Partnership for Our Working Coast: Port Fourchon Phase 1 Technical Report

Beneficial Use Optimization, Subsidence, and Blue Carbon

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Produced for and funded by: Shell, Chevron, Danos, and the Greater Lafourche Port Commission

August 20, 2018

INTEGRATING APPLIED RESEARCH | LINKING KNOWLEDGE TO ACTION | BUILDING PARTNERSHIPS

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SUGGESTED CITATION

Allison, M. Carruthers, T., Clark, R., Di Leonardo, D., Hemmerling, S., Meselhe, E., Moss, L., Weathers, D., White, E., and Yuill, B. (2018). Partnership for Our Working Coast: Port Fourchon Phase 1 Technical Report. The Water Institute of the Gulf. Prepared for and funded by Shell, Chevron, Danos, and the Greater Lafourche Port Commission. Baton Rouge, LA.

Preface

The Public-Private Partnership Plus (P3+) approach used for this effort combines the resources and expertise of public, private, and non-governmental organizations with the aim of enhancing coastal habitat and providing protection to critical infrastructure and communities. This model takes Port Fourchon’s 20-year history of holistic, nature-based resiliency activities, and scales them up using collaborative implementation and state-of-the-art science and engineering. This approach will serve as a model across the Gulf and around the country with respect to collaborative planning and shared funding to construct coastal infrastructure and community protection projects that are nature-based. The nature-based project strategy will benefit multiple stakeholders and will increase quality habitat and help sustain existing habitat.

Acknowledgements

This effort was produced for and funded by Shell, Chevron, Danos, and the Greater Lafourche Port Commission, as part of the mission of the Partnership for Our Working Coast.

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INTRODUCTION

The Greater Lafourche Port Commission (GLPC) operates Port Fourchon, the nation's premier oil and gas services port, services more than 90 percent of all U.S. Gulf of Mexico Deepwater oil and gas exploration and production activities. Port Fourchon is also home to the land booster pump station for the Louisiana Offshore Oil Platform (LOOP), which transfers both foreign and domestically-produced crude oil to large storage tanks and an underground storage facility adjacent to the South Lafourche Airport (GAO) in Galliano, Louisiana.

This same facility is also the land shore base through which both Chevron and Shell's major pipelines bring ashore domestically produced crude from the U.S. Gulf of Mexico for its journey to the marketplaces and refineries along the Mississippi River corridor and many points beyond. Port Fourchon is vital in the production of approximately 20 percent of the nation's oil supply, making it the single most critical costal piece of energy production infrastructure in the United States.

In 2016, the GLPC formally announced its plans to obtain Federal regulatory approval to deepen Belle Pass at the mouth of Bayou Lafourche in Port Fourchon to a target depth of -50 feet in order to provide an additional port facility capable of handling the heavy maintenance, refurbishment and/or decommissioning needs of the deepwater energy industry.

This large-scale dredging project will generate tens of millions of cubic yards of dredged material sediments over its lifespan. The GLPC has made it clear that they intend to see this material used beneficially both for the project's development, environmental mitigation obligations, and as an integral and renewable borrow source for coastal restoration and protection initiatives locally.

Energy industry partners Chevron, Shell, and Danos along with GLPC and The Water Institute of the Gulf came together to form the Partnership for Our Working Coast which takes a science-based approach to maximizing the benefits of coastal restoration efforts to protect energy assets and critical infrastructure as a vital component of industry's risk management and sustainability business drivers. In close collaboration with companies to determine what areas in and around the port were most important from a critical infrastructure perspective, the group has focused its efforts on science and engineering to answer questions around the port concerning (a) options for optimizing the placement of beneficially-used dredged material to create nature-based defenses for critical infrastructure and communities; (b) land subsidence; (c) quantification of the potential for blue carbon capture and sequestration potential of the coastal ecosystems created using the dredged material; and (d) community resilience.

Phase one of this collaboration focused on data collection, characterization, and preliminary analysis for the first three of these issues. This executive summary and the associated technical reports detail the methods and findings for work completed in phase one and outline a potential path forward for phase two.

OPTIMIZING BENEFICIAL USE OF DREDGED MATERIAL

The need:

As part of the GLPC's work gaining federal approval to deepen Belle Pass, one component that needs to be answered is where the dredged material will be placed. The dredging project will provide millions of cubic yards of badly needed sediment that will need to be disposed of, likely in the nearby vicinity.

In order to use this material in the most beneficial way for industry, the port, communities, and the environment, the Partnership for Our Working Coast members engaged the Institute as a way to leverage the work which the GLPC had already directly engaged the Institute to do to support the development of its Environmental Impact Statement (EIS) and related analysis for the channel deepening project, which created a powerful leveraging opportunity.

The Institute undertook the first steps in delineating potential site locations that could accept the dredged material while also providing one or more benefits to industry, the community, and the environment.

What we did:

First, the Institute used numerical modeling to predict how much sediment could be removed from the channel at Port Fourchon over the life of the project including a series of alternative maintained channel bed elevations from -30 to -50 feet.

Second, the Institute analyzed potential locations for the beneficial use around Port Fourchon including developing a map of the current mean water depth.

The distance between dredge pump locations and the center of each potential fill location was determined and for each pump location, the potential fill sites were listed in order of increasing distance. Using an assumed dredging schedule, the closest sites to each dredge location were selected until all of the expected dredged material was accounted for.

The initial list of potential sites was discussed during a field visit with federal agency representatives including the U.S. Army Corps of Engineers and U.S. Fish and Wildlife Service.

For purposes of the EIS preparation, the federal agencies suggested that the material be placed in deep open water with depths greater than three feet; alternatively, it was suggested that the material be used as beach and dune nourishment along West Bell Pass and Caminada headlands. This rendered the vast majority of sites in the first list unsuitable.

A final update to the potential site list was made after GIS Engineering, (the port's primary contractor on the EIS development) conducted a grain size analysis on sediment cores taken at the off-shore dredge locations. This material had relatively low amounts of sand and so the barrier headland dune and beach restoration projects sites were removed from the list. Instead, the material would be placed in the deepwater in the near-shore area of the Gulf of Mexico to nourish the eroding beach and dune habitat of the West Bell Pass and Caminada Headlands.

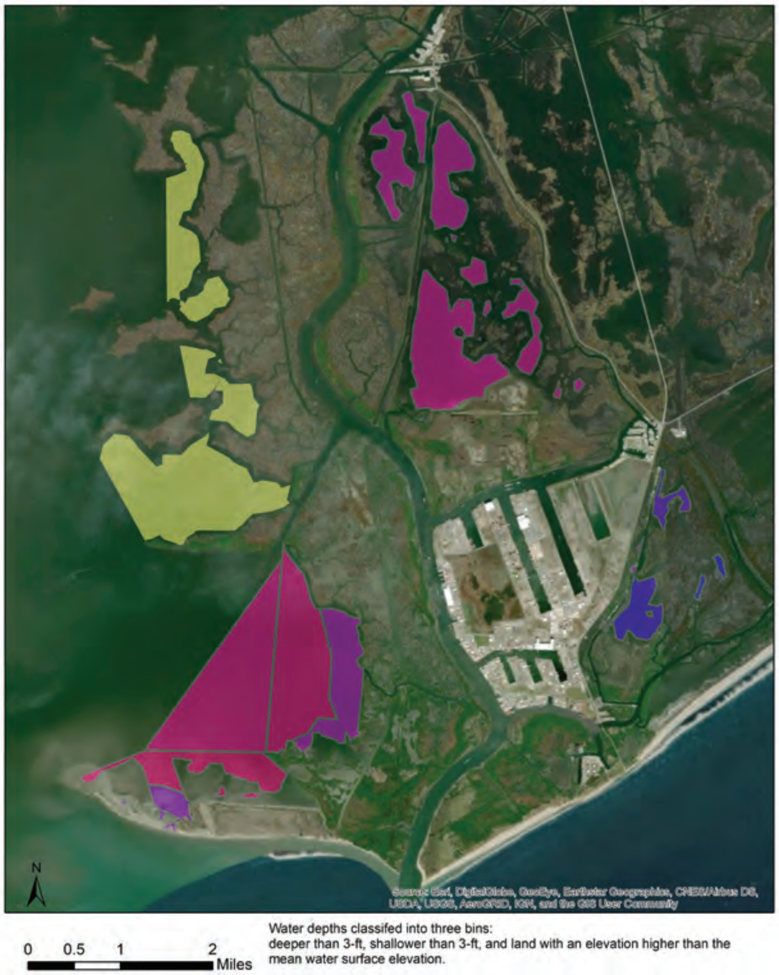
What we found:

Using this updated list of potential deposition sites, and using placement plans outlined by GIS, 13 remaining sites were examined to determine the volume in cubic yards needed to fill the deeper water areas to a four-foot elevation, the land area this could create, as well as the current maximum and average water depth in the area.

The two dredge placement plans provided by GIS, along with a future without action, were analyzed using three scenarios for sea level rise and subsidence.

Although these placement sites are greatly reduced from the initial list generated based on federal input, there are opportunities for the list to be expanded in the future as the project moves towards implementation.

Final deposition sites for beneficial use of dredged material



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Water depths classifed into three bins:
deeper than 3-ft, shallower than 3-ft, and land with an elevation higher than the mean water surface elevation.

Mean water surface elevation determined from 4 closest CRMS sites: 0.43 ft NAVD88.
Bathymetric and topographic elevation data taken from the USGS dataset compiled for the 2017 Coastal Master Plan (30-m XY resolution).

Final deposition sites for beneficial use of dredged material from the construction and maintenance base plan and the tentatively selected plan/locally preferred plan dredge schedules.

SUBSIDENCE

The need:

Many areas of coastal Louisiana experience a higher risk of damage to ecosystems, communities, and infrastructure due in part to high rates of land sinking additive to rates of eustatic sea level rise. There are multiple causes for this "subsidence", mainly related to being located on top of a thick and young package of deltaic sediment. Many of the mechanisms causing subsidence cannot be mitigated, hence, formulating subsidence adaptation plans in coastal areas like Port Fourchon with dense human and industrial infrastructure at risk requires a precise knowledge of the spatial and temporal trends in subsidence rates. Developing adaptation strategies requires answering several main challenges.

First is to accurately measure and monitor where and how fast subsidence is causing land elevations to change.

A fuller understanding of the causes of subsidence and their respective contribution to the total subsidence rate would be helpful in (1) predicting subsidence rates between measured locations and (2) determining whether any of these contributing mechanisms would be predicted to change in magnitude in the future. However, this fuller understanding is more detailed than the Port currently needs to predict its own impact on sustainability of infrastructure and ecosystems. Instead, a well-developed understanding of the total land surface elevation change, regardless of causes, would be the most useful for future planning. Total land surface elevation change is the summation of the total subsidence rate plus the eustatic sea level rise rate minus the addition of any new sediment.

What we did:

In this first phase, the Institute focused on gathering what is currently known about relative sea level rise in south Louisiana (subsidence + eustatic), focusing on the areas around Port Fourchon and the Lafourche headland to as far north as Raceland, LA through a variety of existing data sources including:

- Holocene-Pleistocene subsurface thickness through soil borings
- Geotechnical data from soil-borings and cone penetrometer tests
- Location of salt domes in the subsurface
- Location of faults in the subsurface
- Geodetic levelling
- Tide gauge records
- Coastwide Reference Monitoring Stations (CRMS)
- Continuously Operating GPS Reference Stations (CORS)

- Satellite and airborne Light Detection and Ranging (LiDAR) land elevation surveys
- Coastal wetland extent change maps

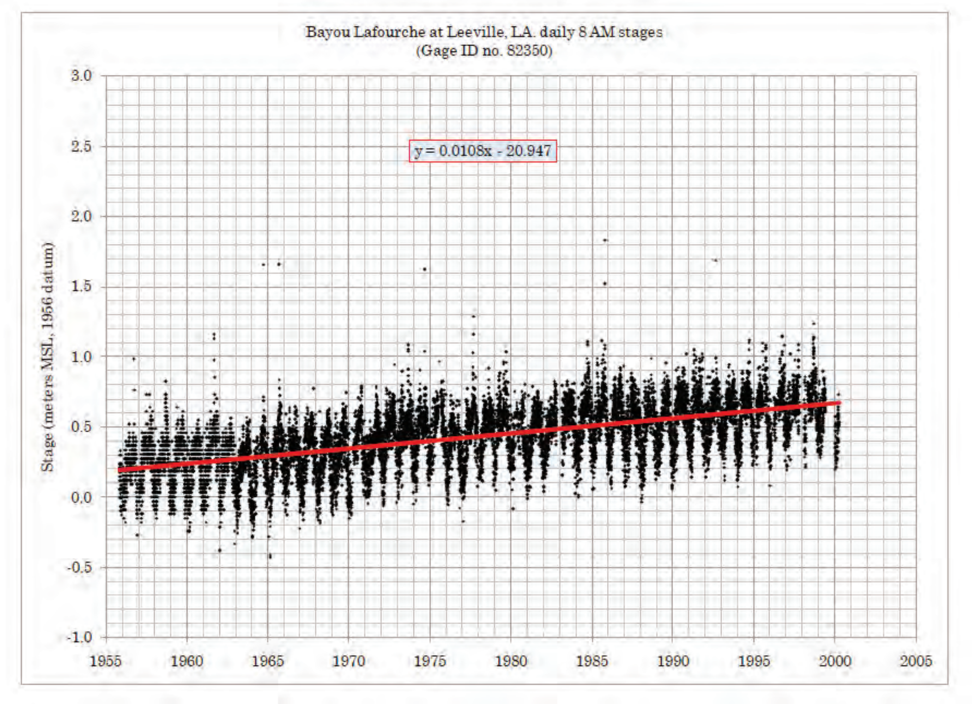
The goal was to populate a map with spatial information about subsidence rates as well as identifying knowledge gaps.

What we found:

In all, more than 100 subsidence rates have been calculated in the Port Fourchon area during the last 15 years using a wide variety of methods, each having its own strength and weakness. The one constant through all of these methods is that subsidence rates differ greatly in space and over time.

Future work will use the cumulated information gathered in this phase to build a subsidence and elevation loss "hazard map" to be used in assessing when, and at what elevation loss, areas around Port Fourchon can be expected to sink below mean sea level.

This information will be crucial as the site selection for future beneficial use of dredged material moves forward. There is a significant subsidence range in the Coastal Master Plan and zeroing in on it in Port Fourchon will help improve future decision making.



Left: Linear regression on daily stage measurements yield the long term relative sea level rise rate at Leeville tide gauge. Reproduced from U.S. Army Corps of Engineers, New Orleans District (2010)

Below: Nicholls State University student takes measurements in the Port Fourchon area.

BLUE CARBON

The need:

Blue carbon refers to the greenhouse gases (GHG), such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) sequestered, stored, and released from seagrass, tidal wetlands, salt marshes and mangroves. Coastal wetland restoration is among the newest project types approved to generate carbon offsets on the voluntary carbon market.

With the Port Fourchon work, and anticipated creation and enhancement of coastal marshes, the possibilities for additional benefits coming from the calculation and potential sale of blue carbon were investigated.

The potential revenue generated through offset sales currently will not cover the full cost of restoration, but can provide support for project components such as long-term monitoring, management, and incentivizing additional restoration investors.

What we did:

The Institute team reviewed existing literature and site-specific data to provide foundational information and a list of items to be considered in developing a blue carbon project in Port Fourchon. This initial feasibility assessment examines the technical and financial feasibility for a project to generate carbon credits and is meant to guide project developers in the decision of whether or not to pursue carbon project development.

The team looked into per acre of carbon storage, per ton dollar value, the question of permanence of any wetlands created, carbon credit prices, the cost of monitoring, carbon net cash flows over a 30-year period, and net emission reductions over a 30-year period.

Blue carbon credits can be maximized through a number of means including using dredged material in shallow areas with less than three feet of water, use maintenance dredging as a source for thin-layer sediment application, and building large areas of marsh for maximum efficiency. A mix of marsh creation and marsh terrace creation may provide for both high amount of stored carbon, as well as greatest permanence of that carbon.

