MISSISSIPPI RIVER FRESHWATER DIVERSIONS IN SOUTHERN LOUISIANA: EFFECTS ON WETLAND VEGETATION, SOILS, AND ELEVATION

A Position Paper by the Technical Panel from the

Workshop on Response of Louisiana Marsh Soils and Vegetation to Diversions

Coastal marsh near Leeville, Louisiana. Photo Credit: Dennis Demcheck (USGS)

Final Report to the

State of Louisiana and
U.S. Army Corps of Engineers through the
Louisiana Coastal Area Science and Technology Program

Coordinated by the
National Oceanographic and Atmospheric Administration

December 5, 2012

This report should be cited as:

Teal, J.M., R. Best, J. Caffrey, C.S. Hopkinson, K.L. McKee, J.T. Morris, S. Newman and B. Orem. 2012. Mississippi River Freshwater Diversions in Southern Louisiana: Effects on Wetland Vegetation, Soils, and Elevation. Edited by A.J. Lewitus, M. Croom, T. Davison, D.M. Kidwell, B.A. Kleiss, J.W. Pahl, and C.M. Swarzenski. Final Report to the State of Louisiana and the U.S. Army Corps of Engineers through the Louisiana Coastal Area Science & Technology Program; coordinated by the National Oceanic and Atmospheric Administration. 49 pages.

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Executive Summary

Coastal Louisiana lost 4,877 km^2 of land area between 1932 and 2010 (Couvillion et al. 2011). Freshwater Diversions are a technique to address one cause of wetland loss: failure to maintain elevations sufficient to support emergent vegetation forming the wetland habitat. This report examines the effects of Freshwater Diversions from an ecological perspective, and focuses on wetland plant community productivity and composition, wetland elevation, and wetland soil strength. Each section assesses available information, information gaps, and identifies data needed to ensure successful marsh stabilization and restoration.

Diversions of river water into adjacent coastal wetlands are a part of all plans to mitigate for the extensive loss of Louisiana's coastal wetlands. Diversions can be broadly characterized as Sediment Diversions, designed for significant land-building in areas that currently are open water, and Freshwater Diversions, designed to flow into existing, but degrading marsh systems to reverse or slow the rates of degradation. This paper explores the effects on marsh properties of diversions in the lower Mississippi River designed for freshwater delivery (i.e. Freshwater Diversions). Evaluation of the effects of Sediment Diversions is not emphasized in this investigation.

Freshwater Diversions may affect wetland plants and their responses to changes in **salinity, nutrients, and herbivory**. Freshwater Diversions represent a major shift in water-quality conditions, with reduced salinity and increased nutrient availability that affect plant communities directly by influencing their distribution (salt tolerance) and their growth characteristics (root:shoot ratios, absolute productivity). Salinity and nutrient conditions also have indirect effects on herbivory, interactively influencing plant communities and marsh stability. Lower salinities lead to shifts in plant species to those more typical of freshwater communities. Nutrient increases brought by Freshwater Diversions may also change aboveground and belowground production and ratios. Better forage quality from nutrient enrichment also stimulates herbivory (e.g. nutria), indicating the importance of including the quantitative impact of herbivory in predictive models on vegetation responses to Freshwater Diversions. A general conclusion on the expected short-term and long-term responses of marsh belowground production to Freshwater Diversions in Louisiana could not be drawn from the available evidence. This uncertainty stems from several research limitations: data collection was highly variable from one diversion project to the next; design review was lacking, especially when considering ecosystem level outcomes; monitoring was highly variable from one site to the next; pre-diversion data for sites were not collected, making it difficult to understand results of diversions; and conditions varied considerably from site to site so data from one site were not necessarily useful at another.

Freshwater Diversions may alter **wetland elevation** trajectories by modifying the processes controlling wetland elevations, which may be physical, biological, and/or hydrological, and operate in response to drivers such as sea level change, river flows, storms, climate change, nutrient loading, and human modifications. One of the many causes of deterioration of Mississippi River Delta wetlands is the separation of the wetlands from the river and its sediment due to control structures and channel stabilization. Diversions may deliver mineral sediment directly to marsh surfaces, increasing rates of accretion and/or freshwater and nutrients to

stimulate plant production (biomass, stem density), which in turn promote sediment deposition and trapping (aboveground) and/or increase organic matter accumulation (primarily belowground where decomposition is slow). Existing data showing diversion effects on marsh accretion or elevation are sparse and based on limited sample sizes and/or inadequate sampling designs. Major information gaps exist with respect to how much diversions may alter marsh elevation trajectories (especially in relation to balancing relative sea level rise), which specific mechanisms influencing soil volume (organic vs. inorganic) might be most affected by diversions, and what other factors might modify the impact of diversions on marsh elevation dynamics. With regard to Freshwater Diversions, data are particularly needed on how changes in water chemistry or plant community composition may influence plant production-decomposition processes and resultant effects on soil volume and elevation change.

Freshwater Diversions may also affect the **shear strength of soils**, which is determined by soil composition (e.g. mineralogy, grain size, particle shape, ionic forces, organic matter content), void ratio, water content, and pore water chemistry (e.g. salinity, pH), the soil structure (e.g. particle arrangement, fissures, cementation), and loading conditions (e.g. magnitude of shear stress, rate, history). It is also controlled by plant roots and rhizomes: it increases proportionally to the cross-sectional area of roots crossing the shear plane. Storm and hurricane surge modeling and predictions of water level, short wave height, pressure field variation and frictional energy dissipation due to bay bottom and wetland vegetation interactions were not included in most storm surge models of the Louisiana coast prior to Hurricane Katrina in 2005. The wave energy lost in passing over marsh vegetation and the ability of the marsh/root/soil complex to hold up against wave shear stress are the reasons wetlands provide a buffer for inland property. Soil strength is expected to increase with depth as a result of compaction by overburden loading. Surface soil drainage and desiccation enhances compaction, which can increase soil strength near the surface. Wetland ponding decreases soil strength and increases wetland vulnerability to storm scour and loss. Plant roots change the depth profile of soil strength, with increased soil strength where roots are present. Abrupt changes in soil strength slope vs. depth, especially from positive to negative slope, can result in failure planes - regions above which entire blocks of wetland soil can be scoured. Diversions can increase scour vulnerability if they result in ponding or decreases in rooting depth or root tensile strength.

All diversion projects would benefit from formal **adaptive management**. These programs function when goals are agreed to among the actors, knowledge of pre-diversion conditions exist, monitoring is done to measure progress toward goals, and there is a process in place to adjust functions to improve the likelihood that goals can be met. At present, considerable investment has been made in designing, engineering and building diversions, and an emphasis of Coastal Protection and Restoration Authority of Louisiana's 2012 Coastal Master Plan is development of a comprehensive Adaptive Management Framework, to be completed in 2013, that will apply to the initial stages of master plan implementation. Elements of the Framework will include expansion and refinement of existing monitoring and modeling efforts, and development of new projects to fill information and management gaps.

A well-designed monitoring program is essential to assess whether diversions are promoting marsh sustainability and to support adaptive management. To answer questions about the spatial extent of diversion influence, it is important to establish multiple monitoring stations at suitable intervals (distances from discharge and in relation to discharge flows) and sufficiently replicated to detect significant differences. Preferably, pre-diversion measurements should be made over a suitable duration to provide baseline trends, including seasonal variation. Monitoring of pore water chemistry (salinity, nutrients, sulfide) would assist in interpreting the influence of diversion discharges on environmental conditions affecting plant growth. Measurements of soil texture (particle size distribution), soil strength, dry bulk density, and organic content conducted at each sampling station would allow more detailed monitoring of changes in soil texture and soil integrity. End of season standing live biomass (above- and belowground) would provide information about the health of the plant community and relationship to elevation changes. Herbivory is a confounding issue because nutria remove both above- and belowground biomass, leading to reductions in soil organic matter, further reducing the ability of the marsh to maintain itself as sea level rises.

The Panel concluded that little evidence was available that any Freshwater Diversion in the Louisiana deltaic plain has significantly reversed the rate of marsh degradation and land loss. While there is evidence that the minor sediment load of Freshwater Diversions has enhanced accretion in localized areas, lack of uniform sheet flow across marshes, coupled with prolonged flooding and ponding of wetland vegetation, and rapid shifts in salinity have compromised the combined processes of macrophyte biomass accumulation, peat accumulation, building of soil strength and building wetland elevation and extent. These processes are necessary for reversing the high rates of wetland loss through most of the Louisiana deltaic plain. It is unlikely that any currently planned Freshwater Diversion without substantial sediment load will reverse wetland loss in Louisiana. Restoration of Louisiana wetlands may only be possible through significant inputs of sediment.

A number of "Sediment Diversions" are planned along lower portions of the Mississippi and Atchafalaya Rivers, but the science is still evolving to inform model predictions on the amount of sediment needed for adequate wetland rebuilding (not addressed here) and the role of high nutrient river water in contributing to or detracting from marsh restoration (addressed here). Effective adaptive management, therefore, will be paramount to ensure that diversions have their intended outcome. To this end, an Adaptive Management Framework is being developed by the Coastal Protection and Restoration Authority of Louisiana (CPRA) as a critical element of the 2012 Coastal Master Plan so that diversion effects can be monitored, future effects more accurately predicted, and management strategies adjusted as needed. The Framework offers an excellent opportunity to develop a comprehensive research design that adequately tests the alternative hypotheses on wetland response to nutrient-rich river water characterized here, as a critical step to ensuring intended outcomes of restoring and sustaining Louisiana wetlands.

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Introduction

John M. Teal

A stable and growing Mississippi delta has many valued features, not only for the citizens of Louisiana, but also for the nation as a whole. The delta protects and preserves the City of New Orleans, it supports the oil and gas industries, protects navigation channels, mitigates storm damage, provides recreational and social benefit to human populations, and preserves and enhances fisheries and wildlife.

Delta formation in coastal Louisiana over the last 6,000 years was marked by shifting geomorphology, with wetland gains and losses through active deltaic lobes. A net increase in wetland area occurred up until the 20th century, after which an estimated 25% loss (4,800 km^2) of coastal wetlands has occurred, due in part to human-related activities that reduced sediment delivery down the Mississippi River (e.g. dams, ship channels), altered marsh flooding and drying cycles (e.g. weirs and pipeline canals), increased subsidence rates (e.g. sediment consolidate and mineral or petroleum extraction), and reduced river input to the deltaic plain (flood control measures such as levees and distributary closures), and sea level rise (Britsch and Dunbar 1993, Barras et al. 1994, Day et al. 2007, 2009a). An estimated 4,877 km^2 of coastal Louisiana wetland area was lost from 1932 to 2010 (Couvillion et al. 2011).

Controlled diversions of river water into adjacent coastal wetlands are a significant part of all plans to mitigate for the extensive loss of Louisiana's coastal wetlands. Diversions can be broadly characterized as Sediment Diversions, designed for significant land-building in areas that currently are open water, and Freshwater Diversions, designed to flow into existing, but degrading marsh systems to reverse or slow the rates of degradation. Sediment Diversions typically have large discharge volumes and transport substantial quantities of mineral sediment. Freshwater Diversions generally have small discharge volumes and carry little mineral sediment. Their main effects are in changing water quality, namely by reducing salinity and adding nutrients. The boundaries between the two types are somewhat blurred. Some diversions primarily intended for freshwater delivery can nonetheless transport substantial mineral sediments (e.g. the Caernarvon Freshwater Diversion transported enough sediment to result in infilling of the Big Mar receiving basin). By the same token, a Sediment Diversion may carry less mineral sediments than some Freshwater Diversions if located in a mineral sediment poor area.

Sixteen constructed diversions currently exist in the lower Mississippi River (defined as starting at the Old River Control Structure), and up to 12 more are proposed through the 2012 Coastal Master Plan (Coastal Protection and Restoration Authority of Louisiana 2012); Figure 1, Table 1. The maximum releases of existing diversions range from 250 cfs (cubic feet per second) to over 740,000 cfs (Table 1). Of the existing diversions in the Lower Mississippi River, 14 may be considered Freshwater Diversions and 4 Sediment Diversions, which were relatively recently constructed (West Bay, Delta Management at Fort St. Phillip, and Channel Armor Gap) or developed naturally (Mardi Gras Pass).

