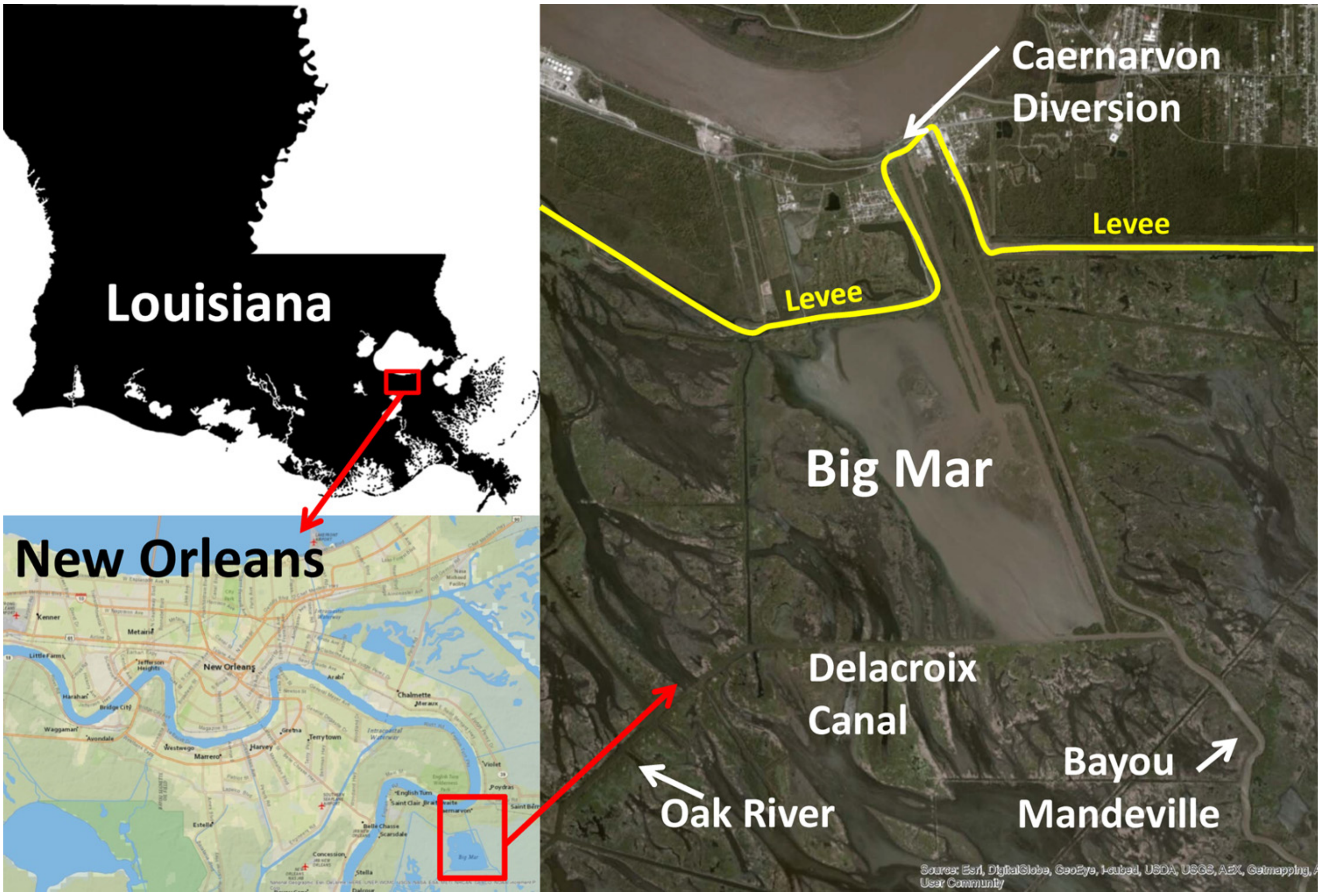


Figure 1. Location of the Caernarvon Diversion and Big Mar along the Mississippi River, south of New Orleans, Louisiana.

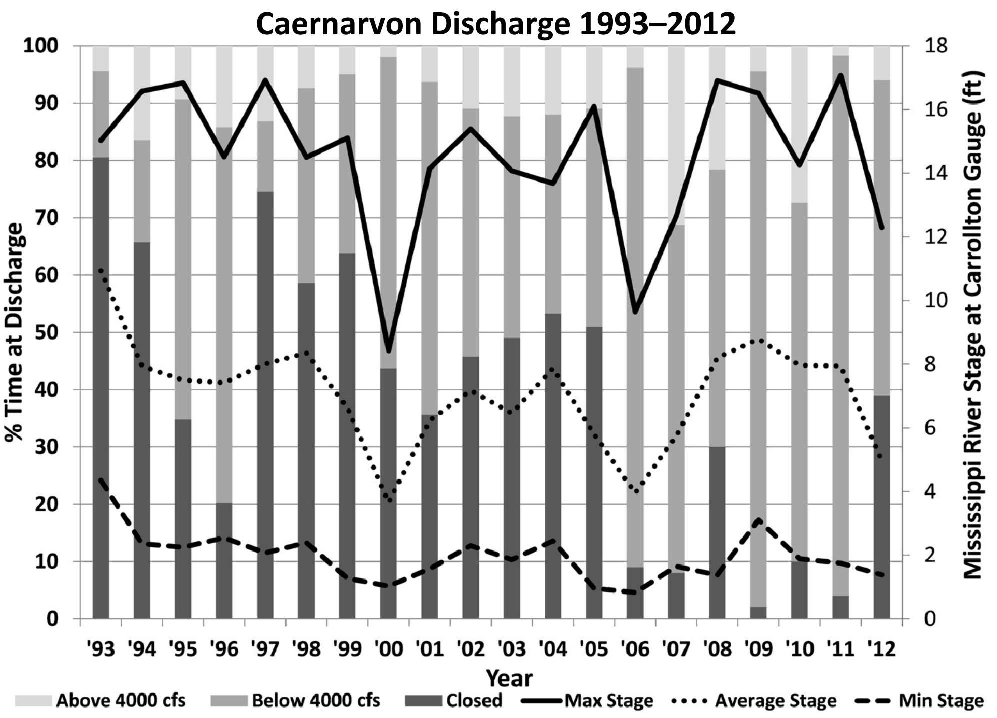
mum capacity of the diversion). By performing these calculations, it was determined that over the same time period, there was a potential for 706,000 yd^3 of sediment to be delivered through the diversion or 168% more sediment than the actual sediment delivered. It is understood that the Caernarvon Diversion cannot be operated at maximum flow at all times in order to maximize sediment capture, because there are salinity concerns in the basin. Therefore, potential sediment delivery was recalculated to maximize the diversion opening only when there was high suspended sediment concentration in the diverted water (during sediment spikes), using measured turbidity data. Under this pulsing regime during high sediment concentrations, 375,000 yd^3 of sediment would have been delivered to the receiving basin or 42% more sediment. Figure 3 illustrates these several important aspects of the diversion and sediment delivery, using 2012 as an example. Often, the diversion is not operated at times when there is high turbidity or sediment load in the water and, therefore, does not maximize potential sediment capture and transfer into the receiving basin (Baker et al., 2013). From a sediment delivery standpoint, the operation of Caernarvon has been highly inefficient.

Caernarvon Delta and Prodelta Growth

Since the construction of the diversion, despite the underoperation and depauperate sediment delivery described above, sediment has been deposited in the Caernarvon receiving area. Over time, there has been enough accumulation in some areas to permanently support emergent wetland plant life. Two studies conducted just south of Big Mar Pond, one from 1996 to 2000 (Lane et al., 2006) and another in 1998 (DeLaune et al., 2003), found significant sediment accumulation in the area, both mineral and organic. In this area, cattail (*Typha* sp.), bulltongue (*Sagittaria lancifolia*), maidencane (*Panicum hemitomon*) and bigpod sesbania (*Sesbania macrocarpa*) have been replacing brackish marsh vegetation.

In Big Mar Pond, prior to 2004, wetland growth (defined as persistent emergent wetland vegetation in formerly open water) was negligible. Since 2004, wetland growth (or land gain) has been significant (Fig. 4) and appears to be accreting annually. Imagery and field survey allow quantification of the annual rate of wetland (delta) growth. Emergence of a delta after 12 yr of prior operation is due to the filling of pre-existing accommodation space, and is consistent with other recent deltas such as the Wax Lake Delta, which did not become emergent until 31 yr after creation of the Wax Lake Outlet. This wetland growth is a result of an active delta that has two distinct zones and, therefore, is referred to as the Caernarvon Delta, including the delta (northeast quadrant) and prodelta (southwest quadrant) areas (Fig. 5). In the delta, near the terminus of the Caernarvon conveyance canal, a mineral soil platform of radiating bars and shallow inter-bars (i.e., the delta platform) has become vegetated. This has the typical delta geomorphology of bars and small bifurcating distributary channels (Fig. 6). In the prodelta, in 2005, Hurricane Katrina pushed marsh balls from the surrounding marsh into Big Mar (Fig. 4). The hurricane deposition in this zone became nucleation points where wetlands have expanded since 2005. This expansion was initially flotant marsh, but is acting as a sediment trap for fine sediment from Carnarvon Diversion discharge, thus comprising part of the sub-aqueous delta. This sub-aqueous delta area was not significantly impacted by Hurricane Gustav in 2008. Further, the establishment and expan-

Figure 2. Discharge at the Caernarvon Diversion from 1993 to 2012 in % time closed, below 4000 cfs and above 4000 cfs. Discharges above 4000, in general, induce overland flow or flooding of the marsh platform in the receiving basin. Also shown is the maximum, average, and minimum stage in the Mississippi River at the Carrollton Gauge over the same time period.