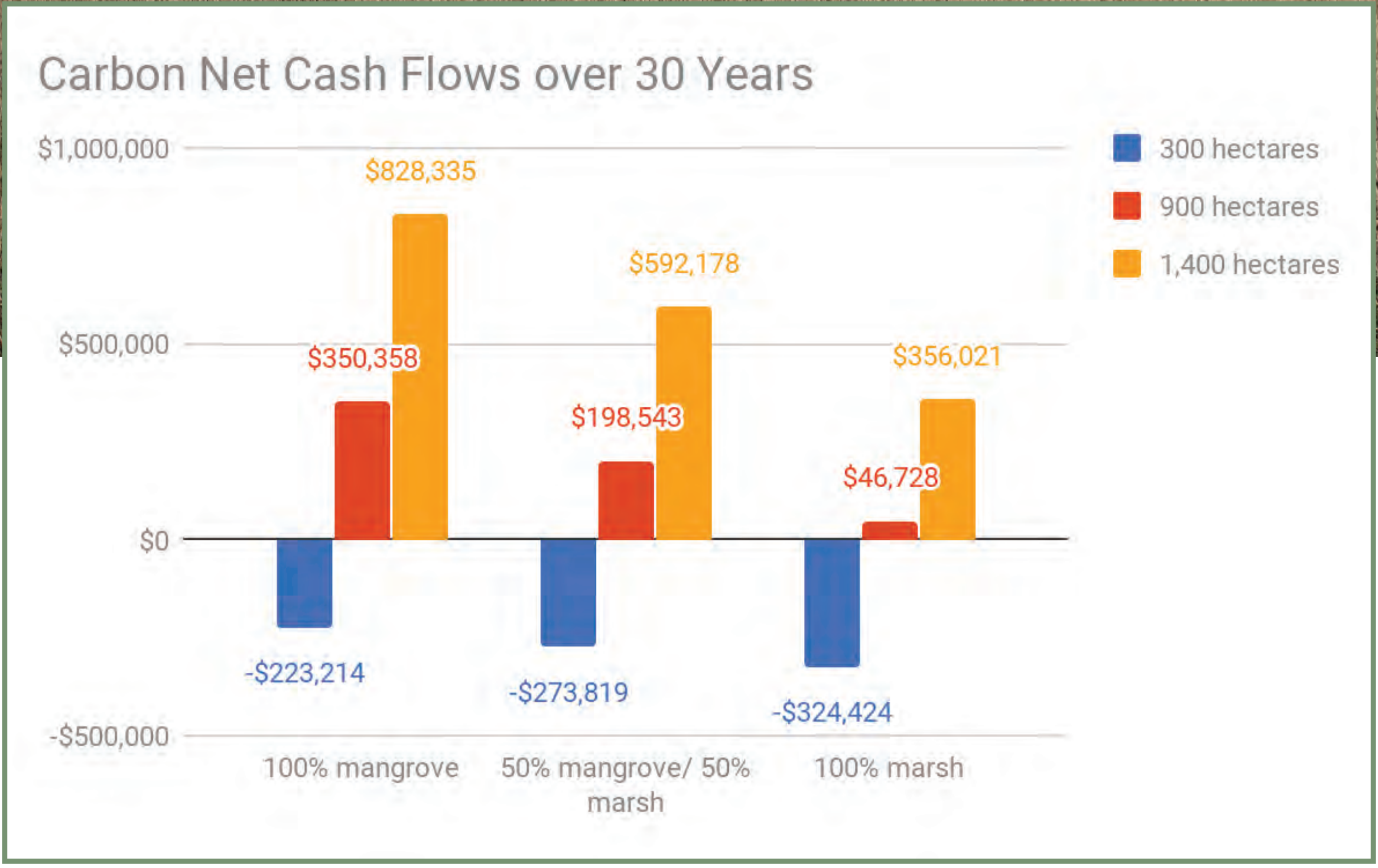
What we found:

At the current time, if developed as a carbon offset project, the Port Fourchon tidal wetland restoration project would be able to sell offsets into voluntary carbon markets; compliance markets do not currently accept offsets from tidal wetland restoration projects.

Voluntary markets are made up of mostly consumer-facing industries looking to voluntarily become more carbon neutral and help combat climate change, especially in situations where emission reductions are cost prohibitive.

Project implementation is still in the planning and design stage.

However presuming each phase of dredging would be used to create some type of new land area, each of these smaller areas on their own would not sequester enough carbon to justify the cost of carbon monitoring, but the aggregation of all phases over time has potential to contribute substantively to the cost of monitoring required to qualify for Blue Carbon credits.



Net cash flow (income from offsets minus project monitoring costs) for the various project areas and for each of the saline wetland vegetation types.

PATH FORWARD

The phase one findings included in this executive summary and in the accompanying technical reports, provide the foundation for work in the Port Fourchon area that will better inform future, more specific efforts With a better understanding of factors influencing the area around the port, the stage is set to move the analysis beyond the feasibility level into the more operational aspects of gaining the most benefit possible for the port, industry, community, and environment as a result of the channel deepening.

In the next phase of the work, the Institute is recommending the following:

Beneficial Use of Dredged Material

Apply numerical predictive models developed at the Institute to optimize the placement and geometry of beneficial use dredge material from the Fourchon Ship Channel to 1) examine the performance of projects selected in Phase I for improving infrastructure protection from storms and relative sea level rise; and 2) provide insight into the location, orientation, and elevation needed for either marsh creation or ridge restoration projects.

Subsidence

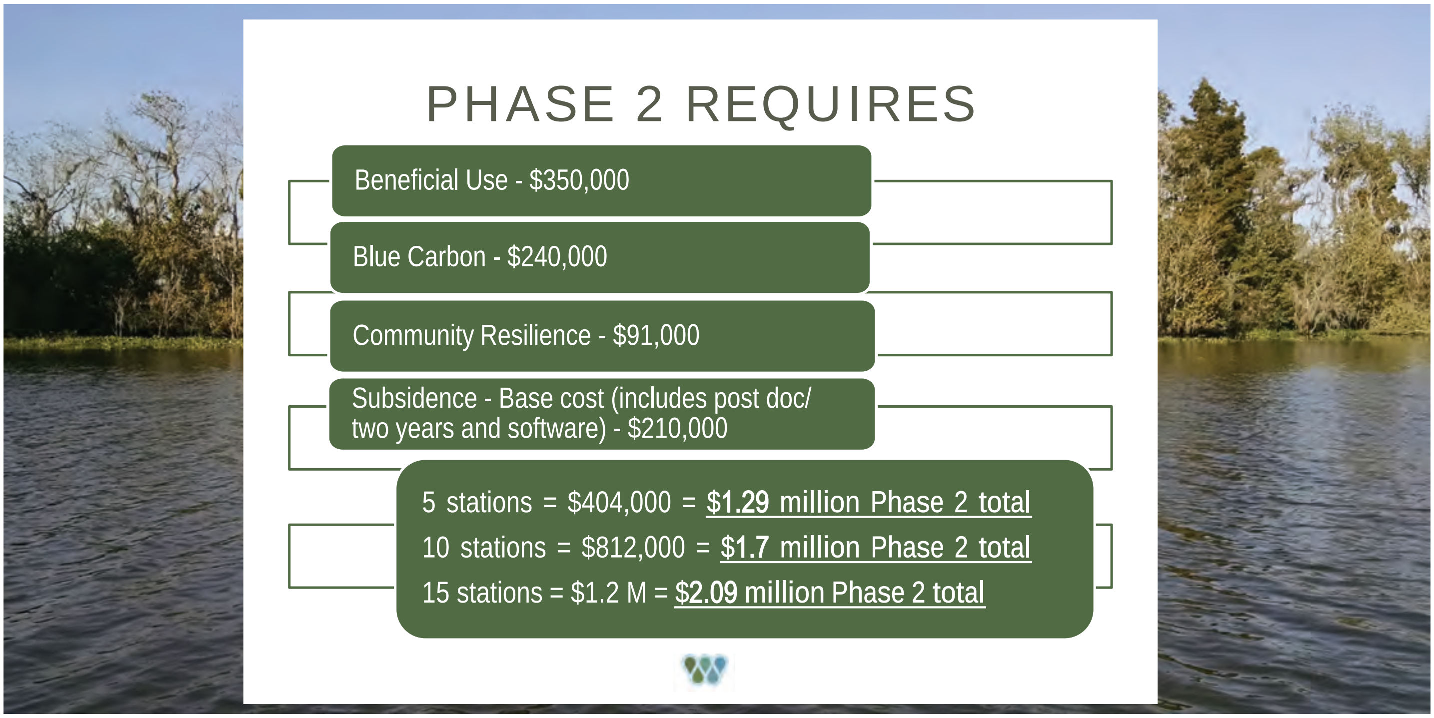
To establish a subsidence monitoring program in the vicinity of the port, to refine both the quality and spatial resolution of subsidence work done in phase 1. This program will allow the port and industry stakeholders to make better informed decisions.

Blue Carbon

Use the ecosystem model to evaluate where to place dredged material beneficially and how long that built land can be sustained through modeling different methods such thin-layer placement for marsh renourishment. In addition, the team will be modeling vegetation with the dominant species in the area being black mangroves to understand potential for infrastructure risk reduction, wave attenuation, and carbon storage.

Community resilience

Use a Social Return on Investment framework to integrate community-based qualitative research, ecological site assessments, and economic valuation to calculate the social value of candidate projects. Potential costs and benefits of each proposed action on nearby communities will be assessed through qualitative research and stakeholder engagement including one-on-one interviews, workshops, and meetings to assess the potential social and economic and cultural outcomes of the candidate projects and to help assess and interpret the Phase 2 model results.



PHASE 2 REQUIRES

Beneficial Use - $350,000

Blue Carbon - $240,000

Community Resilience - $91,000

Subsidence - Base cost (includes post doc/ two years and software) - $210,000

5 stations = $404,000 = $1.29 million Phase 2 total

10 stations = $812,000 = $1.7 million Phase 2 total

15 stations = $1.2 M = $2.09 million Phase 2 total

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PARTNERSHIP FOR OUR
WORKING COAST

Partnership for Our Working Coast: Port Fourchon Phase 1 Technical Report

Chapter 1: Optimizing the Beneficial Use of Dredge Materials

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Produced for and funded by: Shell, Chevron, Danos, and the Greater Lafourche Port Commission

August 20, 2018

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List of Acronyms

Acronym	Term
CPRA	Coastal Protection and Restoration Authority
DEM	Digital elevation model
GIS	GIS Engineering, LLC
LPP	Locally Preferred Plan
NEDP	Base Plan
TSP	Tentatively Selected Plan
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service

Introduction

The proposed channel deepening and development project at Port Fourchon will produce a substantial volume of dredged materials during the construction phase in which the existing shipping channels and slips within the port are to be dredged to an increased depth of 50-feet. Once dredged, these deeper channels will need to be maintained at these new depths, which will require regular maintenance dredging operations. In support of the environmental impact statement (EIS) being prepared for the Port, an analysis was conducted to examine the present-day landscape in the vicinity of the Port to determine its capacity to absorb these construction and maintenance dredge materials in the form of marsh creation projects. This chapter explains the process used to determine where the dredged materials could be used to beneficially build new marsh, how many acres of marsh would be created, and how it would fare as functional marsh into the future under a variety of sea level rise scenarios.

Optimizing the Beneficial Use of Dredge Materials

PREDICTION OF MAINTENANCE DREDGE VOLUMES

Numerical modeling was used to predict the volume of channel bed sediment dredged from the Port Fourchon navigation channel system over the project lifespan. The modeling, which employed the Delft3D morphodynamical modeling suite (www.oss.deltares.nl/web/delft3d), was executed as a component of an auxiliary study to quantify the impact of channel deepening on sedimentation rates. The results of that study, which analyzed a series of alternative maintained channel bed elevations (e.g., -30 to -50 ft NAVD88), in terms of the predicted annual sediment volume removed from the channel from dredging operations is shown in Table 1. These values include all sediment dredged from the maintained Port channels as well as the Port entrance channel that extended into the Gulf of Mexico. A full description of this study is presented in a 2018 report published by The Water Institute of the Gulf (Yuill et al., 2018). This report includes an assessment of the spatial distribution of the predicted sedimentation magnitudes. These predicted magnitude values provide guidance on where and how much dredging will be necessary through the project lifespan.

Table 1: Predicted maintenance dredging volumes for 3 scenarios assessed in the Delft3D modeling study.

Scenario	Upper Port Channel	Entrance Channel
	Station 0+00 to 130+00	*Stations > 130+00*
As-Is	87,365 CY/yr	622,057 CY/yr
-30 ft NAVD88	238,678 CY/yr	795,934 CY/yr
-50 ft NAVD88	238,678 CY/yr	1,164,646 CY/yr

BENEFICIAL USE OF DREDGE MATERIALS – SITE SELECTION

An analysis was undertaken to examine potential deposition areas for beneficial use of dredge material in the vicinity of Port Fourchon. Initial construction dredged sediment volumes from the proposed deepening of Port Fourchon were provided by GIS Engineering, LLC (GIS) for this analysis. Future inputs of dredged sediment resulting from channel maintenance dredging through the project lifespan were estimated from the numerical modeling study discussed in the previous section of this text. The annual sedimentation rates from that study were used by GIS to develop a 50-year maintenance dredge schedule to be implemented post-construction.

A desktop analysis was conducted to identify potential deposition sites for the beneficial use of the dredge sediments and to calculate the capacity of each site in accommodating all of the dredged sediment from both construction and maintenance project phases. The dredging schedule and amount of functional marsh created during each project year are provided in and in provided in Attachment 2 for the Base Plan (NEDP) and in Attachment 3, for a Tentatively Selected Plan/Locally Preferred Plan (TSP/LPP).

Mean sea level and water depth

The digital elevation model (DEM) developed by the US Geological Survey for the 2017 Louisiana Coastal Master Plan was used for this analysis. This DEM provides coverage for the entire coastal zone of Louisiana, including the off-shore portion of the Gulf of Mexico, the spatial resolution is 98.4-ft (30-m), all elevation data are relative to the North American Vertical Datum 1988 Geoid 12A (NAVD88), and the dataset was compiled with best-available data in 2014 (Couvillion, 2017). A present day mean water surface elevation was assumed to be equal to +0.43-ft (NAVD88). This average water level was calculated from the four closest Coastal Reference Monitoring System (CRMS) stations to Port Fourchon. These CRMS sites all monitor hourly water surface elevation and have long-term mean values representing present conditions calculated for a period from 2013 through 2017. Site CRMS0164-H01 has a mean water surface elevation of 0.54-ft, site CRMS0178-H01 has a mean of 0.59-ft, CRMS0292-H01 has a mean of 0.36-ft, and CRMS0310-H01 has a mean water surface elevation of 0.25-ft (all elevations are relative to NAVD88 Geoid 12A). The overall mean water surface elevation of 0.43-ft was used to develop a map of current mean water depth by comparison with the most up-to-date topobathymetric DEM available.

Initial Site Identification

The optimal deposition location for each dredge pump location is a multi-variate problem which should consider: the distance from the location to the dredging site, the volumetric capacity of the deposition site, the volume of dredged sediments, and water depth at the site of deposition (which will affect both the cost of containment and the compaction of deposited sediments). These variables are influenced by the timing, location, and depth of the dredging that occurs. This analysis was initially conducted to consider only the closest potential sites to each dredge location and how many deposition sites will be needed (given assumed fill/compaction assumptions) to accommodate all dredged sediments from each dredge location. Distance and accommodation volume were the only variables considered in this analysis and the optimal solution is therefore predicated on the order of dredging operations.

Once construction and maintenance dredge volumes were identified and scheduled, an initial list of potential deposition sites was compiled. These sites were selected to have the capacity to absorb all dredged sediments from the channel deepening and to be optimized so that each site was selected based upon its proximity to the channel reach being dredged following the construction and maintenance schedules. The initial list of potential sites was compiled during the following steps:

1. An initial list of potential deposition areas were identified by GIS and provided to the Institute (orange polygons in Figure 1).

2. Additional potential depositions areas were identified from marsh creation project locations that were examined and included in the development of the 2017 Master Plan (CPRA, 2017) (blue hatched polygons in Figure 1).
3. The Caminada Headland Back Barrier Marsh Creation (BA-171) is currently undergoing project design for the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) program – the project area was added to the list of potential deposition sites.
4. In addition to the marsh creation sites identified above, locations for potential barrier headland beach and dune restoration and nourishment were identified (yellow polygons in Figure 1). The barrier island restoration template used in the 2017 Master Plan (Figure 2) was simplified and used to determine potential deposition volumes able to be placed on nearby barrier islands.


Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 1. Initial location of potential deposition sites. Orange zones were initially identified by GIS Engineers, blue zones are sites analyzed in the 2017 Coastal Master Plan, and yellow zones are potential barrier headland beach and dune restoration sites.