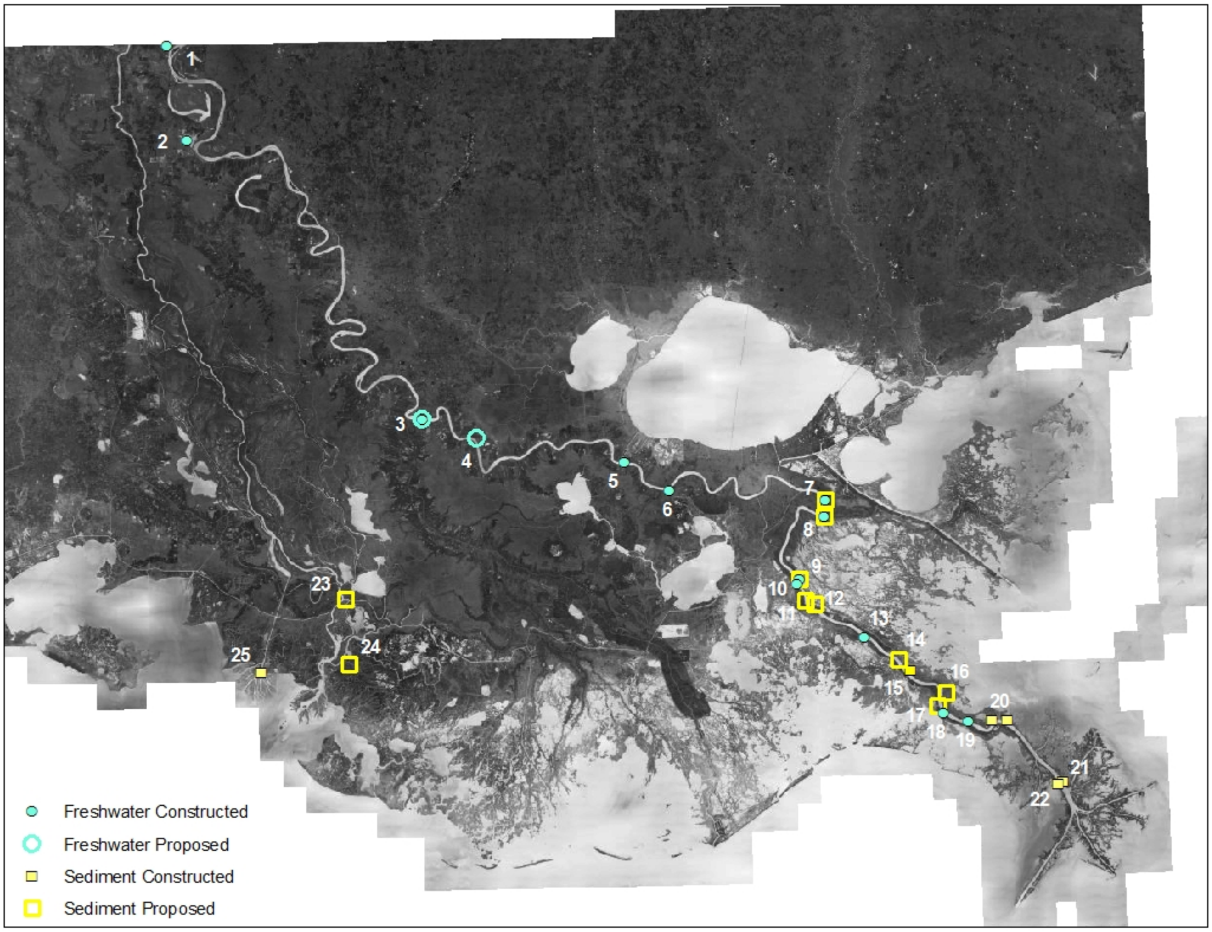

Figure 1. Map of constructed (closed symbols) and proposed (open symbols) Freshwater (blue circles) and Sediment (yellow squares) Diversions. Numbers correspond to diversions listed in Table 1 below.

Table 1. Constructed and proposed diversions from the Mississippi and Atchafalaya Rivers shown in Figure 1 include natural crevasses and structures capable of diverting freshwater as "Freshwater Constructed," including emergency and navigation structures as well as restoration projects. Projects that share identifiers indicate where existing projects overlap with proposed projects, or where multiple proposed projects are being studied. Except for the Bayou Lafourche Diversion, discharges listed for the planned diversions in the State of Louisiana's 2012 Comprehensive Master Plan are indicative of scale (small diversions were modeled at 5,000 cfs; medium diversions were modeled at 50,000 cfs, and large diversions were modeled at 250,000 cfs). The exact discharges for those projects will be determined during future investigations.

Identifier	*Diversion*	*Type*	*Status*	*Constructed Discharge Capacity (cfs)*	*Proposed Discharge Capacity (cfs)*
Diversions Off the Mississippi River					
1	Old River Control Structure	Freshwater	Constructed	740,000	
2	Morganza Floodway *	Freshwater	Constructed	600,000	
3	Walter Lehmann Pump Station	Freshwater	Constructed	300	
	Master Plan Bayou Lafourche Diversion	Freshwater	Proposed		1,000
4	LCA Small Diversion at Convent / Blind River	Freshwater	Proposed		5,000
	Master Plan West Maurepas Diversion	Sediment	Proposed		5,000
5	Bonnet Carré Spillway *	Freshwater	Constructed	250,000	
6	Davis Pond Freshwater Diversion	Freshwater	Constructed	10,650	
7	Violet Siphon	Freshwater	Constructed	300	
	Master Plan Central Wetlands Diversion	Sediment	Proposed		5,000
8	Caernarvon Freshwater Diversion	Freshwater	Constructed	8,800	
	Master Plan Upper Breton Diversion	Sediment	Proposed		250,000
9	White Ditch Siphon	Freshwater	Constructed	250	
	LCA Medium Diversion at White Ditch	Sediment	Proposed		35,000
10	Naomi Siphon	Freshwater	Constructed	2,100	2,100
11	LCA Medium Diversion at Myrtle Grove with Dedicated Dredging	Sediment	Proposed		75,000
	Master Plan Mid-Barataria Diversion	Sediment	Proposed		250,000
12	Master Plan Mid-Breton Diversion	Sediment	Proposed		5,000
13	West Point a la Hache Siphon	Freshwater	Constructed	2,100	
14	Master Plan Lower Breton Diversion	Sediment	Proposed		50,000
15	Mardi Gras Pass	Sediment	Constructed	2,500	
16	Bayou Lamoque Floodgate Removal	Sediment	Proposed		2,500
17	Master Plan Lower Barataria Diversion	Sediment	Proposed		50,000
18	Empire Lock	Freshwater	Constructed	N/A	
19	Ostrica Lock	Freshwater	Constructed	11,000	
20	Delta Management at Fort St. Phillip	Sediment	Constructed	5,400	
21	Channel Armor Gap	Sediment	Constructed	2,500	
22	West Bay Sediment Diversion	Sediment	Constructed	20,000	
Diversions Off the Atchafalaya River					
23	Master Plan Increase Atchafalaya Flow to Eastern Terrebonne	Sediment	Proposed		20,000
24	Master Plan Atchafalaya River Diversion	Sediment	Proposed		150,000
25	Wax Lake Delta	Sediment	Constructed	440,000	
Total Potential for Diversion from Mississippi River				1,655,900	735,600
Total Potential for Diversion from Atchafalaya River				440,000	170,000

* The Morganza and Bonnet Carré Spillways are emergency floodways, with discharge restricted to extreme river flood years. Present project authorizations do not allow for more frequent, non-emergency use.

This paper explores the effects on marsh properties of diversions in the lower Mississippi River designed for freshwater delivery (i.e. Freshwater Diversions). Evaluation of the effects of Sediment Diversions is not emphasized in this investigation. We do not address effects on swamp forests (flood plain hardwoods, cypress stands, etc.) but do mention the increasing importance of black mangroves in the southern delta marshes.

The use of Freshwater Diversions has become a controversial approach for restoring and recreating Louisiana coastal habitats. There remains considerable uncertainty regarding when, where, and how diversions can be used to replenish Louisiana coastal habitats, and the responses of marsh soils and vegetation is a key question in understanding the efficacy of Freshwater Diversions as a tool to restore degrading marshes. The science is still evolving, and our understanding remains incomplete, so that the siting, sizing, timing, and duration of freshwater inflows are not yet refined to the point where we can always be confident that diversions will have the intended effect.

The incomplete knowledge base makes it difficult to know when and where to use diversions, and though we have considerable knowledge, we still don't know enough to predict in any detail the outcomes caused by a particular diversion. Research done in one area or under some salinity regime will not necessarily be applicable in another area or under other conditions. However, because diversions are known to work in some situations, there is pressure to increase the use of diversions to reverse the substantial and continuing loss of coastal wetlands. Clearly, there is a need for additional research to develop the information needed by resource managers to improve our predictive and management capability, and there is an equally pressing challenge to deliver the results of research to decision-makers and the general public to understand the difficulties faced in determining when the use of diversions is the appropriate approach to improve the quality and increase the quantity of coastal habitats.

On 23-24 February 2011, the Louisiana Coastal Area Program (LCA) Science and Technology Office (established by the State of Louisiana and the U.S. Army Corps of Engineers) and National Oceanic and Atmospheric Administration (NOAA) convened the "Workshop on Response of Louisiana Marsh Soils and Vegetation to Diversions" (http://www.mvd.usace.army.mil/lcast/pdfs/DiversionWorkshop.pdf) at the University of Louisiana, Lafayette to evaluate the current scientific understanding of the effects of Freshwater Diversions on Louisiana marshes, develop a consensus to inform coastal managers of expected soil and vegetation responses, and identify gaps in understanding to inform future research priorities and management strategies. The Workshop was the third in a series of meetings to inform the LCA Science and Technology Board, decision makers, and the public on technical issues regarding existing and planned diversions. Support for the Workshop was provided by the NOAA Fisheries Southeast Region, NOAA National Centers for Coastal Ocean Science, NOAA Coastal Services Center, the State of Louisiana, the U.S. Army Corps of Engineers, the United States Geological Survey (USGS) Louisiana Water Science Center, the University of Louisiana, Lafayette, the National Audubon Society, the Coalition to Restore Coastal Louisiana, and The Nature Conservancy.

The Workshop brought together a panel of 10 technical experts, 18 presentations, and an audience of about 250 people. Over the course of the Workshop, a broad range of topics was discussed that examined how introductions of freshwater and nutrients into coastal marshes affect marsh soils and vegetation. The Technical Panel of subject matter experts was selected by the Workshop's Steering Committee. This Position Paper is a consensus assessment of the Technical Panel, based on Workshop proceedings and an extensive literature review, on the state of knowledge and information gaps on expected soil and vegetation responses to Freshwater Diversions in coastal Louisiana. The Position Paper will be presented to the USACE and Coastal Protection and Restoration Authority of Louisiana (CPRA) to inform planning, monitoring, and adaptive management of diversions, and to the Gulf Coast Ecosystem Restoration Task Force to inform incorporation of diversions as a restoration option.

The following sections present theoretical arguments and empirical observations used to examine the potential application of Freshwater Diversions to marsh restoration. They address the influence of Freshwater Diversions on wetland plant community productivity and composition, wetland elevation, and soil strength.

Effects of Freshwater Diversions on Wetland Plants – Response to Changes in Salinity, Nutrients, and Herbivory

Susan Newman, Ronnie Best, Jim Morris, and Jane Caffrey

Background

The vegetation communities of coastal Louisiana marshes are defined by their location along a salinity gradient. They range from the low salinity freshwater and intermediate marshes, to brackish and saltwater marshes. Freshwater marshes represent over one-third of the coastal wetland area, the largest spatial extent of marshland in the region (Sasser et al. 2008). With salinities less than 0.5 ppt, they are dominated by the freshwater plants, *Sagittaria lancifolia* and *Panicum hemitomon*. A unique community observed in this environment is the floating marsh. Dominated by emergent vegetation, primarily *P. hemitomon*, healthy floating marshes have thick highly organic buoyant mats of intertwined roots and rhizomes (Sasser et al. 1995). More recently, though, "thin" mats, dominated by *Eleocharis baldwinii*, have become more prevalent (Visser et al. 1999). Intermediate, low salinity (0.5-5 ppt) marshes encompass 26% of the coastal marsh and are dominated by species characteristic of both freshwater and brackish environments, *S. lancifolia*, *Schoenoplectus americanus*, and *Spartina patens*. *S. patens* is also one of the dominant species in brackish marshes, along with the more salt tolerant *Spartina alterniflora*. Brackish marsh represents 21% of the coastal marsh area, while the remaining 17% is true saltwater marsh, dominated by *S. alterniflora*. However, over the last 20 years, *Avicennia germinans* (black mangrove) has expanded into these areas (Henry and Twilley 2011). While there is no good estimate of the aerial expanse of *A. germinans*, a 5-fold increase in abundance from 2002 to 2009 (Michot et al. 2010) suggests the mangrove community is expanding rapidly.

