Researching Uncertainties Related to Sediment Diversions: Fresh Water, Nutrient and Sediment Effects to Coastal Louisiana Receiving Basins

Research Work Plan

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TABLE OF CONTENTS

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INTRODUCTION

The State of Louisiana has proposed the construction of multiple Mississippi River sediment diversions as a significant component of the 2012 Coastal Master Plan (CPRA, 2012). The objective of these sediment diversions is to serve as tools to combat land loss by restoring some of the natural sediment pathways between the Mississippi River and the coastal marshland. There are approximately nine large (i.e., > 50,000 cfs at peak discharge) sediment diversions proposed in the 2012 Coastal Master Plan and most of them are located on the lower Mississippi River, below the city of New Orleans (CPRA, 2012). It is expected that the final locations of the diversions will be selected based on multiple factors including: predicted land building, construction costs (including real estate costs), and environmental effects. The methods used to estimate predicted land building and construction costs are fairly well established. For example, predictions of land building are computed using measurements of flow and sediment as inputs into coupled numerical hydrodynamic and morphological models. However, predicting the environmental effects from sediment diversions remains challenging. There are no current operational sediment diversions located within the Mississippi River delta so the actual range of environmental effects and their magnitude are uncertain. Previous efforts to estimate the environmental effects of sediment diversions have attempted to extrapolate observations from existing freshwater diversions, despite the fact that these diversions were designed to divert low riverine discharges (<10,000 cfs) for salinity control measures. There is evidence that the proposed sediment diversions will have significantly different environmental effects compared to the freshwater diversions and that the existing freshwater diversions may not serve as appropriate analogues (Allison & Meselhe, 2010; Wang et al., 2014). Therefore, there is a need for new research that addresses the uncertainties related to the environmental consequences of the proposed sediment diversions.

Louisiana's CPRA has identified a series of sediment diversion effects of special concern due to their potential significance to coastal marshes, i.e., the environment in which the sediment-diversion receiving-basins will be located, based largely on the results of previous research (CPRA, personal communication). The general areas in which these concerns may be categorized include the sustainability of wetland soils and vegetation; the water quality in adjacent open water bodies receiving diversion flows; and wildlife and fisheries. The first two areas are similar because they relate to the environmental changes borne by the receiving basin land and water. Because of this, the uncertainties related to these environmental effects may be resolvable by a series of complementary research activities. Because issues related to wildlife and fisheries are less similar to first two areas, they are not covered in this work plan. This report documents a work plan that includes activities to address key technical uncertainties within these areas. The technical uncertainties were identified using expert counsel from multiple institutions and agencies including CPRA, the Institute, and from academia.

WORK PLAN OVERVIEW

The Institute was tasked by CPRA to develop a research work plan that addresses key technical uncertainties in the receiving basins related to the operation and maintenance of sediment diversions in the lower Mississippi River. CPRA recognizes a need for a greater scientific understanding of the effects of diverted riverine fresh water, nutrients, and sediment to the coastal receiving basins. CPRA conducted a comprehensive technical review on sediment diversions that identified uncertainties related to the effects of sediment diversions on: (1) the sustainability of wetland soils and vegetation,

(2) the water quality in adjacent open water bodies receiving diversion flows, and (3) wildlife and fisheries (although issues related to this topic are not covered in this work plan). Insight gathered by this review was communicated to the Institute during a series of meetings and helped guide development of the work plan that is presented in this document.

To supplement the uncertainties identified by CPRA, the Institute solicited expert counsel from senior researchers in each of four fields of interest: (1) estuarine water quality, (2) wetland vegetation, (3) wetland soils and strength, and (4) estuarine hydrodynamics and sediment transport. These four fields of interest were selected because they broadly represent the environmental uncertainties of the receiving basins related to the operation and maintenance of the proposed sediment diversions and reflect the types of potential sediment diversion effects of concern to CPRA (CPRA, personal communication). The expert counsel consisted of a short, approximately 10-page, technical memorandum that identified and discussed uncertainties related to each researcher's field of interest. The Institute, in coordination with CPRA, used these memoranda as a basis for drafting a comprehensive list of the critical uncertainties and defined general research activities that could be used to address each uncertainty (see list in Appendix III). Research activities that could likely produce meaningful results within a short timeframe (~18 months) were developed. The Institute, again in coordination with CPRA, prioritized (i.e., high, medium, and low) the list of critical uncertainties and the respective research activities for incorporation into the final work plan.

This research work plan investigates the environmental effects of the operation and management of sediment diversions to the coastal receiving basins. The work plan contains research activities that address the technical uncertainties that were determined to be a high priority based on the urgency of the technical need. Appendices I and II include brief descriptions of research activities proposed to address technical uncertainties that were determined as medium and low priority.

During work plan development, a field site for many of the research activities was suggested: the crevasse splay and proximal marsh near Fort Saint Phillip between the Mississippi River and Breton Sound (Figure 1). This site was identified because it contains a distributary channel system that produces processes and environments, in terms of marsh types, hydrology, and geology, similar to that expected to be produced by sediment diversion operation. At high river discharges, crevasses at this location divert discharges exceeding 100,000 cfs, a value approximate to the expected peak discharges of some the proposed sediment diversions. No other diversion sites located within the lower Mississippi River delta discharge at a similar magnitude, nor are they located in an equivalent marsh environment. Therefore, this location could serve as a useful case study for researching uncertainties related to diverted fresh water, nutrients, and sediment. It is important to note that flow diverted at this site is uncontrolled, while the proposed sediment diversions will be controlled, which may contribute to significantly different hydrograph shapes and flood frequencies. Also, the riverside entrance to the crevasse splays at this site have been armored and stabilized by the U.S. Army Corps of Engineers, mitigating further natural evolution. The riverside entrances are also relatively shallow, preventing the entrance of deep riverwater and river bedload sediment. Despite these properties, the Fort Saint Phillip area still contains many of the most important natural processes related to sediment and nutrient transport expected to be active in the planned sediment diversions.

Last, many of these research activities have a similar uncertainty theme (e.g., flooding effects on geological and ecological processes) and if executed together, with modifications to the experimental design, could provide a collaborative approach that might allow for more certainty in the understanding of sediment-diversion related effects.

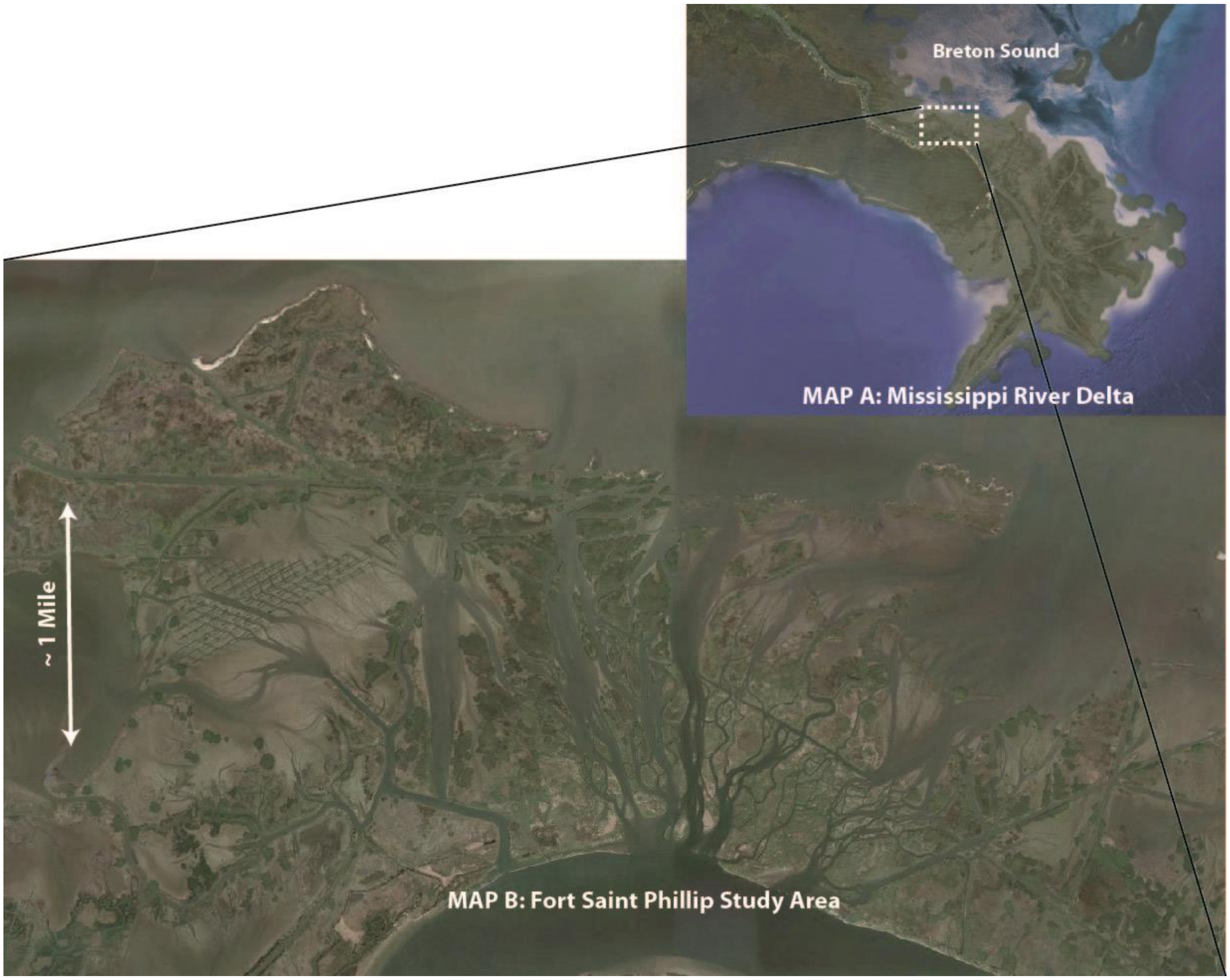

Figure 1. Location of Fort Saint Phillip crevasse splay. Map A shows the position of the site within the lower Mississippi River delta. Map B shows an aerial view of the study site, which is located at approximately river mile 19 above the Head of Passes. Images obtained from Google Earth Pro.