The distance between dredge pump locations and the centroid of each potential fill location (identified above) was determined in ArcGIS (Attachment 4). For each pump location, the potential deposition sites were listed in order of increasing distance. As an assumed dredging schedule was followed, the closest sites to each dredge location were selected until enough sites were chosen in which the cumulative fill volume at the respective sites exceeded the volume of dredged sediments pumped from the given dredge location. Any given deposition site was only allowed to be selected for one dredge location - so the further along the assumed dredge schedule, the further the sediment may need to be pumped to find a potential deposition site that had not already been filled in previous dredge schedule steps.

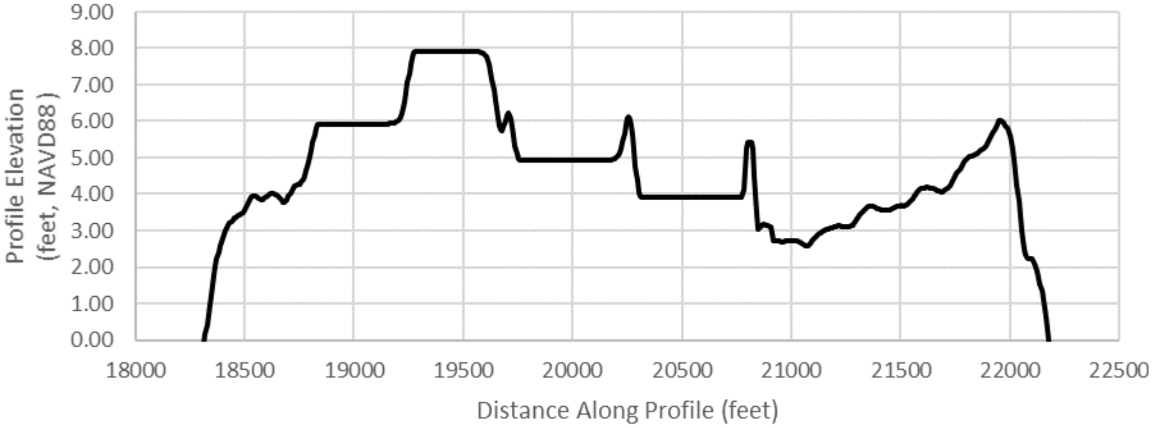

Figure 2. Barrier island/headland cross-shore profile design template developed for the 2017 Coastal Master Plan. The template is implemented on an existing cross-shore profile – assumed construction elevations begin at profile distance 18750 and extend through the back-barrier marsh platform which ends at distance 20800.

Updated List of Potential Deposition Sites with Agency Guidance

Upon compilation of the first list of potential deposition sites, engineering staff conducted a field visit with federal agency employees from the US Army Corps of Engineers (USACE) and US Fish and Wildlife Service (USFWS) to solicit guidance and input. Upon examination of the sites, and throughout follow-up conversations, the federal agency employees provided guidance which resulted in an updated list of potential sites. An objective of the updated site list was to minimize negative environmental impacts to existing marsh habitat (in particular, with respect to wetland value assessments). It was advised that any beneficial use of dredge material should be placed only in deep open water habitat (defined as water with a mean depth greater than 3.0-ft) or to be used as beach and dune nourishment along the West Belle Pass and Caminada headlands. This guidance rendered the vast majority of the sites included in the initial list as unsuitable for placement of dredged materials. Therefore, the initial list was edited by taking the closest site to each dredge pump location (as described above) and finding the nearest area of water deeper than 3.0-ft.

The guidance to avoid dredge disposal deposition on top of any existing marsh habitat also impacted the barrier headland beach and dune restoration and nourishment sites. As stated previously, the fill capacity volume on the headland was calculated from an adjusted version of the barrier island restoration project template developed for the 2017 Coastal Master Plan (Figure 2); this template included a portion of back-barrier marsh creation which had to be removed from the barrier headland deposition sites in order to comply with USFWS guidance.

Updated List of Potential Deposition Sites to Account for Sediment Grain Size Analysis

One final update to the potential deposition sites was made after GIS Engineering conducted a grain size analysis on sediment cores taken at the off-shore dredge locations. The sediment to be dredged during construction phases had a relatively low quantity of sand, a potential concern for placement on beach and dune habitat during restoration projects. Therefore, the barrier headland dune and beach restoration project sites were removed from consideration. The sediment that was originally intended for deposition on the barrier headland sites was now assigned to be deposited in deep water in the near-shore area of the Gulf of Mexico. This near-shore nourishment was recommended by the USFWS staff in order to provide some sediment nourishment to the eroding beach and dune habitat of the West Belle Pass and Caminada Headlands, while not incurring any negative impacts upon the existing beach and dune habitat that is currently present on these headlands.

FILL VOLUME CALCULATIONS

Two potential dredge disposal plans were provided by GIS for this analysis, a Base Plan (NED Plan) and a Tentatively Selected Plan/Locally Preferred Plan (TSP/LPP). These disposal plans provided volumes of dredged sediment for each project year (for both construction and maintenance phases) and identified a deposition site to which the sediment was pumped to build a marsh creation project. For each deposition site, the existing topobathymetric digital elevation model (DEM) was used to calculate the created habitat footprint area. Initial elevation and land cover data were taken from data files generated in 2014 for use in the 2017 Coastal Master Plan (Couvillion, 2017). The existing elevation value for each 98.4-ft (30-m) raster pixel in the DEM was compared to an assumed design fill elevation. This vertical fill depth was then multiplied by the pixel area of 0.22-acres (900-m^2) to calculate the required fill volume for each raster pixel. The fill volume pixels were then summed for each potential deposition site, resulting in a total fill volume capacity for each deposition site. If the dredged sediment volume provided in the dredge plan was less than the total capacity of the corresponding deposition site, then the filled area footprint was reduced to account for the limited amount of dredged sediment; for example, if a 100-acre deposition site (Site A) could accommodate 100,000-yd^3, but only 80,000-yd^3 was dredged from Reach A (which was closest to Site A), then only 80-acres of marsh were assumed to be built at Site A. The total fill capacity of the final list of sites, the footprint area of the site, and the water depth statistics of each site are provided in Table 2.

The fill elevation for the marsh habitat was assumed to be 4.0-ft North American Vertical Datum (NAVD88); this assumption was based on a compaction curve (Figure 3) for a nearby marsh creation project under design for the Coastal Wetland Planning, Protection, and Restoration Act (CWPPRA) (CPRA, 2016). Site-specific geotechnical analyses will need to be conducted during engineering design to accurately parameterize compaction properties of the actual dredged sediments from this project. These updated compaction curves will then need to be used with updated bathymetric surveys, sea level rise rates, and subsidence assumptions to develop a final design elevation for the marsh creation projects. For this analysis, it was assumed that the highest fill elevation (4.0-ft) would be used in order to estimate a conservative (e.g. minimum) area of created marsh from beneficial use of dredged materials. If during the engineering design process, lower sea level rise or compaction rates are used, a larger amount of marsh creation area would be able to be built than that calculated in this analysis. Additionally, the higher the assumed fill elevation, the longer the created marsh will remain functional before being overwhelmed by the higher rates of relative sea level rise in the future.

Table 2. Fill capacity, area, and depth statistics for each of the final deposition sites.

Site	Volume to Fill Deep Water Area to 4-ft NAVD88 (cubic yd)	Total area of site footprint (acres)	Maximum Water Depth (ft)	Mean Water Depth (ft)	Standard Deviation of Water Depth (ft)
MC_004	4,305,072	334.5	5.68	4.44	0.72
MC_005	4,722	0.4	3.01	3.00	0.00
MC_006	912,275	85.4	7.27	3.18	0.45
MC_015	657,175	55.2	4.48	3.71	0.46
MC_016	1,801,227	149.4	4.63	3.90	0.47
MC_017	244,536	21.6	4.27	3.45	0.34
MCN_001	4,155,836	310.7	7.42	4.74	1.58
MCN_002	9,134,917	638.5	8.48	5.30	0.86
MCN_003	13,530,021	878.9	8.54	5.96	1.27
MCN_004	8,815,022	716.6	5.20	4.05	0.51
MCN_005	156,211	12.5	4.49	3.46	1.32
MCN_006	12,043,183	900.3	5.53	4.73	0.52
MCN_007	7,902,469	634.9	5.33	4.17	0.60

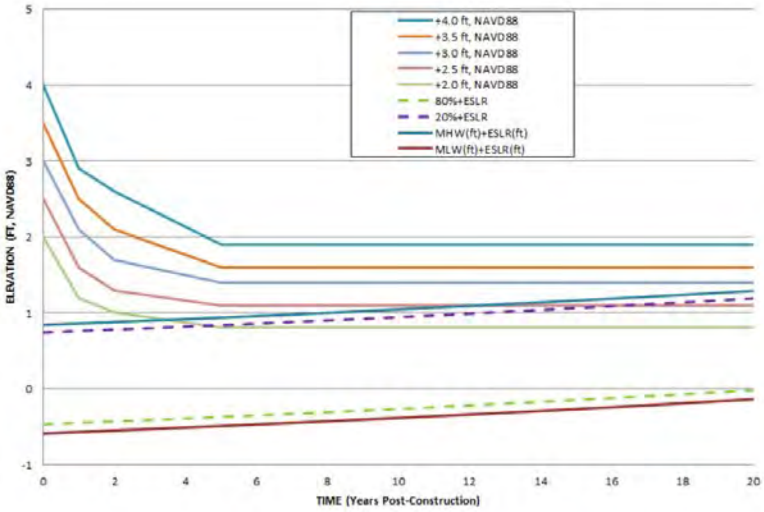

Figure 3. Marsh creation fill and compaction curves developed for the CWPPRA BA-171 project. This compaction curve graphic includes the sea level rise assumption used for BA-171 and does not reflect the scenarios assumed for this analysis (figure from CPRA, 2016).

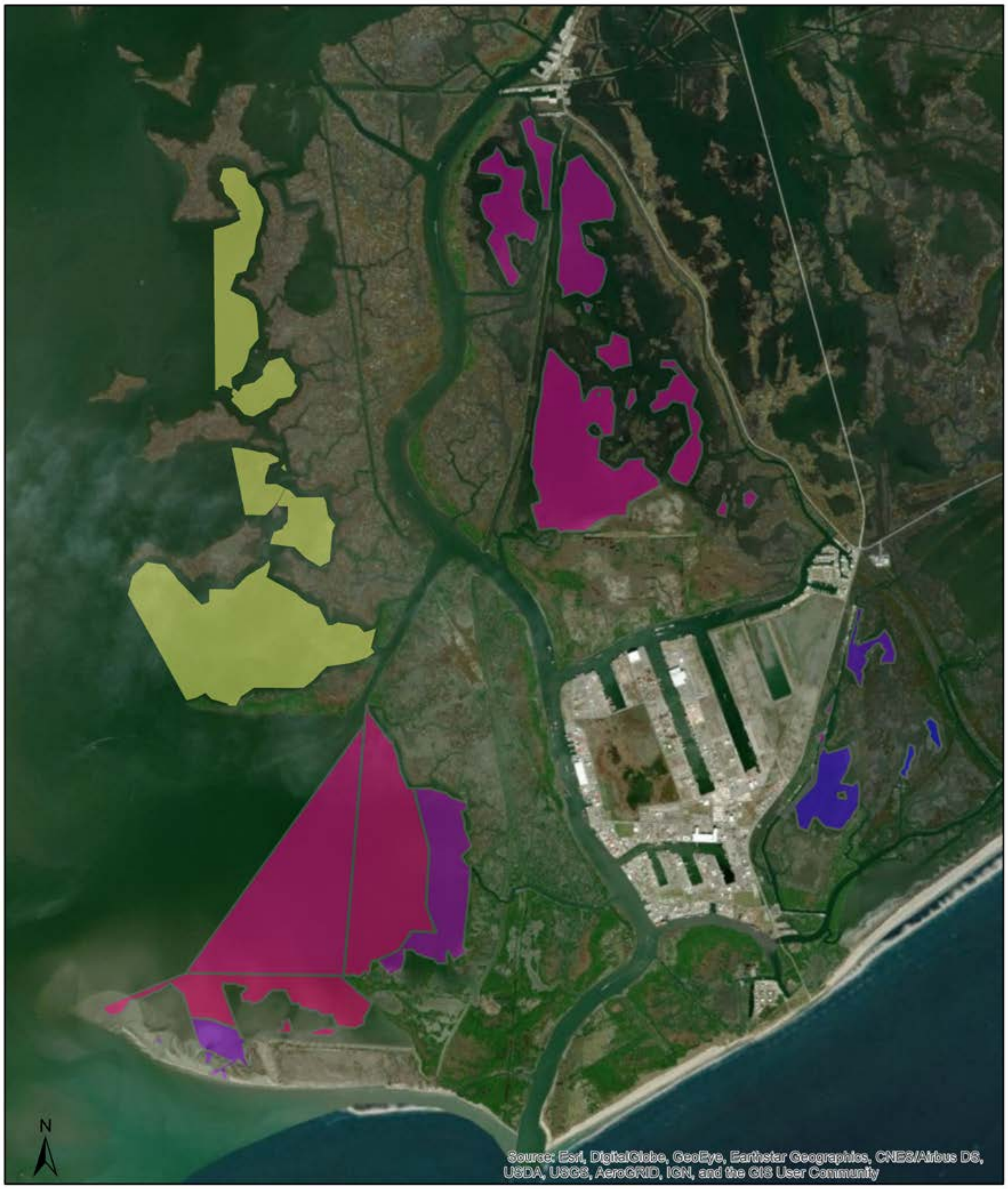

Figure 4. Final deposition sites for beneficial use of dredged materials from the construction and maintenance NEDP and TSP/LPP dredge schedules.

INITIAL ELEVATION DATA

Marsh and open water areas

The topobathymetric DEM used to define initial condition elevations for the water, emergent marsh, and other land areas (excluding the barrier headlands) for this analysis was developed by the U.S. Geological Survey in 2014 for use in Louisiana's 2017 Coastal Master Plan. The elevation data is relative to

NAVD88, Geoid 12A and has a 98.4-ft (30-m) horizontal resolution. The DEM has a spatial coverage of the entire coastal zone of Louisiana and extends into the Gulf of Mexico; it was developed from the most recent Lidar data that was available in 2014 as well as the most recent bathymetric soundings. The data sources, methods, detailed imagery, metadata, and discussion of errors and uncertainties of the data are documented in the technical appendices to the 2017 Coastal Master Plan (Couvillion, 2017).

In February 2018, staff from the U.S. Army Corps of Engineers, the U.S. Fish and Wildlife Service, GIS Engineering, and The Water Institute of the Gulf conducted a field visit to the potential disposal sites. During this field visit, bathymetric transects were conducted in several water bodies to cross-check the bathymetric elevation values represented in the topobathymetric DEM. The transect depths were measured throughout the course of an entire day, and no observations were made regarding the tidal cycle for the day. The tidal amplitude for the nearest Coastal Reference Monitoring System (CRMS) site (CRMS0292-H01, located adjacent to the Port, just west of Bayou Lafourche) varies from approximately 0.5-ft to 1.5-ft (observed data was only available up to 2/6/2018 at the time that this report was prepared). The depths as represented by the mean water surface elevation (described below) and the topobathymeric DEM were within the range of the tidal amplitude at all transects measured (Table 2), with the exception of one transect (MC016_TR_03), which had a difference of 1.6-ft. This indicates that, at least at the sites examined, there are no large discrepancies between the DEM and the actual water depths recorded in the field.

Table 3. Comparison of field-collected water depth transects to the topobathymetric DEM-derived water depths at each respective transect location.

	Depth (feet) from Topobathymetric DEM			Depth (feet) from Site Visit on 2/26/2018		
Transect	Mean	Min	Max	Mean	Min	Max
BC_Tr_01	2.37	1.40	3.14	2.47	1.1	4.2
BC_Tr_03	2.10	0.15	2.91	2.63	1.3	3.2
BC_Tr_04	3.12	1.93	3.40	2.62	1.1	3.3
BC_Tr_05	2.66	0.46	4.51	2.37	1	3.3
BC_Tr_06	2.54	0.49	4.03	3.08	1.6	5.2
MC016_Tr_01	2.00	0.77	2.53	2.07	0.6	3
MC016_Tr_02	3.11	1.80	4.03	2.92	0.4	4.4
MC016_Tr_03	0.34	-0.94	2.31	1.94	1	3.8
MP006_Tr_01	1.65	0.17	3.56	2.22	1.2	3.2

Barrier headland areas

The topobathymetric DEM described above was under development during the construction phases of the Caminada Headland Beach and Dune Restoration Project (CPRA, 2017). Therefore, the topobathymetric DEM only included a relatively coarse (~100-ft grid) representation of the original project design elevations. Since then, post-construction elevation survey data of the restored Caminada Headland have been made publicly available (John Chance Land Surveys, Inc., 2016). These survey data were used to develop a current set of cross-shore profiles that were used in the 2017 Coastal Master Plan barrier island morphology model (BIMODE) to determine dune and supratidal habitat areas under both a future without additional action (FWOA) and a future with both the Base and Locally Preferred Dredge Disposal Plans, as described below.