Although nutrient availability is a controlling factor for the productivity of wetland plants, with different species having different nutrient requirements, there is no grey literature or peer reviewed literature that indicates coastal Louisiana marshes are suffering from a lack of nutrients. Nutrients in the Mississippi and Atchafalaya Rivers can be high due to high nutrient inputs in the watersheds of the Mississippi River (Turner and Rabalais 1991). Total nitrogen concentrations in the river are between 137 and 140 µM (1.9 to 2.0 mg N/L), with 60 to 90% of the nitrogen in the form of nitrate (Turner and Rabalais 1991, Lane et al 1999, 2004). Total phosphorus in the river ranges from 5.1 to 7.4 µM (0.16 to 0.23 mg P/L) (Turner and Rabalais 1991, Lane et al. 2004). Thus, freshwater from river flooding or through diversions represents a significant nutrient input to marsh communities which can rapidly reduce these concentrations (Lane et al. 2004). Nitrogen concentrations within the estuaries and marshes not receiving direct riverine inputs are much lower, with nitrate concentrations less than 20 µM (0.28 mg N/L) and ammonium concentrations about 10 µM (0.14 mg N/L) (Caffrey and Day 1986, Madden et al. 1988). Nutrient inputs to coastal marshes from the Louisiana continental shelf and Gulf of Mexico are low because concentrations are usually less than 5 µM (0.07 mg N/L) and 1 µM (0.03 mg P/L) of nitrate and dissolved inorganic phosphate, respectively (Lohrenz et al. 1999).

Herbivory by large mammals such as nutria and muskrats can be significant in Louisiana wetlands (Shaffer et al 1992, Evers et al. 1998). The effects of large mammal herbivory have been more thoroughly studied than herbivory by waterfowl or invertebrates such as grasshoppers or snails. While some damage to marshes by muskrats has been documented, grazing by nutria is concentrated in fresh and brackish marshes, particularly since the decline of the fur industry in the late 1980s (Scarborough and Mouton 2007). Nutria, native to South America, were released in coastal Louisiana in the late 1930s and have few natural predators except for adult alligators (Keddy et al. 2009).

Environmental factors that alter wetland plant communities

To put Freshwater Diversions into context, it is important to understand how environmental factors independently, and interactively, influence wetland plant communities. Freshwater Diversions represent a major shift in water-quality conditions, with reduced salinity and increased nutrient and herbicide availability (Swarzenski et al 2008). Agricultural runoff from the midcontinent spring flush characterizes water quality of the inflowing water during the spring flush now, as opposed to before the 1950s. Changes in salinity and nutrients affect plant communities directly by influencing their distribution (salt tolerance) and their growth characteristics (root:shoot ratios, absolute productivity), and these responses can be manifested in altered marsh plant production, composition, and diversity. Salinity and nutrient conditions may also have indirect effects on herbivory, interactively influencing plant communities and marsh stability.

Effects of salinity on plant productivity

Diversions of freshwater from the Mississippi River into adjacent wetlands and bayous reduce the salinity of receiving wetlands and water bodies (e.g. Sasser et al. 1986). Extensive canal dredging has increased the number of tidal channels across the Delta, resulting in localized saltwater intrusion and the conversion of large areas of low-salinity marsh to open water (Sasser et al. 1986). Consequently, diversions that reduce salinity are a prerequisite for restoration of forested and fresh marsh communities that have been damaged by salt intrusion.

Generally, increased salinity is associated with reduced wetland plant species numbers and biomass (Gough and Grace 1998). In general, all higher plants have problems dealing with salt.

Even halophytes (salt tolerant plants) such as *S. alterniflora* grow better at lower than higher salinity (Nestler 1977). Plants are directly affected by the salinity of the pore water (the water in the pores between grains of sediment), but only indirectly affected by the surface water or flood water salinity effect. Pore water salinity is usually lowest near sources of fresh water and often increases at elevations where neap flood tides are not high enough to consistently inundate the site. Evapotranspiration can concentrate the salts in sediment and raise the salinity to levels that exceed the salinity of tidal flood water. High salinity in pore water affects plant gas exchange and stunts growth. A reduced rate of gross photosynthesis, reduced transpiration, and a higher aboveground respiration rate are common responses to elevated salinity (Hwang and Morris 1984, Pezeshki et al. 1987, Hester et al. 2001).

The pore water salinity of brackish and salt marsh is rarely constant, fluctuating with storms, flood frequency, evapotranspiration, and rainfall (Morris 1995). The variability in salinity has an effect that is somewhat independent of the actual concentration. That is, plants can be acclimated to a higher concentration of salt that may be lethal if experienced as a pulse. Sensitivity to rapid changes in salinity is probably greater for oligohaline marsh macrophytes than for salt marsh species, and even among the oligohaline species there are differences in sensitivity. For example, growth of *Scirpus americanus* was actually stimulated by exposure to 6 g/L of salt, and was able to recover even under the most extreme conditions of exposure to 12 g/L salinity for 3 months, while the ability of *Eleocharis palustris*, *P. hemitomon*, and *S.lancifolia* to recover from salt exposure decreased with increased salinity and increased duration of exposure (Howard and Mendelssohn 1999). Recovery was also suppressed in these species by a rapid salinity influx rate compared to a slow influx rate. The conclusion is that short-term exposures to salt can change plant community composition and species dominance, depending on the pattern of exposure (Howard and Mendelssohn 1999), and the pattern of exposure in wetlands receiving Freshwater Diversions will depend on the operation of the pumps and siphons.

There also are effects of salt exposure on the allocation of biomass between growth above- and belowground. Loss of soil strength, which would increase the erosion of sediment, has been postulated to be one of the side-effects of nutrient-rich, Freshwater Diversions from the Mississippi River (Turner 2011b). Soil strength is affected by the production of roots and rhizomes, and any factor, such as salinity, that modifies the absolute growth of roots and rhizomes is relevant. Osmond (1980) posited that the root:shoot ratio of halophytes decreases with increased salinity, while Munns and Termaat (1986) suggested that the root:shoot ratio of glycophytes (non-halophytes) increases with increased salinity due to a dramatic reduction in shoot biomass. Parrondo et al. (1978) reported that *S. alterniflora* and *Spartina cynosuroides*, grown in a controlled environment, had similar responses to salinity in that increasing the salinity of the root medium reduced the shoot growth more than root growth, raising the root:shoot ratio. Likewise, Hester et al. (2001) found increased root:shoot ratios in *S. alterniflo*ra with elevated salinity. These studies indicate a direct relationship between salinity and root:shoot ratio in the tested halophytes – the implications to short- and long-term responses of plant production, soil strength, and wetland elevation in brackish or saline marshes receiving low salinity water remains open.

Experimental responses in environmental regulation of root:shoot ratios in isolation may be misleading, and should be considered in conjunction with responses in absolute production of roots and rhizomes, which can be more relevant to soil strength and sediment accretion. Although Parrondo et al.'s (1978) study of several salt marsh species showed an increased root:shoot ratio with increased salinity of the root medium, both shoot and root growth decreased. Results from a European study were consistent. Five of six marsh species tested had reduced root growth when plants were grown under saline conditions (Cooper 1982). Similarly, Pezeshki and Delaune (1993) reported reduced root growth in *S. patens* when grown at 25 ppt compared to growth at 0-15 ppt. In general, there appears to be a negative growth response of roots to salt stress and the response is greatest among glycophytes, but there are exceptions. There are differences among species; roots and shoots of the true halophytes such as *Salicornia* spp. grow best at moderate salinity. Other differences may be related to environmental conditions like nutrient availability, waterlogging, and the level of salinity, all of which interactively control growth.

Effects of salinity on plant nutrition

There are important interactions between salinity and nutrients at a physiological level that can affect plant nutrition and the nutrient balance of marshes. A variety of organic solutes such as sorbitol, proline, and quaternary ammonium compounds accumulate in the cytoplasm where they serve as nontoxic osmotica, i.e. these compounds reduce the water potential of the cells and serve the essential function of maintaining turgor pressure when the plant is exposed to salt-stress or drought (Jefferies et al. 1979). The nitrogen-based compounds proline and glycinebetaine are used for this purpose by *S. alterniflora* (Cavalieri 1983). These compounds accumulate more or less depending on the soil salinity and availability of nitrogen (Cavalieri and Huang 1979, 1981, Hester et al. 2001). Their cellular concentrations increase when plants are fertilized with nitrogen, which increases their tolerance of high salinity and their productivity (Cavalieri and Huang 1981).

Ironically, nitrogen uptake is depressed at high salinity due to competition among ammonium ions and seawater cations for carriers on the root membrane. Increasing the salinity of aerobic nutrient solutions from 3 to 32 ppt decreased V_{max} (the maximum root-weight specific rate of uptake) by 30% in *S. alterniflora* and *S. patens*; while under anoxic conditions this same increase in salinity decreased V_{max} in *S. patens* by 57% but had no effect on *S. alterniflora* (Morris 1984). Similarly, Brown et al. (2006) found significant decreases in uptake by *S. alterniflora* of all nutrients in response to increases in salinity. These same interactions between salinity and nutrient uptake should be common in all plants, because these are physiological principles that apply to all.

Changing salinity levels also effect changes in sediment chemistry and thus nutrient cycling. The ammonium exchange capacity of sediments is greatly affected by salinity. There is competition among cations for exchange sites on silt and clay particles, and, owing to the super abundance of sea water cations that greatly exceed cations such as NH_4^+, the exchange sites will be completely occupied by seawater cations Na^+ and K^+. Consequently, ambient exchangeable ammonium concentrations in freshwater sediments are generally higher than those reported for marine sediments (Seitzinger et al. 1991). Sundareshwar and Morris (1999) reported that the phosphate sorption capacity of sediments from a freshwater marsh was higher than the sorption capacity of sediments from brackish and saline marshes, due perhaps to differences in Fe and Al availability, surface area of sediment particles, and anion exchange capacity.

Another salt-related factor that appears to control nitrogen release from sediment is inhibition of nitrification by sulfide, which is typically abundant in anoxic marine sediments. In estuarine sediments amended with 60 and 100 µM hydrogen sulfide, the rate of nitrification was inhibited by 50 and 100%, respectively (Joye and Hollibaugh 1995). A freshening of sediment, which would lower the sulfate and sulfide concentrations, should lead to greater rates of nitrification and, consequently, denitrification. In addition, the sulfate concentration of waters is an extremely important variable controlling phosphorus release from sediments, presumably due to competition between phosphate and sulfide for iron (Caraco et al. 1989). Thus, for a variety of physical and biochemical reasons, a freshening of sediment should lead to greater nutrient availability to wetlands. Consequently, to the extent that Freshwater Diversions reduce salinity, the efficiency of nitrogen uptake by the plant community should be increased, while the requirement for intracellular osmotica should decrease.

<u>Effects of increased nutrient loads on plant productivity</u>

There is a significant interaction between nutrients, salinity, and vegetation responses. In salinities < 0.8 ppt, salinity stress of *S. patens* can be reduced by the addition of nutrients (Foret 2001, DeLaune et al. 2005, Merino et al. 2010). However, freshwater species, such as *P. hemitomon* and *S. lancifolia,* are particularly sensitive to salinity increases, with mortality occurring at 4 and 6 ppt, respectively (Spalding and Hester 2007). Unlike more salt tolerant species, increased nutrients did not alleviate the effects of even minor increases in salinity in *P. hemitomon* (Hester and Fisher 2011).

In theory, the elimination of nutrient limitation will increase marsh productivity. However, there is variable experimental evidence for this occurring in Louisiana marsh communities. Significant increases in *P. hemitomon* shoot, root, and rhizome biomass were observed in experimental floating mats exposed to nitrogen loads of 50 g/m^2/y relative to 25 g/m^2/y (Mayence and Hester 2010). Graham and Mendelssohn (2011) observed that 11 years of nutrient enrichment of a *S. lancifolia* dominated marsh with nitrogen (20-120 g m^2/y), phosphorus (6.6-39.6 g m^2/y) and potassium (6.6-39.6 g m^2/y) did not significantly affect belowground production. Similarly, while increased nitrogen loads (55-900 g/m^2/y) to field plots of *S. alterniflora* resulted in 18-138% greater live aboveground biomass, there was no effect on live belowground biomass (Darby and Turner 2008a). By contrast, live belowground biomass decreased 40-60% when phosphorus or iron was added, as fewer roots were required to acquire limiting nutrients. Comparing the effects of nutrient enrichment on root accumulation in two brackish and one salt water marsh, McKee (2011b) found that there was no consistent pattern either within a site or over time. What is apparent from these studies is that belowground responses to increased nutrient loads are inconsistent and as a result, it is difficult to draw general conclusions.

Nutrient enrichment has frequently been shown to provide a competitive advantage to species capable of rapid uptake and growth (Grace and Tilman 1990). So while biomass of *P. hemitomon* may increase upon nutrient addition, nutrient additions may alter community composition and reduce species richness of these freshwater mats (Visser et al. 1999, Hester and Fisher 2011). Increased nutrients were one of the factors suggested to contribute to the 37% decrease in aerial cover of *P. hemitomon* in coastal wetlands from 1968-1992. This vegetation was replaced by *Eleocharis* spp. dominated marshes, whose aerial extent increased from 3-41% during the same time period. The influence of nutrient enrichment on plant community compositional changes was confirmed by Hester and Fisher (2011). Nitrogen additions at 35 $g/m^2/y$ decreased the relative abundance of *P. hemitomon* and increased abundance of *Leersia hexandra*, while a combination of nitrogen + phosphorus (35 and 15 $g/m^2/y$, respectively) resulted in a significant increase in the relative abundance of *Eleocharis* spp. and *Hydrocotyl* spp.