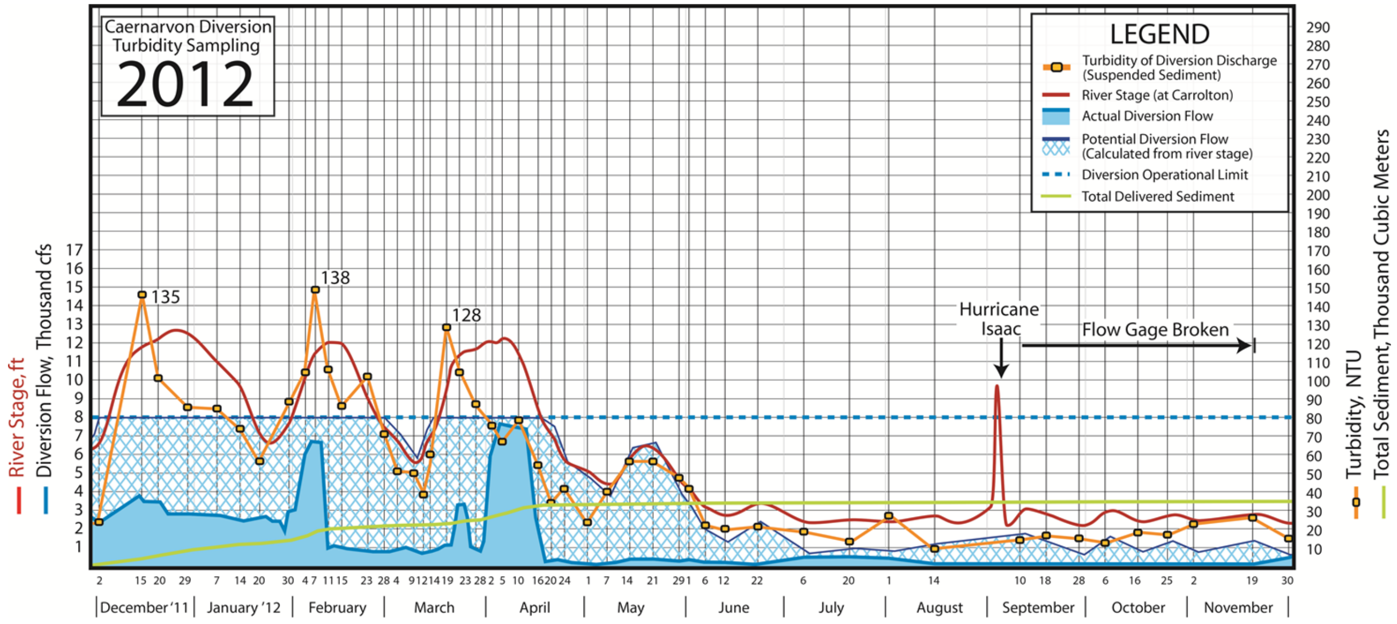


Figure 3. Record of Caernarvon Freshwater Diversion discharge and turbidity for 2012, as an example of the discrepancy between timing of diversion operations and sediment spikes entering the Caernarvon Receiving Basin. Also illustrated is the under-operation of the diversion during high stage events in the Mississippi River. The difference between the solid blue area and the hachured is the potential additional flow that was not allowed due to management of the diversion. The orange line is the turbidity of the discharge, which shows that the few times when the diversion was operated at higher flow it was often not when turbidity was elevated.

sion of woody vegetation, mainly black willow (*Salix nigra*), indicates that much of the flotant marsh has converted into attached marsh.

It is estimated that there were19 ac of wetland growth from 1998 to 2004, and that the total wetland growth in Big Mar Pond from 1998 to 2011 was 600 ac (Fig. 7). Of this total, 581 ac were new growth since 2004. The USGS dataset indicates 23 ac growth from 1998 to 2004, and 321 ac of wetland growth from 2004 to 2010. Data produced by the LPBF indicate that the wetland growth rate in Big Mar Pond from 1998 to 2004 was 3 ac/yr. The rate of growth from 2004 to 2011 was 83 ac/yr (Henkel et al., 2011). As mentioned above, in the Summer of 2010, the Caernarvon Diversion was opened for 15 weeks at full capacity in response to the BP oil spill. The LPBF has estimated that over 125,000 yd^3 of sediment entered the marsh during this time (Baker and Lopez, 2011). From 2010 to 2011, there was significant growth of the vegetated delta in the northwest quadrant in Big Mar Pond. In March of 2011, a flyover of the area revealed

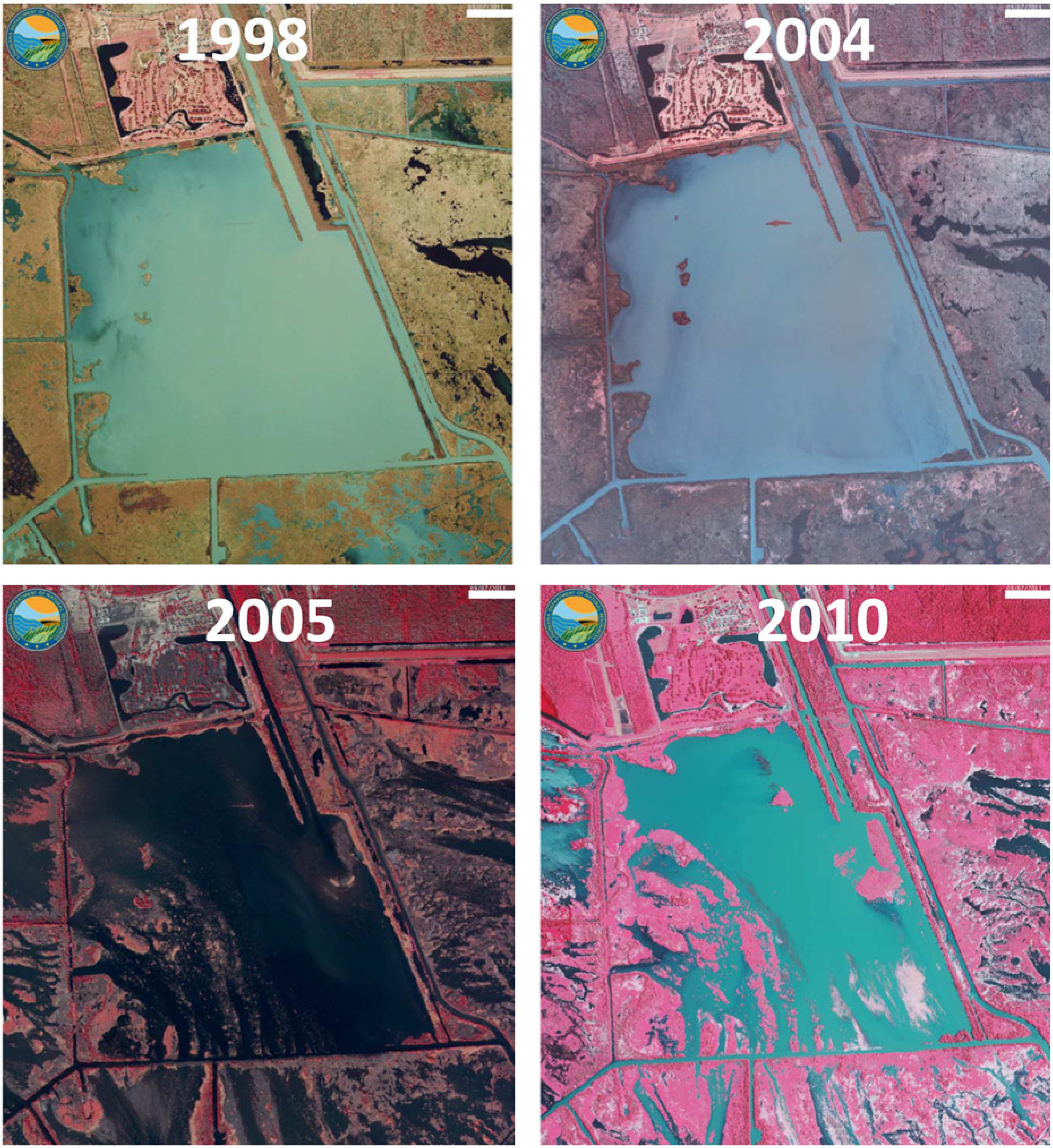


Figure 4. Land change in Big Mar Pond from 1998 to 2010. Notice the wrack and marsh balls deposited by Hurricane Katrina in 2005 and significant delta growth by 2010.