SEA LEVEL RISE SCENARIOS

The Wetland Value Assessment (WVA) input variables for emergent marsh and barrier headland habitats were developed for the two dredge disposal plans and a future without additional action; all three disposal plans were analyzed across three scenarios of eustatic sea level rise (ESLR). The low scenario (e.g. most optimistic) scenario assumed that historic rates of ESLR would continue, resulting in 1.0-ft (0.31-m) of ESLR by the year 2100. A medium scenario assumed that there would be 3.3-ft (1.0-m) of ESLR by 2100, and the high scenario assumed an ESLR by 2100 of 4.9-ft (1.5-m). These rates only represent the changes to eustatic mean sea level and adjustments were made to account for local vertical land movement (from subsidence and sediment compaction) to determine a project-specific rate of *relative* sea level rise (RSLR).

Subsidence

To approximate rates of vertical land movement, the regional values of expected subsidence rates that were utilized in both the 2012 and 2017 Coastal Master Plans were used here. These plans both utilized a range of expected subsidence rates and in accordance with both the low and medium scenarios assumed in the 2017 Master Plan, the 20th percentile subsidence rate for the Port Fourchon region was assumed for this WVA analysis. This assumption resulted in a constant annual subsidence rate of 0.35-in/yr (8.8-mm/yr) which was applied to the three ESLR rates described above to develop three RSLR scenarios.

Mean sea level

A present day mean water surface elevation was assumed to be equal to +0.43-ft (NAVD88). This average water level was calculated from the four closest CRMS stations to Port Fourchon. These CRMS sites all monitor hourly water surface elevation and have long-term mean values representing present conditions calculated for a period from 2013 through 2017. Site CRMS0164-H01 has a mean water surface elevation of 0.54-ft, site CRMS0178-H01 has a mean of 0.59-ft, CRMS0292-H01 has a mean of 0.36-ft, and CRMS0310-H01 has a mean water surface elevation of 0.25-ft (all elevations are relative to NAVD88, Geoid 12A). The overall mean water surface elevation of 0.43-ft was used to both define the current water depth (when compared against the topobathymetric DEM) and the starting water surface elevation to which all assumed ESLR scenarios were applied.

FUNCTIONAL MARSH AREA CALCULATION

Compaction of freshly deposited materials

The fill elevation for the marsh habitat was assumed to be 4.0-ft NAVD88; this assumption was based on a compaction curve (Figure 3). for a nearby marsh creation project under design for CWPPRA. The 95% engineering design report for the nearby CWPPRA project Caminada Headland Back Barrier Marsh Creation (CWPPRA BA-171) was used for this analysis (CPRA, 2016). Site-specific geotechnical analyses will need to be conducted during engineering design to accurately parameterize compaction properties of the actual dredged sediments from this project. These updated compaction curves will then need to be used with updated bathymetric surveys, sea-level-rise rates, and subsidence assumptions to develop a final design elevation for the marsh creation projects.

The compaction curve used for this analysis assumed that all marsh creation sites were to be filled to an elevation of 4-ft (NAVD88), with a final, settled elevation of 1.9-ft (NAVD88). The compaction curve was followed for the first four years, after which the assumed subsidence (described above) and vertical accretion rates (described below) were the only factors affecting the vertical position of the marsh surface within the tidal frame.

Vertical accretion

In addition to the subsidence and compaction acting to decrease the elevation of the created marsh surface over time, an assumed vertical accretion rate was also included to increase marsh surface elevation in the calculations. The vertical accretion values were taken from a combination of observed and simulated data; the organic component was taken from observed CRMS data while the inorganic (e.g. mineral) sediment deposition was taken from numerical hydrodynamic simulations conducted for the 2017 Coastal Master Plan.

As input data for the 2017 Coastal Master Plan model runs, a spatial dataset of soil organic matter and bulk density was derived from CRMS data for each habitat type (e.g. saline marsh, brackish marsh, fresh marsh, etc.). From data at all CRMS sites state-wide, the organic matter and bulk density data were averaged by marsh habitat type and coastal basin. For example, an average organic matter value for all brackish marsh CRMS sites located within Terrebonne Basin would have a separate value than all brackish marsh sites located with Barataria Basin. Based upon present day marsh habitat (and observed salinities) in the vicinity of Port Fourchon, it was assumed that all emergent marsh habitat built from dredge disposal deposits would be saline marsh. The average annual organic accumulation from all saline marsh CRMS sites within Terrebonne and Barataria basins is 488 g/m^2. The average soil bulk density from these same saline sites within the Terrebonne and Barataria basins is 0.30 g/cm^3. In the 2017 Coastal Master Plan model runs, the model predicted an approximate annual inorganic sediment deposition rate of 80 g/m^{2}in the Port Fourchon/Bayou Lafourche region of the model. These assumed bulk density, organic and inorganic loading values resulted in an and annual net positive vertical accretion of the marsh platform elevation of 0.09 in/yr.

Functional marsh area multipliers

Due to the initial fill height (e.g. land elevation above the tidal prism before compaction), the total area which received dredge disposal/deposition was not assumed to immediately be functional marsh. Rather, over time, as the deposited material compacts and marsh vegetation emerges, the area of created land that is considered to be functional marsh will increase. Per recommendations from the U. S. Fish and Wildlife Service, the functional marsh area was adjusted in the first five years post-construction in the following manor:

- 10% of the deposition area is functional marsh in years 1 and 2, if no plantings are made. If the site is planted, 25% of the area is assumed functional.
- 30% of the deposition area is functional marsh in years 3 and 4, if no plantings are made. If the site is planted, 100% of the area is assumed functional.
- 100% of the deposition area is functional marsh in year 5 whether or not plantings occur.

This analysis assumes that no manual plantings will be made on the dredge disposal sites.

Inundation-induced marsh collapse & shallow water determination

The same inundation-induced collapse thresholds used for saline marsh areas in the 2017 Coastal Master Plan were assumed here to determine the persistence of created emergent marsh habitat under future RSLR and accretion scenarios (as described in sections above). The thresholds used here were developed from height in the tidal frame (as measured at CRMS sites) and the prevalence of the vegetation coverage, as represented by the normalized difference vegetation index (NVDI). Inundation collapse thresholds were defined for three salinity-tolerant marsh habitat types: intermediate marsh, brackish marsh, and saline marsh (Couvillion and Beck, 2013). It was assumed in the master plan models (and repeated for this analysis) that saline marsh would collapse to open water if inundated by the annual mean water level by at least 9.2-in (23.5-cm), as determined from the NVDI methodology.

Once a created marsh area was inundated too deep to persist as emergent marsh, the WVA input variable for emergent marsh was decreased to zero, and the entire deposition area was assumed to be shallow water habitat. This shallow water habitat would persist until the RSLR (from both ESLR and subsidence assumptions) continued at such a rate in which the water depth was greater than 1.5-ft, which is no longer considered shallow for WVA purposes.

BARRIER HEADLAND PROFILE CHANGES

BIMODE simulations

The determination of emergent marsh and shallow water habitat WVA input variables are fairly straightforward functions of fill height, saline marsh inundation tolerance, and assumed accretion and RSLR scenarios. The determination of dune and supratidal habitat WVA input variables for the barrier headland WVA equations, on the other hand, are slightly more complex and required the use of a numerical tool which can simulate both long-shore and cross-shore sediment transport processes. To that end, the barrier island morphology model (BIMODE) developed for the 2017 Coastal Master Plan (Poff et al., 2017). BIMODE, was used for calculating the change in dune and supratidal habitat area on both West Belle Pass and Caminada Headlands as a function of the RSLR scenario and dredge disposal plan.

BIMODE is a temporal model developed to simulate barrier island morphological changes for a set of cross-shore profiles that are spaced at 328-ft (100-m) in the long-shore direction and have an elevation point at every 6.5-ft (2-m) in the cross-shore direction. The morphological changes to each cross-shore profile are modeled based on a set of SBEACH simulations which were run a priori to develop a “lookup library” of cross-shore profiles and respective profile change due to simulated storm conditions. For each profile in the model domain, a single model timestep consisted of a month of average tidal and wave conditions and (if scheduled) a storm surge and wave event. If a storm event was scheduled to occur in the simulation, the respective modeled timestep would also include the associated storm surge and wave conditions. For the 2017 Coastal Master Plan, the historic hurricane record from 1964 through 2013 was used, and it was for this analysis as well (with year 1 corresponding to 1964).

At each timestep, both cross-shore and long-shore transport processes were simulated, and the resultant profile shape was compared to the profiles contained in the lookup library. The pre-simulated profile that matched the closest with the timestep’s resultant profile was used to replace the modeled profile for the next time step. In this manner, the event-based SBEACH model was utilized in a temporally dynamic manner which substantially reduced computational time and resources required for multi-decadal simulations. The BIMODE simulations are therefore dependent on the shape of profiles that were run a priori in SBEACH; which included both a suite of existing cross-shore profiles and a suite of profiles that were adjusted to fit into the 2017 Coastal Master Plan barrier island template (as described above).

As discussed in previous sections, the post-construction surveys for the Caminada Headland Beach and Dune Restoration project were used to update the initial starting elevation for each BIMODE profile. The three RSLR scenarios were then simulated for 50-years, with the historic hurricane record, and the same assumed subsidence rate as used for the marsh deposition sites. Both the Base and Locally Preferred Plans for dredge disposal assume the same amount of sediment is deposited at the potential barrier headland sites, following the construction template shown in Figure 2. The marsh creation portion of the template (located on the bay-ward side of the dune) was incorporated into the emergent marsh WVA analysis, and the dune and beach portions of each BIMODE profile were analyzed to determine the amount of dune and supratidal habitat that would be present for each simulated year. For this analysis, supratidal habitat was defined as area on either side of the dune that was between 2.0-ft and 5.0-ft above the annual mean water level. Dune habitat was defined as any portion of the beach that was greater than 5.0-ft above the annul mean water level. As the water surface elevation increased over time due to the assumed RSLR scenarios, this relative height above water value remained constant. Therefore, an area with an elevation at 6.0-ft NAVD88 was initially considered dune habitat since it was 5.57-ft above the initial mean water surface elevation of 0.43-ft NAVD88. However, after 0.57-ft of RSLR, this same area would no longer be considered dune habitat, but instead would be classified as supratidal.

As the BIMODE simulations progressed in time, the location of the dune consistently migrated bay-ward under both future with and without the two dredge schedule options (NEDP and TSP/LPP). As the dune migrated, the back-bay marsh area that had previously been considered emergent marsh habitat, would be subject to overwash deposition and would transition to higher supratidal and/or dune habitat. To account for this overwash and migration phenomena, the spatial extent over which the dune and supratidal habitats were tabulated had to be adjusted each year.

The cross-shore profiles for the initial year were first analyzed to find both the shoreline location (again assuming a mean water surface elevation of 0.43-ft NAVD88 and the furthest bay-ward extent of supratidal habitat. These two extents defined the initial zones of barrier headland habitat and emergent marsh habitat for the potential deposition sites on West Belle Pass and Caminada Headlands. The model output was then examined to determine the furthest bay-ward extent to which the dune migrated throughout the 50-year simulations. While the migration rate varied over time as a response to the storm strikes, the overall migration was used to calculate an average annual migration rate for the dune. The initial zone for dune and supratidal habitat was extended bayward by 45-ft each simulation year to account for this overall average overwash/dune migration. As the dune and supratidal habitat footprint increased in size each year, the corresponding emergent marsh habitat areas on the bay-ward side of the headlands were reduced by the same spatial extent to conserve the overall project footprint area and to not double-count overwash areas in both the dune/supratidal and emergent marsh WVA quantities.

Similar to the calculation of functional emergent marsh in the years immediately post-project, the same multipliers used for years 1 through 4 were used for dune and supratidal areas. As suggested by the U.S. Fish and Wildlife Service, calculated dune and supratidal areas were reduced to 10% of the total area during years 1 and 2, while vegetation was assumed to be establishing. The area reduction was 30% for years 3 and 4. For years 5 and after, the dune and supratidal areas were assumed to be 100% functional habitat.

While this analysis examined the capacity of the barrier headland locations to absorb dredged materials to reach the design elevations of the Coastal Master Plan barrier headland design template, the final site selection (Figure 4) excluded any barrier headland sites from consideration. This decision was made by GIS and the permitting/regulatory staff completing the EIS based upon sediment cores that were taken in the proposed channel deepening location offshore. These sediment cores indicated sediment grain size distribution with a relatively low portion of sand-sized sediments. Previous barrier headland restoration projects at Caminada utilized dredged sediments from Ship Shoal, which contain a high portion of sand. The team decided that sediment characteristics of the proposed deep channel location were likely not suitable for barrier headland deposition and only the marsh creation sites were selected as potential beneficial use deposition sites.

Off-shore beach nourishment disposal in open water areas

Both the Base and Locally Preferred Plan dredge cycles include a portion of the dredged sediments to be disposed of in the open water portion of the Gulf of Mexico immediately adjacent to the Caminada and West Belle Pass headlands, with the expectation that this near-shore placement would result in entrained sediment reaching and nourishing the beach and dune areas under normal tidal and wave conditions. However, the profiles included in the BIMODE lookup library did not account for any sediment nourishment in the off-shore open water areas. Theoretically, the project template (Figure 2) could be updated to include these nourishment deposits in open water; however, since no profiles representing this condition were included during the model development phase, this deposition would essentially be "smoothed over" at the end of the first model timestep.

Due to this inability to capture the beach and dune nourishment that may occur as a result of deposition in the off-shore open water areas adjacent to the shoreline, the dune and supratidal input variables to the barrier headland WVA are likely under-represented in both the Base and Locally Preferred Plans. However, since this deposition is to occur off-shore, it is our understanding that there would be no negative WVA impact from this placement (e.g. it is not being placed overtop existing dune or supratidal habitat). Therefore, by excluding this nourishment deposition, it is assumed that the dune and supratidal WVA benefits under the future with both plans are likely under-predicted in this analysis. This nourishment disposal plan was unable to be assessed with the BIMODE simulations and is therefore excluded from the WVA input variables.

Conclusion

This analysis utilized existing datasets of topobathymetric elevation, assumed sea level rise values, assumed marsh accretion and subsidence rates, and marsh collapsed under inundation stress to examine the viability of created marsh area from beneficial use of dredge materials. The analysis was founded on construction dredge volumes and schedules provided by GIS Engineers that are being submitted in an environmental impact statement for the Port's proposed development and expansion projects. Additional dredge volumes from channel maintenance operations were estimated with a Delft3D model and provided for an assumed project life cycle of 50-years. The selection of potential deposition sites were constrained by input from regulatory staff throughout the process of preparing the EIS. The final site selection determines the footprint of present open water that will likely be required to absorb the entire volume of dredge materials from the channel deepening construction project and operational maintenance.

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PARTNERSHIP FOR OUR
WORKING COAST

Partnership for Our Working Coast: Port Fourchon Phase 1 Technical Report

Chapter 2: Impacts of Subsidence on Critical Infrastructure and Communities in The Port Fourchon Region

Phase 1: Data Gathering and Gap Analysis

DIANA DI LEONARDO, MEAD ALLISON

Produced for and funded by: Shell, Chevron, and Danos

August 20, 2018

INTEGRATING APPLIED RESEARCH | LINKING KNOWLEDGE TO ACTION | BUILDING PARTNERSHIPS

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SUGGESTED CITATION

Di Leonardo, DR and MA Allison. (2018). Supporting the working coast: Impacts of subsidence on critical infrastructure and communities in the Port Fourchon region, Task 1: Data gathering and gap analysis. The Water Institute of the Gulf. Prepared for and funded by Shell, Chevron, and Danos. Baton Rouge, LA.

Preface

In September 2017, the Water Institute was contracted by the Supporting the Working Coast: Port Fourchon Coalition to collect and synthesize existing data to build a better understanding of the subsidence rates in the Port Fourchon region—both in refining the ranges and the spatial variability. The goal of this work was to (1) provide a better assessment of the future risks that subsidence might pose to the Port's infrastructural assets and to surrounding communities on the headland from Larose, LA to the Gulf, (2) provide the best available rates of the subsidence contribution to local relative sea level rise to apply in predictive modeling that is another sub-task of the Water Institute's effort, and (3) identify gaps in extant subsidence information that could be used to develop a Phase 2 plan targeting additional site-specific data collection and analysis of subsidence rates in the Port Fourchon region. This work was carried out by the Physical Processes & Sediment Systems (PP&SS) team at the Water Institute. For further information, the chief technical contact is the lead author, Diana Di Leonardo from PP&SS, who can be reached at ddileonardo@thewaterinstitute.org.