It is difficult to make direct comparisons between studies testing the effects of elevated nutrients associated with diversions because of differences in the form of nutrients used, particularly whether nitrogen was added as NH_4 vs. NO_3, study conditions (e.g. greenhouse vs. field), study duration, and the magnitude of added loads. The majority of the studies were short-term (< 1 year), and while many studies used nutrient loads similar to Caernarvon peak mean annual nitrogen and phosphorus outflow loads of 50 g $N/m^2/y$ and 10 g $P/m^2/y$, respectively (Lane et al. 1999), they were considerably higher than recently reported nitrogen and phosphorus loads within the upper basin of 4.8 to 8 and 0.56 to 1.2 $g/m^2/y$, respectively (Hyfield et al. 2008). Therefore, changes in biomass and production associated with extremely high loads used in those studies are unlikely to be observed under field conditions.

Effects of herbivory on plant communities

Research on herbivores in coastal Louisiana has shown that large vertebrate herbivores, both mammals and waterfowl, can reduce aboveground biomass by 50% (Shaffer et al. 1992, Evers et al. 1998, Holm et al. 2011). Specifically, herbivory by nutria, particularly eat outs where large areas are heavily grazed, is principally confined to fresh and brackish marshes, with few examples of eat outs in salt marshes. The classic paradigm that disturbance associated with herbivory leads to changes in plant succession that then alter herbivore populations may not apply to wetlands with nutria because populations remain continually high. In experimental exclosures in the Pearl River Basin, plant biomass and cover of palatable species like *S. americanus* were higher than in plots without exclosures (Ford and Grace 1998). Herbivory associated with nutria may amplify the effects of other disturbances such as fire, which may enhance plant nutritional quality (McFalls et al. 2010). Thus, regrowth of vegetation in burned areas may be preferentially targeted by nutria. In a coastal marsh, *S. lancifolia* and *Panicum virgatum* were enhanced by fire and exclusion of herbivores at the expense of *S. patens*, while the dominance of *S. patens* was unchanged in plots that were burned and not fenced (Ford and Grace 1998).

While nutrients may increase plant growth, under field conditions primary production may be reduced by secondary consumers. Salt marshes with higher nitrogen levels generally have higher muskrat populations (Visser et al. 2006). Visser and Sasser (2011) observed a significant linear increase in the number of muskrat houses as water column total Kjeldahl nitrogen concentrations increased. Herbivore grazing by waterfowl and nutria in the Atchafalaya and Wax Lake deltas significantly reduced end of season aboveground biomass between 25 and 50% (Evers et al.

1998). Shaffer (2010) described how nutria became a nuisance in a waste water treatment wetland where plants developed elevated nitrogen concentrations in their tissues. Note that nutrients are more concentrated in waste water than Mississippi River water, thus their impacts may differ. Nonetheless, the cumulative impacts of nutrients and salinity on the flora and fauna need to be studied.

Observed effects of diversions on vegetation communities

The Caernarvon diversion provided the most documented effects of Freshwater Diversions on vegetation communities. The Caernarvon project consisted of a structure built in the levee that periodically diverts fresh water and its accompanying nutrients and sediments from the Mississippi River into coastal bays and marshes in Breton Sound for fish and wildlife enhancement. The introduction of fresh water from the Mississippi River was intended to reduce the local degradation of wetlands and enhance marine resources in Breton Sound.

The diversion significantly changed both salinity and nutrients within the Breton Estuary (Lane et al. 2007). Water was fresh in the upper estuary and increased to 14 and 30 ppt in the lower estuary; however during spring pulses, the entire estuary was fresh for short time periods (< 1 month). From 1999 through 2004, Hyfield et al. (2008) calculated that precipitation provided 48 to 57% of freshwater input to the estuary, while the diversion provided 33 to 48% and accounted for 60 to 71% of nitrogen and 43 to 62% of phosphorus loads. Sites closest to the discharge tended to have higher nutrient concentrations than further downstream, though nutrient regeneration was suggested to occur throughout the basin (Day et al. 2009b).

Aerial mapping of vegetation types within the Caernarvon project area suggests that diversions caused a significant increase in freshwater marsh area and an associated decrease in brackish area (GEC 2011). However, this conclusion assumes no change in marsh aerial coverage from 1988 until the diversions started in 1991. On-the-ground sampling confirmed that the diversion caused significant shifts in vegetation with increased coverage of submersed aquatic vegetation (Rozas et al. 2005). At sites influenced by the diversion, SAV coverage averaged 66%, almost four-fold higher than the 18% average observed at sites unaffected by the diversion. Similarly, while end-of-season peak live aboveground biomass of the emergent marsh was highly variable, the greatest biomass was found at sites within 20 km of the discharge (Day et al. 2009b).

Unfortunately in 2005, Hurricane Katrina confounded future field assessments of the sites used by Day and his colleagues. Hurricane Katrina created a lateral fold which, along with an adjacent spoil bank, caused hydrologic isolation of one of the paired transects. However, it also provided opportunities for direct comparisons of a system with and without the influence of river water, albeit with few sites and no replication, as well as an examination of recovery following hurricane disturbance. Using this diminished number of sites, Moerschbaecher (2008) observed that aboveground biomass did not show any trend with distance from inflow. By contrast, belowground responses appeared to show a significant positive response to river water inputs. All sites exhibited increased belowground biomass during the year-long study, showing rapid recovery from hurricane disturbance.

Pore water salinity was significantly lower at sites nearest the Caernarvon diversion in response to freshwater input and highest when diversion discharge was lowest. Sulfide levels were highest at the sites that had greater salinity and when redox levels were lowest, suggesting that the anoxic soil conditions were a controlling factor in sulfate reduction in more saline areas. Total soluble sulfide levels ≥ 1 mM inhibit biomass production of *S. alterniflora* (Koch and Mendelsohn 1989). However, while a couple of sites had sulfide values > 1 mM in March 2006, most sites were well below 1 mM (Moerschbaecher 2008), suggesting that these sulfide levels were not likely to adversely impact biomass production.

Direct, large scale studies of the effects of herbivores on plant communities at diversion sites such are Caernarvon are lacking. The effects of herbivory may be altered by diversions in several ways. First, increased nitrogen loading associated with diversions may enhance eat outs compared to areas without diversions. Nutria (and other herbivores) prefer nitrogen-rich plants, so that experimental fertilization plots are sometimes preferentially targeted for grazing compared to unfertilized areas (McFalls et al. 2010). The scale of field studies is an important issue. Targeted enrichment at small sites can attract herbivores to a location compared to large-scale enrichment which would lead to an increase in herbivore populations. While examples of large-scale nutrient enrichment leading to increased herbivory are less common, some areas receiving treated sewage have experienced increased herbivory by nutria (Lundberg 2008, Shaffer et al. 2009). Also, increased freshwater associated with diversions will likely increase flooding frequency and reduce salinity levels leading to changes in plant community composition. Any enhancement of more palatable species would enhance herbivory leading to reduced aboveground biomass during the growing season and reduced belowground biomass in the winter when nutria target rhizomes. Finally, nutria abundance in the marsh will be lower when the diversion is active and water levels are high, so that grazing effects will be concentrated during periods when water levels are low.

Information needed

Greenhouse studies, as well as results from the Caernarvon diversion, suggest that freshwater inflows will reduce salt water intrusion and thus benefit freshwater plant communities. However, there is significant uncertainty regarding the effects of additional nutrient loads that occur as part of river water diversions, particularly the potential to increase belowground decomposition of both roots and organic matter (Swarzenski et al. 2008; also covered in further detail in “Effects of Diversions on Soil Strength” section). In addition, despite the differential response of belowground production compared to aboveground production observed in greenhouse studies, limited field measurements of belowground production have been made. Historically, belowground measurements are limited because they are labor intensive. While recent advances such as computed tomography (Davey et al. 2011) may be used for greater assessment of root responses and thus also capturing the deterioration of the organic matter, these approaches are still limited.

Ideally we could predict the net nutrient exchange between the water column and the sediments of wetlands receiving diversions of river water. Nutrient exchange will vary with time as well as with salinity. We can predict qualitatively that as salt desorbs and diffuses from sediments, that ammonium will gradually sorb onto the sediments. However, over time the sorption of ammonium should diminish as exchange sites become fully saturated. This type of information could be helpful for forecasting changes in water quality.

Because soil salinity fundamentally impacts sediment biogeochemical processes, and the diversion of water and sediment from the Mississippi River will impact salinity as well as nutrient flux, information is needed on how these variables interact. First and foremost, more information is needed about the impact of a change in salinity, particularly a lowering of salinity, on the nutrient balance of the wetland soils. As discussed above, the cation exchange properties of sediments change dramatically with salinity. Sediments will sorb nutrients as salinity is reduced, but the capacity will likely depend on the degree of freshening. Additionally, anticipating the pulses of salinity brought in by storms, it would be useful to know how the sediment nutrient balance changes with aperiodic salt intrusions.

Studies to evaluate the best pulsed approach to maximize sediment transport to the downstream marsh, while also providing freshwater flow when the probability of salt water intrusion to the freshwater marshes is greatest, would provide much needed information.

Increased wave action and high diversion flow rates were both expected to have negative effects by increasing the potential to uproot vegetation. However, limited documentation of such effects exist, particularly flow rates. Floating marshes were particularly sensitive to hydrologic disturbance, but also returned quickly. Thus, greater information on the effects of flow and wave action would be beneficial in understanding plant community responses.

The effects of freshwater pulses on floating mats appear dependent on the stage of mat development, thus a greater understanding of mat successional trajectories would improve predictability of responses to diversions.

Information is needed on the degree to which invasive species (e.g. *Phragmites, Typha*) will expand following a freshening of salt and brackish marshes. The effect of freshening on invasive species will have direct as well as indirect effects. Because many studies were short-term and laboratory-based, there is limited information on plant community composition changes as a result of increased nutrients. Invasive species like *Phragmites* may expand as a consequence of increased nutrients as well as reduced salinity. Recent evidence confirms that *Phragmites australis* communities along the Louisiana coast are comprised of both native and non-native geonotypes (Howard et al. 2008). The non-native genotype spread to cover about 82% of the plots to which it was introduced. By contrast, the native genotype only covered 18%. Thus further information on the spatial extent of non-native *Phragmites* should be obtained so that true estimations of invasion potential under changing salinity and nutrients can be obtained. Also, invasion of *Typha* species with softer belowground roots/tubers is possible, and could be detrimental overall. *Typha* occurrence is frequently correlated with ponding water in coastal Louisiana freshwater systems (Penfound and Hathaway 1938).

While the consensus among many Louisiana wetland scientists at the NOAA Diversion Workshop held in Lafayette, Louisiana, in February 2010 (http://www.mvd.usace.army.mil/lcast/pdfs/DiversionWorkshop.pdf) seems to be that eat outs do not lead to fundamental changes in a wetland, confirming this view appears to be the big unknown, especially in the context of diversions and changes in plant communities.

Managers have the following specific information needs:

1. What is the potential threat of salt water intrusion and how could diversions be operated to mitigate for this poorly understood possibility?
2. What is the effect of diverted river flow on the partitioning into below- and aboveground production of plant communities? Will this partitioning affect marsh sustainability?
3. Do diversions result in plant communities that are less or more resilient to scour from hurricane storm surge and other heightened hydrodynamic flows?
4. In what ways does the marsh vegetation response depend on the operation of the diversion (duration, discharge rates, seasonality, etc.)?
5. What is the effect of diverted river flow (primarily nutrients, but other components as well) on herbivory of wetland vegetation? Do diversions result in herbivory levels that would outweigh potential benefits to other ecological resources?
6. Would it be possible to eliminate nutria (it was done in England on a small scale)? Would the enhancement of large predators (e.g. large alligators) reduce nutria populations?

Conclusions

- In assessing the responses of marsh vegetation to Freshwater Diversions, it is important to consider the effects of low salinity, high nutrient water on both absolute plant production and the relative production of aboveground and belowground portions, the latter an important factor in maintaining soil strength critical for long-term marsh sustenance.
- A general conclusion on the expected short-term and long-term responses of marsh belowground production to Freshwater Diversions in Louisiana could not be drawn from the available evidence:
    - Salinity responses: Freshening of sediments should lead to greater efficiency of nutrient uptake by wetland plants, based on physiological considerations, and some studies have shown an inverse relationship between salinity and root (belowground) growth in Louisiana marsh plants; however, a direct relationship between salinity and root:shoot ratio (belowground to aboveground production) was found in experiments with tested halophytes. Freshening of sediments should lead to greater rates of denitrification and alter the partitioning of phosphate in sediment.
    - Nutrient responses: Studies on the response of marsh production to nutrient increases also drew variable conclusions, but in general, aboveground biomass increased and belowground production was either not affected, increased, or decreased in response to nutrient enrichment.
- Studies on the Caernarvon Freshwater Diversion found that freshwater marsh area was increased by diversions, with highest aboveground biomass near the discharge site. Following Hurricane Katrina, a relative increase in belowground production was observed at Caernarvon sites receiving river water, indicating a stimulatory effect of diversions on belowground production at least in the short-term (i.e. rapid recovery from hurricane disturbance).
- Evidence suggests that nutrient enrichment from Freshwater Diversions could cause plant

species compositional changes (e.g. experimental findings that nitrogen additions decreased the relative abundance of *P. hemitomon*), but a precise understanding of expected compositional responses is limited because many studies were short-term and laboratory-based.
- Evidence supports an effect of secondary consumers (e.g. herbivores such as nutria) in responding to nutrient-enriched plants (i.e. better forage quality) and reducing aboveground biomass; the quantitative impact of herbivory on vegetation responses to Freshwater Diversions needs to remain a focus in predictive models.