exposed mudflats with little vegetative cover, which represented expansion from 2010. By August of 2011, there had been more delta growth and the formerly exposed mud flat was almost 100% vegetated. The growth of the vegetated delta from 2010 to 2011 is estimated to be approximately 104 ac, which is significant growth in one growing season (Fig. 8). The delta growth and vegetation establishment and expansion on newly exposed mudflat continued through 2013 (the end of this study) (Fig. 8). Both LPBF and USGS data clearly indicate an increase in rate (1400%) of wetland growth after 2004 (Fig. 7). The total area of Big Mar Pond is 1720 ac and the emergent portion of the Caernarvon Delta occupies 35% to 50% of Big Mar Pond and the remaining open water areas are <1 ft deep under normal marsh water levels. Based on the observed trends of wetland emergence, LPBF projects the annual rate of wetland growth to be approximately 80 ac/yr in Big Mar Pond as long as the Caernar-

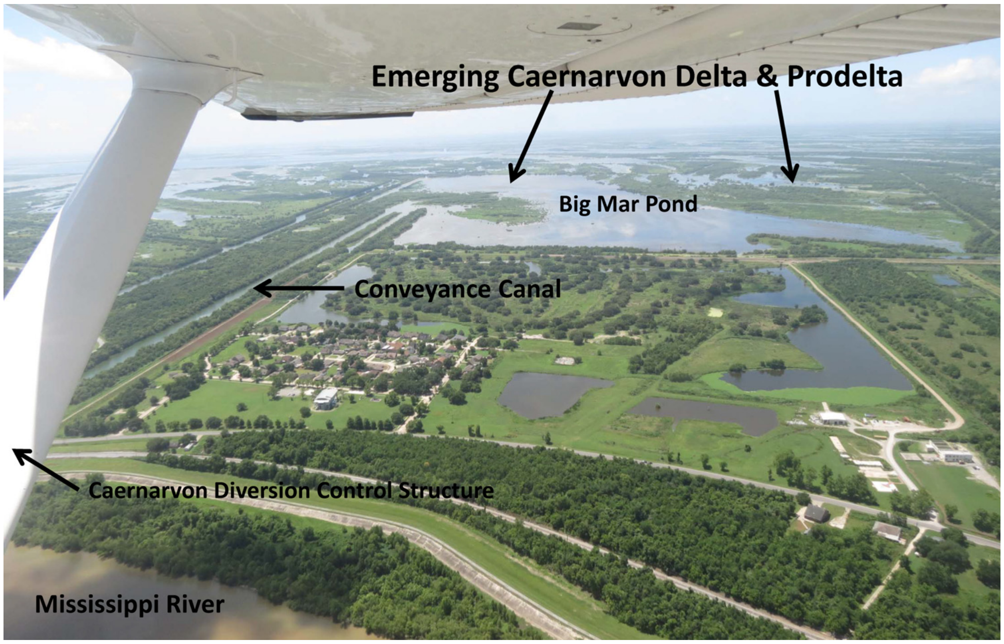


Figure 5. Relative location of the Caernarvon Freshwater diversion, Big Mar Pond, and the Caernarvon Delta (northeast corner) and prodelta (southwest corner) areas of wetland growth, making up the Caernarvon Delta Complex.

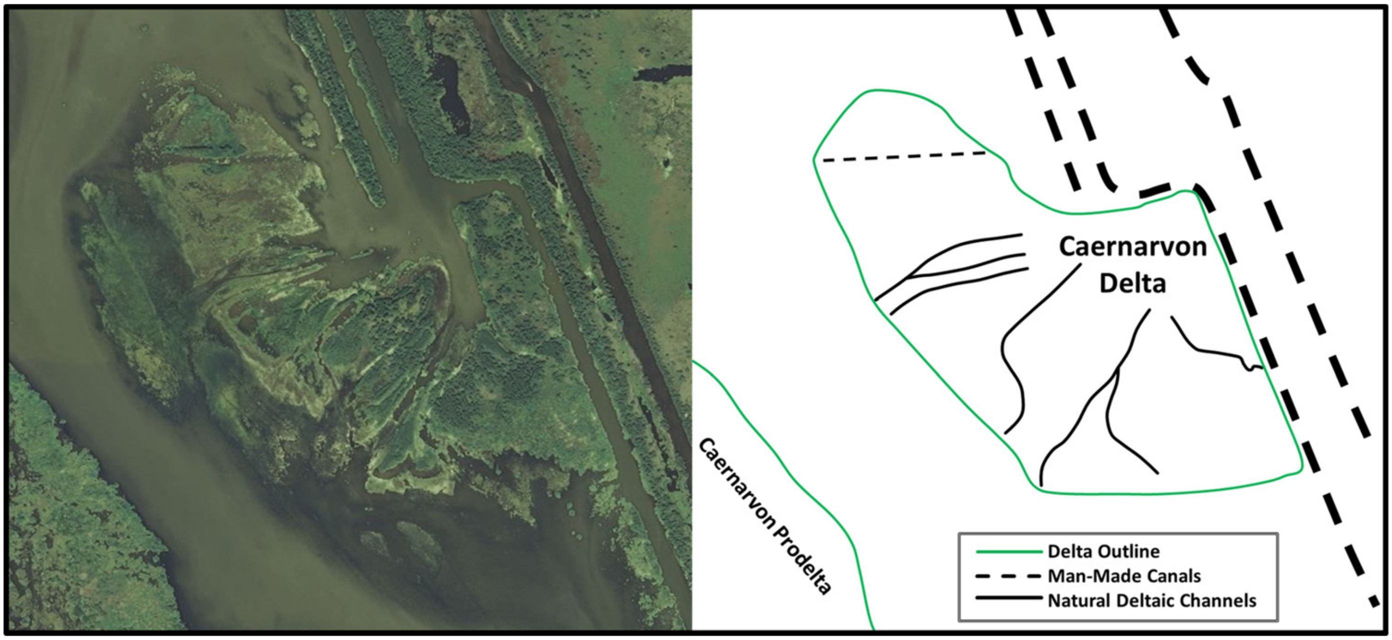


Figure 6. Aerial photo from 2011 illustrating man-made canals and natural distributary channels that carry discharge from the Carnarvon Freshwater Diversion through Big Mar Pond.

von Diversion has at least average operational flows. However, Big Mar Pond is filling with sediment, and it may be reaching a threshold capacity to retain sediment. Most likely, the entire area will not become emergent wetland since channels will be maintained to allow water and sediment to bypass Big Mar Pond. This process suggests there is potential for future wetland accretion or emergence outside Big Mar Pond as accommodation space diminishes in the pond.

As mentioned above, there has been extensive natural recruitment of plants to the emerging Caernarvon Delta over time. A general survey of plant species in the delta and prodelta was conducted in 2011. In the delta, dominant herbaceous native plants were elephant ear (*Xanthosoma* sp.), bulltongue (*Sagittaria lancifolia*), and gooseweed (*Sphenoclea zeylanica*). Other herbaceous species included giant cutgrass (*Zizaniopsis miliacea*), alligator weed (*Alternanthera philoxeroides*), cattail (*Typha* sp.), fragrant flatsedge (*Cyperus odoratus*), roseau cane (*Phragmites australis*) and panic grass (*Panicum* sp.). Invasive species include water hyacinth (*Eichhornia crassipes*). In addition to the herbaceous vegetation listed above, there has been extensive establishment and expansion of the dominant black willow populations on the delta. In the prodelta (southwest corner) giant cutgrass, smartweed (*Polygonum punctatum*) and alligator weed are the dominant herbaceous plants with cattail and elephant ear mixed in. Again, the woody tree, black willow, is prevalent and continues to expand in the area. The Big Mar Pond area is currently thriving with different kinds of birds and water fowl, numerous alligators, and diverse insect life.

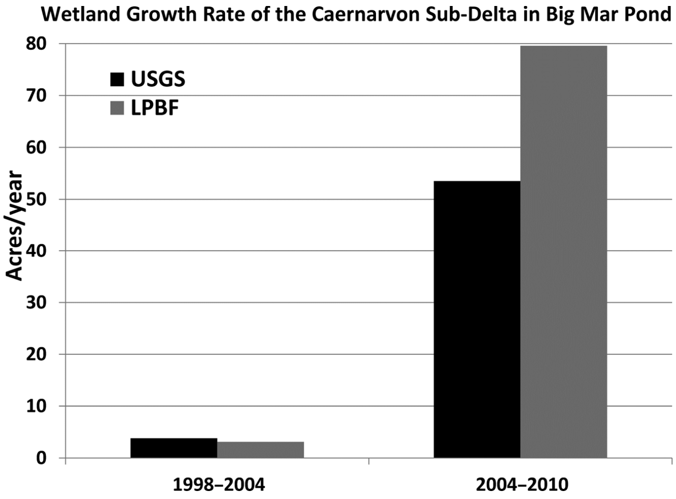


Figure 7. Bar graph showing wetland growth rates in Big Mar Pond calculated by the LPBF and USGS from 1998 to 2011.