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List of Acronyms

Acronym	Term
ALACE	Airborne LiDAR Assessment of Coastal Erosion
CPRA	Coastal Protection and Restoration Authority
CoNED	Coastal National Elevation Database
CORS	Continuously Operating Reference Stations
CRMS	Coastwide Reference Monitoring System
JALBTCX	Joint Airborne LiDAR Bathymetry Technical center of Expertise
LADOTD	Louisiana Department of Transportation and Development
LECZ	Low elevation coastal zone
LiDAR	Light Detection and Ranging
LGS	Louisiana Geological Survey
NOAA	National Oceanic and Atmospheric Administration
NGS	National Geodetic Survey
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

Acknowledgements

Thanks to Ryan Clark of The Water Institute of the Gulf (the Institute) as well as Margaret Keogh, Krista Jankowski, and Anjali Fernandes for help with data acquisition during the development of this report.

This report was reviewed by Brendan Yuill of the Institute.

This project was supported by Shell, Chevron, Danos, and the Greater Lafourche Port Commission.

1.0 Introduction

Subsidence is known to be a major challenge along the Louisiana coast, and due to the low-lying nature of the Louisiana coast, threatens infrastructure in many areas (Coastal Protection and Restoration Authority of Louisiana, 2012, 2017). The causes and rates of subsidence vary across the state and are an area of active research (eg., Meckel, 2008; Shinkle & Dokka, 2004; Törnqvist et al., 2008; Yuill et al., 2009; Kolker et al., 2011; Jankowski et al., 2017). The plausible range of subsidence rates across Louisiana reported in the 2012 Coastal Master Plan is 0 to 35 mm/yr (0 to 1.38 in/yr). Port Fourchon is a low-lying area of the Louisiana coast and an area with significant infrastructure that is important to the economy in the U.S. and Louisiana. It is also within an area that is predicted within the Master Plan to see subsidence rates of 6 to 25 mm/yr (0.24 to 0.99 in/yr).

Port Fourchon has a significant impact on the oil and gas industry, and hence, on the U.S. economy. According to the Greater Lafourche Port Commission, over 250 companies use Port Fourchon as a base of operations. Port Fourchon plays a strategic role in furnishing the United States with about 18% of its entire oil supply. Over 1.5 million barrels of crude oil per day are transported via pipelines through the port. Overall, Port Fourchon presently services over 90% of the Gulf of Mexico's deep-water oil production. In addition, this port is the land base for LOOP (Louisiana Offshore Oil Port), which handles 10-15% of the nation's domestic oil, 10-15% of the nation's foreign oil, and is connected to 50% of US refining capacity. LOOP is the only US deep-water port capable of offloading VLCCs (Very Large Crude Carriers) and ULCCs (Ultra Large Crude Carriers).

Loren C. Scott & Associates estimated the impact on the U.S. economy of a three-week loss in services from Port Fourchon due to damage from a hurricane, a terrorist attack, or some other destructive phenomenon. The results of *The Economic Impact of Port Fourchon: An Update, 2014* imply that a three-week loss in services would lead to a loss of $11.2 billion in sales at U.S. firms; a loss of $3.2 billion in household earnings in the U.S., and a loss of 65,502 jobs nationwide.

This report aims to provide (1) a summary of location-specific subsidence rates from existing literature studies and (2) a map-based presentation of these subsidence rates to highlight the spatial variability of subsidence rates around Port Fourchon.

2.0 Study Area

The Port Fourchon region is centered over the Lafourche subdelta of the Mississippi Delta: this 10,000 km^2 (3,861 mi^2) subdelta was active in forming deltaic deposits that make up the near surface stratigraphy from about 1.6-0.6 ka (1,600 to 600 years before present) (Tornqvist et al., 1996; Hijma et al., 2017; Chamberlain, 2018). Bayou Lafourche, that transects the area from north to south, was the last trunk channel of the Mississippi River in the subdelta's growth and reached its seaward shoreline limit by about 0.6 ka (600 years before present) (Figure 1; Chamberlain, 2018). These were the last phase of deltaic growth over the Fourchon region in the late Holocene (e.g., last 7.5 ka), and hence provide one guide (natural geomorphological boundaries) for defining the bounds of the area of interest to the present study. The study area considered in this report (Figure 2) encompasses the area around Bayou Lafourche from

Grand Isle and Port Fourchon in the south, to north of Larose, Louisiana; Bayou Lafourche, because it roughly follows Louisiana Highway 1, also forms the main corridor for communities whose populace works at the Port, and in other professions that are reliant on the natural systems (e.g., fisheries, tourism, etc.) that surround the headland. Marshes approximately 15 - 25 km (9.3 to 15.5 mi) to the east and west of Bayou Lafourche were also included in the present assessment, based in part, on available aerial LiDAR coverage.

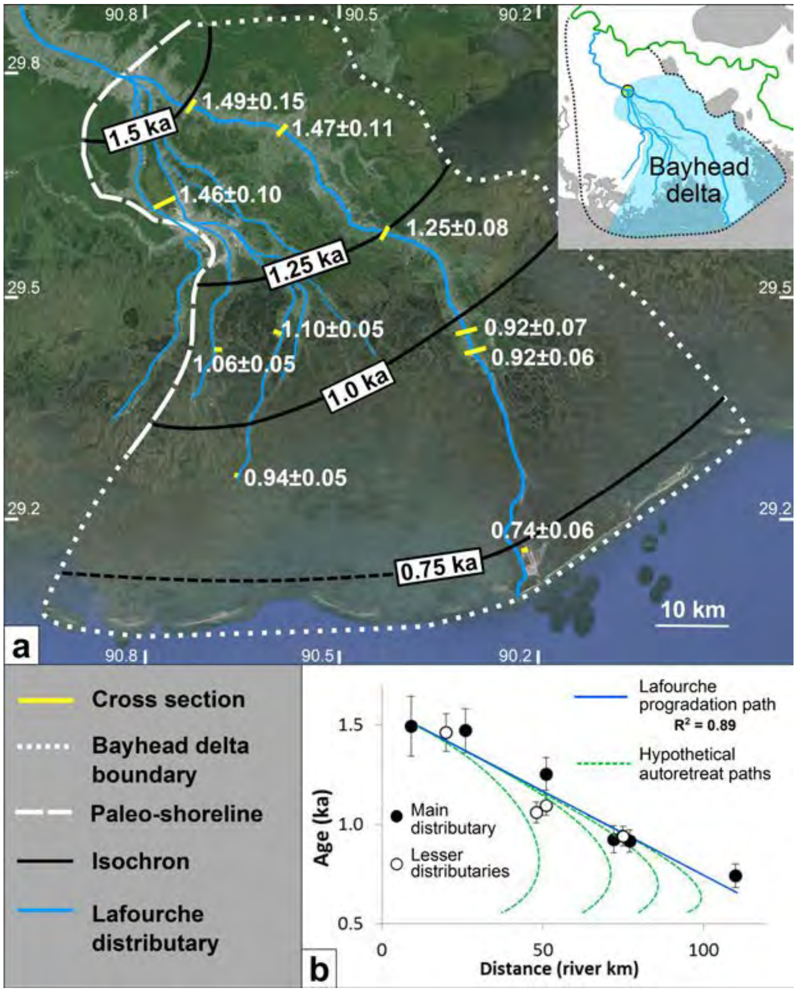


Figure 1. Growth history of the Lafourche subdelta from 1.6 to 0.6 ka. a. dated deposits (white numbers) used to construct the black lines that represent accretion extent through time. The bayhead delta is bounded to the north and west by a paleo-shoreline, to the south by transgressive (modern) Lafourche barrier islands, and to the east by open water (interdistributary lakes). b. The progradational history of mouth-bar deposits associated with the main channel (filled symbols) and lesser distributaries (open symbols) compared to the hypothetical paths that could be expected due to autoretreat (green dashed lines) of the Lafourche headland (from Chamberlain, 2018).

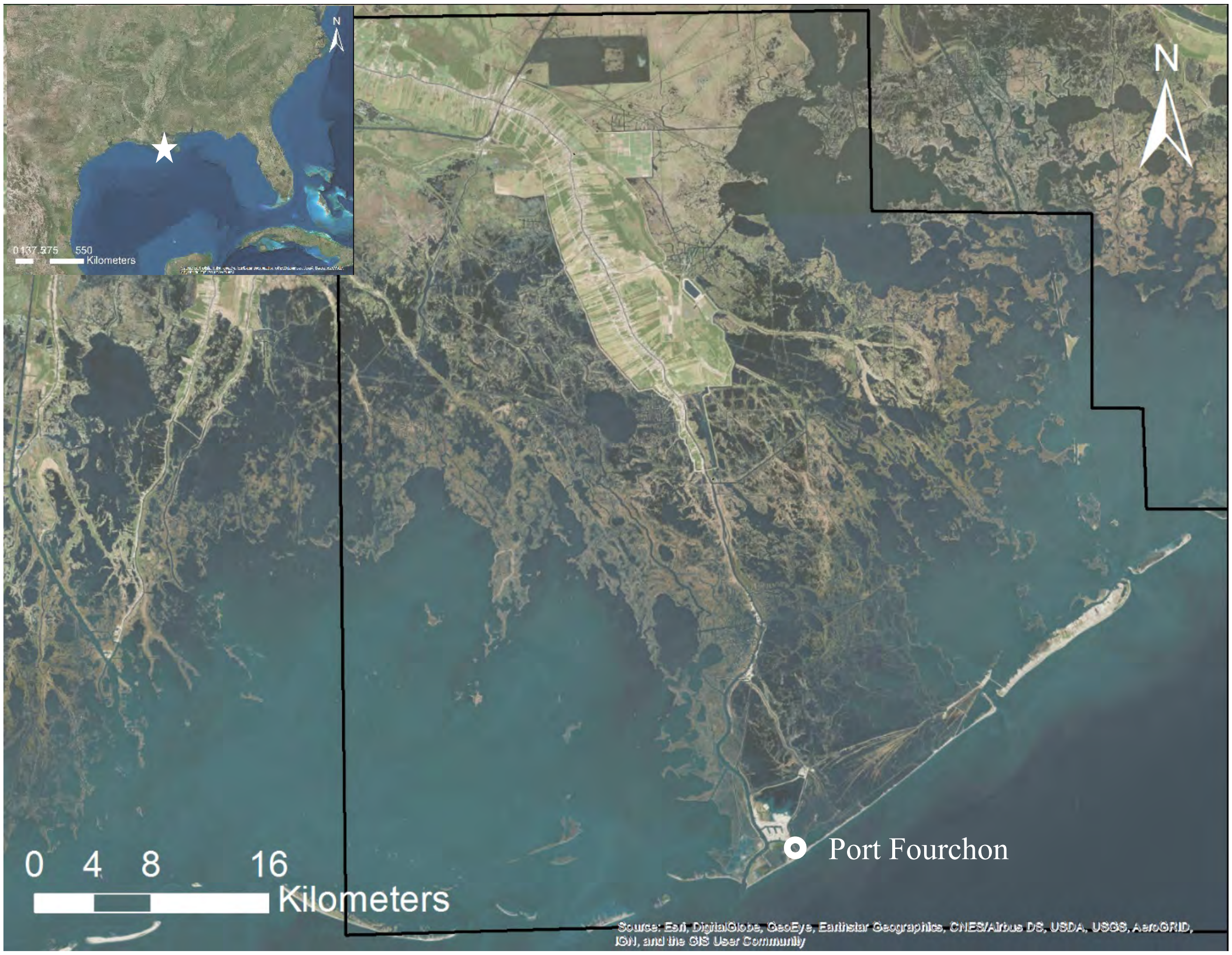


Figure 2. The study area covered by this report is shown within the black box. Port Fourchon is located at the southern end of the map and marked by the white circle. The Gulf of Mexico inset map shows the study area marked with a white star. All base map imagery was accessed through ESRI ("World Imagery, Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community," n.d.)

3.0 Subsidence in the Mississippi Delta: Mechanisms and Measurements

Low elevation coastal zone (LECZ, <10 m or 98 ft) areas are particularly vulnerable to climate change effects forecast for the 21st century—this includes the threat of inundation by accelerating climate-driven sea level rise and potential increases in severity and/or frequency of tropical storm surges. Natural and human-driven subsidence greatly compounds the risk of climate-driven elevation loss. The relative sea level rise (eustatic + subsidence) threat coincides with a worldwide surge in human population in coastal areas, including cities. In the US, the population in coastal counties rose from 47 million in 1960 to 87 million in 2008 (29% of total US population) and is forecast to rise even further in population percentage in the next 50 years. In addition, coastal settings are major centers for agriculture, fisheries, navigation, and hydrocarbon production, and for the built infrastructure that serves these industries, which increases both the risk, and because of industrial consequences, potentially the subsidence rates in and around coastal cities and industries.

Selected areas of the Gulf Coast are at a high risk of damage to ecosystems and built infrastructure caused by coastal subsidence at rates that significantly outpace present rates of eustatic sea level rise. Coastal subsidence risks to the Gulf coastal zone are focused in two regions, each driven by distinct subsidence mechanisms and with varying degree of amelioration possible. These two high risk areas are river deltas and cities. Subsidence in Gulf Coast river deltas—primarily the Mississippi-Atchafalaya delta that composes approximately two-thirds of the Louisiana coastal zone, but also potentially impacts relative sea-level rise in smaller Gulf deltas (e.g., Mobile-Tensaw, Rio Grande, Brazos) is a natural process that is primarily a response to compaction of thick, young, water-rich sediments laid down rapidly by deltaic processes. In unaltered deltas, this rapid compactional elevation loss is offset by equally rapid deposition of mineral (river-derived) and organic (wetland accumulation) sediments to maintain elevations at or near mean sea-level. In the Mississippi-Atchafalaya, alterations to river sediment supply from the basin caused by river management (e.g., dams, river control), artificial channel levees, and hydrological alterations beginning in the 18th century have reduced this offsetting process, leading to rapid coastal land loss and a threat to the remaining coastal wetland belt and the infrastructure built atop it (Coastal Protection and Restoration Authority of Louisiana, 2017). Two million residents of a unique Franco-American mélange culture live in the delta and support a fishery and navigation industry of national importance. In addition, billions of $US of oil and gas infrastructure (including Port Fourchon) is built on the most rapidly subsiding seaward part of the delta: including pipelines, ports, and refining facilities that service the deep-water production in the Gulf of Mexico. As outlined below, the spatial trends in subsidence across the Mississippi-Atchafalaya delta (and other Gulf deltas) remain poorly constrained.

Fluid extraction presents another major driver of coastal subsidence and creates "hotspots" of high risk throughout the Gulf Coast that become important to sustainability in low elevation areas. It is particularly important around cities, where fluids are extracted for potable and industrial uses, and for agriculture in surrounding rural belts. In satellite radar mapping of subsidence in New Orleans, Jones et al. (2016) identified circular areas of high subsidence under areas where groundwater is being extracted for cooling water (e.g., power plants, petrochemical facilities). In the Houston-Galveston area, subsidence from groundwater removal for industrial purposes is also recognized to have been a major driver of subsidence and wetland loss around Galveston Bay, and may be the most adversely impacted metropolitan area yet identified in the US (Coplin & Galloway, 2002). In fast growing Gulf cities of low elevation, the demands for potable, agricultural, and industrial water presents a major future elevation loss threat. Unlike deltaic subsidence, if extraction is halted, subsidence rates decline over a period of several decades. While groundwater has been identified as a key mechanism for subsidence in several Gulf cities, the potential role of deeper, hydrocarbon extraction over wider coastal areas since the 1930's remains poorly understood.