Suggestions for moving forward

- Measurement of aboveground biomass alone is insufficient to assess the impacts of a Freshwater (or Sediment) diversion on plant production.
- Existing Freshwater Diversions offer an experimental setting to examine some aspects of their effects on plant communities but only with rigorous statistical designs, sufficient replication, and appropriate reference marshes. Key studies include:
  - partitioning between above- and belowground biomass
  - plant community composition
  - herbivory

Effects of Diversions on Wetland Elevation

Karen L. McKee

Background

Controlled diversions to build land and promote wetland sustainability in coastal Louisiana were reported beginning in the early 1970s (Gagliano et al. 1973, Roberts et al. 1984, Soileau 1984, van Heerden 1994, USACOE and LADWF 1998, Council 2006, NRC 2006). There is some confusion in the literature over the stated purpose(s) of diversions with respect to “reducing marsh loss”. It is important to know whether a diversion was designed to reduce marsh loss by directly altering surface accretion of mineral sediment or by modifying plant growth through changes in salinity and/or nutrient regimes. Some diversions were initially designed primarily to reduce “saltwater intrusion”. For example, the Caernarvon Freshwater Diversion was created to address **“the alarming rate of loss of these wetlands….caused by many factors, among them saltwater intrusion.”** (USACE and LADWF 1998). However, a later report (LADNR 2003) stated that one of the objectives was to reintroduce sediments, along with freshwater into marshes of Breton Sound estuary. This 2003 report, based in part on several studies conducted by scientists at Louisiana State University and University of Louisiana-Lafayette, reported effects of the diversion on salinity, wildlife, and vegetation (mainly shifts in marsh vegetation type related to salinity changes). However, this 2003 report was mainly focused on salinity and consequent effects on wildlife and vegetation composition, and did not include an examination of elevation changes (although accretion rates were measured by Delaune et al. 2003).

The underlying assumptions (relative to wetland vegetation) apparent in these reports are that: (1) saltwater intrusion was the primary cause of wetland loss, because saltwater intolerant species were killed faster than tolerant species could invade, and (2) amelioration of salinity stress would promote vegetative growth overall (perhaps aided by addition of nutrients and sediment). Several early reports suggested that introduction of freshwater and nutrients, in addition to sediments, might offset factors causing deterioration of brackish and freshwater marshes (Gagliano et al. 1973, Roberts et al. 1984). These assumptions can be traced, in part, to Gagliano et al. (1973), who pointed out that, in addition to sediment from controlled diversions to build land, "***relatively small amounts of fresh water introduced into the upper ends of interdistributary estuary systems could be used to offset salinity intrusion and introduce badly needed nutrients, both of which would offset conditions leading to rapid deterioration of brackish and fresh marshes.***" Nowhere in this early report, however, are there data supporting the contention that the rapid deterioration of wetlands was caused by saltwater intrusion or lack of nutrients. Clearly, these early workers were proposing that freshwater introduction would lower salinity and deliver nutrients, but would be conducted in conjunction with sediment loading sufficient to build land. A later Louisiana Department of Natural Resources (LADNR) report (Roberts et al. 1984) developed specific recommendations for a Freshwater Diversion into Barataria Basin (Davis Pond). This report also emphasized modification of salinity regimes and restoration of freshwater marsh, but predicted that nutrients and sediments would increase marsh productivity and that ***"..increased organic production along with increased suspended sediment input will help retard subsidence-induced marsh loss in the basin."***

The key point is that since the early 1970s scientists have recognized the need for interventions that directly address the cause of wetland loss: failure to maintain elevations sufficient to support emergent vegetation forming the wetland habitat. For sustainable wetland restoration, marsh soil and vegetation responses to low salinity/high nutrient water influx should be considered in light of the long-term maintenance of elevation.

Wetlands must maintain their soil surfaces relative to prevailing water levels to persist. This balance is achieved when the rate of land building equals the rate of submergence (Cahoon et al. 2006). Despite this simple relationship, the processes involved are complex and interconnected by feedback linkages (Figure 2). The processes controlling wetland elevations may be physical, biological, and/or hydrological, and operate in response to drivers such as sea level change, river flows, storms, climate change, nutrient loading, and human modifications. If the rate of submergence increases, soil accretion rates must also increase. If not, increased depth and duration of flooding at a lower soil elevation will stress the plants (Mendelssohn and Morris 2000), eventually exceed their tolerance limits, and cause plant death and wetland loss (Kirwan et al. 2010). The processes occurring at or below the soil surface that influence vertical movement of a wetland include deposition/erosion of organic or mineral sediment on the soil surface, physical compaction of deposited material, soil shrinkage/expansion due to water flux, and organic matter production/decomposition (Cahoon et al. 2006, Cahoon et al. 2011, McKee 2011a,b). These processes do not occur in isolation, but interact to drive elevation change.

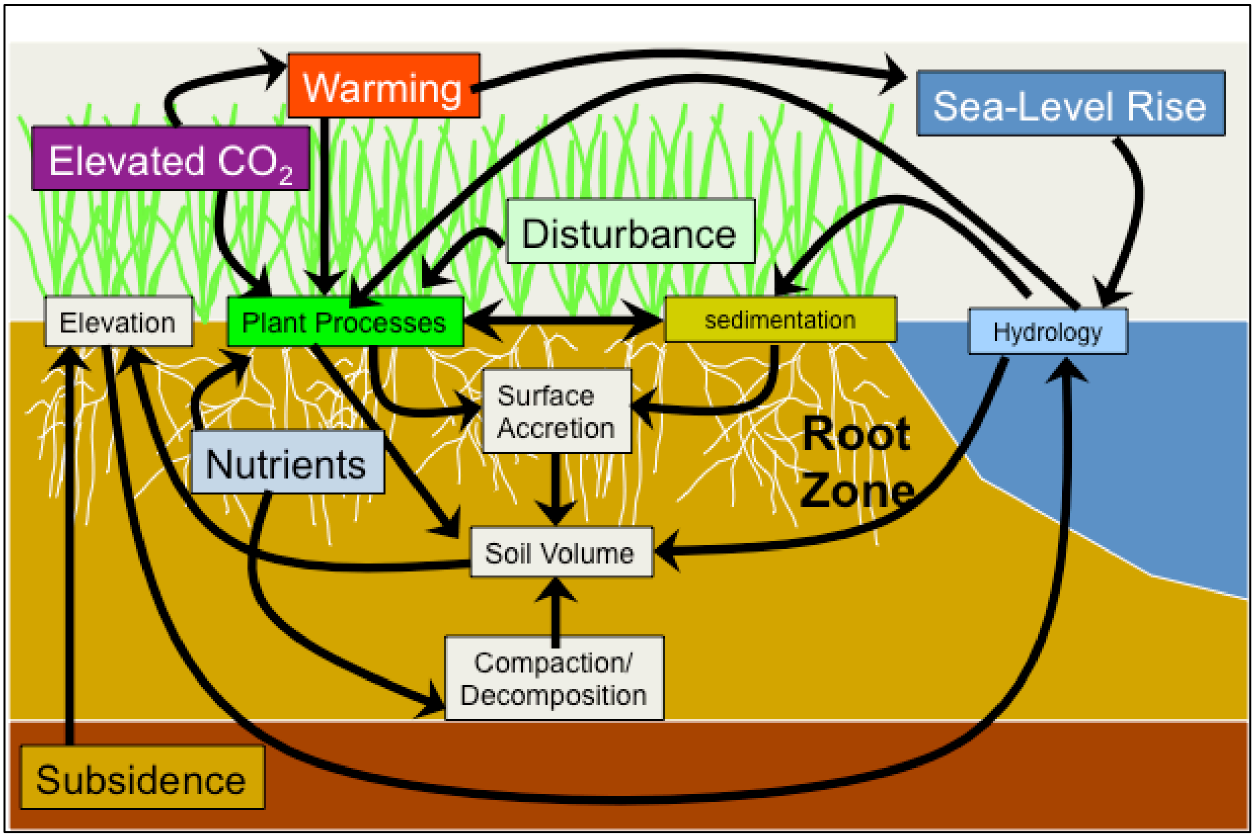

Figure 2. Diagram showing processes and feedback linkages influencing marsh elevation. Many wetlands, including those in the Mississippi River Delta, depend on both mineral and organic inputs to soil volume for elevation maintenance (Turner et al. 2006, Neubauer 2008, McKee 2011b), although the relative contribution may vary with wetland type and location; e.g. freshwater versus saline, inland versus coastal. Consequently, any alteration in conditions influencing accumulation of organic or inorganic materials may alter elevation dynamics and marsh stability. Wetlands in the Mississippi River Delta portion of coastal Louisiana are deteriorating because levees and control structures along the Mississippi River starve the wetlands of sediment and prevent the river from switching course to form a new delta (Blum and Roberts 2009). Activities such as canal dredging, fluid withdrawal, spoil bank construction, and impoundment construction have altered hydrology, salinity regimes, and subsidence rates (Boesch et al. 1994).

River diversions may change conditions such that either organic or inorganic contributions to soil volume increase. A diversion might contribute to elevation gain by delivering: (1) material (mineral sediment) directly to marsh surfaces, increasing rates of accretion and/or (2) freshwater and nutrients to stimulate plant production (biomass, stem density), which in turn promote sediment deposition and trapping (aboveground) and/or increase organic matter accumulation (primarily belowground where decomposition is slow). Plant production in coastal wetlands may be modified by changes in factors such as salinity (Broome et al. 1995, Merino et al. 2010), nutrients (Darby and Turner 2008b), and phytotoxins (sulfide) (Koch and Mendelssohn 1989), as discussed above, or flooding depth/duration (Broome et al. 1995, Howard and Mendelssohn

1995).

Environmental factors that alter marsh elevation

Mississippi River diversions deliver freshwater and constituents (e.g. nutrients, sulfate, and other dissolved ions), usually in pulses, that change water chemistry in the receiving basin and alter marsh productivity and organic accretion. The Caernarvon diversion greatly modified salinity in the Breton Sound estuary, generating a pattern from fresh in the upper estuary to 14 to 30 ppt in the lower estuary; spring pulses, however, propagated freshwater conditions throughout the estuary for short periods (< 1 month) (Lane et al. 2007). A lowering of salinity may benefit freshwater plant communities, which are vulnerable to saltwater intrusion (Flynn et al. 1995), and enhance plant growth in intermediate or brackish marshes (Broome et al. 1995, DeLaune et al. 2005). However, changes in salinity may also drive shifts in plant community composition (Sasser et al. 1986, DeLaune et al. 1987, Baldwin et al. 1996) with concomitant changes in production-decomposition processes influencing organic matter accumulation in soils.

Nutrient inputs may also stimulate plant production, either through a direct fertilization effect (DeLaune et al. 2005, Izdepski et al. 2009, Merino et al. 2010) or indirectly by introducing iron, which may precipitate phytotoxic sulfides (DeLaune et al. 2003). Conversely, addition of nutrients may reduce belowground production of biomass, since fewer roots would be required to forage the soil for limiting nutrients (Darby and Turner 2008a, Ket et al. 2011, see previous section, "Effects of Freshwater Diversions on Wetland Plants"), or may increase organic matter decomposition (Laursen 2004, Turner 2011a,b). However, no studies have been conducted that experimentally examined the direct effects of river diversions on organic matter decomposition, although one study correlated Mississippi River water influx with more decomposed root mats in a *P. hemitomon* freshwater marsh in the Penchant basin (Swarzenski et al. 2008). The marsh with riverine input had more reducing soils, higher sulfide (a phytotoxin), and higher alkalinity in addition to faster decomposition and loss of soil strength, compared to a marsh without river influence. Greenhouse and field studies are needed to establish a cause and effect relationship between river input and marsh response (in different marsh types) and to better predict how diversions that alter nutrient regimes may influence marsh-building processes.