Caernarvon Tree Plantings

From 2010 to 2013, the LPBF and the Coalition to Restore Coastal Louisiana (CRCL) planted 2300 baldcypress (*Taxodium distichum*), green ash (*Fraxinus pennsylvanica*) and water tupelo (*Nyssa aquatica*) trees on the Caernarvon Delta and prodelta (majority baldcypress). This project's goal was to establish a baldcypress swamp in newly emerged wetlands created by an artificial river outlet. This planting was not the first attempt to re-establish a cypress swamp in the Pontchartrain Basin, but it is the first to be done in an area under influence of an artificial river diversion.

To date, the trees (with nutria excluder devices) have demonstrated 70% survival (this includes one site that experienced high mortality due to Hurricane Isaac induced storm surge) and good growth rates. Extensive baldcypress planting has been done along Pass Manchac starting around the 1980s. Most of these trees were killed by high salinity in the drought of the late 1990s (G. Shaffer, 2011, personal communication). Another intense local baldcypress planting was at the Hammond Wastewater Assimilation project (also in the Lake Maurepas area). These trees have suffered from severe nutria herbivory, in part due to the enhanced nutria activity associated with the assimilation project (Day et al., 2011). Both these projects indicate the potential importance of a riverine source of freshwater and nutrients for baldcypress reforestation. The recent emergence of the Caernarvon Delta associated with the nearby Caernarvon Diversion is an unprecedented opportunity in the Pontchartrain Basin to pursue baldcypress reforestation under the more natural condition of riverine flow and delta formation from the Mississippi River. In addition, an established cypress forest will enhance storm surge protection to nearby communities and levees.

Discussion: Caernarvon Diversion

This pattern of dramatic increase in the rate of wetland growth is similar to that documented for other larger diverted flows, such as the Wax Lake Delta and the Atchafalaya Delta (Roberts et al., 1980, 1997). In similar cases of introduced river flow, there is an initial delay in wetland growth as mineral soil platforms vertically accrete to a threshold on which emergent vegetation can survive. Once this occurs, a much higher rate of wetland growth occurs. Nevertheless, the current higher growth rate in Big Mar Pond was not expected considering that: (i) the diversion was designed to minimize sediment delivery; (ii) the maximum discharge capacity is small; (iii) the diversion has been under-operated; (iv) the diversion has not been operated to efficiently deliver sediment; and (v) most of the discharge does not flow into Big Mar Pond. Beyond Big Mar Pond, there is undoubtedly a much larger area of mineral accretion, that is, the submerged prodelta. For example, there is a mud platform in Lake Lery where Bayou Mandeville discharges Caernarvon flow 4.9 mi away from the Caernarvon Diversion. Although to date only isolated sites of land building have occurred outside of Big Mar Pond, it is likely that, in the future, new wetland creation will begin appearing outside of it. This delta emergence is more likely if the Caernarvon Freshwater Diversion is operated in a manner that effectively delivers sediment to the receiving basin. It is likely that the rate of growth could be increased by a different operation scheme to increase efficiency of sediment delivery.

BOHEMIA SPILLWAY

Location and History

The Bohemia Spillway was authorized by the state of Louisiana in 1924 to create an outlet for Mississippi River flood waters downstream of New Orleans, as a measure to help protect New Orleans from rising river stages. The Bohemia Spillway is on the east bank of the Mississippi River, 40 river mi below New Orleans (Fig. 9). The "construction" of the Bohemia Spillway was simply the removal of existing artificial river levees, thereby allowing un-encumbered flow across the river's natural levee during high river stages. Remarkably, the levee removal was completed in 1926, just months before the onset of the Great Mississippi Flood of 1927 (Times Picayune, 1925, 1926a). To further relieve the flood threat in 1927, the artificial river levee was intentionally breached at a site immediately below New Orleans, which lowered river levels even further (Barry, 1998). This levee was repaired but 65 yr later was the site of the Caernarvon Freshwater Diversion. Due to the success of the historic outlets, during the Summer following the 1927 flood there were numerous proposals to create permanent flood outlets (Times Picayune, 1926b), and by 1932 the U.S. Army Corps of Engineers (USACE) constructed the Bonnet Carré Spillway, which has now been successfully operated ten times (Fig. 9). Current USACE protocol to open the Bonnet Carré Spillway prevents river stage from rising above 17 ft in New Orleans, which also limits the maximum stage downriver at the Bohemia Spillway to 7.5–8 ft.

The current landscape of the Bohemia Spillway and the documented changes to the landscape reflect a record of its 87-yr existence. It provides a record of influence of river flows into the adjacent wetlands. The written record or documentation of the Bohemia Spillway is sparse. The LPBF has released a report detailing the history of the Bohemia Spillway and all research that has been conducted on it through 2012 (Lopez et al., 2013). Below is a summary description of these studies and observations conducted during the 2011 Mississippi River flood.

Bohemia Spillway Geomorphology

The Bohemia Spillway is 11.8 mi long and approximately 3 mi wide from river to sound. Except for three small segments of the artificial levee that are still present in the spillway totaling ~0.5 mi in length (Fig. 10), the spillway landform can generally be thought of as a linear ridge with an asymmetric profile that is flatter toward the marsh and steeper toward the river. The peak of the ridge is the crown of the natural levee with a swath of forest that transitions into marsh moving away from the river towards the sound. There is 5.4 mi^2 of forest and 17.8 mi^2 of marsh, most of which is salt marsh (13 mi^2). It is the levee crown that flood water must overtop to be diverted into the spillway. Because there are superimposed on this natural terrain, manmade features such as Bohemia Road, oil and gas canals, borrow

Figure 8. Oblique aerial photographs of the Caernarvon Delta. Note expanded vegetation on bars and growth of the wetland forest.

pits, and navigation canals, water overtopping the crown must pass through this modified landscape to reach the sound. Bohemia Road runs along the crown of the natural levee and may locally be the controlling elevation for Mississippi River flood waters. Elevations along the road range from 4 to 8 ft on the natural levee, except in the short segment where the road is also on top of the short reaches of remnant artificial levees, in which case the road is approximately 9 ft.

Natural geomorphic features in the Bohemia Spillway include six internal drainage sub-basins that drain rainfall off the natural levee. They include small bayous and tidal channels which are part of the integrated drainage network. The water flow may be driven by tides, rainfall or river flood events, with water flowing generally from the river toward Breton Sound except for tidal flow. Harris Bayou is the best example of an integrated, 3rd order, tributary drainage basin, which drains the sloping topography of the natural levee away from the levee crown, across the marsh and to the sound (Fig. 11). Cox Bay has been highly altered by man-made canals.

Man-made geomorphic features present in the Spillway include segments of the artificial levees, navigation canals such as the Back Levee Canal, oil and gas canals, diversion conveyance canals, pipeline canals, borrow pits and canals, and trenasses. The trenasses (colloquial for small linear ditches) were likely built for trapping, drainage, or logging. Gullies are also small ditches but are not artificially dug, but rather are the result vigorous flow and erosion due to the interaction of oil and gas canals and the natural levee. These gully flows are ephemeral, and in some instances flow passes underground and discharges into the oil and gas access canals as localized high flow or small waterfalls.

An extraordinarily rare occurrence for coastal Louisiana is observed in the Bohemia Spillway in which some canals segments have been reclaimed by marsh simply due to the processes associated with the flow of river water through the spillway. This natural restoration can be seen in the infilling of segments of the Back Levee Canal, which appears to have occurred in the initial discharges through the Bohemia Spillway (1926 to 1932). Figure 12 identifies two in-filled sections of the Back Levee Canal. Due to the infilling, boat traffic now detours through Fucich Bayou and Cox Bay to reach southern end of the Bohemia Spillway. Other oil and gas canals are also partially in-filled or converted back to marsh.