Multiple drivers operate at a range of spatial, temporal, and depth scales in the Mississippi Delta to control the magnitude of coastal subsidence in any particular area. A list of the major mechanisms operating in deltas are:

1. Sediment Compaction – A relatively shallow subsurface process caused by the reduction in porosity of sediments as they are compressed by rapid loading of additional sediments. Common, high-rate subsidence mechanism in thick, young, wet sediments deposited by deltas in the late Holocene.
2. Glacial Isostatic Adjustment – A deep process caused by the release in loading of the northern continental ice sheet and the rebounding of the crust of the Earth, including areas southward of the ice extent (e.g., forebulge collapse). Changes in magnitude with increasingly southerly latitude and is likely a minor process in Louisiana.
3. Regional Sediment Loading – A deep process caused by kilometers-thick sediment sections over locations like deltas deforming the underlying crust of the Earth. Likely active under the Mississippi Delta but at rates below 1 mm/y (0.04 in/yr).
4. Faulting – Growth faults are commonly forming at depth in the Mississippi Delta primarily along an E-W trend. Geophysical tracing of these faults and their offsets (which are indications of rates of slippage) has not been possible in the young, easily deformable sediments of the Holocene Mississippi Delta, but, indirect evidence, such as surficial marsh scarps, suggest they may be active at human time-scales at rates that are significant for coastal relative sea level rise (e.g., >1 mm/y) (0.04 in/yr).
5. Salt Dynamics – Deep-seated process of salt migration upward from the basal Jurassic Gulf of Mexico deposit that creates salt domes that penetrate the near surface in the coastal region. Unknown whether actively migrating upward and also unknown is the degree to which faulting and salt dynamics is inter-related.
6. Subsurface Fluid Withdrawal—Shallow (water) and deeper (hydrocarbon) processes of sediment compactional subsidence (mainly from fine-grained layers between aquifers) caused by reduction in pore pressure and re-alignment of sediment grains. Well-established in New Orleans and elsewhere as a subsidence cause associated with groundwater withdrawal. Has been observed with hydrocarbon withdrawal in other global areas of extraction, but hydrocarbon withdrawal not established definitively to date (see Kolker et al., 2011) as a mechanism for subsidence in the Mississippi Delta.
7. Realignment of Natural Drainages (decomposition and oxidation of organic material)—Most typically observed associated with shallow groundwater withdrawal (e.g., New Orleans), which depresses the water table, exposing organic-rich soils in the subsurface to oxygen-induced oxidation (organic matter converted to CO_2) and collapse.

Subsidence rates engendered by shallow processes such as sediment compaction and fluid withdrawal can be one to two orders of magnitude greater than the rate of climate-driven sea level rise predicted for the remainder of the 21st century (Figure 3). The risk of rapid coastal subsidence to infrastructure and economies, as well as to the natural environment in the Mississippi Delta is acute. These subsidence effects are compounded when compensating clastic sediment supply is sealed off by flood control or storm-protection levees.

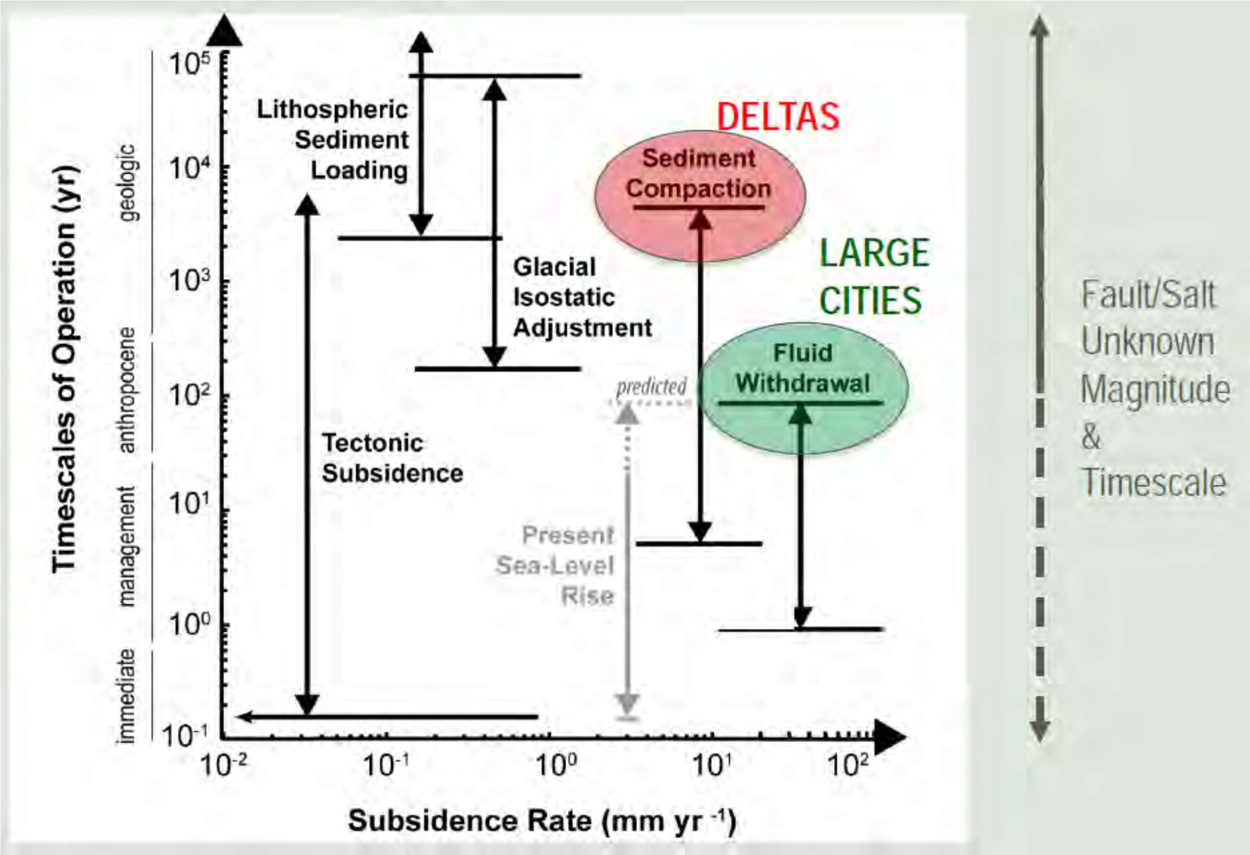


Figure 3. Plot of major coastal subsidence mechanisms and their rates and timescales of operation. The rates of subsidence and their operation on human time-scales (10^{-1} to 10^{2} years) remain poorly constrained. The present eustatic sea level rise and the predicted eustatic sea level rise by 2100 (possible range shown by dotted line) are also plotted, demonstrating the important contribution of subsidence to relative sea level rise in coastal areas. (Eustatic sea level changes are driven by changes in the volume of water in the ocean or changes in the shape of ocean basins rather than by land elevation changes.) Modified from Allison et al. (2016).

Burgeoning LECZ demand for groundwater, particularly in and around urban areas, to utilize for potable, industrial (power plant cooling, etc.), and agriculture purposes also accelerates subsidence by reducing aquifer fluid pore pressures. A dramatic example can be found in the Huang He Delta, China, where groundwater removal for coastal aquaculture has resulted in subsidence hot spots of 250 mm/yr (9.8 in/yr) (Higgins et al., 2013). Major hydrocarbon production zones are also sites of rapid subsidence, where fluid withdrawal can generate accelerated subsidence that can last for up to several decades after the extraction period (Kolker et al., 2011). Coastal areas often contain extensive Holocene-age peat deposits that are the product of carbon burial in wetlands. When shallow aquifers are deflated by water use or drainage for urbanization or other land use changes, they are exposed to oxidation and respond by rapidly collapsing (subsiding). In Southeast Asia, these peatlands are predicted to be reduced from 90% to 20% intact between 1990 and 2020 due to deforestation and drainage for agriculture, resulting in subsidence rates of up to 30-60 mm/yr (1.2 to 2.4 in/yr) (Hooijer et al., 2012).

Deeper processes that result in vertical motion including, for example, thermal subsidence, compaction and fault motion, also contribute to coastal subsidence and their rates are often poorly constrained across the LECZ. However, these deeper processes typically contribute less than 1 mm/yr (0.04 in/yr). Developing subsidence mitigation plans to reduce elevation loss in coastal areas like Port Fourchon that are at risk from increased flooding caused by sea level rise and large storms requires a combination of measurement and monitoring strategies capable of addressing several main challenges. The first challenge is accurately measuring the spatial and temporal changes in elevation associated with subsidence. Ground-based monitoring stations that measure ground elevation can be expensive, if comprehensive. Proxy methods like tide gauges, GPS stations and geodetic levelling surveys only show the portion of the total subsidence rate at a site that is related to their depth of foundation. Satellite methods are becoming available, such as Interferometric Synthetic Aperture Radar (InSAR), but have not been applied in the Mississippi Delta to date beyond New Orleans. The second challenge is deconvolving the drivers and quantifying their respective contributions to the total subsidence rate expressed at the land surface. While this is critical to a scientific understanding of the processes, that can ultimately lead to the development of multi-parameter numerical models that can predict subsidence in an area, this is not critical to the needs of the Port Fourchon corridor in our estimation. A well-developed spatial understanding of the total subsidence rate (e.g., total elevation change) is most critical for future planning for infrastructure and population protection. The total subsidence rate is related to the total elevation change at a site by different factors depending on if it is a natural (wetland) or human-modified (leveed towns and agricultural areas). In a wetland, total elevation change is the total subsidence rate plus the eustatic sea level rise rate (relative sea level rise) minus the accretion of new sediment (organic + mineral). In leveed areas where there is presumably no new accretion, relative sea level rise rate defines the total elevation change.

4.0 Subsidence Data for the Port Fourchon Area

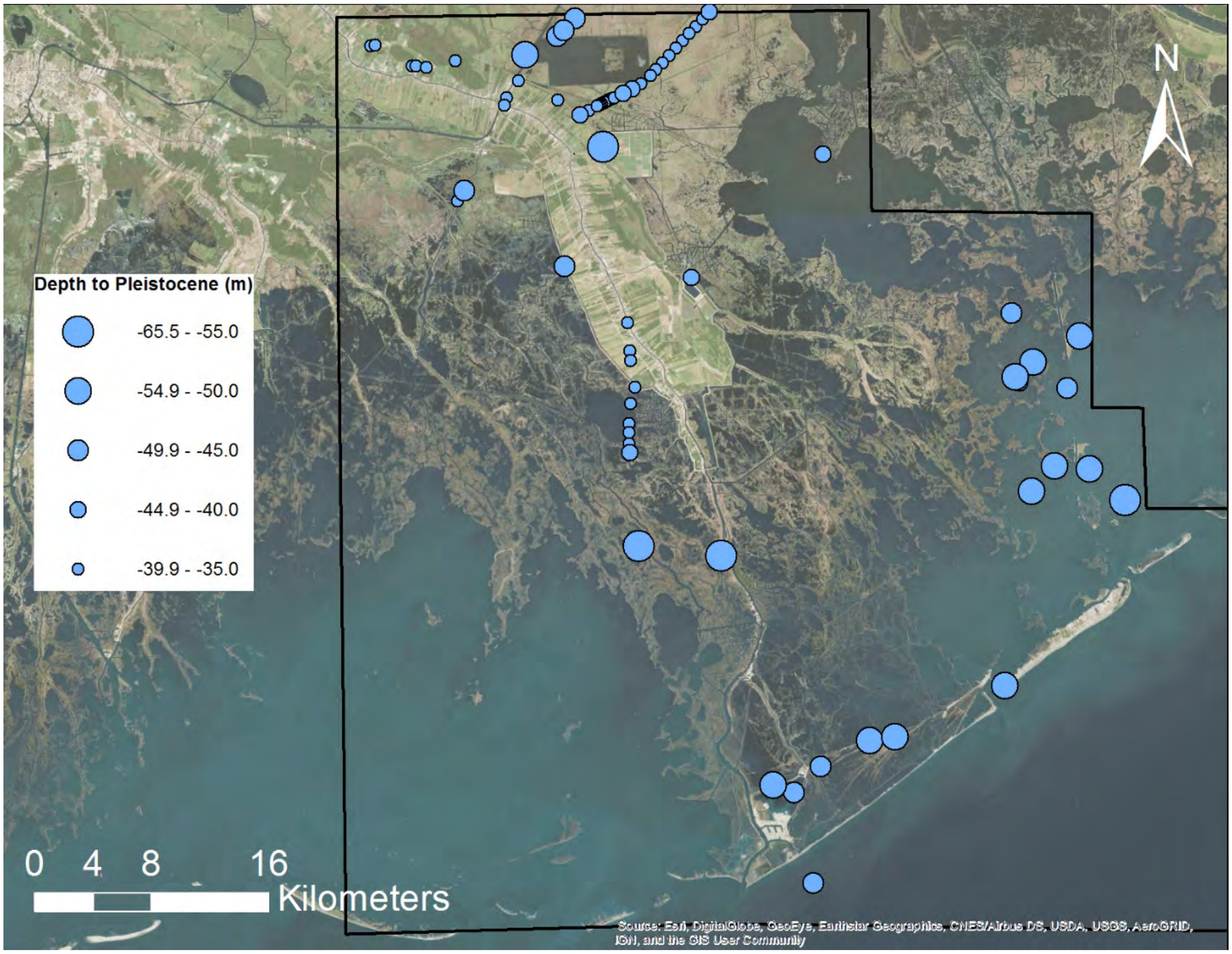
The following sections define individual indicators of subsidence in the study area. Some, such as thickness and character of the young (Holocene) sedimentary section, are not direct indicators, but provide information that may be informative about the possibility and magnitude of compaction-induced subsidence. Others are direct indicators (e.g., levelling surveys, tide gauges, etc.) but only measure subsidence over a portion of the total subsurface from the ground to the center of the Earth. Some combined methods presented below (CRMS stations plus continuous GPS) have been used to derive a total subsidence rate. Finally, remote sensing methods (e.g., LiDAR and InSAR) can be used as proxies for subsidence by measuring total elevation change).

4.1. SUBSURFACE DATA

4.1.1. Holocene-Pleistocene Surface

In 2015 the Louisiana Geological Survey (LGS) completed an investigation into existing borehole records in Louisiana to develop a Holocene-Pleistocene surface (H-P surface) model (Heinrich et al., 2015). The report combined 3,012 data points across Louisiana, of which 75 are located within the study area. From the H-P surface the relative thickness of Holocene sediment deposits as well as changes in thickness can be determined. Holocene thickness is useful for subsidence studies because sediment compaction occurs primarily in these relatively recent deposits (Törnqvist et al., 2008). Holocene thicknesses in the study area (the Lafourche delta) range from 35 m (115 ft) to more than 65 m (213 ft)and are generally greater to the south (Figure 4).

This trend in the thickness of the youngest fluvio-deltaic sedimentary section deposited in the Fourchon area would generally suggest an increased compactional subsidence potential for the southern section of the study area. However, this generalization can be influenced by the age of the units at various depths, and by sediment type(s). A recent study in the Lafourche corridor by Chamberlain (2018) showed a positive correlation between the amount of compaction-induced subsidence units deposited at sea level had undergone since deposition (i.e., greater thickness of sediment above the unit was correlated with greater compaction), but no correlation with overall Holocene thickness. This may suggest that compactional subsidence at depth in the Holocene section may slow if there has been little recent sediment loading. However, data are not available for how recently that slow-down in deposition has to occur to impact subsidence rates: Lafourche lobe deposition halted some 0.6 ka (600 years before present), for instance.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 4. Holocene-Pleistocene contacts as identified by Heinrich et al. (2015). Each circle represents the location of a soil boring and is scaled to the depth below the surface of the contact.

4.1.2. Soil Borings and Cone Penetrometer Data

The Louisiana Department of Transportation and Development (LADOTD) completed a dense data set of soil borings and cone penetrometer measurements from Golden Meadow to Port Fourchon between 2003 and 2011 as part of Highway 1 bridge foundation planning (Figure 5; Figure 6). Soil borings reached depths between 24 m (79 ft) and 69 m (226 ft) below the surface. Cone penetrometer (CPT) measurements were done to depths between 7 m (23 ft) and 63 m (207 ft). While borings and cone penetrometer measurements to these depths do not necessarily penetrate completely through the Holocene, they still provide valuable information about soil types that can be used to infer the future potential of sediments to compactionally subside. Sediments in this area are composed largely of interbedded layers of organic soils and peats and mixtures of clay, silt, and sand. While there is a wealth of data in these logs (Figure 5; Figure 6), a detailed spatial analysis of stratigraphic trends of individual layers and their geotechnical properties would require a significant organizational effort. This was not undertaken for the present Phase 1 effort due to the difficulty in linking past compaction, and future compaction potential with specific sediment types in the delta. With further analysis, the data in these logs can be expected to provide additional data points to map the H-P surface (Figure 4) that would augment those gathered by Heinrich et al. (2015).