Some river diversions may deliver sediment to the receiving basin and contribute to accretion directly, although the amounts vary with the diversion structure, magnitude of flow, and river stage (Snedden et al. 2007). The Caernarvon diversion, for example, delivered 1.64×10^3 t/d in sediment discharge when the Mississippi River was falling and 3.29×10^3 t/d when it was rising (Snedden et al. 2007). These inputs, however, were orders of magnitude lower than historical discharges (via crevasses or uncontrolled diversions) and deemed insufficient to offset current sea level rise. How much of the discharged sediment ends up on the marsh surface depends upon a suite of interacting forces, including water velocity, tides, winds, water levels, and suspended sediment load (Day et al. 2009a). Measured deposition can be as high as 2.3 cm/y in the short-term (sediment traps), but lower (0.26 to 0.30 cm/y) over longer time periods (^{210}Pb or ^{137}Cs geochronology) (DeLaune et al. 2003, Wheelock 2003). A key question is where deposition measurements were made in the marsh landscape: in the interior marsh or near waterways? Wheelock (2003) found that deposition of mineral sediment (short-term sediment traps) from Caernarvon varied with distance from the diversion, proximity to a major waterway, and with season. Sediment deposition decreased with distance from the diversion at exterior (marsh edge) positions, but was low and did not vary with distance at interior marsh sites. This finding has important implications for monitoring and predicting movement of sediments delivered by diversions into areas with existing (but deteriorating) marshes.

Observed effects of diversions on marsh elevation

To our knowledge, there are few published data reporting effects of diversions on marsh accretion (DeLaune et al. 2003, Wheelock 2003, Lane et al. 2006, Moerschbaecher 2008, Day et al. 2009a) and only one study that measured elevation change in relation to diversion structures (Lane et al. 2006). This lack of data is surprising considering the importance of such information. A study by Delaune et al. (2003) used both feldspar markers and ^{137}Cs dating to assess short-term and long-term accretion rates in the Breton Sound estuary marshes at different distances from the Caernarvon diversion (total of 20 sites). Sites were grouped into those in the upper basin (closest to the diversion) and those in the lower basin. Highest rates of accretion were measured closest to the diversion discharge (within ~12 km: 1.72 cm/y) compared to farther away (~12 to 30 km: 1.34 cm/y). Long-term rates measured by ^{137}Cs dating also were higher closer to the diversion. In addition to accretion of mineral matter, organic matter accumulation (above feldspar) was higher closest to the diversion (432 vs. 166 g/m/6 mo). Wheelock (2003) also found higher short-term and long-term deposition closer to the diversion, although this pattern only held for sites closest to waterways and not in interior marsh; sedimentation was additionally influenced by seasonal variation in winds and other factors.

These results must be viewed with caution, since there were no reference sites (outside the diversion basin) or pre-diversion measurements of accretion, which would be required to conclusively demonstrate that the observed differences between upper and lower basins were due to effects of the diversion (rather than natural variation across the basin). Also, accretion does not equal elevation change, which determines whether a marsh is keeping up with the rate of submergence. To fully assess how a diversion may be affecting marsh capacity to keep up with relative rates of sea level rise, it is necessary to determine rates of surface elevation change in relation to a stable benchmark. The technology to make high-resolution measurements of marsh elevation change, accretion, and shallow subsidence has existed for at least ten years (Cahoon et al. 2000, Cahoon et al. 2002a, Cahoon et al. 2002b), and is in use at most Coastwide Reference Monitoring System (CRMS)-Wetlands monitoring stations (http://www.lacoast.gov/crms2/Home.aspx).

Studies by Day and coworkers are the primary sources of information on how diversions may affect marsh elevations. Based on a series of field investigations, they concluded that the marshes near diversions were generally healthy, accreting, and keeping pace with relative sea level rise (Lane et al. 2006, Moerschbaecher 2008, Day et al. 2009a). One field study investigated the effects of three diversions (Caernarvon, West Pointe a la Hache (WPH), and Violet) on accretion, subsidence, and elevation change rates in the receiving basin marshes (Lane et al. 2006). At each diversion, three sampling distances were used, each with duplicate stations where measurements were made from summer 1999 to spring 2000. This sampling design specifically allowed testing of whether the measured rates varied with increasing distance from the diversion structures. All sampling stations at Caernarvon and WPH showed sediment accretion and elevation gains over the study period, whereas substantial elevation losses occurred at all Violet sites (Table 2, Figure 5 in Lane et al. 2006). The results, however, did not show a consistent pattern with distance from the diversion structures, which would be expected if the diversions were influencing elevation dynamics. At Caernarvon and WPH, there were no significant differences in elevation change rates with distance from diversions, and elevation losses were significantly greater at stations closest to the Violet diversion (Figure 5 in Lane et al. 2006). Accretion rates at WPH were significantly higher closest to the diversion, but at Caernarvon, the highest accretion occurred farthest from the diversion; there were no differences in accretion with distance at Violet (Figure 5 in Lane et al. 2006). A companion study of the Caernarvon diversion examined effects on plant biomass production in Breton Sound estuary from March 2006 to October 2007 in duplicate plots located at 3.4, 12.3, and 18.1 km from the diversion structure (Moerschbaecher 2008). This study found high above- and belowground biomass in the Breton Sound study area, comparable to or exceeding reference marshes. Biomass production did not vary consistently with distance from the diversion structure, but this evaluation was confounded by the spatial variation in plant community composition across the sampling stations (freshwater species closer to the diversion, saltwater species farther away).

Failure to detect a significant difference with distance might be attributable to insufficient replication or a sampling design unable to account for other environmental or biological (e.g. species composition) gradients. Even though the studies by Day and coworkers were unable to detect a clear effect of diversions on marsh elevations, the data indicated that the marsh areas sampled were for the most part productive and keeping pace with relative sea level rise. However, these results cannot say whether these sites were already productive and accreting or if these values reflect an effect of the diversion. Also, it is unlikely that these data are representative of the entire receiving basins. Considering the areal extent (Caernarvon: 1100 km^2, Violet: 50 km^2, West Point a la Hache: 68 km^2) and range of marsh types present (freshwater, brackish, and saline), six sampling stations are inadequate to characterize the marshes or determine health and stability throughout the areas of interest.

In summary, existing data showing diversion effects on marsh accretion or elevation are sparse and based on limited sample sizes and/or inadequate sampling designs. These points are raised to emphasize data gaps and key considerations in designing future monitoring plans. The existing data are nonetheless useful because they provide some insight into accretion and elevation dynamics in diversion basin marshes. Published work on salinity and nutrient effects on marsh production-decomposition processes also provide hints as to how changes in water chemistry might alter organic contributions to soil volume. However, many questions remain with regard to how changes in water chemistry may influence elevation dynamics.

Information needed

Data on how diversions influence marsh elevations and dynamics are needed, but have not been acquired in any systematic or comprehensive manner. Specifically, the following questions should be addressed:

1. Do diversions promote accretion (mineral or organic) and elevation gains that balance rates of submergence in receiving basin marshes? The answer requires knowledge of

pre-diversion rates and/or rates in reference marshes unaffected by diversions.

2. How far does the influence of diversions on marsh elevation extend from the discharge structure, and does the zone of influence coincide with measured changes in sediment accretion, environmental conditions, and/or changes in plant community composition or productivity?
3. Which processes controlling marsh elevations (e.g. accretion/erosion, subsidence, organic matter accumulation) are most influenced by diversions, and what environmental changes (sediment, nutrients, salinity) are most influential in this regard?
4. What are the tradeoffs among factors controlling marsh elevations that are affected by diversions (e.g. nutrient effects on biomass production vs. decomposition)?
5. Are elevation dynamics in all marsh types similarly affected by diversions (or are some more sensitive to certain changes in environmental conditions caused by diversions)?
6. What existing features might modify the impact of a diversion on elevation dynamics (e.g. barriers to water flow)?

Conclusions

- For wetlands to persist, they must maintain their soil surfaces relative to prevailing water levels.
- For river diversions to succeed in the goal of reversing marsh loss, they must contribute to vertical land development at a rate that balances relative sea level rise (change in ocean surface height plus local land movement).
- Diversions may promote vertical land development by (1) adding mineral sediment directly to marsh surfaces increasing rates of vertical accretion or (2) by stimulating plant production that promotes sediment deposition and trapping (aboveground) or by increasing organic matter accumulation (belowground) and soil volume.
- Delivery of nutrients or lowering of salinity may stimulate plant production but may also increase rates of organic matter decomposition, the latter potentially leading to loss of soil volume. However, empirical data showing a cause and effect relationship between river-induced changes in water chemistry and marsh response are lacking.
- A limited number of studies have examined sediment accretion rates in relation to diversions and the results show variable deposition patterns depending on distance from the diversion, proximity to major waterways, existence of barriers to flows, and with season.
- Only one study has directly examined the effect of diversions on marsh elevations and did not conclusively show that diversions increased net elevation gain.
- Overall, there have been few studies to examine diversion effects on marsh accretion and elevation and, although providing some insights, were based on limited sample sizes and/or inadequate sampling designs (necessary to rigorously test the effects of diversions on either accretion or elevation change).
- Major information gaps exist with respect to how much diversions may alter marsh elevation trajectories (especially in relation to balancing relative sea level rise), which specific mechanisms influencing soil volume (organic vs. inorganic) might be most affected by diversions, and what other factors might modify the impact of diversions on marsh elevation dynamics.

Suggestions for moving forward

- Measurement of accretion (i.e. deposition of organic or inorganic sediment on the soil surface) alone is insufficient to assess the impacts of a freshwater (or sediment) diversion on the long-term stability of a wetland. Information about subsurface movement, along with regional sea level trends, is necessary to evaluate the capacity of a wetland system to avoid submergence.
- Existing freshwater diversions offer an experimental setting to examine some aspects of their effects on elevation dynamics, but only with rigorous statistical designs, sufficient replication, and appropriate reference marshes.
- Existing permanent monitoring stations (e.g. the Coastwide Reference Monitoring System) provide additional means to quantify spatial and temporal variation in marsh-building rates and correlations among processes, which will aid in interpreting observed responses at existing diversions.
- Emerging data from wetland elevation studies conducted both within and outside the region can contribute to adaptive management of existing freshwater diversions by suggesting possible outcomes of specific modifications and by contributing to a more comprehensive database to guide decisions.

Effects of Diversions on Wetland Soil Strength

Charles Hopkinson and William Orem

Background

Soil strength describes the geotechnical characteristics of soils and is typically used in designing earthworks and foundations. Geotechnical investigations include surface and subsurface exploration of a site and *in situ* and laboratory tests that measure soil properties. Shear strength defines the ability of soils to resist displacement or deformation when subjected to shear stresses. However, there are no American Society for Testing and Materials (ASTM) standard test methods for determining the shear strength of coastal wetland soils, which are typically fine-grained cohesive sediments (silts and clays) with high organic matter content, oftentimes extensive root mats, and flooded or at least saturated with water during high tide. Shear strength is thought to be an indicator of wetlands resistance to shear stresses (e.g. vegetative cover loss) from storm-induced waves, currents, and pressure fluctuations, for example during a hurricane.

The shear strength of soils is affected by numerous factors including soil composition (e.g. mineralogy, grain size, particle shape, ionic forces, organic matter content), void ratio, water content and pore water chemistry (e.g. salinity, pH) , the soil structure (e.g. particle arrangement, fissures, cementation), and loading conditions (e.g. magnitude of shear stress, rate, history). Shear strength of a soil is also controlled by plant roots and rhizomes: it increases proportionally to the cross sectional area of roots crossing the shear plane. Roots add strength because of the tensile force required to break individual roots and rhizomes (Howes et al. 2010). Roots also contribute strength through their frictional contact with soils.

Two instruments have been employed in coastal Louisiana wetlands to gauge shear stress: the

Dutch cone penetrometer (Are et al. 2002, Mullins and Fraser 2006) and field vanes (Howes et al. 2010, Holm et al. 2011). The penetrometer is widely used in geotechnical analyses of soils. It provides measures of tip resistance and shear resistance with depth in soil and can be used to calculate other important parameters of soft clay wetland soils, including soil cohesion and stress strain modulus. The field-vane torque meter as used in Louisiana wetland soils measures the combined resistance along the length of vanes. It must be used with extracted cores or with extensions to examine how strength varies with depth. It must be used carefully to examine the degree to which the top root mat is tied or bound to lower depths. Additional geotechnical analyses provide insight into strength discontinuities in the soil profile, for example bulk density, organic matter content, rooting depth, and root density/strength.

Environmental factors that alter soil strength

Information on wetland soil strength helps us better understand the processes and factors that contribute to the sustainability of Louisiana coastal wetlands. Theoretically, if shear stress (e.g. during storms) exceeds soil strength, wetland soils will be lost or swept away. There are distinct differences in soil strength in wetlands undergoing rapid degradation and loss versus other wetlands that show little degradation over the past couple of decades (Day et al. 2011, Holm et al. 2011). Discontinuities in the soil profile of soil strength can increase the vulnerability of overlying wetlands regardless of degradation condition (Howes et al. 2010). We need to know how soil strength changes when subjected to Freshwater Diversions and associated decreases in salinity, increases in nutrients, and alterations in flooding and wetting regimes.