Hydrology of the 2011 Flood

In 2011, the Mississippi River watershed and flood works constructed under the Mississippi River and Tributaries Act experienced an historic flood similar to the 1927 flood (USACE, 2012). The flood event downriver of New Orleans was not as extreme as the mid-west due to the regulation of flow passing in the river at New Orleans, and therefore at the Bohemia Spillway. To mitigate flood damages, the USACE opened designated spillways at three locations: (1) South of Cairo, Illinois; (2) the Morganza Spillway north of Baton Rouge, Louisiana; and (3) the Bonnet Carré Spillway north of New Orleans, Louisiana. These spillways all served to divert water from the main channel of the

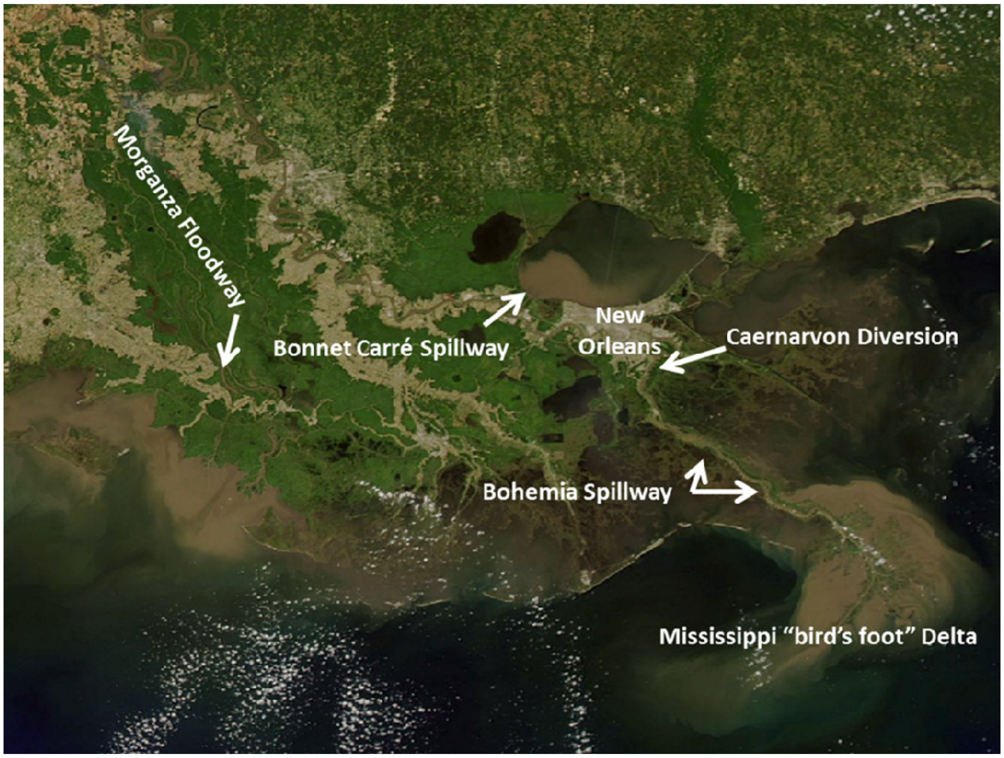


Figure 9. Location of the Bohemia Spillway in relation to New Orleans and other river outlets. Also shown is Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery obtained on May 16, 2011, during the 2011 Mississippi high water, with discharge plumes of the Mississippi River. The plumes initiate from various engineered and non-engineered outlets from the river, and they trace how freshwater and sediment is currently distributed into coastal environments during high water events.

river, thus lowering the river's stage. While it did not divert as much water as the other spillways, the Bohemia Spillway still captured flow along with sediment and nutrients from the Mississippi River which flowed into the adjacent marshes along lower Breton Sound. Figure 9 indicates how the high water event distributed sediment in southeast Louisiana's coastal zone based on the natural and engineered outlets of the river.

Unlike the other three spillways, there was no high profile decision and no visually impressive event marking the opening of the Bohemia Spillway. As the river rose to levels near the crest of the natural levee, river water began to trickle over the road and into the Bohemia Spillway. As the river continued to rise, the flow increased until it peaked with the crest of the river stage on May 17, 2011. The LPBF's surveys indicate that at the river's peak in 2011, an estimated 30,000–50,000 cfs flowed from the main channel of the Mississippi river into the Bohemia Spillway.

The discharge into the Bohemia Spillway during the 2011 Mississippi high water event provided an ideal opportunity to investigate and study the hydrology of the Spillway. Therefore, LPBF conducted three separate but related field surveys at Bohemia during the high water: (1) a 2011 flood overbank hydrologic survey including the key hydrologic variables of depth, velocity, and direction; (2) a Mississippi River flow survey using an Acoustic Doppler Current Profiler (ADCP) with measurements at three transects that crossed the river adjacent to the Bohemia Spillway; and (3) a marsh hydrology survey using an ADCP in canals in the marsh. In addition, computer simulations of the river's discharge into the Bohemia Spillway were conducted to develop a historical rating curve using newly acquired elevation data by LPBF. Together these surveys and the computer modeling provide data adequate for a comprehensive analysis of the hydrology of the Bohemia Spillway during the 2011 high water.

2011 Flood Overbank Hydrologic Survey: Field Methods

Our hydrologic survey consisted of two teams, each of which would survey assigned segments of the road on a given survey day. The teams would walk their assigned segments, collecting data that included the start and end points of the dry road segments (termed "Dry Points"), short spans of low flow ("Shallow Area"), and depth, velocity, and direction roughly every 500 ft for long segments of overtopping ("Overbank Flow"). When velocity measurements were taken, water depth was also measured. Velocity measurements were taken by releasing a float and recording the time lapsed as it moved a measured distance. Direction of flow was measured using a compass pointed in the direction the float moved. Flow data were collected over 26 d from May 11, 2011, to June 6, 2011, during the height of the flood.

In addition to measurements taken along Bohemia Road, LPBF's survey team also obtained basic observations on the marsh drainage network (between Bohemia Road and Breton Sound), including salinity, turbidity, and depth at various locations. A flow meter (General Oceanics Model 2030 Mechanical Flowmeter) was used to more precisely measure flow velocity at a handful of specific locations. Various data were obtained from 55 locations distributed throughout the marsh drainage network between Bohemia Road and Breton Sound. Additional features that influence the Bohemia Spillway's hydrology, such as culverts, were also noted, and when possible basic characteristics, such as the location and dimensions, were obtained.

While walking the length of Bohemia Road, two major breaches in the road with water flowing freely through them were observed. Because of the significance, the survey team returned to these locations on numerous later dates and obtained comprehensive measurements related to the dimensions and flow through these breaches. In addition to measuring water depth, a basic survey instrument (Stanley FatMax AL24 Laser Level with a DeWalt DW0737 Heavy Duty Tripod Type 1) was utilized to survey the length of the breach and height of the road relative to the water surface. Additionally, the velocity was measured using the flow meter. Of note, both of these breaches occurred near previous breaches observed during the 2008 high water event. The breach near the Diversion Canal continued to enlarge as the waters receded, demonstrating headward erosion towards the

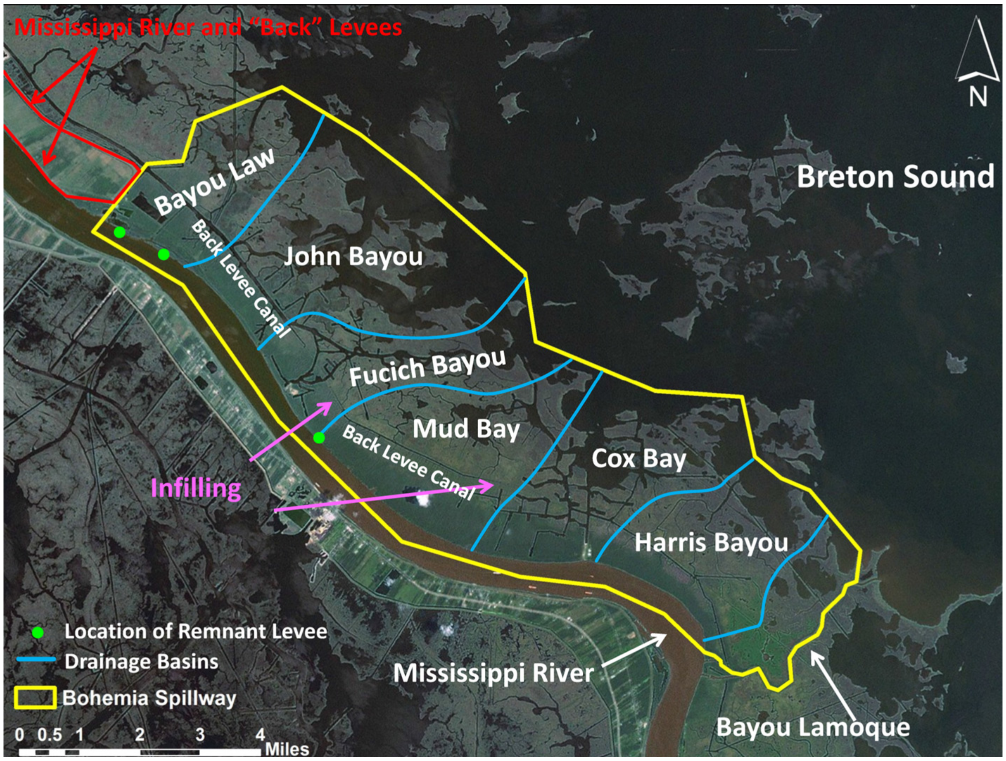


Figure 10. The Bohemia Spillway was created in 1926 by removal of artificial levees along the Mississippi River. The sub-basins within the Bohemia Spillway are interpreted from dendritic stream patterns and channel morphology. Some sub-basins are highly altered by man-made canals.

river through a sand bar that had developed along the river's edge over the last 40 yr. During another high water event in early 2012, the headward erosion continued and eventually cut to the river creating a new distributary that was named Mardi Gras Pass (more information on Mardi Gras Pass can be found at saveourlake.org, including a new report released in 2014). At a third location, we observed significant scour in the road and believe that this may have formed a breach if given enough time and flow.

Analysis and Results

In total, the field survey teams obtained 317 points along Bohemia Road, including 184 depth measurements of which 141 points have flow velocity measurements. Different types of flow were observed from fast with ripples to stagnant or very slow flow. Additionally, 104 points were dry locations and these were used to denote the beginning and end of road segments that were not flooded by the river. The remaining data points relate to culverts, canals, washouts, and areas of little flow or stagnant shallow water.