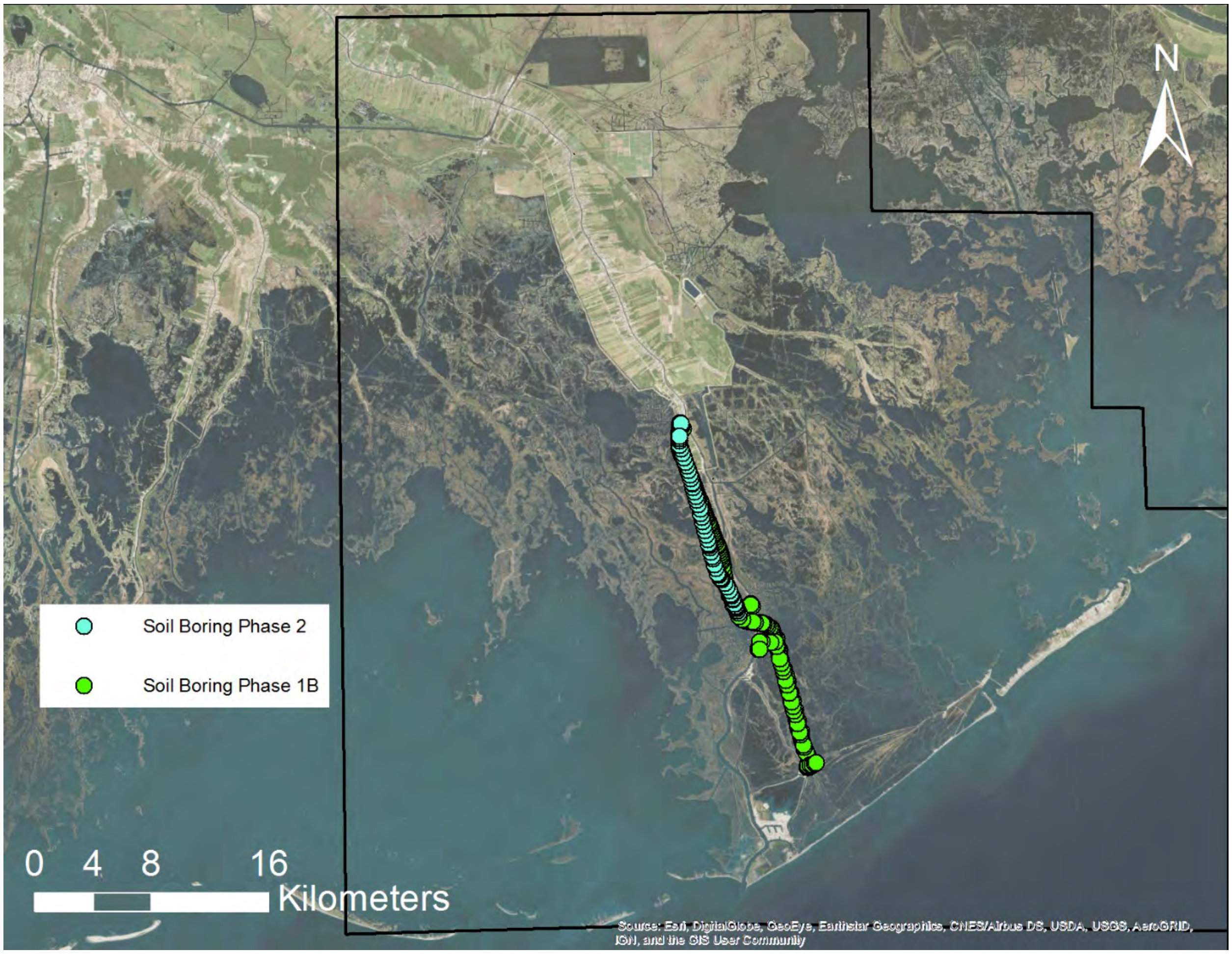


Figure 5. Soil borings completed by the LADOTD. The location of each boring is a circle on the map. Phase 1B represents borings completed in 2003 and 2004. Phase 2 represents borings completed in 2010 and 2011. In addition to the visible Phase 1B borings, they exist for the observed extent of Phase 2 borings.

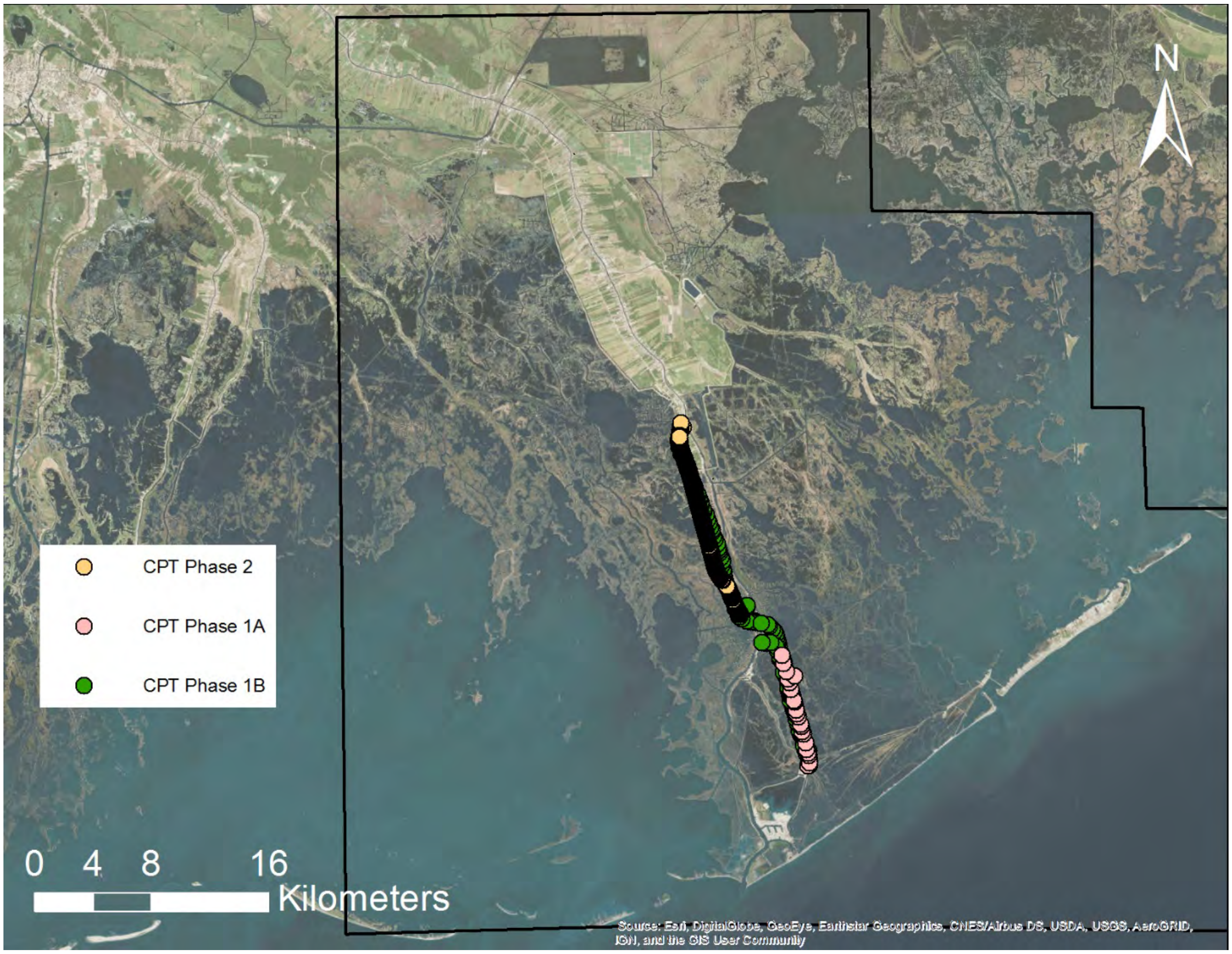


Figure 6. Cone Penetrometer (CPT) measurements by the LADOTD. Each circle on the map is a measurement location. Measurements from Phase 1A were completed in 2007. Phase 1B was completed in 2003 and 2004. Phase 2 was completed in 2010 and 2011. Phase 1B measurements also exist for the observed extent of Phase 2 borings.

4.1.3. Salt Domes

Salt domes are known to exist in the study area, but little information is publicly available, since most of the 3D information that identifies their extent in the subsurface was gathered by geophysical methods in proprietary industry field areas. Datasets provided by SEI: Seismic Exchange are the most accurate published map of salt dome extent in the subsurface in the Fourchon region (reproduced as Figure 7). However, these datasets of salt dome extents lack specific depth information about where the features are located (Nancye Dawers, personal communication).

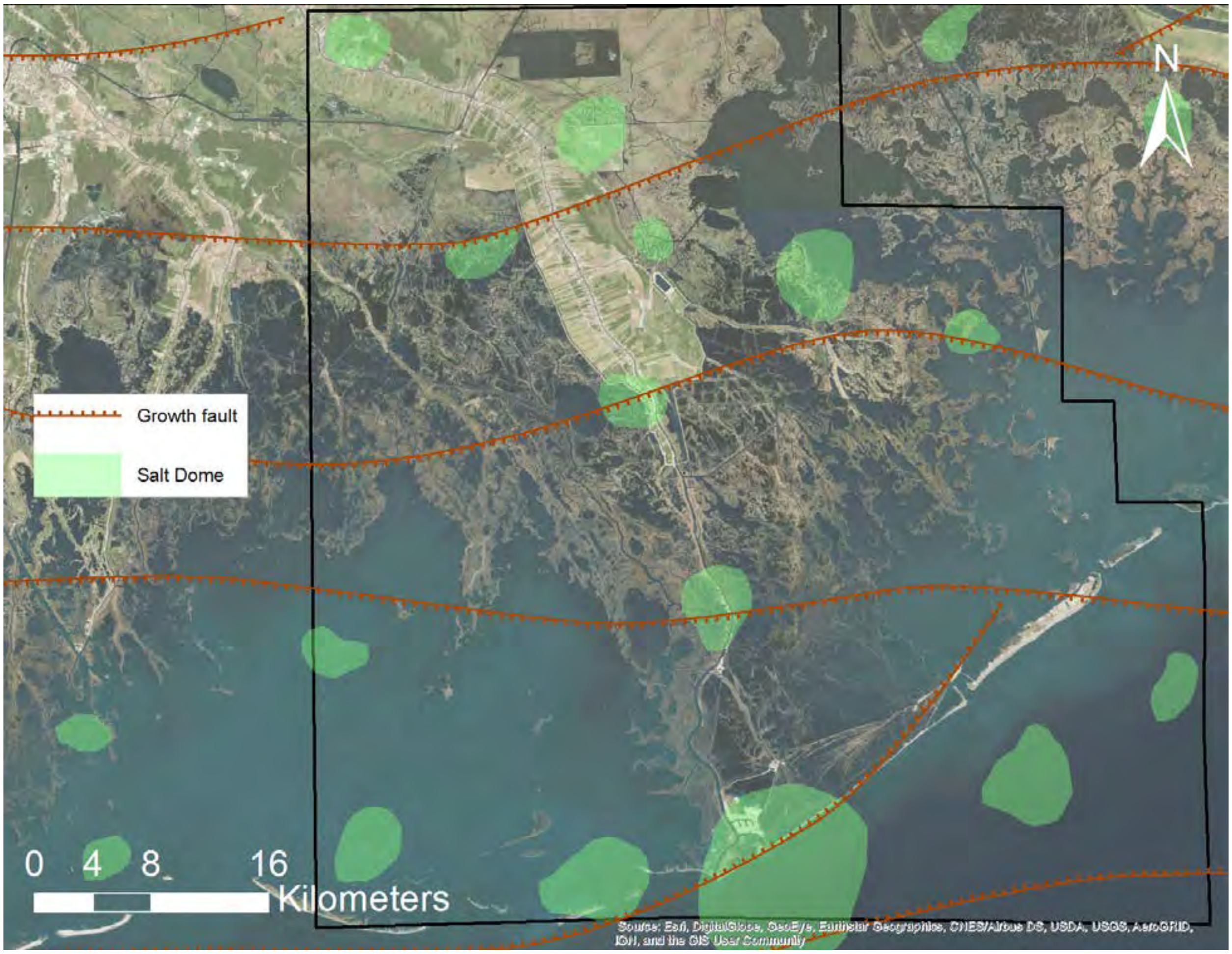


Figure 7. Map of salt domes and growth faults in the study area. Salt data was obtained from SEI Seismic Exchange. Growth fault data from the Database of the Geologic Map of North America (Garrity & Soller, 2009; Reed et al., 2005).

4.1.4. Faults

There are numerous faults in southern Louisiana as a result of Mississippi River delta growth and Gulf of Mexico Basin development (Yuill et al., 2009). Faults only induce subsidence if displacement along the fault causes lowering of the land surface. Multiple growth faults, including the Golden Meadow Fault, transect the study area (Figure 7; Kuecher et al., 2001; Reed et al., 2005; Garrity & Soller, 2009). Previous studies have demonstrated that fault slip is a driver of subsidence in Louisiana (Dokka, 2006), but whether or not faults are contributing to subsidence in the study area at present is an open question (and is an area of active research, Nancye Dawers, personal communication).

4.2. GEODETIC LEVELLING

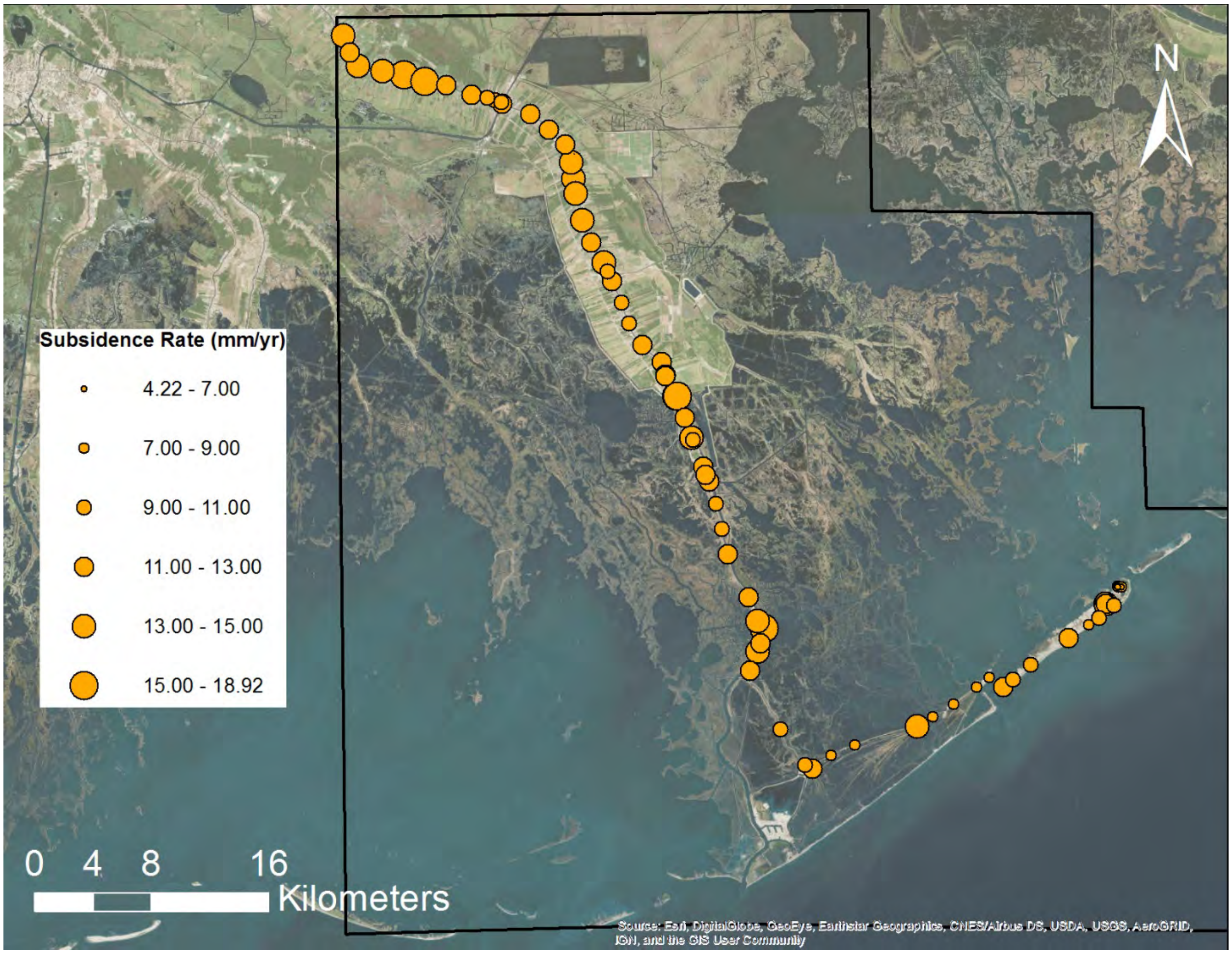
In 2004, Shinkle and Dokka analyzed over 2,700 National Geodetic Survey (NGS) benchmarks to compute vertical velocities in SE Louisiana using levelling surveys conducted by the NGS between 1920 and 1995. A levelling survey re-measures the elevation of benchmarks working from site-to-site using ground-based measurement methods; more recent levelling surveys use GPS measurement methods. The levelling surveys discussed in Shinkle and Dokka (2004) use ground-based measurement methods. If subsidence has occurred at a benchmark, the levelling survey would reveal it as a reduction in elevation, and knowing the time between measurements, a subsidence rate can be calculated. One of the levelling lines re-measured by the NGS in multiple levelling surveys during the 20th century runs through the study area along LA Hwy 1 from Raceland to Grand Isle (Figure 8). This levelling line was surveyed in 1965, 1982, and 1993. Within the study area there are 83 points at which a subsidence rate was computed for the 2004 study. The rates computed by Shinkle and Dokka (2004) using the levelling surveys were also compared to subsidence rates the study authors computed from Continuously Operating Reference Stations (CORS) GPS data (explained in more detail in section 3.5) and tide gauge estimates of subsidence in order to verify the levelling survey rates.