Storm and hurricane surge modeling and predictions of water level, short wave height, pressure field variation, and frictional energy dissipation due to bay bottom and wetland vegetation interactions were not included in most storm surge models of the Louisiana coast prior to Hurricane Katrina (NRC 2006). The wave energy lost in passing over marsh vegetation and the ability of the marsh/root/soil complex to hold up against wave shear stress are the reasons wetlands provide a buffer for inland property. These factors are critical to the sustainability of wetlands. Wave shear stress is related to the wave friction factor, which is influenced by stem density, canopy height, and leaf geometry (Suhayda and Jacobsen 2008, Howes et al. 2010).

Examples abound in the Louisiana coast that hurricanes can rearrange the deltaic landscape and contribute directly to wetland loss through storm surge and shear physical force (Barras et al. 2008). Such loss has been documented both in newly emergent marshes formed in the vicinity of the mouth of the Atchafalaya River and in geologically older marshes that maintain elevations above sea level primarily through organic accretion (Howes et al. 2010). Failure of both types of wetlands, across strong gradients in marsh type and mineral and organic content, demonstrates that multiple factors contribute to wetland soil strength and influence how marshes respond to excessive wave shear strength.

In 2005, hurricanes Katrina and Rita caused marsh loss throughout coastal Louisiana, including Breton Sound marshes in the immediate outfall area of the Caernarvon freshwater diversion (Barras 2006, 2007). Raynie (2011) attributed the loss of wetlands in this location to natural processes, and excess hydraulic energy in this area due to the funnel configuration of the elevated levees. Howes et al. (2010) attributed the extensive loss in the Breton Sound marshes in part to geomorphic amplification of wave shear stress as well as soil strength weaknesses due to shallow rooting depths and weak layers in the soil profile. A lens of inorganic material deposited by a deliberate levee breach of the 1927 flood was thought responsible for the weakness because it lacked the abundant roots and rhizomes present above. Kearney et al. (2011) documented patterns of marsh loss in the same area and hypothesized that operation of the Freshwater Diversion contributed disproportionately to the loss of marsh in this area, in part by the weakening of organic soils through excess nutrient influx. Considerable uncertainty remains therefore whether Freshwater Diversions serve to exacerbate or ameliorate the effects of natural physical forces, such as storm surge, on the marsh landscape.

Soil strength increases linearly with increasing live belowground material, when comparing across a variety of wetland species (Holm et al. 2011). This relationship is very strong for the freshwater plant *P. hemitomon* and the salt marsh plant *S. alterniflora*. The relationship is weaker for the fresh marsh plant, *S. lancifolia*, and the black mangrove, *A. germinans*. Of the marsh sites studied to date, *Panicum* demonstrated the highest live root mass and the highest shear strength while *S. lancifolia* showed the lowest live root mass and the lowest shear strength. Thus type of marsh per se (i.e. salt, brackish, or fresh) seems to bear little relation to soil strength. It is the species present and its root biomass in various marshes that is most important (Holm et al. 2011).

Howes et al. (2010) may have over-generalized when they concluded that fresh marsh was more susceptible to hurricanes than salt marsh. Their conclusion may reflect site specific properties that could be expected to differ greatly from site to site within Louisiana. At their study sites, *S. patens* growing in tussock form with low and shallow root mass in an organic rich fresh soil contributed less to soil strength than *S. alterniflora* growing with high and deep root mass in a higher mineral content salty soil. If their study had compared *P. hemitomon* and *S. alterniflora* marshes, the fresh vs. salt marsh conclusion may have been reversed.

Compaction brought about by desiccation, drainage, or overloading also contributes to soil strength even within the same type of marsh (e.g. salt marsh). Day et al. (2011) showed that Bayou Chitigue marshes, which seldom drain, generally lose surficial mineral deposits while Oyster Bayou marshes, which do drain and dry out, retain surficial sediments. This is especially important when surficial deposits are comprised of fine grain mineral matter and organic matter (Paola et al. 2011). Shear strength of Oyster Bayou surface marsh sediment was 10 time stronger than at Bayou Chitigue. Drainage and desiccation tend to reduce void space, increase strength, and thereby resist subsequent depositional loads without deformation. The Day et al. study confirmed results of Holm et al. (2011) and Howes et al. (2010) by showing that root growth contributes to soil strength, even while contributing to void space, which otherwise translates into soil weakness.

The mechanical strength of well-preserved peat deposits (fibric peat) derives from the preservation of plant biopolymers (mostly lignocellulose) in the deposited organic material, and extensive root structure from macrophytes living on the peat substrate. Degraded peats (sapric) and peats with less extensive rooted biomass have lower mechanical strength and may be subject to erosion (e.g. roll up and sloughing) during storm surge. There is limited evidence that nitrogen and phosphorus loading promotes peat degradation and thereby lowers soil strength below the rooting zone (Turner 2011b), but only under loading rates in excess of those used on highly fertilized agricultural fields. Similar levels of loading have not caused declines in soil strength in the rooting zone.

Observed effects of diversions on soil strength

River diversions have introduced nutrients, sulfate, and other chemical species into freshwater wetlands that were previously low ionic strength oligotrophic environments (Meade 1995, Goolsby et al. 1999, Goolsby 2000, Goolsby and Battaglin 2000). Decreases in organic soil strength resulting from such diversions has been suggested (Darby and Turner 2008a,b, Swarzenski et al. 2008, Turner et al. 2009, 2011b) as one factor in the well documented loss of wetland area in this region (Boesch et al. 1994, Barras et al. 2003, 2008). Other studies suggest that river diversions promote peat growth and do not decrease the mechanical strength of organic soils (DeLaune et al. 1983, 2003, Nyman 2011).

Water quality could impact soil strength in several ways. Nutrients stimulate macrophyte growth, but because the nutrients are available in the surface water, plant roots may not be as extensive or deep as in wetlands not affected by diversions (Darby and Turner 2008a). A wetland could have luxuriant macrophyte growth on the surface, but lack extensive belowground growth providing peat stability. Considering that root distribution and biomass correlate with soil strength, it is important to document changes not only in aboveground plant growth and root:shoot ratios, but also absolute changes in root mass and distribution when evaluating the effects of changes in river water and associated properties on soil strength. Nitrogen enrichment and eutrophication may change macrophyte community composition, which might also affect soil strength. Eutrophic-adapted species may replace species adapted to more oligotrophic conditions, and this change may impact soil strength. For example, in eutrophied portions of the Florida Everglades cattails have displaced sawgrass as the dominant macrophyte. Cattail peat is much more sapric compared to the fibric nature of the sawgrass peat, and therefore more subject to degradation and erosion. On the other hand, nutrients promote aboveground plant growth and additional biomass for accumulation, which would seemingly work to increase peat growth and the trapping of suspended solids when flooded.

Nutrients may stimulate overall microbial activity leading to a greater rate of organic matter decomposition and hence loss of soil strength (Turner 2011b). Stimulation of nitrate and sulfate reduction following changes in diversion water flow may lead to enhanced nutrient release, further stimulating overall anaerobic microbial activity; but of course enhanced nutrient release could promote greater plant root growth. Furthermore, these terminal anaerobic processes may increase the degree of syntrophy in peat soils leading to increased overall biodegradation.

Are river diversions causing degradation of peat soil in south Louisiana through destabilization of soil strength, or are they a positive influence promoting plant growth and peat accretion with no adverse impact on organic soil strength? Unfortunately, there is no clear cut answer so further research will be needed to resolve this question. While differences in experimental design or measurement approaches could explain the different results from various research studies, perhaps the differences also reflect real differences in effects from different settings. This will need to be resolved.

Information needed

It is important to determine the suite of factors acting simultaneously that result in soil strength changes. For instance, if a change in soil strength is observed in wetlands receiving diversion materials (water, sediment, nutrients), is the change due to singular changes in salinity or nutrient levels, or to the combined effects of salinity and nutrients as well as any resultant changes in wetland plant composition? The effects of diversions on soil strength in wetlands undergoing severe and rapid successional change have not been clearly determined.

It is useful to consider idealized profiles of shear strength versus soil depth and how variations in those profiles contribute to degradation vulnerability and loss during storms. With uniform wetland soil composition over depth, we expect soil strength to increase with depth, primarily as a result of compaction by overburden loading. Surface soil drainage and desiccation enhances compaction, which can increase soil strength near the surface. Wetland ponding, regardless of cause, decreases soil strength and increases wetland vulnerability to storm scour and loss. Plant roots also change the depth profile of soil strength, resulting in increased soil strength in shallower soils where roots are present. Abrupt changes in soil strength slope vs. depth, especially from positive to negative slope, can result in failure planes - regions above which entire blocks of wetland soil can be scoured (Howes et al. 2010). Diversions can increase the scour vulnerability if they result in ponding or decreases in rooting depth or root tensile strength.

Specific information needs include:

1. Is soil strength a good indicator of the ability of marshes to resist scour or destruction from storm surge and waves?
2. What is the critical point between soil strength and the shear stress where the marsh plant/root system separates from the underlying sediment and how do soil strength vs. depth profiles affect critical points?
3. How do measures of soil strength obtained using the field-vane torque meter compare to the Dutch penetrometer in spatial patterns of soil strength in Louisiana wetland soils? How do results of these instruments compare in providing mechanistic understanding of soil strength and its ability to predict wetland resilience?
4. What is the role of initial condition (e.g. elevation, degree of impoundment, soil strength, species composition, salinity regime, flooding/draining regime) on changes in soil strength following a river diversion?
5. To what extent is soil strength a reliable indicator of long-term marsh sustainability in coastal Louisiana; e.g. in the face of sea level rise and the ability of marshes to resist degradation from high storm surge shear stress?
6. When diversions cause rapid and strong changes in salinity, nutrient loading, and plant community composition, how does soil strength change over time? With the Mississippi River historically switching distributaries every several hundred years, the initial input of low salinity, low ionic strength, relatively nutrient-rich floodwaters into degraded wetland interdistributary basins mimics, in a sense, what happens with a diversion. Land building as a result of these historic switches was primarily due to new sediment inputs, which occurred regardless of changes in soil strength and hurricanes. How important

were changes in soil strength during these events relative to susceptibility to hurricane shear and overall land building?

7. What is the relative importance of the factors that contribute to soil strength, including grain size, organic content, degree of organic matter decomposition, root type and distribution, bulk density, ionic strength, and water content? If we could predict the distribution of these factors affecting soil strength, could soil strength profiles be predicted in Louisiana wetlands?
8. How does soil strength change during geological and biological succession following the termination of a diversion program or a switch in river distributaries?
9. What is the optimal flooding/drainage regime that promotes marsh accretion and building soil strength?
10. How do the effects of high level surface fertilization vs. low level floodwater fertilization on soil strength compare?
11. Is the occasional loss of vegetation following severe hurricane passage significant in the long-term (> 5 to 10 y) as long as sediment remains within the system and thereby contributes to elevation gain elsewhere? Turner (2009) and Howes et al. (2010) have shown the importance of hurricanes in redistributing sediments onto the marsh platform.
12. What are the cumulative, long-term effects of vertical discontinuities in soil strength caused by inorganic layers deposited following storms or even planned diversions? Regions of low soil strength (weak layers) can increase the vulnerability of marshes (that develop over such deposits) to loss following the passage of storms with wave shear stress in excess of soil strength at those layers.

Conclusions

- It is crucial to recognize the differences in diversions and their intended goals in retarding or reversing wetland loss in coastal Louisiana, specifically the few Sediment Diversions which are designed to deliver sediment, and the more numerous Freshwater Diversions, which deliver limited amounts of sediment but lots of river water of uncertain quality for marsh sustainability.
- The Sediment Diversions appear to be beneficial in building coastal wetlands and deltas, but are few in number.
- The effectiveness of the Freshwater Diversions, which deliver mostly river water containing high nutrients and other chemical constituents, in mitigating for marsh loss, is unclear from the available research.
- Some research suggests that the Freshwater Diversions deliver sediments and nutrients, which benefit wetland plant growth and organic soil accumulation, while other research suggests that these Freshwater Diversions deliver nutrients and other chemical substances to the system, which negatively impact belowground biomass growth (root mat development) and cause organic soil deterioration.
- Some of the confusion in the previous research on the benefits/costs of diversions comes from invalid comparisons between Sediment Diversions, which deliver significant sediment loads, and Freshwater Diversions, which deliver mostly water, or between wetlands with mostly sediment substrate and those with mostly peat substrate.
- There is also a need to develop a measurement of soil strength that is widely accepted as accurate and is easily used by researchers. Intercomparisons should be made between

penetrometer and vane-type meters – to what extent are they interchangeable?

- Research studies are needed on the following questions: (1) How do Freshwater Diversions of mostly river water and little sediment impact soil strength in fresh, brackish, and salt water wetlands with organic soil, (2) How do the Freshwater Diversions impact the factors that control soil strength including root and rhizome mass distribution, species distribution, organic and water content, and organic soil accumulation, and (3) Is soil strength a strong predictor of wetland sustainability?
- It is unclear what factors, if any, related to the operation of Freshwater Diversions for coastal restoration may serve to enhance or ameliorate the impacts of natural physical forces, such as flooding and storm surge, in shaping diverse deltaic landscapes.