After the entire length of the spillway was divided into eighteen reaches, and sub-reaches within the reaches, the following quantities were calculated for each sub-reach: wet length of the sub- reach (as % of total length for the reach, based on the dry points); average depth measured for the sub-reach; and average velocity measured for the sub-reach. Using those calculations, the discharge for each sub-reach could be calculated using the equation: $Q_{\text{sub-reach}}$ = wet length x avg. depth x avg. velocity. The discharges for the sub-reaches were summed to obtain the total discharge per reach and then the discharges for the reaches were summed to obtain a discharge for the entire Spillway.

Hydro-Geomorphic Classification

A hydro-geomorphic classification was developed to categorize the dominant geomorphic control on water flow during a high river overbank flood event such as in 2011. The Bohemia Road overflow survey was analyzed into 18 different reaches. These flow analyses along with geomorphic and other cumulative observations in the spillway provide a basis for a hydro-geomorphic classification and description. The length of the spillway was classified generally into one of the following hydro-geomorphic types.

Trenasses–Back Levee Canal

Examination of aerial photography revealed that much of the marsh side of the natural levee had a rectilinear pattern of small channels. These are typically less than 30 ft wide and less than 6 ft deep. It is likely these canals are trapper canals that predate the creation of the Bohemia Spillway in 1926. A subset of these trenasses actively captures overbank flow, which is then generally discharged into a back canal that runs most of the length of the spillway.

Natural Levee–Back Levee Canal

This natural levee canal association is entirely in the lower reach of the Bohemia Spillway where the Harris Bayou drainage basin is present. This basin has an integrated drainage pattern flowing across and away from the natural levee and toward Breton Sound. The drainage is slightly influenced by some linear trenasses, but most flow appears to be captured initially by the natural meandering drainage that flows into and across the Back Levee Canal. Flow continuing past the Back Levee Canal does reach the shallow bay of the larger Breton Sound. In the late 1930s, Harris Bayou breached into the river but was dammed in 1940 (Louisiana State Board of Engineers, 1940). Although at this time, Harris Bayou does not have a direct channel connection to the river, no evidence of a dam was found.

Oil and Gas Canals

Oil and gas canals were dredged with development of the Potash and Cox Bay oil and gas fields first discovered in 1937/1938. USACE land change maps indicate canal dredging was primarily from 1932 to 1956, but as late as 1974 (Britsch and Dunbar, 1996). These canals have typical widths (80 to 150 ft) of south Louisiana oil and gas canals with a typical rectilinear

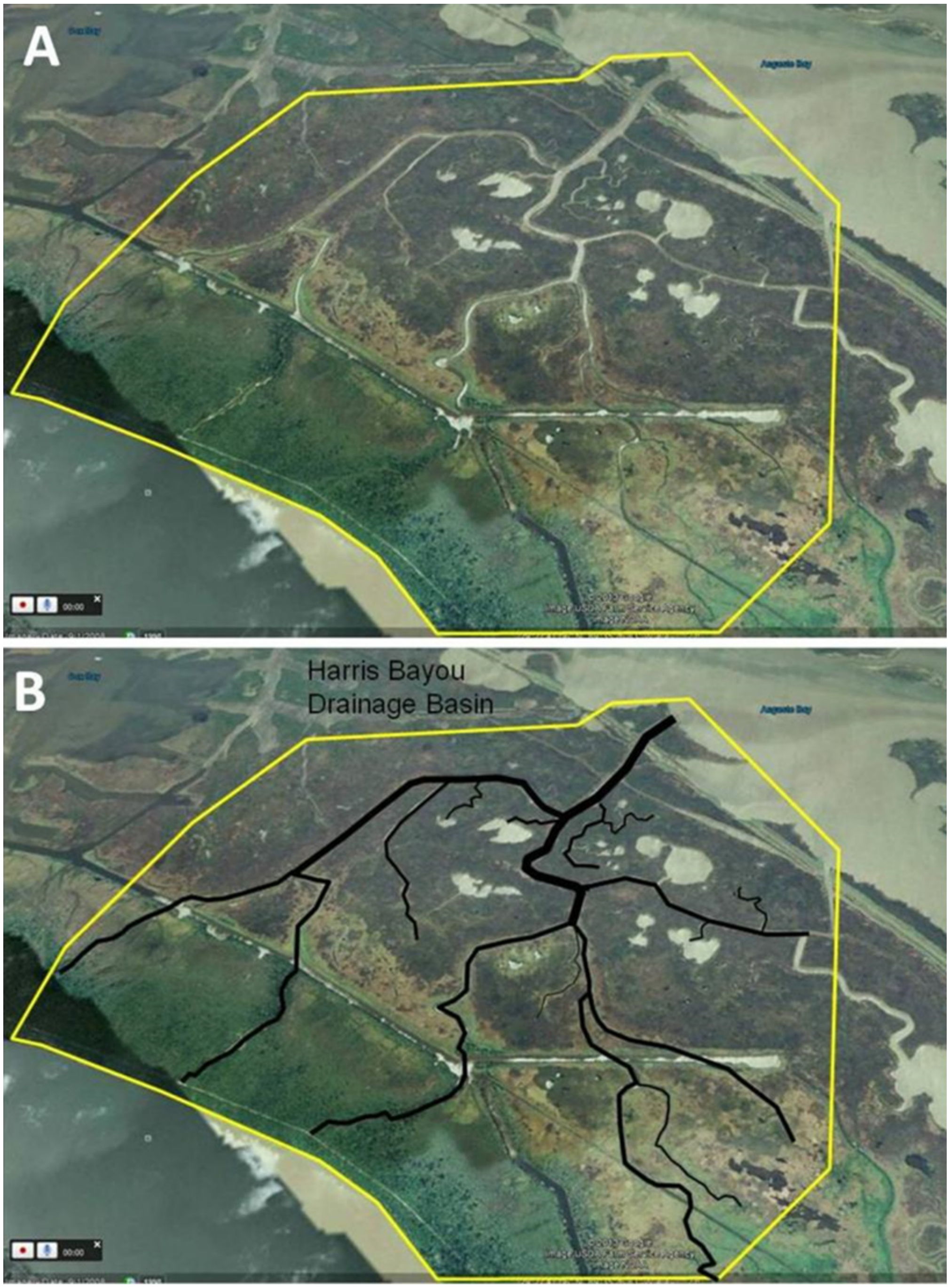


Figure 11. Aerial view of the Harris Bayou drainage basin showing (A) aerial view and natural drainage patterns of Harris Bayou and (B) aerial view with the drainage network emphasized.

distribution. However, the canals are often shallower than typical oil and gas canals, some as shallow as 1 or 2 ft (typical depths are 8 to 10 ft). Some of these canals were dredged relatively close to the river and therefore, at a high bank elevation since they are cut into the natural levee. These canals significantly affect local overflow patterns through the spillway. For example, many of the oil/gas canals have prominent erosional gullies near their termination close to the river. Some of these gullies had significant flow during the flood (2000 to 3000 cfs). The spoil banks are generally present and where present may deflect or impound flow.

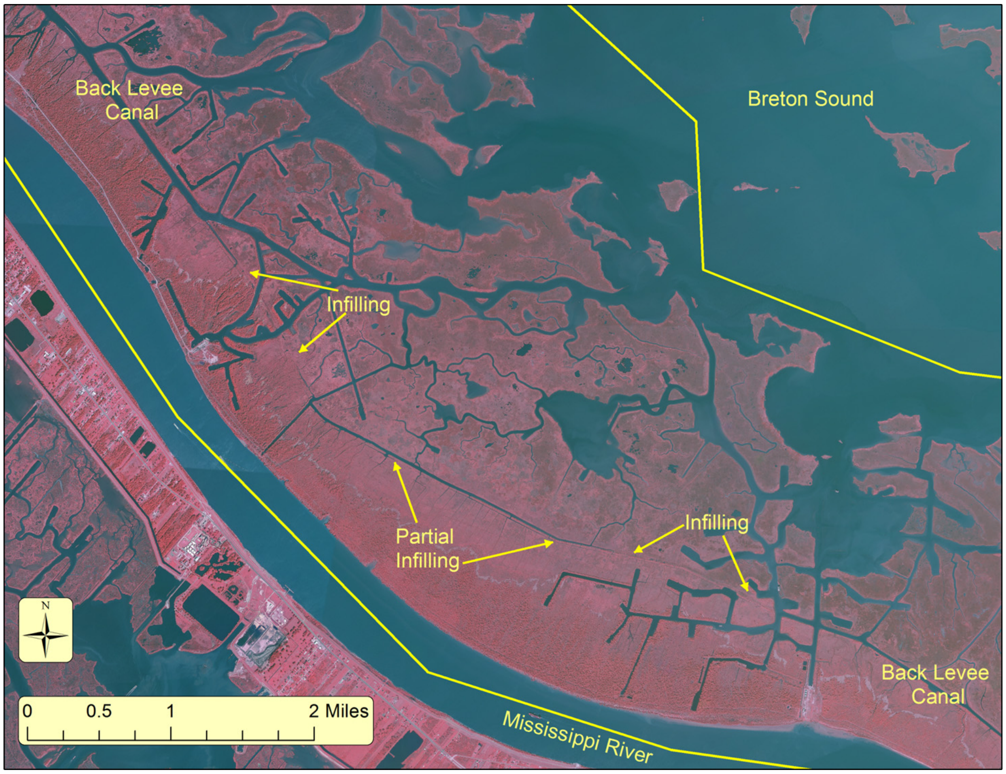
Road Blocking or Deflecting Flow

In a few places, it was apparent that the road elevation was significant enough to impede or deflect flow. This was most evident near the northern end of the Bohemia Spillway where two parallel roads are present, which together significantly reduce the discharge.