DESCRIPTION OF HIGH PRIORITY RESEARCH ACTIVITIES

This section contains a description of the research activities proposed for each technical uncertainty that was determined to be a high priority. The research activities are grouped by the four fields of interest that cover the environmental characteristics of the receiving basin, defined as: (1) estuarine water quality, (2) wetland vegetation, (3) wetland soils and strength, and (4) estuarine hydrodynamics and sediment transport.

ESTUARINE WATER QUALITY

Nutrient Removal Processes in the Receiving Basins

Nitrogen is often the limiting nutrient for primary production in coastal marine ecosystems, and high nitrogen loading can lead to high algal production that produce eutrophic conditions (Graneli, Wallstrom, Larsson, Graneli, & Elmgren, 1990; Mitsch et al., 2001; Nixon, 1995). A common symptom of eutrophic aquatic ecosystems is bottom-water hypoxia or low oxygen conditions, as observed offshore of coastal Louisiana (Rabalais, Turner, & Scavia, 2002). Phosphorus and silica are also essential nutrients for primary producers and with nitrogen, their ratios can help predict which nutrients will be limiting to phytoplankton growth.

Biogeochemical processes that remove nutrients (i.e., species of nitrogen, phosphorus, and silicon) from the estuary are an important factor in determining the availability of nutrient concentrations and ratios, for predicting the likelihood of nutrient enrichment and eutrophication within the estuary, and for determining the potential for outwelling to the offshore waters. Rates of nutrient removal processes, such as denitrification in wetland soils and estuarine sediments, and assimilation (biological uptake of dissolved nutrients) by estuarine primary producers (e.g., wetland vegetation, estuarine phytoplankton, submerged aquatic vegetation, and floating aquatics) vary because of the wide range of influencing environmental factors such as residence time, salinity, oxidation/reduction state, soil type, and temperature (DeLaune, Jugsujinda, Peterson, & Patrick, 2003; DeLaune, Pezeshki, & Jugsujinda, 2005; Lane et al., 2003; Rivera-Monroy et al., 2010; VanZomeren, White, & DeLaune, 2013). Denitrification is a permanent loss of nitrate (and nitrite) from the ecosystem because when it is converted to a gaseous form, such as dinitrogen gas, it is lost to the atmosphere, while nutrients that are assimilated into the biomass of primary producers (i.e, phytoplankton) can be more of a short-term loss from the ecosystem because the nutrients can be regenerated later via mineralization.

CPRA has reviewed this topic and has identified research needs specifically relating to: (1) nutrient budget studies about the transformation and assimilation pathways of the diverted nutrients in the receiving basins, (2) development/improvement of models to predict the occurrence of eutrophication in response to the sediment diversions, and (3) the capacity of the receiving basins to remove diverted riverine nutrients prior to entering the northern Gulf of Mexico. Improved estimation of the amount of riverine nutrients removed by the receiving basins would also benefit Louisiana's Nutrient Management Strategy which has the goal of reducing nutrient input to the Gulf (CPRA, personal communication).

Uncertainty

- What are the rates and spatial variability of biogeochemical processes within the receiving basin that control the short-term and long-term removal of nitrogen, phosphorus, and silicon in riverine water introduced by sediment diversion operation during periods of peak flow (and, therefore, short residence times) and during average flow conditions?

- After estimating the nutrient removal rates, what is the estimated outwelling of nutrients—especially nitrate—from the estuary (e.g., Barataria Bay, Breton Sound) to offshore waters?

Research Activities

Activity 1

Field Data Collection and Laboratory Analysis

A combination of field and laboratory work are recommended to measure the likely nutrient removal rates of the receiving basin that will be affected by the proposed sediment diversions. Phytoplankton and wetland vegetation samples will need to be collected from the field and brought to the lab for measurement of nutrient assimilation rates. Wetland soil cores and estuarine sediment cores will also be collected for measurement of denitrification. The phytoplankton, vegetation and soil/sediment samples will all be used to measure nitrogen (i.e., nitrate, ammonium), phosphorus (i.e., soluble reactive phosphorus), and silicon (i.e., silicate) transformations or removal. Because diversions have not been constructed on the scale that is being contemplated by the Master Plan, there is currently no field site that represents all the key discharge constituents (e.g., high suspended sediment, fresh water, and nutrients) that are anticipated for the proposed sediment diversions that also represent the ecological conditions (e.g., organic wetland soils, brackish and saline wetland vegetation) of the proposed receiving basins. Most of the existing river diversion sites (i.e., Caernarvon or Davis Pond) only represent one or two of the constituents and some of the receiving basin conditions. Therefore, laboratory setups like flumes with flow-through conditions may help mimic typical peak flow conditions (i.e., short residence time, high nutrients, high turbidity, low light, cold water temperatures, and low salinities) as well as a range of nonpeak flow conditions.

As mentioned in the Work Plan Overview, a field data collection campaign could be held at Fort Saint Phillip to serve as a case study to estimate nutrient removal processes with expected environmental conditions at high flow rates and high nutrient and sediment concentrations to a receiving basin. Fort Saint Phillip is a naturally occurring diversion/crevasse near river mile 40 on the east bank of the Mississippi River. The major limitation with this case study is that the receiving basin vegetation is composed of fresh and intermediate wetland vegetation, which is not the more saline vegetation that is typical at the proposed Master Plan sediment diversion sites. Four collection trips could be conducted to bracket conditions corresponding with the peak river discharge, one before, during, after, and the final at the end of the growing season. These collection trips that spatially span the study area (from wetlands to coastal bays to adjacent open water) would assist with understanding the nutrient removal processes during the changing riverine conditions (i.e., nutrient concentrations, turbidity, and water temperature) and subsequent impacts to the receiving basin conditions (i.e., residence time, salinity, and light levels). Each trip could include in-situ nutrient concentration measurement, and both water samples and soil/sediment cores or samples could be brought back to the laboratory (as mentioned above) for incubations that mimic the likely conditions and measurement of the appropriate nutrient (nitrogen, phosphorus, and silicon) removal processes and the rates can be calculated.

Activity 2

Modeling

Modeling of nutrient outwelling from the receiving basins can provide an estimate of nutrient loss from the estuary. Outwelling of nutrient fluxes (N, P, Si) through the Barataria Bay and Breton Sound passes will be estimated when the proposed sediment diversions are operating, particularly at peak flow, but also at a range of operational regimes including average flow conditions that would be typical throughout a year. A coupled hydrodynamic and nutrient dynamic model (such as modeling efforts proposed in Barataria and Breton Basins) could provide estimates of nutrient outwelling based on rates calculated from Activity 1 datasets. Once a nutrient dynamics module is calibrated and validated, the model can be used to estimate the outwelling of nutrient fluxes through the passes when sediment diversions are operating throughout the year. In addition, the modeling efforts on nitrogen fluxes to offshore waters will be useful because nitrate is often used to predict the area of summer hypoxia in the northern Gulf of Mexico (Justić, Bierman, Scavia, & Hetland, 2007; Turner, Rabalais, & Justic, 2008).

Ongoing modeling efforts in Barataria and Breton Basins could be leveraged through this activity to help answer the uncertainty about outwelling of nutrient fluxes. An estimated two months of model calibration, validation, run-time, and analysis would be required to perform the array of model simulations needed to address the uncertainty about nutrient outwelling.

Products

Based on field and laboratory data collections as well as a comparison to literature values (Activity 1), the nitrogen, phosphorus, and silicon removal rates and their spatial variability will be included for a set of representative operational/receiving basin conditions that will include up to five production runs (Activity 2). For example, a production run could include one year of current receiving basin conditions without a sediment diversion, another production run could include one year of current receiving basin conditions with the proposed sediment diversions, and another production run could include the proposed sediment diversions and the projected 50 year receiving basin conditions (e.g., newly built land) to capture the potential nutrient assimilation capacity. In addition, the modeling efforts should include output and assessment of nutrient outwelling to offshore waters from the model simulations. The final deliverables should include not only a comprehensive model development and results report, but also all raw and transformed data collected in Activity 1.