Suggestions for moving forward

- Major Mississippi River distributaries have deposited tremendous loads of sediment onto the Louisiana continental shelf over the past 6,000 years resulting in a mosaic of deltaic lobes with sufficient soil strength and integrity to withstand storm surge over vast periods of time. Switching of river distributaries is a normal geologic process and future adaptive management that emulates this process should be encouraged.
- Organize a panel of experts to recommend the best and most informative method for measuring soil strength, and then use this method consistently in future studies.
- Statistically determine how soil strength varies across the south Louisiana wetlands in relation to type of marsh (salt, brackish, fresh), type and vertical distribution of soil composition (e.g. grain size, organic content, uniformity over depth), elevation, plant species composition, flooding and draining regime, and relative damage from recent storm surge events.
- Develop a predictive understanding of the relation between the vertical and horizontal distribution of soil strength, wave shear stress, and marsh scalping, degradation and loss.
- Fund studies of the effects of small Freshwater Diversions on marsh soil strength, organic soil accumulation, and vertical accretion in a way that enables the effects of sediment load, nutrient load, and flooding regime to be determined individually. These studies might include: (1) mesocosm studies, (2) field comparisons of different locations, (3) measurements of major factors influencing soil strength such as root density and depth, microbial activity, soil stratigraphy, etc.
- Prolonged flooding or ponding of all types of marshes has been demonstrated to cause marsh degradation and is correlated with low soil strength. It should be avoided through appropriate water management.

Monitoring and Adaptive Management

As evident from the present papers' conclusions, predictions of the short- and especially long-term effects of constructed and planned Freshwater Diversions on Louisiana wetlands are limited

– too few representative systems have been studied, ecologically relevant designs are lacking, and measurements of some key indices of vegetation and soil responses are rare. It is within this realm of uncertainty that formal adaptive management is most valuable because it is designed to support action when scientific knowledge is limited. Adaptive management functions when goals are agreed to among the actors, knowledge of pre-diversion conditions exist, monitoring is done to measure progress toward goals, and there is a process in place to adjust functions to improve the likelihood that goals can be met.

The 2012 Coastal Master Plan contains an overview of an Adaptive Management Framework that will apply to the initial stages of Master Plan implementation (e.g. proposed diversions in Figure 1, Table 1) – a more comprehensive framework is in preparation by CPRA to be completed in 2013. The adaptive planning process has three steps leading to development of the 2017 Coastal Master Plan. These include evaluation of the decision-making process and stakeholder acceptance of the 2012 Coastal Master Plan (Step 1), evaluation of the tools and models used to inform development of the 2012 Coastal Master Plan, and their key uncertainties (Step 2), and to incorporate feedback from Steps 1 and 2 in developing a strategy and budget for research and management in the next four years to inform revisions in the 2017 Coastal Master Plan.

Elements of the Adaptive Management Framework will include expansion and refinement of existing monitoring and modeling efforts, and development of new projects to fill information and management gaps. Specific tasks related to monitoring include:

- Bolster current monitoring and data collection efforts; appropriate spatial and temporal performance measures will be identified in later versions of the Adaptive Management Framework;
- Determine when and where monitoring might dictate adjustments to the planning process and/or project implementation and operations that would result in a change to how projects interact, are sequenced or whether they are removed from the master plan.

Below, we provide some general suggestions for a comprehensive and effective monitoring program to inform management of diversions.

A well-designed monitoring program is essential to assess whether diversions are promoting marsh sustainability and to support adaptive management of diversions. For example, if an existing diversion is failing to produce marsh elevation gains sufficient to match rates of relative sea level rise, the information from a good monitoring program should point to where deficiencies lie and suggest ways to improve future diversions. Numerous books and articles describe appropriate sampling designs, particularly for the assessment of human modifications affecting natural ecosystems. Many of these resources emphasize the need to address spatial and temporal variation in response variables as well as any environmental gradients that might exist in the study area. Both spatial and temporal replication are needed to distinguish effects due to the modification under study from those due to natural gradients or cycles (Underwood 1994). In particular, replication of the main effect “diversion” is desired to test whether or in what direction diversions influence marsh sustainability. Equally important is the use of multiple reference sites (that encompass the range of habitats encountered in the diversion basin). A preliminary survey of vegetation and soils across the diversion basin would provide information to guide sampling design and potential locations of sampling stations. To answer questions about the spatial extent of diversion influence, it is important to establish multiple monitoring stations at suitable intervals (distances from discharge and in relation to discharge flows) and sufficiently replicated to detect significant differences. Preferably, pre-diversion measurements should be made over a suitable duration to provide baseline trends in elevation dynamics, including seasonal variation. Alternatively, measurements conducted before and after major discharge events might be used to assess effects of a diversion on marsh elevation trends.

The existing network of CRMS sites across the MR Delta is an effective starting point for monitoring changes in marsh productivity, species composition, salinity, elevation, soil strength, and herbivory. The Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) authorized funding in 2003 for CPRA and USGS to implement the CRMS as a mechanism to monitor and evaluate the effectiveness of CWPPRA projects across the region (Steyer et al. 2003). A consequence of this monitoring program was the selection of reference sites that have been used to establish the status and trends of existing wetlands. A total of 390 sites with a fixed annual sampling design were approved and secured for CRMS data collection. These 390 CRMS sites located within nine coastal basins covering the entire Louisiana coast are sampled annually using a fixed design. Sample collection from the ground began in 2005, and will be an important complement to remote sensing techniques.

For comparison purposes, establishment of additional sampling sites within the footprint of diversions would ensure that sampling designs are sufficiently replicated. To accomplish this, the number of CRMS sites, for example, might be expanded in response to the start and placement of new restoration projects. Placement of monitoring sites is critical, e.g. along a gradient downstream of any diversion to record changes in salinity, nutrients, and species composition and biomass. Landscape features that reduce the footprint of land affected by diversions may need to be modified, e.g. remove spoil banks that, along with Hurricane Katrina folding, resulted in hydrologic isolation of one section downstream of the Caernarvon diversion. It is also desirable to alternate flooding and drainage of marshes receiving diversion runoff as this promotes retention of allochthonous materials and contributes to soil strength.

Changes that would enhance the existing and future diversion projects are:

- Transects downstream of diversions with detailed assessment of changes in community composition, detailed hydrology, and nutrient chemistry.
- The addition of sentinel sites within different vegetation communities along nutrient and hydrologic gradients specifically geared to evaluate belowground production and root distribution.
- Because water quality effects are one of the key uncertainties associated with river diversions, add nitrogen and phosphorus to the list of parameters routinely measured in the coastal reference network soil and/or plants to assess accumulation and potential eutrophication.

Herbivory is a confounding issue in many studies and is an important factor to consider in future studies. Because one effect of nutria is to remove aboveground biomass, this could lead to reductions in soil organic matter, further reducing the ability of the marsh to maintain itself as sea level rises. It would be useful for studies examining how diversions affect soil organic matter accumulation and soil strength to have an explicit component addressing the effects of herbivory on these processes. Because many of the studies showing enhanced grazing of fertilized plots are based on experiments at a relatively small scale, herbivores can target these small areas. Experiments at larger scales comparing grazing within the diversion and in a reference area are necessary in order to address the impact of herbivory on accumulation of soil organic matter. Monitoring of nutria and alligator populations in diversions and reference sites would be useful. In adaptive management, managers may target nutria removal or limit hunting of large alligators in diversion areas to reduce nutria populations.

With regard to marsh elevations, monitoring stations instrumented with Surface Elevation Tables (SETs) (elevation change), along with marker horizons (surface accretion), provide information about elevation dynamics. These are currently monitored at CRMS sites. Together, these measures can be used to estimate shallow subsidence. Guidelines for installation of SETs, data collection, and statistical analysis are available in the literature (Cahoon et al. 2002b) and online (http://www.pwrc.usgs.gov/set/). Measurements of soil texture (particle size distribution), soil strength, dry bulk density, and organic content conducted at each sampling station would allow more detailed monitoring of changes in soil texture and soil integrity. End of season standing live biomass (above- and belowground) would provide information about the health of the plant community and relationship to elevation changes. Monitoring of pore water chemistry (salinity, nutrients, sulfide) would assist in interpreting the influence of diversion discharges on environmental conditions affecting plant growth.

Models are needed to predict shear stresses on marshes under varying hurricane and storm surge scenarios, and to spatially predict maps of marsh scour depths based on soil strength depth profiles as a function of shear stresses. There presently are not enough data on soil strength to come to any definitive conclusions about the impacts or benefits of river diversions with respect to the soil strength of Louisiana wetland soils. Short-term effects may be quite different than long-term ones. We also lack fundamental predictive understanding of what role soil strength plays in marsh rebuilding and long-term resilience. Some evidence indicates that an adverse outcome from Freshwater Diversions is more likely than benefits. Some of the experimental studies are of limited use for understanding the impacts of Freshwater Diversions on soil strength. For example, of the presentations given at the February 2011 “Workshop on Response of Louisiana Marsh Soils and Vegetation to Diversions”, Graham and Mendelssohn’s (2011) experimental field plots are of limited value for soil strength considerations (as pointed out in their talk) because ammonium rather than nitrate was used. Turner's (2011a) experiments also used ammonium in very high concentrations, making interpretation with respect to impacts on organic soil strength difficult. Hester and Fisher’s (2011) study provides perhaps the best experimental data available, on balance, as nitrate was used at approximately environmentally relevant concentrations. This experiment suggests degradation of the organic substrate rather than build-up resulting from the nitrate additions.

Monitoring is one way of evaluating Freshwater Diversions once they have been implemented, and using a scheme of iterative adaption and design modification as data become available is helpful in optimizing application of this technique. However, the cost of building even a small

Freshwater Diversion can reach several hundreds of million dollars. It seems sensible and cost-effective to engage in a comprehensive research program with both greenhouse and field studies, and with investigators with diverse fields of expertise, from organic geochemists to plant physiologists and wetland hydrologists, that address key uncertainties associated with the use of freshwater diversions for mitigation of marsh loss.

Summary

The 2012 Coastal Master Plan (Coastal Protection and Restoration Authority of Louisiana 2012), which was recently approved unanimously by the Louisiana Legislature, includes plans for major river diversions and channel realignment to divert sediment and freshwater from the Mississippi and Atchafalaya Rivers into adjacent receiving basins such as Breton Sound and Barataria Bay. The success of these proposed diversions will depend on a number of factors, but will provide new opportunities to establish comprehensive monitoring plans and to answer some of the questions raised in this document. One must distinguish between the large-scale Sediment Diversions and the typically much smaller Freshwater Diversions which deliver water but little sediment. The differences between these two types of diversions cannot be overemphasized. For example, some of the contradictions among datasets presented at the February 2011 "Workshop on Response of Louisiana Marsh Soils and Vegetation to Diversions" regarding soil strength impacts arose from comparing results from these two types of diversions. If flows are too low, clays and silts cannot be carried into the marshes, and water chemistry interacting with organic matter buildup determines the success in marsh restoration.

This Position Paper is an assessment by the Workshop Technical Panel on the state of knowledge and information gaps on expected soil and vegetation responses to Freshwater Diversions in coastal Louisiana. Freshwater Diversion effects were evaluated based on responses of wetland plant productivity, elevation, and soil strength. The Panel concluded that little evidence was available that any Freshwater Diversion in the Louisiana deltaic plain has significantly reversed the rate of marsh degradation and land loss. While there is evidence that the minor sediment load of freshwater diversions has enhanced accretion in localized areas, lack of uniform sheet flow across marshes, coupled with prolonged flooding and ponding of wetland vegetation, and rapid shifts in salinity have compromised the combined processes of macrophyte biomass accumulation, peat accumulation, building of soil strength and building wetland elevation and extent. These processes are necessary for reversing the high rates of wetland loss through most of the Louisiana deltaic plain. It is unlikely that any currently planned Freshwater Diversion without substantial sediment load will reverse wetland loss in Louisiana. Restoration of Louisiana wetlands may only be possible through significant inputs of sediment.

A number of "Sediment Diversions" are planned along lower portions of the Mississippi and Atchafalaya Rivers, but the science is still evolving to inform model predictions on the amount of sediment needed for adequate wetland rebuilding (not addressed here) and the role of high nutrient river water in contributing to or detracting from marsh restoration (addressed here). Effective adaptive management, therefore, will be paramount to ensure that diversions have their intended outcome. To this end, the Adaptive Management Framework being developed by CPRA as an element of the 2012 Coastal Master Plan emphasizes application of modeling and monitoring to inform management strategies and "course-correct" actions as needed. The Framework offers an excellent opportunity to develop a comprehensive research design that adequately tests the alternative hypotheses on wetland response to nutrient-rich river water characterized here, as a critical step to ensuring intended outcomes of restoring and sustaining Louisiana wetlands.

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