Artificial River Levee

At three locations in the Spillway, the road is more uniformly elevated (7 to 9 ft), and there is also present a partial concrete embankment. It is strongly suspected these are remnants of the original front line river levee constructed prior to 1926. Records indicate that at least 90% of the “front line” river levees were removed in February 1925 and September 1926 (Louisiana State Board of Engineers, 1926), and thus brackets the physical creation of the spillway. A pre-construction engineering report says a short “spur” of the Bohemia levee would be left in place at the upper end of the spillway (Orleans Levee Board, 1926). The

Figure 12. Location of infilling and partial infilling in the Back Levee Canal in the Bohemia Spillway. The Back Levee Canal was constructed pre-1932 along the entire length of the Spillway, but subsequently was blocked by marsh that had recolonized the in-filled canal segments shown.



remaining levees represent approximately 3% of the length of the spillway. It is interesting that during the 2011 flood these remnant levees were not overtopped even though they presumably have not been maintained as levees since prior to 1926. Therefore, this situation implies that if the levees had not been removed in 1926, they would still be effective at preventing flow into the Bohemia Spillway with recent high water events.

Constructed Hydrologic Features

There are basically two types of engineered hydrologic structures, round culverts and box culverts, in the Bohemia Spillway. Round metal culverts have been placed underneath Bohemia Road at various locations to reduce damage to the road when it is overtopped by river overflow. These culverts vary from approximately 2.5 to 6 ft in diameter. Altogether there are eight, round metal culverts at four locations that have been identified in -place in 2011. The other type of constructed hydrologic feature is a structure composed of 4 concrete box culverts (4 ft by 4 ft) located near the upper end of the Bohemia Spillway. These culverts have adjacent conveyance canals running toward the river and to the Back Levee Canal. These features are referred to as the Bohemia box culverts. The structure was built in 1979 by Louisiana Wildlife and Fisheries or Plaquemines Parish. It's currently inoperable, and largely blocked by siltation prior to the 2011 flood.

The overall discharge through Bohemia Spillway is roughly evenly distributed through three of the hydro-geomorphic types with natural levee–back levee canal (34%), trenasse–back levee canal (26%), and oil and gas canals (32%). Analyses suggest that the flow is slightly suppressed by the oil and gas canals, and by the presence of the road blocking or deflecting flow reaches. Overall the effect of flow reduction due to anthropogenic features is estimated to be less than 15% of the overall discharge through the Spillway.

Bohemia Spillway Land Change: 1932–2010

To obtain land loss rates, two datasets were used because both had strong and weak points for the Bohemia Spillway Region. The USACE dataset covers land loss from 1932 to 2001 and tends to map land loss due to canal construction accurately but does not seem to capture land loss due to shoreline erosion. USGS dataset covers loss from 1932 to 2010 and tends to capture shoreline land loss accurately but does not capture loss due to canal construction and this dataset also includes land gain. For the Bohemia Spillway, the USACE dataset demonstrates 2.5 mi^2 of loss and the USGS dataset demonstrates a net land loss of 2.99 mi^2. Because the two datasets capture different areas of loss (although there is some overlap), a hybrid dataset was created by merging the two datasets (Fig. 13). When the two datasets were merged, there was a total loss of 3.4 mi^2, showing that both datasets individually underestimated the rates of land loss in the region. In the Bohemia Spillway, most of the land loss occurred during the time periods of 1956 to 1973 and 1973 to 1975 (Fig. 14). Much of this loss is due to the construction of canals. The USGS dataset indicated that there was 1.08 mi^2 of land gain in the Bohemia Spillway. However, there is also some land gain that has occurred and can be field observed, but is not quantified by the USGS dataset, such as areas where canals have been filled in as well as areas where new emergent marsh vegetation can be seen encroaching into the oil and gas canal, effectively narrowing the canal. The latest data show negligible net rates of loss.

Discussion: Bohemia Spillway

The current dynamics in the Bohemia Spillway may offer a model of restoration as well as provide insight into historic flooding processes when the Mississippi River overflowed its banks into adjacent wetlands, before the construction of river levees. The Bohemia Spillway is the only un-leveed portion of the Lower Mississippi River above Fort Saint Phillip on the east bank, and above Venice, Louisiana, on the west bank. The fact that the marsh in the Spillway seems to be stable, and there is evidence of land gain and natural canal filling indicates that the overtopping in the Spillway is sustaining and restoring the landscape. During the 2011 flood, it was observed that the water overtopping the natural levee was captured quickly by small gullies and streams and eventually canals and bayous. Overland flow only occurred close to the river in the forest, reaching the marsh as channelized flow, indicating that sediment it not directly delivered to the marsh through the overtopping process, which was a surprising result. The observations in the Bohemia Spillway do not fit the generally proposed model of historic (pre-levee) river flooding, whereby the natural levee is overtopped during river floods and overland flow is extensive into the adjacent marshes directly delivering sediment and therefore maintaining marsh health. Rather, an alternative model is proposed where sediments are delivered by storms and fronts, introducing a pulse of sediments at irregular intervals. Bohemia Spillway may be considered to have sources of sediment from both the river and bay side. This may also explain the lack of development of a sub-delta from Bohemia discharge because accommodation space and deposition is at first within channels, and then later distributed as storm deposits within existing marsh. The observations in the Bohemia Spillway also have implications for restoration activities in southern Louisiana, especially for the proposed sediment diversions. The initial and final fate of introduced sediment should be evaluated carefully for new diversions.

DISCUSSION—CAERNARVON DIVERSION AND THE BOHEMIA SPILLWAY

It is instructive to compare the natural processes of overbank flow, sediment delivery and deltaic land building of the two river outlets described in this paper. Neither of the outlets was built for these purposes, but both are delivering water, sediment and nutrients to basin side marshes. Caernarvon Diversion is a 23-yr-old, controlled outlet through the USACE river levee, whereas, the Bohemia Spillway is an 88-yr-old, uncontrolled outlet without river levees. The modern, maximum discharge of the Bohemia Spillway is equivalent to a Caernarvon Diversion maximum discharge located every 2 mi within Bohemia Spillway, or every 0.5 mi at Caernarvon's actual historical discharge. During the early high discharges, Bohemia Spillway discharged the equivalent of 38 times the Caernarvon Diversion discharge at its maximum. The Caernarvon Diversion is a point source of discharge, whereas Bohemia Spillway is a linear length of discharge. In part, due to this distributed flow, there is little overland flooding. However, the Caernarvon Diversion has been intentionally pulsed to cause overland flooding as a desired effect.

Historically, the Bohemia Spillway had minimal management or maintenance, whereas the Caernarvon Diversion structure has a record of significant maintenance needs and mechanical problems. In Bohemia Spillway, discharge was never actively managed since the overflow was uncontrolled, and was simply as result of the river stage. Lack of active management resulted in over eight decades of flood events through the Spillway. The Caernarvon Diversion has always been proactively managed, using various annual operational plans that seem too often to be influenced by lawsuits and public rancor. Active management of the diversion has resulted in inconsistent management and two decades of underutilization. However, due to changes in regional management of the lower river itself, the potential discharge through Bohemia Spillway has been reduced by 85%, whereas the Caernarvon Diversion can still easily meet its maximum design discharge with modest river stage under the current river management. It is also worth noting that the first three decades of discharge of the Bohemia Spillway were not just higher, but also likely had greater sediment concentrations, since post-1950 sediment load was reduced by dams upriver (Keown et al., 1986; Kesel, 1989).

The landscape response for the Bohemia Spillway and the Caernarvon Diversion has similarities and differences. The Bohemia Spillway has not built a delta, but it has in-filled some canals, and more importantly, has prevented the pattern of indirect wetland loss due to canals, or "interior" wetland loss due to relative sea level rise or other more regional processes. Wetland loss due to these processes are significant in many areas of coastal Louisiana (Boesch et al., 1994), but are virtually absent in the Bohemia Spillway. Caernarvon Diversion has built a small delta. but has suffered significant wetland loss over a much larger area that may, in part, be attributable to the diversion due to some reduction in tolerance to physical stress. However, it is more likely due to decades of sediment deprivation further into the basin. which was then severely impacted by Hurricane Katrina. Capture of sediment in Big Mar and Lake Lery may exacerbate sediment deprivation in more distant marsh with the current practice of underutilization of Caernarvon Diversion. The Bohemia Spillway area suffered minimal wetland lost from Hurricane Katrina or other recent storms. Overall, the Bohemia Spillway is clearly more resilient, and this is probably due to the combination of higher discharges and greater sediment loads early in its history. However, it may also be attributed to other differences such as the lack of overland flow under current conditions or an inherent difference in underlying geology.