WETLAND VEGETATION

SEDIMENT LOADING, INUNDATION, AND NUTRIENT LOADING TRADE-OFFS TO PLANT RESPONSES

Wetland vegetation is potentially impacted both positively and negatively by the changing environmental conditions produced by the proposed sediment diversions. Changing salinity, nutrient concentrations, suspended sediments and inundation, and their interactions will impact the fresh- to saline vegetation types in unique ways; those effects are often nonlinear, making it more important to understand the individual and combined responses (Merino, Huval, & Nyman, 2010; Morris, Shaffer, & Nyman, 2013). For example, high riverine discharge is required to deliver suspended sediment to receiving basins that will potentially help increase the wetland surface elevation and be a positive effect on wetland vegetation, but soil flooding conditions will also be stressful to the marsh vegetation. Most of the proposed sediment diversion sites on the lower Mississippi River (i.e., Central Wetland, Upper-Breton, Mid-Breton, Lower Breton, Mid-Barataria, and Lower Barataria) will be diverting into marsh types ranging from intermediate to saline (CPRA, 2012). Few areas of freshwater/flotant wetlands currently exist in the areas surrounding the proposed sediment-diversion sites.

CPRA has recommended that future field and laboratory studies of sediment diversion related effects to wetland vegetation should mirror the delivery of nitrogen, phosphorus, silica, and sulfate onto the surface of the marsh via surface water inflows. Further, CPRA recommends future studies use the concentrations and forms of nutrients contained in riverine flows (e.g., nitrogen applied as dissolved nitrate instead of ammonium or urea, or in granular forms on the marsh surface) and apply the nutrient additions in a continuous-flow application (e.g., flume or mesocosm studies) to mirror a multiweek flow regime of a sediment diversion (CPRA, personal communication). Such studies are of particular interest to CPRA because they could improve understanding of the fate and effect of nutrients on the soils and vegetation.

Uncertainty

- What changes in marsh vegetation occur related to the trade-off between: (1) the "positive" effects of the introduction of new sediment to the marsh surface during and after periods of elevated water levels and sediment introduction, and (2) the "negative" effects of the increase in inundation-related stressors and effect of high nutrient concentrations associated with high river inflows on intermediate/brackish/saline marsh vegetation?

Research Activities

Activity 1

Systematic Assessment of Literature

Conduct a systematic, empirical assessment of existing datasets (e.g., Webb, Wallis, & Stewardson, 2012) to determine the range and extent of the effects of freshwater inundation, salinity changes, nutrient enrichment, and sedimentation to wetland vegetation above- and belowground plant responses.

Activity 2

Field Data Collection and Laboratory Analysis

Research on the interactive effects of freshwater flood duration and depth (inundation) in addition to sediment characteristics (e.g., sedimentation rate, mineralogy) and nutrient loading are needed to understand any changes in the above- and belowground responses of intermediate, brackish, and saline marsh vegetation associated with proposed sediment diversions.

A field campaign to the Fort Saint Phillip study site could serve as a case study to estimate wetland vegetation responses in a receiving basin with fresh and intermediate wetland vegetation exposed to high flow conditions. A case study approach at this location will also capture the concerns of CPRA with the flow delivery of nutrients and the species and concentrations of the nutrients (see above for details). This location may allow for a multiple effects investigation based on distance from the outfall point—such as the near-field habitat—that would likely experience the high loading of fine sediment, nutrients, and fresh water, while the midfield area would likely experience lower sediment loading but similar loading of nutrients and fresh water compared to the near-field site. The far-field site will likely experience a salinity change induced by the high riverine flow and the loading of the suspended sediments and nutrients would be reduced compared to the near and mid-field sites (Morris et al., 2013). Each site would be sampled during four collection trips to correspond with the peak river discharge, one before, during, after, and later at the end of the growing season, and assist with understanding the nutrient removal processes during the changing riverine conditions (i.e., nutrient concentrations, turbidity, and water temperature). This activity could also be coordinated with Activity 1 of the Estuarine Water Quality field of interest.

At each site, multiple parameters should be measured to better understand the changing environmental conditions involved with the tradeoffs of sediment delivery and fresh water and nutrient loading, such as measuring pore water salinity, nutrient concentrations, hydrogen sulfide concentrations, and soil Eh. Feldspar markers could also be used to measure gradients in sediment deposition. These environmental conditions can be related to values in the literature in order to predict the likely plant above- and belowground responses.

Wetland above- and belowground biomass (alive and dead) of all vegetation species could be collected during the four collection campaigns at each site over time to estimate primary productivity, one of many vegetation responses (Linthurst & Reimold, 1978; Smalley, 1959). It is likely that the productivity responses of the vegetation do not immediately reflect the current conditions of the sites, but will over time respond to the long-term conditions. The marshes around Fort Saint Phillip have experienced inundation by riverine water, sediment deposition, and nutrient loading via numerous crevasses for decades; these sites could be used to determine the long-term net effect of sediment deposition, inundation, and nutrient loading to the current wetland vegetation. Moreover, these sites may need further wetland soil investigations for historic organic and mineral content to determine if they represent the high organic soils that will be prominent in the proposed sediment-diversion sites.

Additional sites with brackish and saline marsh vegetation may be needed to test the vegetation responses of these marsh types to the changing environmental conditions, particularly because many of the proposed sediment diversions will be diverting fresh water, sediment, and nutrients into brackish and saline marshes that consist of primarily organic soils. Marsh organs in the field could be used to investigate variations in flooding effects at the various vegetation types (e.g., Fahey & Knapp, 2007). Marsh sods (soil and vegetation) could be removed from field sites and brought into the greenhouse or laboratory for mesocosm studies to assess plant responses to diversion-type conditions and the experimental design and treatments would need to reflect CPRA criteria outlined above. Mesocosm methodologies based from other wetland-oriented studies (Ahn & Mitsch, 2002; Baldwin & Mendelssohn, 1998; Padgett & Brown, 1999) could be used to conduct this research.

Products

A report on the findings of Activity 1 and Activity 2 of the effects of freshwater inundation, sediment, and nutrient loading to marsh vegetation below- and aboveground plant responses will be provided. In addition, all raw and transformed data will be included in the report.

WETLAND SOILS AND STRENGTH

DEVELOPMENT OF A STANDARD METHODOLOGY TO ASSESS SOIL STRENGTHS IN COASTAL MARSHES

There are a wide variety of methodologies to assess the strength of marsh soils (Howes et al., 2010; Sasser, Evers-Hebert, Milan, & Holm, Jr., 2013; Turner, 2011). Multiple instruments are routinely used to measure the same general geotechnical property (e.g., shear vanes and cone penetrometers are both used to test soil strength) yet different instruments may not produce directly comparable measurement values. This is because the instruments measure the response to slightly different physical phenomenon, such as measuring soil strength by displacing soil at different depths, integrating over different areas, or in different directions (i.e., horizontal vs. vertical). However, soil strength in coastal marsh environments is expected to be typically more variable than other environments due to the abundance of soil biomass, pore water, organics, and widely varying grain-size distributions. This lack of a uniform assessment methodology adds uncertainty to the comparison of different studies on marsh soils and adds complexity for attempting to draw broad conclusions from multiple studies. Because of this, CPRA has identified a need to standardize measurement methods (CPRA, personal communication).

Uncertainty

- There is no standard methodology for the in-situ characterization of the shear strength of coastal marsh soils. Currently, there are no identified best practices to offer guidance as to what spatial and temporal intervals the soil strength should be sampled in coastal marshes to accurately resolve the gradients at which the properties significantly vary. There is no widely accepted preferred instrument for the measurement of soil shear strength in coastal marshes.

Research Activities

The objective of this research activity is to identify a preferred methodology to assess shear strength in sediment-diversion receiving-basin soils and sediments. Ideally, the methodology will be applicable to the full range of marsh vegetation types located within the receiving basins. A preferred method to measure soil shear strength will be identified using field tests, and a manual describing its proper use will be developed and tailored for coastal marsh environments.

Activity 1

Data Review

A comprehensive review of technical literature and existing data sources will be performed to identify all of the instruments commonly used to measure shear strength in soil. Instruments that exhibit a precedent of successful use in marsh soils will be selected for use in Activity 2.

A review of technical literature, existing soil datasets and soil maps will also be performed to characterize coastal marshes along the Mississippi River delta based on soil type(s). This review will be coupled with a GIS analysis to produce a map documenting the spatial distribution of primary soil types and their associated shear strengths along the coastal marshes of the Mississippi River delta.

Activity 2

Field Data Collection

Soil shear strength will be measured as a series of field sites located along the Mississippi River delta. Field sites will be selected to characterize each marsh vegetation type differentiated by soil type during Activity 1. Field sites located within the Fort Saint Phillip region will be given preference.

The soil shear strength measurement instruments selected for use during Activity 1 will be employed in this field data collection campaign. The number of sampling locations and their spatial distribution within each field site will be determined by the research team. The sampling design will be developed to measure soil shear strength at a high spatial resolution as assessed by professional judgment. The extent of the sampled area at each site should be large enough to cover the range of geomorphic variability (in terms of marsh landforms) likely to be present in a sediment-diversion receiving basin

The field data collection campaigns will be repeated at the same locations for multiple different time periods. The different time periods will be selected to vary the seasonally dependent environmental conditions, such as soil moisture or biomass content, in which the samples were collected. Additional soil cores will be collected at each site to derive site-averaged values of soil bulk density, organic matter, soil moisture content, and grain-size distribution. These variables will be used to help correlate indicative soil types with marsh types. The relative accuracy of each field instrument will be assessed based on its performance with respect to mean values of soil strength computed from the full suite of other tested field measurement methods coupled with laboratory analysis of sediment samples collected from the field sites. The most accurate instrument will be identified as the preferred methodology.

A manual will be developed that describes the proper execution of the preferred methodology. The manual will recommend a sampling protocol for the in-situ measurement of soil shear strength using the preferred methodology in coastal marshes, including specific instructions to optimize the method for each marsh category and providing context on the physical phenomenon that the instrument is actually measuring. The manual will also document the relative performance of each instrument tested.

Products

A technical report that includes a manual will be produced that identifies field methodologies for the assessment of soil strength and describes each methodologies' potential applicability for use in Louisiana coastal marsh soils. The technical basis for the report's recommendations will also come from a synthesis of current literature (Activity 1 and 2). A synthesis of field and laboratory activities and raw and transformed data will also be included.

A manual will be produced that describes a preferred method for in-situ measurements of soil shear strength applicable to coastal marsh environments along the Mississippi River delta. The manual will also document the field tests that were conducted to identify the preferred methodology.

Biomass Effects on Soil Strength

Above- and belowground biomass monitoring can be used separately as potential indicators of soil strength (Sasser et al., 2013). By considering them together, the data can be utilized as a root:shoot ratio to determine effects of changing environmental drivers such as those caused by a sediment diversion (e.g., nutrient and freshwater loading, low water temperatures). The root:shoot ratio is often assumed to be positively correlated to soil properties (Darby & Turner, 2008; Deegan et al., 2012; Ket, Schubauer-Berigan, & Craft, 2011; Twilley & Nyman, 2002). This assumption is based on observations that indicate plants optimize their nutrient allocation, putting more energy into roots if nutrients are low (Agren & Franklin, 2003; Bloom & Chapin, 1985). However, it is not well understood if changes in the root:shoot ratio due to sediment-diversion operation will also produce a similar change in soil strength, as observed in more natural settings. For example, sediment diversion operations may increase shoot growth much faster than root growth due to the delivery of new nutrients to the marsh surface. If so, it is uncertain that this equates to a loss of resiliency similar to a situation where root biomass decreases with static or increasing shoot biomass (CPRA, personal communication).

Uncertainty

- How do changes in above- and belowground biomass and their ratios contribute to the strength of coastal marsh soils?
- How would sediment diversions change the magnitude of above- and belowground biomass and their ratios in the receiving basins and how does this change affect soil strength?

Research Activities

Activity 1

Field research will be conducted by testing multiple parameters of soil strength in different soil plots that have a range of biomass content, such as those that span the expected range of values observed in previous studies of coastal Louisiana marshes. Field plots should have: (1) single vegetation species to identify how individual species influence soil strength, and (2) ratios of multiple species that are indicative of native coastal marsh environments, to identify how vegetation generally influences soil strength in realistic environments. Plot size and vegetation type distribution will be determined by the research team based on the chosen field site characteristics and will approximate values used in similar studies (White, Weiss, Trapani & Thien 1978; Sasser et al., 2013). The number of sites measured with replicate plots needs to cover the spectrum of wetland vegetation types throughout coastal Louisiana. Sampling sites could be tied in with Coastwide Reference Monitoring System (CRMS) sites. There is an advantage to use CRMS sites because of the supplemental data that have been historically collected at those sites. The disadvantage to using CRMS sites would be the restrictions on who or when sampling can be done. Multiple instruments, such as the Seiken Field Vane (Howes et al., 2010), the Dunham E-290 Hand Vane Tester (Turner, 2011) and the Wetland Soil Strength Tester (Sasser et al., 2013) should be used to measure soil strength. Sampling strategies will be tested to identity preferred (in terms of minimizing labor and cost and maximizing accuracy) soil strength and biomass assessment methods. For aboveground sampling, all of the living and dead biomass will be collected via clip plot quadrats (e.g., 0.25 m^2) and transported to a laboratory for measurement. In belowground sampling, there are two common alternative methods: (1) the collection of all belowground biomass via a soil core collected from a quadrat, and (2) the collection of ingrowth cores, which determines the amount of belowground root growth into the cleared soil. In-growth cores could potentially help illustrate the likely responses of roots and rhizomes to the newly deposited sediment from sediment diversions.

Laboratory analysis is necessary for both soil strength and biomass assessments. Soil strength could be measured in in-situ or in the laboratory and could use results from a previous research activity (Development of a Standard Methodology to Assess Soil Strength in Coastal Marshes) to determine which soil strength instrument to use. Laboratory measurements could employ the Wykeham Farrance Lab Vane (Howes et al., 2010) or a similar instrument that measures soil strength at a high degree of precision. The aboveground vegetation would be sorted by species; above- and belowground biomass would both be measured by separating the live portions from the dead. This above- and belowground material would then be dried and weighed to determine the biomass. The dried material could also be further used for nutrient analysis of tissue and root samples to estimate nutrient loading. Nutrient levels have a significant impact both on above- and belowground biomass and therefore need to be measured in order to give context to the strength and biomass data. A statistical analysis will be undertaken of data gathered to correlate above- and belowground biomass and their ratio to soil strength by wetland vegetation type or species and to define any coherent relationships between the variables.

Products

A report will be provided on the field and laboratory data collections as well as the data analysis on the effects of above- and belowground biomass to soil strength. All raw and transformed data will be provided.

ESTUARINE HYDRAULICS AND SEDIMENT TRANSPORT

The Effect of Hydroperiod on Coastal Ecosystem Resilience and Sustainability

The diversion-related hydroperiod occurs when the sediment diversion is in operation and is the interval of time when the marsh surface of the receiving basin is inundated by water over and above that which would occur due to normal tide or meteorological forcing. Inundation (duration and depth) by freshwater has both benefits and costs related to coastal ecosystem resilience and sustainability, especially as it relates to marsh vegetation and soils. For example, hydroperiods created by diversion operation produce a period in which the marsh surface is accessible to new inputs of riverine nutrients and fluvial sediment. This increased accessibility may result in increased rates of nitrogen uptake in inundated areas and a wider distribution of sediment deposition throughout the receiving basin, which are typically regarded as benefits (Cahoon & Reed, 1995; Rozas, 1995; Friedrichs & Perry, 2001; Day et al., 2009). However, freshwater hydroperiods are also associated with high flow velocities which can cause local erosion within the bed and banks of the receiving basin and stress saline wetland vegetation located on the flooded marsh surfaces, which are typically regarded as environmental costs (Alexander & Dunton, 2002; Kolker, Miner, & Weathers, 2012).

In a sediment-diversion receiving basin, the marsh hydroperiod will be influenced by the diversion operation, which may flood the marsh surface with river water, and it will also interact with high water events created by tidal dynamics, storm surges, and cold fronts. During the occasions when the marsh surface is inundated due to diversion operations, the flood water, sourced from the river, will be less saline than when the inundation is due to other high water events. The duration of the diversion-related hydroperiod will have a first-order control of the magnitude of each of these environmental benefits and costs relating to marsh vegetation and soils (Friedrichs & Perry, 2001). In an effort to maximize coastal ecosystem resilience and sustainability, diversions should be operated in a way as to create a hydroperiod that maximizes its environmental benefits and minimizes its environmental costs (i.e., to produce an “optimal” hydroperiod).

There has been little research conducted on defining an “optimal” diversion hydroperiod for coastal marshes along the Mississippi River delta, the area likely affected by the future construction and operation of sediment diversions. The definition of an “optimal” diversion hydroperiod requires identification of what marsh properties will be significantly affected by increased inundation, and how does the duration of inundation influence those marsh properties. The focus of this activity is directed on marsh properties related to vegetation and soils because they are properties previously identified to be heavily affected by freshwater inundation (CPRA, personal communication). While few research studies have attempted to investigate the integrated effects of river diversions on receiving basin marshes, there have been numerous studies (Delaune & Jugsujinda, 2003; Lane, Day, & Thibodeaux, 1999; Snedden, Cable, Swarzenski, & Swenson, 2007) examining how diversions affect individual marsh properties, including those related to marsh vegetation and soils.

Uncertainty

What is the likely range of hydroperiods produced by the operation of sediment diversions and what is the spatial extent of their influence?

What marsh properties related to vegetation and soils are affected by the hydroperiod created and controlled by sediment diversion operation?

Research Activities

The first objective of this activity is to use models, such as improved versions of the coupled hydrodynamic and nutrient dynamic model under development for the Barataria and Breton Basins, to determine the range of potential hydroperiods that is likely during operation of the sediment diversions. The use of these models would require improved spatial resolution relative to those currently envisaged to precisely characterize the marsh surface elevation and surface water elevations, which together control the computed hydroperiod for a specific site. The hydroperiods will be examined with various production runs, such as the range in discharge flows (e.g., 50,000 cfs to 250,000 cfs) and the potential interactions of these flows with tidal and cold fronts. The spatial extent of the marsh flooding will also be examined and compared to non-sediment diversion conditions to determine the near-, mid-, and far-field flooding effects.

The second objective of this research activity is to use the model output of the range of hydroperiods and the spatial extent to identify which properties of marsh vegetation and soils will likely be significantly affected. Part of the analysis would be to compare results from the model output to other studies to identify and define the full range of marsh properties related to vegetation and soils that will be significantly be affected by the freshwater hydroperiod.