The history of the Bohemia Spillway does suggest resiliency may be achieved by high discharges and high sediment concentrations early in the life history of the outlet followed by years of lower discharge as the diversion becomes a tool for wetland maintenance rather than wetland building. The need for the later phase of maintenance can be also inferred from the Caernarvon Diversion pre-history as well. Because the river levee was intentionally breached at Caernarvon during the 1927 flood, a 5.8 in clay layer was deposited, which was followed by a much lower rate of deposition for at least the next 38 yr (Wheelock, 2003), reflecting the 65-yr hiatus in regular sediment input before the Caernarvon Diversion became operational. It seems likely that this sediment starvation may have contributed to weakening of the marsh and to the regional wetland loss occurring during hurricane events pre- and post-operation of the Caernarvon Diversion.

For both Bohemia Spillway and the Caernarvon Diversion, there are clearly benefits to sustaining or increasing wetland areas. However, the two outlets also provide a contrast in the future possibilities. Precisely replicating Bohemia Spillway by levee removal is generally not feasible because of the ongoing need for protection from river floods. However, a controlled diversion built and operated to more efficiently capture, and deliver sediment in ways that emulate more natural processes, such as the Bohemia Spillway, may hold great promise for coastal restoration in coastal Louisiana rather than the obsolete design and operational goals of a diversion such as Caernarvon.

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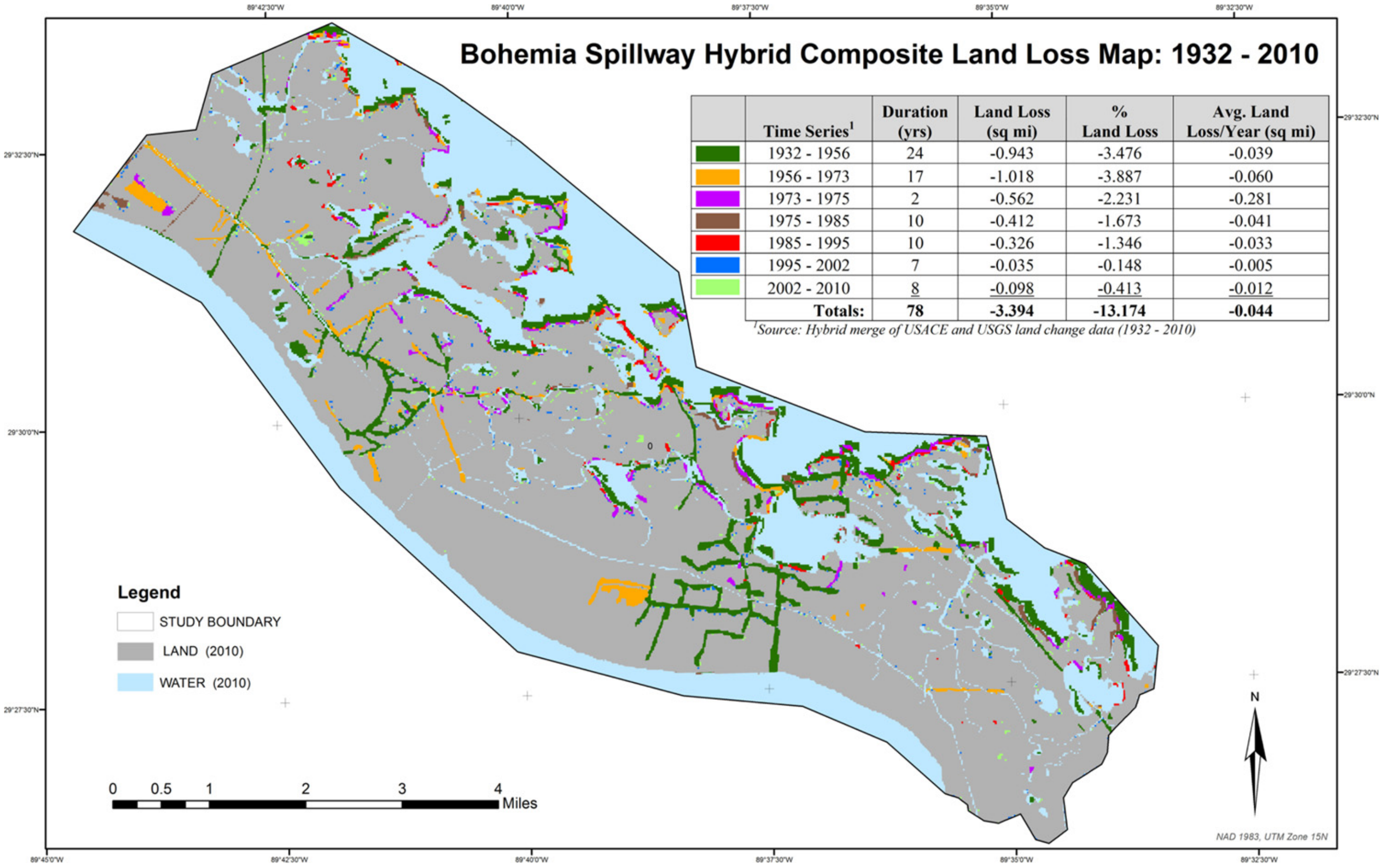

	Time Series[1]	Duration (yrs)	Land Loss (sq mi)	% Land Loss	Avg. Land Loss/Year (sq mi)
🟩	1932 - 1956	24	-0.943	-3.476	-0.039
🟧	1956 - 1973	17	-1.018	-3.887	-0.060
🟪	1973 - 1975	2	-0.562	-2.231	-0.281
🟫	1975 - 1985	10	-0.412	-1.673	-0.041
🟥	1985 - 1995	10	-0.326	-1.346	-0.033
🟦	1995 - 2002	7	-0.035	-0.148	-0.005
🟩	2002 - 2010	8	-0.098	-0.413	-0.012
	Totals:	78	-3.394	-13.174	-0.044

[1] Source: Hybrid merge of USACE and USGS land change data (1932 - 2010)

Figure 13. Bohemia Spillway composite land loss hybrid map using both USGS and USACE data from 1932–2010. Most land loss is due to direct oil and gas canal footprints or due to shoreline erosion near the sound. Note the lack of interior patterns of land loss common through much of coastal Louisiana and often associated with canals.

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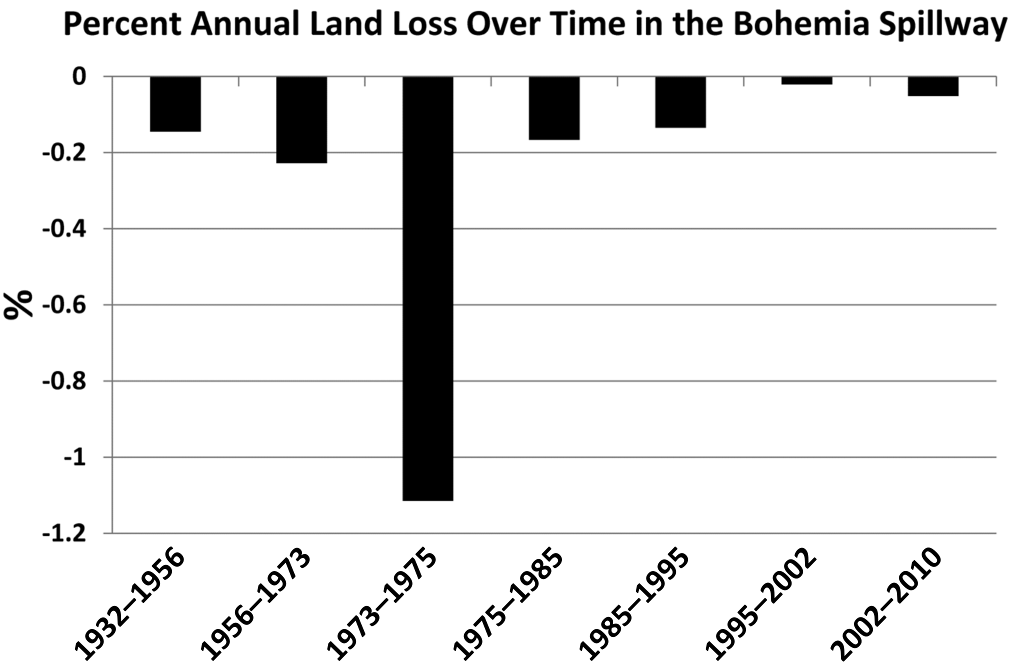

Figure 14. **Percent annual land loss in the Bohemia Spillway over time using the hybrid data set (USACE and USGS estimates of land loss). Most land loss occurred from 1932 to 1975, due mostly to the construction of canals for the oil and gas industry and to shoreline erosion.**

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