Activity 1
Literature Review
A review of the technical literature will be performed to identify which marsh properties related to vegetation and soils are significantly affected by exposure to low-salinity inundation (duration and depth), and how the effects may change with changes in inundation duration and depth. Determining if a property is significantly affected by diversion-type inundation is interpreted from the stated conclusions of each study, which may be presented in terms of statistical significance. An example list of marsh properties related to vegetation and soils that could be reviewed for examination of freshwater inundation include:

- Surface accretion;
- Surface and pore water nutrient concentration;
- Surface and pore water salinity;
- Vegetation above- and belowground biomass;
- Soil strength;
- Soil erodibility.

Results from other research activities in this work plan (i.e., Wetland Vegetation) such as the tradeoffs in wetland vegetation responses to sediment, nutrient and fresh water loading could also be used in this activity to better understand how freshwater inundation will impact the marsh properties.

Activity 2
Modeling
A coupled hydrodynamic and morphology model (such as modeling efforts active in Barataria and Breton Basins) could be utilized to determine the range of likely hydroperiods produced from sediment diversions, and how they may change as landscape change occurs over time.

Products
The range of hydroperiods and its spatial extent based from model output will be used to determine the likely responses of marsh properties. Examples of a model run include: (1) one year of current receiving basin conditions without proposed sediment diversions to capture the baseline seasonality of hydroperiods, (2) one year of current receiving basin conditions with the proposed sediment diversions to capture the seasonality of hydroperiods, (3) one year of current receiving basin conditions with the proposed sediment diversions and the addition of tidal, storm, and cold front interactions, and (4) projected 50-year receiving basin conditions (e.g., newly built land) to capture the future hydroperiods. In addition, the modeling efforts will include output and assessment of the sediment-diversion hydroperiods—including the spatial extent— in the receiving basins. The report will include the modeling output (Activity 2) and summary of the literature marsh property values (Activity 1) that will

provide a discussion on which hydroperiods produce the most favorable outcomes, in terms of coastal ecosystem resilience and sustainability, as they relate to marsh vegetation and soils.

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Appendix I: Medium Priority Uncertainties

Appendix I – Medium Priority Uncertainties and Research Activities

The following uncertainties and research activities were determined to be a "medium" priority by CPRA, versus being determined to be "high" or "low" priority, based on the urgency of the technical need and the dependence of results from other (ongoing or planned) research activities. These uncertainties and research activities are organized into three general subject areas: (1) estuarine water quality, (2) wetland soils and strength, and (3) estuarine hydrodynamics and sediment transport. Descriptions of final products are not provided because the following uncertainties are listed as a medium priority.

ESTUARINE WATER QUALITY

Phytoplankton Composition in Receiving Basins

The estuarine phytoplankton community is made up of nonharmful algal bloom taxa, such as diatoms, chlorophytes, and cyanobacteria, and harmful algal bloom (HABs) taxa, such as certain diatom and dinoflagellate taxa that are common in the more saline waters and genera of cyanobacteria e.g., *Microcystis* and *Anabaena* that are typical in more freshwater conditions. Each of these taxa is affected by optimal environmental factors (e.g. light, turbidity, temperature, salinity) and will therefore be competitive under differing conditions. In some diversion monitoring research projects, when there is high flow that causes turbulence and the water is turbid, diatom species are the most likely to be dominant, but after a closure or when water flow is reduced and the water clears, potentially toxic cyanobacteria may increase (Bargu, White, Li, Czubakowski, & Fulweiler, 2011; Garcia, Bargu, Dash, Rabalais, Sutor, Morrison, & Walker, 2010). In addition, CPRA identified that the differences in algal populations among potential estuarine receiving basins and the potential for varying responses to the introduction of river water should be the subject of study (CPRA, personal communication).

Uncertainty

- What are the likely phytoplankton biomass and community composition responses and relationships to flow conditions likely produced by freshwater and sediment diversion operations? These flow conditions likely include turbulence, increased nutrients, cold water temperatures, and low light and salinities.

- Will phytoplankton blooms occur during the peak flow of diversion or occur after the peak flow as a delayed response? How will this compare to the baseline phytoplankton population?

- Will the timing and spatial distribution (e.g., temporal and spatial variance) of phytoplankton blooms be altered by freshwater and sediment-diversion operation?

- What is the variability in phytoplankton community structure among basins? Are the communities similar? Are the phytoplankton populations in one basin more or less sensitive/responsive to diversions than the other basins?

Research Activity

Laboratory experiments could be conducted with mono- and mixed-algal cultures that are created by collecting water samples from receiving basins. These cultures could be treated with a prescribed range of conditions, including varying one or several of the following variables: nutrient concentration, turbidity, light level, water temperature, and salinity to determine their likely biomass and composition responses.

Field collections will allow sampling of phytoplankton communities that cover an array of spatial and temporal intervals for the range of likely environmental conditions produced by sediment-diversion operations to the extent that they are available across the coast. The spectrum of analyzed environmental conditions would be set to include the expected range of flow residence times, nutrient concentrations, turbidities, water temperatures, and salinities. The Fort Saint Phillip site could be a potential field location that would capture these environmental conditions and other locations would be needed to capture the variability in phytoplankton community structure among basins. The results of the field data collection would be used to determine the optimal environmental conditions that induce phytoplankton blooms.

Field collection of phytoplankton composition samples along an estuarine gradient is being conducted in an ongoing study to calibrate and validate the nutrient dynamics module of a Deltft3D model of basin dynamics. This research activity could leverage the samples collected from that work and conduct a more detailed analysis on the phytoplankton community composition differences between Breton Sound and Barataria Bay. This research activity could be conducted after completion of these other studies.

Harmful Algal Blooms and Potential Toxins in Receiving Basins

Harmful Algal Blooms

The increase in HABs is often associated with higher levels of nutrients and warmer water temperatures. HABs and their effects can be highly varied, depending on which of the many estuarine species are being assessed and their associated toxin production, along with the various environmental conditions that promote algal blooms and toxin production (Dortch, Parsons, Rabalais, & Turner, 1999; Parsons, Dortch, & Doucette, 2013). Dortch et al. (1999) noted the degree of toxicity can vary in coastal Louisiana and at high toxin levels can cause fish kills and even be lethal to humans. In addition, CPRA has also identified the need to investigate the relationships between controlling factors for toxic and nontoxic algal blooms, river diversions, and receiving basin geometry. They also note that the response of Lake Pontchartrain algal populations to Bonnet Carré operations is poorly understood and may not be typical of other estuaries in Louisiana receiving Mississippi River water. Operations of the spillway in different years have resulted in varying responses by harmful and nonharmful populations. Empirical studies are necessary during spillway and nonspillway years to determine the forces driving varying responses, including the timing and seasonal availability of nutrients, nutrient species or ratios, competition among algal species, physical limiting factors (e.g., temperature, wind, turbidity), and the potential influence of inputs from outside the system, such as northshore rivers.

Uncertainty

- If, based on the research from the phytoplankton biomass and community composition uncertainty, it seems likely that HABs may increase their frequency and biomass in response to diversion-related nutrients, what will be the expected algal toxin water concentrations throughout the estuary?

- What will be the magnitude of bioaccumulated algal toxins in grazers (nekton and oysters)? Are the algal toxin levels in potentially contaminated seafood (e.g., oysters, crabs, and shrimp) a threat to human health?

Research Activities

These research activities could be included with the phytoplankton composition study above and will depend on the results within relevant basins.

Activity 1
Few studies have examined current algal toxin concentrations in the Louisiana estuaries and in tissues of estuarine grazers. Initial field work might be needed to understand the baseline conditions of algal toxins in the phytoplankton cells and in tissues of grazers (nekton and oysters). Data collection of the existing environmental conditions of water and grazer tissue concentrations of algal toxins in the vicinity of existing freshwater diversions are needed to determine their typical ranges. Aliquots of water for toxin analysis could also be taken from algal culture laboratory experiments (as mentioned in response to "Estuarine Water Quality," Uncertainty 2) that reflect typical sediment diversion conditions that are not commonly observed in the field.

Field collection samples to identify phytoplankton composition are being proposed for ongoing work to calibrate and validate a nutrient dynamics model, but additional samples could be collected for phytoplankton toxin analysis. This research activity could leverage results from existing field collection efforts and additional laboratory analysis could be conducted on filtered water samples to determine the baseline algal toxicity conditions in Breton Sound and Barataria Bay. This research activity should be kept on hold until results from previous research activities are better understood.

Coordination with the Louisiana Department of Health and Hospitals could help determine if toxin levels in potentially contaminated seafood are a real threat to human health. Current algal toxin standards and research should be coordinated with personnel. In addition, the World Health Organization has human consumption guidelines that could be utilized (Garcia et al., 2010; World Health Organization, 1998).

Activity 2
Execute laboratory experiments that examine the effects of different algal toxin ingestion and clearance rates (related to residence time) and concentrations of algal toxins on bioaccumulation rates in grazers (nekton and oysters).

WETLAND SOILS AND STRENGTH

Yield Stress and Erodibility and Compressibility of Sediment Deposits

The yield stress of a sedimentary material is the threshold stress value that, if exceeded by the downward stress exerted by the accumulated overburden, will significantly increase the rate of compression that the material will experience (Burland, 1990). This compression from increased yield stress is a necessary consideration as it must be combined with deep subsidence processes and relative sea-level rise estimations to determine the potential cumulative total of relative elevation reduction associated with sediment diversion land building.

Uncertainty

- What is the "yield stress" of the underlying substrate in coastal marshes proximal to the lower Mississippi River (i.e., the environment where the sediment diversions will build land)? It is not well understood if certain types of marsh substrate have characteristic yield stresses or what marsh properties (e.g., soil type, vegetation type, and density) influence the yield stress and sediment compressibility in general.

Research Activity
For this uncertainty, three independent research activities were proposed. The successful execution of one activity is not dependent on the execution of the others.

Activity 1
Complete laboratory and field geotechnical characterization of marsh soil compressibility to define: (1) the typical yield stress thresholds, and (2) the change in soil compressibility caused by exceeding the yield stress threshold for prospective sediment-diversion receiving basin environments. Properties of the marsh environment will also be measured to examine how well they correlate to the measured values of soil compressibility. Examples of these properties could include soil type, soil bulk density, and belowground biomass.

The priority of this activity was reduced because a current research program is investigating this uncertainty using similar methods. The priority of this activity may be increased to "high," pending analysis of the ongoing research results.

Activity 2
Computational modeling experiments could be conducted to examine how sediment diversions will alleviate new stresses on the marsh substrate by promoting the deposition of sediment (i.e., sediment loading). Experiments can be designed to specifically examine how different diversion operation scenarios (e.g., different peak flows, different discharge hydrograph shapes) influence the magnitude and the spatial distribution of the sediment loading. The predicted values of the sediment loading can be compared to measured values of marsh yield stress to predict how different marsh areas may respond to sediment-diversion operations, in terms of the compression of the underlying substrate and how this compression may result in increased local shallow subsidence. Models can be generated for a range of different marsh types and receiving basin geometries to explore how multiple parameters affect the magnitude and spatial distribution of sediment loading within the receiving basin.

Activity 3
Develop a numerical model of receiving basin sediment compaction. The model would simulate the physical processes of load-induced sediment compaction and sediment consolidation and would be parameterized with measurements of receiving basin soil compressibility. The measurements of soil compressibility could be produced by conducting new data collection campaigns or by leveraging geotechnical data collection efforts currently supporting other diversion-related research. The purpose of such a model would be to compute estimates of soil compaction in receiving basins due to sediment loading using inputs such as sediment aggradation rate, generalized subsurface geology and average soil type, and receiving basin geometry.

Erodibility and Compressibility of Diversion Sediments
It is hypothesized that the sediments delivered by the sediment diversions to the receiving basins may have different geotechnical properties than the existing substrate. This difference may influence how effective the sediment is for land building by affecting the sediments susceptibility to subsidence and erosion processes.

Uncertainty
- What is the difference in erodibility and compressibility between recent (<50 years BP) riverine sediment deposits (i.e., the type of sediment deposits that will form due to the sediment

diversion operation) and the soils and other sedimentary material currently composing the coastal marsh environments proximal to the lower Mississippi River?

Research Activity

This uncertainty could be addressed by conducting laboratory geotechnical analyses of sediment samples retrieved from: (1) potential receiving basins (i.e., coastal marshes proximal to the lower Mississippi River), and (2) areas of the modern Mississippi River delta that currently experience active sediment deposition. Measured values of sediment erodibility and compressibility can be directly compared to identify the differences, if present, between the sediment deposits from the two different environments. Knowledge of the geotechnical properties of the recent sediment deposits relative to the properties of the substrate composing the potential sediment-diversion receiving basins adds insight as to how sediment diversion operations might affect the receiving basins (e.g., how the new sediment might affect the basin shallow subsidence rate).

Fresh Water Effects on Soil Properties

Sediment diversions will introduce large volumes of fresh water that will leach into the pores of receiving basin soil. When the diversions are operated at low flow or turned off, relatively dense saline water may re-enter the soil pores, replacing the fresh water. Repeated initiation and termination of flooding flows will cause multiple cycles of these processes, and the cumulative effect of these cycles may also affect the soil properties in unique ways. Hydrologic alterations within the receiving basin may mean that some areas influenced by the diverted fresh water will take longer to return to saline conditions.

Uncertainty

- How does the episodic inundation and saturation of potential receiving basin soils by both fresh and saline water affect the geotechnical properties of the soil in terms of erodibility and compressibility?

Research Activity

Employ laboratory or controlled field experiments that simulate the pulsed fresh and saline water flooding of soils. Example measurements would include: (1) the rate at which saline and fresh water leach into the underlying soil column, and to what depths, (2) the change in soil compressibility and soil strength in response to saturation in fresh water relative to saturation in saline water, and how these properties change in response to multiple cycles of saturation in both types of water, and (3) the change in the soil bulk density in response to multiple cycles of saturation in both fresh and saline water.

ESTUARINE HYDRAULICS AND SEDIMENT TRANSPORT

The Effect of Basin Morphology on Land Building

The fundamental metrics of receiving basin geometry include properties such as basin shape and dimensions (e.g., length, width, depth), edge and bed roughness, aspect, connectivity to other water bodies, and bed slope. These metrics heavily influence how flow, wind, and waves generate the currents and bed stress that drive the sediment transport processes in the receiving basin. In depositional environments such as actively building deltas, the spatial distribution of currents and bed stress will affect the formation of distributary channels and flow circulation patterns that will control how and where sediment is dispersed throughout the receiving basin (Shaw & Mohrig, 2013). The objective of research activities related to this topic would be to identify potential sediment diversion locations with receiving basins that have morphological characteristics conducive to land building.

Uncertainty

- How might fundamental metrics of receiving basin geometry influence the flow of fresh water and sediment through the potential receiving basin?

Research Activity

The role of key receiving basin properties can be explored by employing computational models, such as Delft3D, that simulate receiving basin dynamics and evolution. Each property can be systemically varied to quantify how sensitive model predictions are to the marginal change of the parameter.

The results of previous computational modeling studies (Cobell, Zhao, Roberts, Clark, & Zou, 2013; Edmonds, 2012; Georgiou et al., 2009; Karadogan & Willson, 2010; Rego, Meselhe, Stronach, & Habib, 2010) can be examined to identify the effects of common model inputs that are related to receiving basin geometry. Insights gained from a meta-analysis of existing modeling studies can be supplemented by: (1) field observations of existing receiving basins in coastal Louisiana and elsewhere, and (2) by employing existing observations (Dean, Wells, Fernando, & Goodwin, 2013; Parker & Muto, 2003) or (3) deriving new analytical models of receiving-basin evolution based on geometric principles and physics.

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Appendix II: Low Priority Uncertainties

Appendix II – Low Priority Uncertainties and Research Activities

The following uncertainties and research activities were determined to be a "low" priority by CPRA, versus being determined to be "high" or "medium" priority, based on the urgency of the technical need and the dependence of results from other (ongoing or planned) research activities

WETLAND VEGETATION

Vegetation Diversity and Recruitment on Newly Built Land

Species richness and diversity is dependent just as much on environmental factors impacting vegetation survival as those affecting seed supply and germination success (Baldwin, Egnotovich, & Clarke, 2001). Understanding the available source of seeds and their ability to recruit will help to determine the wetland vegetation succession on newly built land.

Uncertainty

- As new land is built, what will be the seed source and diversity in colonizing plant types? How will the seed source change over the lifetime of the diversion project? Will the Mississippi River provide an invasive seed source that is likely to colonize the newly built land?

Research Activity

Perform a field experiment that creates non-vegetated land (or use a suitable analogue such as a recently constructed sediment retention berm) in coastal marshes proximal to the lower Mississippi River to examine the composition and biomass of natural plant recruitment.

Carry out field data collection of the seed bank at potential sediment-diversion receiving-basin locations. Observe laboratory germination of collected seeds to identify potential species available for colonization at each location.

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Appendix III: List of Uncertainties and Research Activities

Appendix III – Original List of Uncertainties and Research Activities

The Institute developed a list of significant technical uncertainties related to the operation and management of sediment diversions in coastal Louisiana. The list contains short descriptions of each uncertainty and potential research activities that could be conducted to address these uncertainties. The focus of this list is on uncertainties that are currently resolvable through research, as opposed to uncertainties related to the sediment diversion location or design, which are difficult to address until more specific information about the diversion is known.

Based upon personal communication with CPRA, four "fields of interest" were defined to classify potential uncertainties: (1) estuary water quality, (2) wetland vegetation, (3) wetland soils and strength, and (4) estuarine hydraulics and sediment transport.

To aid in the identification of the uncertainties, the Institute solicited guidance from one technical expert in each of the four fields of interest. The experts were selected after a meeting with CPRA, who provided recommendations and comments. The experts included: (1) Dr. Carl Friedrichs, Virginia Institute of Marine Sciences, (estuarine hydraulics and sediment transport), (2) Dr. Guerry Holm, CH2M Hill, (wetland vegetation), (3) Dr. Michael Parsons, Florida Gulf Coast University, (estuary water quality), and (4) Dr. Gregg Zhang, University of Massachusetts, (wetland soils and soil strength). Each expert provided a short technical memorandum based on a template provided to them by the Institute. The objective of the technical memorandum was to identify and describe the key uncertainties related to the operation and management of sediment diversions specifically relating to the field of interest that the expert was assigned.

The technical memoranda were received by the Institute as requested and the information presented within each memorandum was synthesized into the list of key uncertainties, as described in the next section. A draft of this list of key uncertainties was discussed with CPRA on December 16, 2013. The list of key certainties contains a list of potential research activities that could be conducted to address each uncertainty. The descriptions of the research activities are general and are designed to communicate a recommended research approach. More detailed and specific research activities will be identified during the drafting of the final work plan.

This document contains the technical uncertainties and proposed research activities listed in the Institute's technical memorandum entitled "List of Uncertainties and Research Activities." That technical memorandum was submitted to CPRA on December 30, 2013. This document also contains technical uncertainties related to sediment diversions, partitioned into the same four fields of interest used by the technical memorandum, as identified by CPRA.

ESTUARY WATER QUALITY

Nutrient Removal Processes in the Receiving Basins

Biogeochemical processes that remove nutrients from the estuary are an important factor in determining the nutrient concentrations available in the receiving basins. Nutrient removal processes vary as a result of a large range of environmental factors such as residence time, salinity, and temperature (DeLaune & Jugsujinda, 2003; DeLaune et al., 2005; Lane et al., 2003; Rivera-Monroy et al., 2010; VanZomeren et al., 2013). Nitrogen is often the limiting nutrient for primary production in coastal systems and is correlated with eutrophication events (Mitsch et al., 2001; Graneli et al., 1990).

Uncertainty

- What are the rates and spatial variability of biogeochemical processes (i.e., assimilation, denitrification) that remove nitrate in riverine water introduced by sediment diversions during periods of peak flow (and, therefore, short residence times) and during average flow conditions?

- After estimating the nitrate removal rates, what is the estimated outwelling of nutrients from the estuary (e.g., Terrebonne Bay, Barataria Bay, Breton Sound) to offshore waters?

Research Activities

- Conduct field and laboratory-based research that involves collecting water samples and sediment cores and incubating them under conditions that mimic typical peak flow conditions (i.e., short residence time, high nutrients, high turbidity, low light, cold water temperatures, and low salinities) as well as a range of nonpeak flow conditions to estimate nitrate assimilation and denitrificaton rates. Estimate the percentage of nitrate removal and removal rates for Barataria and Breton Sounds.

- Estimate the outwelling of nutrient fluxes through the passes when sediment diversions are operating particularly at peak flow but also at a range of operational regimes. This approach could utilize a coupled hydrodynamic and nutrient dynamic model.

PHYTOPLANKTON MONITORING

The phytoplankton community is made up of a varied composition including: nonharmful algal blooms, such as diatoms, chlorophytes, and cyanobacteria and harmful algal blooms (HABs), such as *Microcystis* and *Anabaena.* Each of these types of species is affected by optimal environmental factors (e.g. light, turbidity, temperature) and will therefore dominate under differing conditions. In some diversion monitoring experiments, when there is high flow and the water is turbid, diatom species are the most likely to be dominant, but after a closure or when flow is reduced, potentially toxic cyanobacteria may increase (Bargu et al., 2011; Garcia et al., 2010).

Uncertainty

- What are the likely phytoplankton biomass and community composition responses and relationships to flow conditions likely produced by freshwater and sediment diversion operations? These flow conditions will likely include high discharge, increased nutrients, cold water temperatures, and low light and salinities.

- Will phytoplankton blooms occur during peak flow or occur after peak flow as a delayed response? How will this compare to the baseline phytoplankton population?

- Will the timing and spatial distribution (temporal and spatial variance) of phytoplankton blooms be altered by freshwater and sediment diversion operation?

- What is the variability in phytoplankton community structure among basins? Are the communities equivalent? Are the phytoplankton populations in one basin more or less sensitive/responsive to diversions than in other basins?

Research Activities

- Laboratory experiments with algal cultures that are treated with a prescribed range of conditions. These conditions would include varying one or a multiple of the following variables: nutrient concentration, turbidity, light level, water temperature, and salinity to determine their likely biomass and composition responses.

- Field collection that samples phytoplankton and covers an array of spatial and temporal intervals for the range of likely environmental conditions produced by sediment diversion operations to the extent that they are available across the coast. The spectrum of analyzed environmental conditions would be set to include a range of flow residence times, nutrient concentrations, turbidities, water temperatures, and salinities. The results of the field data collection would be used to determine the environmental conditions that most influence phytoplankton blooms.

Harmful Algal Blooms

- The increase in HABs are often associated with higher levels of nutrients. The effects of HABs can be highly varied, depending on which of the many species is being assessed, ranging from attenuating light in the water column to high toxin production (Dortch et al., 1999). Dortch et al. (1999) also noted the degree of toxicity can vary, but at higher levels can cause fish kills and even be toxic to humans.

Uncertainty

- If, based on the research from the phytoplankton biomass and community composition uncertainty, it seems likely that HABs may increase their frequency and biomass in response to diversion-related nutrients, what will be the expected algal toxin water concentrations throughout the estuary?

- What will be the magnitude of bioaccumulated algal toxins in grazers (nekton and oysters)?

Research Activities

- Few studies have examined current algal toxin concentrations in Louisiana estuaries and in tissues of estuarine grazers. Initial field work might be required to understand the baseline conditions of algal toxins in the phytoplankton cells and in tissues of grazers (nekton and oysters). Data collection of the existing environmental conditions of water and grazer tissue concentrations of algal toxins in the vicinity of existing freshwater diversions are needed to determine their typical ranges. Aliquots of water for toxin analysis could also be taken from algal culture laboratory experiments (as mentioned in research activities of "Phytoplankton Monitoring") that reflect typical sediment diversion conditions that are not commonly observed in the field.

- Execute laboratory experiments that examine the effects of different algal toxin ingestion (related to residence time) and concentrations of algal toxins on bioaccumulation rates in grazers (nekton and oysters).

- The response of Lake Pontchartrain algal populations to Bonnet Carré operations is poorly understood and is not typical of other estuaries in Louisiana receiving Mississippi River water. Operations of the spillway in different years have resulted in varying responses in harmful and nonharmful populations. Empirical studies are necessary during spillway and nonspillway years to determine the forces driving varying responses.

- Are the responses in algal populations due to timing and seasonal availability of nutrients, nutrient species or ratios, competition among algal species, physical limiting factors (such as temperature, wind, turbidity), or other factors?

- Are there important inputs from outside the system (such as northshore rivers) that might be controlling algal populations in Lake Pontchartrain?

WETLAND VEGETATION

SEDIMENT LOADING, INUNDATION, AND NUTRIENT LOADING TRADE-OFFS RELATED TO PLANT RESPONSE

Wetland vegetation is potentially impacted both positively and negatively by the altered environmental conditions caused by river diversions. Each factor that is changed (e.g. salinity, nutrient concentration, suspended sediment) will impact the various vegetation species in unique ways with those effects not often being a linear relationship (Merino et al., 2010).

Uncertainty

- What changes in marsh vegetation productivity occur related to the trade-off between: (1) the "positive" effects of the introduction of new sediment to the marsh surface during peak flow and (2) the "negative" effects of the increase in physiological inundation related stressors from peak flow on brackish/saline marsh vegetation?

Research Activity

- Field or laboratory experiments examining the interactive effects of freshwater flood duration and depth in addition to sediment characteristics (e.g., sedimentation rate, mineralogy) on the productivity of brackish/saline marsh vegetation and the physiological inundation stress of sulfide toxicity.

- Meta-analysis of existing datasets to determine the range and extent of the effects of freshwater inundation and sedimentation on wetland vegetation health.

VEGETATION DIVERSITY AND RECRUITMENT ON NEWLY BUILT LAND

Species richness and diversity is dependent just as much on environmental factors impacting vegetation survival as those affecting seed supply and germination success (Baldwin et al., 2001). Understanding the available source of seeds and their ability to recruit will help to determine the vegetative succession on newly built land.

Uncertainty

- As new land is built, what will be the seed source and diversity in colonizing plant types? How will the seed source change over the lifetime of the diversion project?

Research Activity

- Perform a field experiment that creates non-vegetated land (or the use of a suitable analogue such as a recently constructed sediment retention berm) in coastal marshes proximal to the lower Mississippi River to examine the composition and biomass of natural plant recruitment.

- Carry out field data collection of the seed bank at potential sediment-diversion receiving-basin locations. Laboratory germination of collected seeds to identify potential species available for colonization at each location.

WETLAND SOILS AND STRENGTH

COMPACTION AND EROSION OF RECEIVING BASIN SUBSTRATE

The yield stress of sedimentary material is the threshold stress value that, if exceeded by the downward stress exerted by the accumulated overburden, will significantly increase the rate of compression that the material will experience (Burland, 1990). This compression from increased yield stress is a necessary consideration as it must be combined with deep subsidence processes and relative sea-level rise estimations to determine the potential cumulative total of relative elevation reduction.

Uncertainty 1A

- What is the “yield stress” of the underlying substrate in coastal marshes proximal to the lower Mississippi River (i.e., the environment where the sediment diversions will be built)? It is not well understood if certain types of marsh substrates have characteristic yield stresses or what marsh properties (e.g., soil type, vegetation type, and density) influence the yield stress and sediment compressibility in general.

- Is it possible to build new marsh without exceeding the yield stress of the existing marsh substrate?

Research Activity 1A

- Complete laboratory and field geotechnical characterization of marsh soil compressibility to define (1) the typical yield stress thresholds, and (2) the increase in soil compressibility caused by exceeding the yield stress threshold for prospective sediment-diversion receiving-basin environments. Properties of the marsh environment will also be measured to examine how well they correlate to the measured values of soil compressibility. Examples of these properties could include soil type, soil bulk density, and belowground biomass.

- Computational modeling experiments could be conducted to examine how sediment diversions will generate new stresses on the marsh substrate by promoting the deposition of sediment (i.e., sediment loading). Experiments can be designed to specifically examine how different diversion operation scenarios (e.g., different peak flows, different discharge hydrograph shapes) influence the magnitude and the spatial distribution of the sediment loading. The predicted values of sediment loading can be compared to measured values of marsh yield stress. This can estimate how different marsh areas may respond to sediment diversion operations, in terms of the compression of the underlying substrate, and how this compression may result in increased local subsidence. Models can be generated for a range of different marsh types and receiving basin geometries to explore how multiple parameters affect the magnitude and spatial distribution of sediment loading within the receiving basin.

- Development of a numerical model of receiving basin sediment compaction. The model would simulate the physical processes of load induced sediment compaction and sediment consolidation and would be parameterized with measurements of receiving basin soil compressibility. The measurements of soil compressibility could be produced by conducting new data collection campaigns or by leveraging geotechnical data collection efforts currently supporting other diversion-related endeavors. The purpose of such a model would be to compute estimates of soil compaction in receiving basins due to sediment loading using inputs such as sediment aggradation rate, generalized subsurface geology and average soil type, and receiving basin geometry.

Uncertainty 1B

- What is the difference in erodibility and compressibility between recent (< 50 years BP) riverine sediment deposits (i.e., the type of sediment deposits that will form due to the sediment diversion operation) and the soils and other sedimentary material currently composing the coastal marsh environments proximal to the lower Mississippi River?

Research Activity 1B

- This uncertainty could be addressed by conducting laboratory geotechnical analyses of sediment samples retrieved from (1) potential receiving basins (i.e., coastal marshes proximal to the lower Mississippi River), and from (2) areas of the modern Mississippi River delta that currently experience active sediment deposition. Measured values of sediment erodibility and compressibility can be directly compared to identify the significant differences, if present, between the sediment deposits from the two different environments. Knowledge of the geotechnical properties of the recent sediment deposits relative to the properties of the substrate composing the potential sediment-diversion receiving-basins adds insight as to how sediment diversion operations might affect the receiving basins (e.g., how the new sediment might affect the basin shallow subsidence rate).

Freshwater Effects on Soil Properties

Sediment diversions will introduce large volumes of fresh water that will leach into the pores of receiving basin soil. When the diversions are operated at low flow or turned off, the relatively dense saline water may re-enter the soil pores, replacing the fresh water. Repeated initiation and termination of flooding flows will cause multiple cycles of these processes, and the cumulative effect of these cycles may also affect the soil properties in unique ways. However, certain locations flooded by fresh water outside channelized areas may not be reachable by the returning saline tides.

Uncertainty

- How does the episodic inundation and saturation of potential receiving basin soils by both fresh and saline water affect the geotechnical properties of the soil, in terms of erodibility and compressibility?

Research Activity

- Laboratory or controlled field experiments that simulate the pulsed fresh and saline water flooding of soils. Example measurements would include: (1) the rate in which saline and fresh water leach into the underlying soil column, and to what depths, (2) the change in soil compressibility and soil strength in response to saturation in fresh water relative to saturation in saline water and how these properties change in response to multiple cycles of saturation in both types of water, and (3) the change in the soil bulk density in response to multiple cycles of saturation in both fresh and saline water.

Development of a Standard Methodology to Assess Soil Strengths in Coastal Marshes

There are a wide variety of methodologies available to assess properties of marsh soil. Multiple instruments are routinely used to measure the same general geotechnical property (e.g., shear vanes and cone penetrometers are both used to test soil strength) yet different instruments may not produce directly comparable measurement values. This is because the different instruments measure the response to slightly different physical phenomenon, such as measuring soil strength by displacing soil at different depths, integrated over different areas, or in different directions (i.e., horizontal vs. vertical).

Uncertainty

- There is no standard methodology for the in-situ characterization of the geotechnical properties of coastal marsh soils. Currently, there are no identified best practices to offer guidance at what spatial and temporal intervals the geotechnical properties should be sampled in coastal marshes to accurately resolve the gradients at which the properties significantly vary. There is no instrument currently available that has been widely adopted and designed to test the unique geotechnical soil properties in marsh environments, such as abundance of soil biomass, soil pore water, soil organics, and widely varying grain-size distributions.

Research Activity

- Develop a manual that describes best practices to measure key geotechnical properties of coastal marsh soil. The manual can be synthesized from expert opinions provided by active researchers currently conducting geotechnical analyses of coastal marsh soils.

Biomass Effects on Soil Strength

Above- and belowground biomass monitoring can be used separately as comparative assessments of soil strength (Sasser et al., 2013). Above- and belowground biomass can be compared to each other as a root:shoot ratio used to determine impacts of changing factors such as those caused by a diversion (e.g. increased fresh water, added nutrients, decreased temperature). The root:shoot ratio usually assumes the higher the ratio, the higher the soil strength, but increasing and decreasing of the ratio due to a diversion may or may not correlate to sediment strength. A decline in the root:shoot ratio does not necessarily mean root biomass is decreasing or even remaining the same.

Uncertainty

- How does above- and belowground biomass contribute to the strength of coastal marsh soils?

Research Activity

- Field or laboratory experiments that test multiple parameters of soil strength in different soil plots that have a range of biomass content (i.e., that span the expected range of values observed in coastal Louisiana marshes). Experimental plots will have (1) single vegetation species to identify how individual species influence soil strength, and (2) ratios of multiple species that are indicative of real-world coastal marsh environments, to identify how vegetation generally influences soil strength in realistic environments. Multiple instruments and sampling strategies will be tested to identity preferred (in terms of minimizing labor and cost and maximizing accuracy) soil strength and biomass assessment methods.

ESTUARINE HYDRAULICS AND SEDIMENT TRANSPORT

THE EFFECT OF HYDROPERIOD ON LAND BUILDING

The freshwater hydroperiod is the temporal interval when, due to diversion operations, the marsh surface of the receiving basin is inundated by fresh river water. Inundation by fresh water has both benefits and costs related to coastal ecosystem health and integrity. For example, longer hydroperiods produce a longer period in which the marsh surface is accessible to new inputs of fresh river water, river nutrients, and fluvial sediment. This increased accessibility may result in increased rates of nitrogen uptake in inundated areas and a wider distribution of sediment deposition throughout the receiving basin, which are typically regarded as benefits. However, longer hydroperiods are also associated with large flooding flows that produce high flow velocities which can cause local erosion within the bed and banks of the receiving basin and stress vegetation located on the flooded marsh surfaces.

Uncertainty

- What are the cumulative benefits of maximizing the receiving basin hydroperiod versus the environmental costs of doing such? This, in turn, leads to the uncertainty of the optimal freshwater hydroperiod for a sediment-diversion receiving-basin.

Research Activity

- Undertake multi-criteria decision analysis of the predicted benefits and costs of different diversion operation scenarios that consider land building rate and ecosystem health (e.g., marsh vegetation health, estuarine pelagic and benthic habitat integrity). Existing data from published literature can be mined for insight into the environmental costs and benefits of sediment diversions and the environmental processes influenced by the hydroperiod related to sediment diversion operation.

THE EFFECT OF BASIN MORPHOLOGY ON LAND BUILDING

The fundamental metrics of receiving basin geometry include properties such as basin shape and dimensions (e.g., length, width, depth), edge and bed roughness, aspect, connectivity to other water bodies, and bed slope. These metrics heavily influence how flow, wind, and waves generate the currents and bed stress that drive the sediment transport processes in the receiving basin. In depositional environments such as actively building deltas, the spatial distribution of currents and bed stress will affect the formation of distributary channels and flow circulation patterns which will control how and where sediment is dispersed throughout the receiving basin (Shaw & Mohrig, 2013).

Uncertainty

- How might fundamental metrics of receiving basin geometry influence the flow of fresh water and sediment through the potential receiving basin?

Research Activities

- The role of key receiving basin properties can be explored by employing computational models, such as Delft3D, that simulate receiving basin dynamics and evolution. Each property can be systemically varied to quantify how sensitive model predictions are to the marginal change of the parameter.

- The results of previous computational modeling studies (e.g., Georgiou et al., 2009; Karadogan & Wilson, 2010; Rego et al., 2010; Edmonds, 2012; Cobell et al., 2013) can be examined to identify the effects of commonly employed model inputs that are related to receiving basin geometry. Insights gained from a meta-analysis of existing modeling studies can be supplemented by (1) field observations of existing receiving basins in coastal Louisiana and elsewhere, and (2) by employing existing (e.g., Parker & Muto, 2003; Dean et al., 2013) or deriving new analytical models of receiving-basin evolution based on simple geometric principles and physics.

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