Over all, Shinkle and Dokka (2004) found that subsidence rates along coastal Louisiana are higher than those further inland. For the Raceland to Grand Isle levelling line, subsidence rates showed significant variability through space, ranging from 4.2 to 18.9 mm/yr (0.17 to 0.74 in/yr) (Figure 8). Grand Isle displays a lower subsidence rate than the rest of the LA Hwy-1 corridor to Raceland. Calculated subsidence rates for the 1982 to 1993 interval of the study for Grand Isle range from 4 to 6 mm/yr (0.16 to 0.24 in/yr), while rates near Leeville range from 12 to 15.5 mm/yr (0.47 to 0.61 in/yr).

Subsidence rates calculated by this method also change through time. Where there were data from more than two levelling surveys, Shinkle and Dokka (2004) computed the subsidence rate between each subsequent pair to look at temporal changes. Levelling lines from 1965, 1982, and 1993 were analyzed for the Grand Isle to Raceland corridor yielding a rate from 1965 to 1982 and a rate from 1982 to 1993. The mean subsidence rates were 7.7 mm/yr (0.30 in/yr) for the first time period and 11.1 mm/yr (0.44 in/yr) for the second time period. No simple geographic trend was found in the change in subsidence rates.

The surface elevations and subsidence rates computed in this report are tied to the North American Vertical Datum of 1988. Because of active subsidence in Louisiana and especially because subsidence is not uniform in either space or time, this datum is no longer valid for surveys in Louisiana. Throughout Shinkle and Dokka (2004) elevations are extrapolated or interpolated using the calculated subsidence rates to co-locate elevations in time. Any small errors in subsidence rates would compound over time in the elevations. A second problem is associated with the depth of foundation of each benchmark. In these areas of thick Holocene sediments (35-65 m or 115-213 ft, as reported above), the foundation depth of the benchmark rests somewhere in the Holocene section and is different at each site. This fact means that if significant compactional subsidence is occurring in the Holocene section, the interval between the sediment surface and the bottom of the foundation is not included in the calculated subsidence rate (e.g., only measures subsidence deeper than the foundation depth to center of the Earth). Thus, while the subsidence rates in these levelling reports provide useful information, the elevations should not be considered quantitative or comprehensive for a site. GPS based datums are a better choice for our subsiding coast. These datums use a mathematical model of the earth in combination with GPS satellites to measure the elevation of any point.

Zou et al. (2015) attempted to interpolate this levelling survey analysis across Louisiana to evaluate the spatial pattern of subsidence. Rates across the Bayou Lafourche area ranged from approximately 15 to 20 mm/yr (0.59 to 0.79 in/yr). Rates were found to be highly spatially variable and increasing towards the south, echoing findings from the original study. However, the caveats mentioned in the previous paragraph also hold true for these results.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 8. Subsidence rates derived from the levelling survey study completed by Shinkle and Dokka (2004). Each of the 83 subsidence rates are represented by a circle scaled to the magnitude of the rate.

4.3. TIDE GAUGES

Analysis of tide gauges has long been a method of estimating subsidence (e.g., Penland & Ramsey, 1990; Shinkle & Dokka, 2004; Morton & Bernier, 2010; U.S. Army Corps of Engineers, New Orleans District, 2010; Kolker et al., 2011; Letetrel et al., 2015; Veatch, 2017). Tide gauges represent a relatively long term (multiple decades), continuously recording (hourly or sub-hourly rate), stable (in terms of horizontal position) monuments, which are an asset for subsidence studies. A challenge when using tide gauges to calculate subsidence is that the effect of atmospheric/meteorological, astronomical, and eustatic sea level rise must be removed from the data to capture only changes in the land surface. Hence, tide gauges must be operating long enough to capture the full range of variability induced by these processes within their records, typically exceeding about a 20-year period of record.

Two tide gauges within the study area have been operating long enough to be used for subsidence studies (Figure 9). The Grand Isle tide gauge is operated by the National Oceanic and Atmospheric Administration (NOAA) and has been in operation since 1947 (Kolker et al., 2011). The Leeville tide gauge on Bayou Lafourche was operated by the U.S. Army Corps of Engineers (USACE) and was in operation between 1955 and 2000 (U.S. Army Corps of Engineers, New Orleans District, 2010; Veatch, 2017).

Using a tide gauge in Pensacola, Fl as a vertically stable (non-subsiding area) platform, Kolker et al. (2011) was able to remove the effect of eustatic sea level rise from the Grand Isle record to calculate a long-term subsidence rate of 7.59 +/- 0.23 mm/yr (0.30 +/- 0.009 in/yr) (Figure 10; Figure 11). This study also found that the subsidence at the tide gauge changed over time. From 1948 to 1958, the subsidence rate at Grand Isle was 3.16 +/- 1 mm/yr (0.12 +/- 0.04 in/yr). From 1958 to 1991, a time period of peak subsurface fluid withdrawal in the area, the subsidence rate increased to 9.82 +/- 0.33 mm/yr (0.39 +/- 0.01 in/yr). From 1992 to 2006, the subsidence rate decreased to 1.04 +/- 0.97 mm/yr (0.04 +/- 0.04 in/yr).

Veatch et al. (2017) calculated the relative sea level rise (RSLR) rate for 30 USACE gauges in Louisiana with at least 40 years of data. The analysis applied a simple linear trend in the data for the entirety of the record. In order to calculate a subsidence rate from the reported RSLR rate, a eustatic sea level rise rate of 2 mm/yr (0.08 in/yr) was assumed. The RSLR rate at the Leeville gauge is reported as 10.8 mm/yr (0.43 in/yr), yielding a subsidence rate of 8.8 mm/yr (0.35 in/yr) (Figure 12).

It should also be noted that tide gauge records used for subsidence are also impacted by the foundation issue mentioned for levelling surveys. That is, a typical tide gauge is referenced to a set of benchmarks placed on a land—a primary benchmark with a deep foundation, and shallower secondary and tertiary benchmarks that are emplaced to test whether the primary benchmark has been disturbed. In the case of both the Grand Isle and Leeville tide gauges, the primary benchmark depth of foundation is in the Holocene section, and hence, does not measure shallow compactional subsidence of the Holocene above the foundation depth. Thus, the rates reported must be treated as <u>minimum</u> estimate of subsidence rates for the sites.

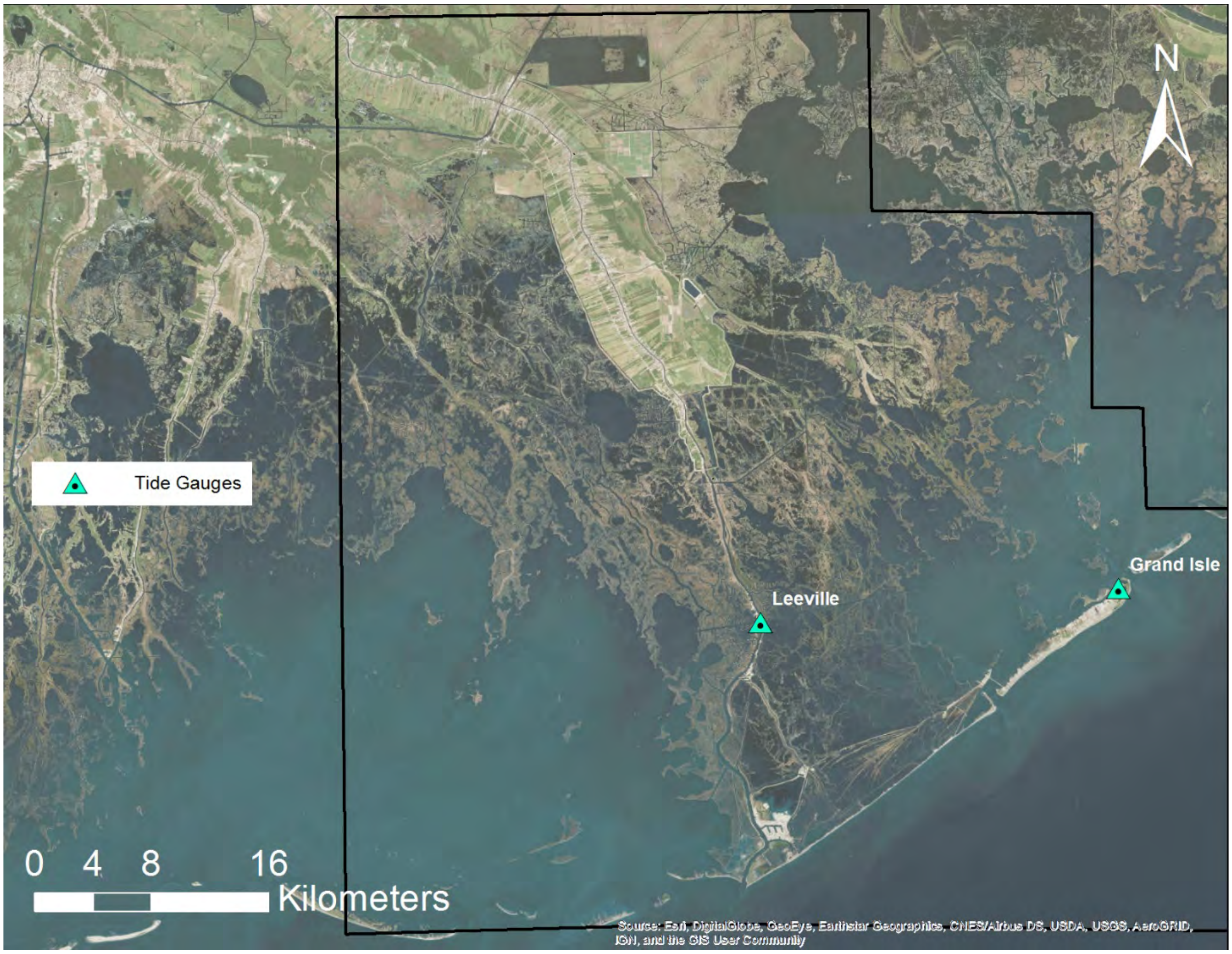


Figure 9. Tide gauges located within the study area. Only two tide gauges within the study have a record that is sufficiently long for subsidence rate calculations. The Grand Isle gauge is operated by NOAA. The Leeville gauge was operated by USACE until 2000.

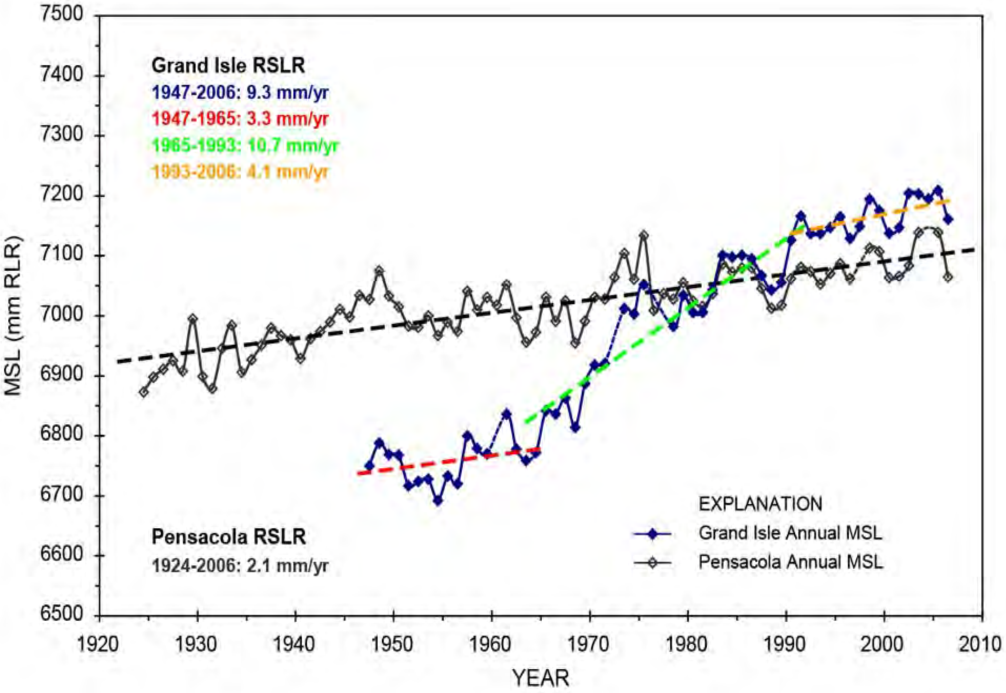


Figure 10. Sea level rise from the Pensacola and Grand Isle tide gauges. The Pensacola tide gauge is located on stable carbonate basement; thus, it records eustatic sea level rise. The Grand Isle tide gauge shows additional RSLR not attributable to eustatic sea level rise. Reproduced from Kolker et al. (2011).

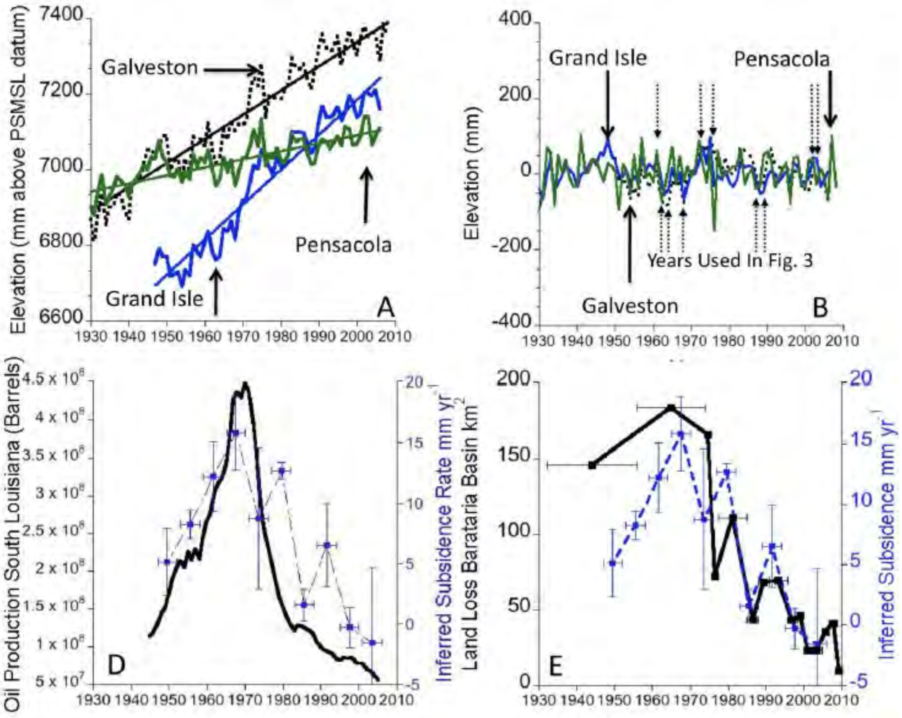


Figure 11. Sea level records from three Gulf coast tide gauges. A. Raw tide gauge data with Grand Isle in blue, Pensacola in green and Galveston in black. B. Detrended RSLR. D. Oil production in south Louisiana (black line; Meckel, 2008) and inferred subsidence rate for six year periods at Grand Isle (blue line; mm/yr). E. Land loss in Barataria Bay (black line) and inferred subsidence rate at Grand Isle (blue line; mm/yr; Couvillion et al., 2011). Reproduced from Kolker et al. (2011).

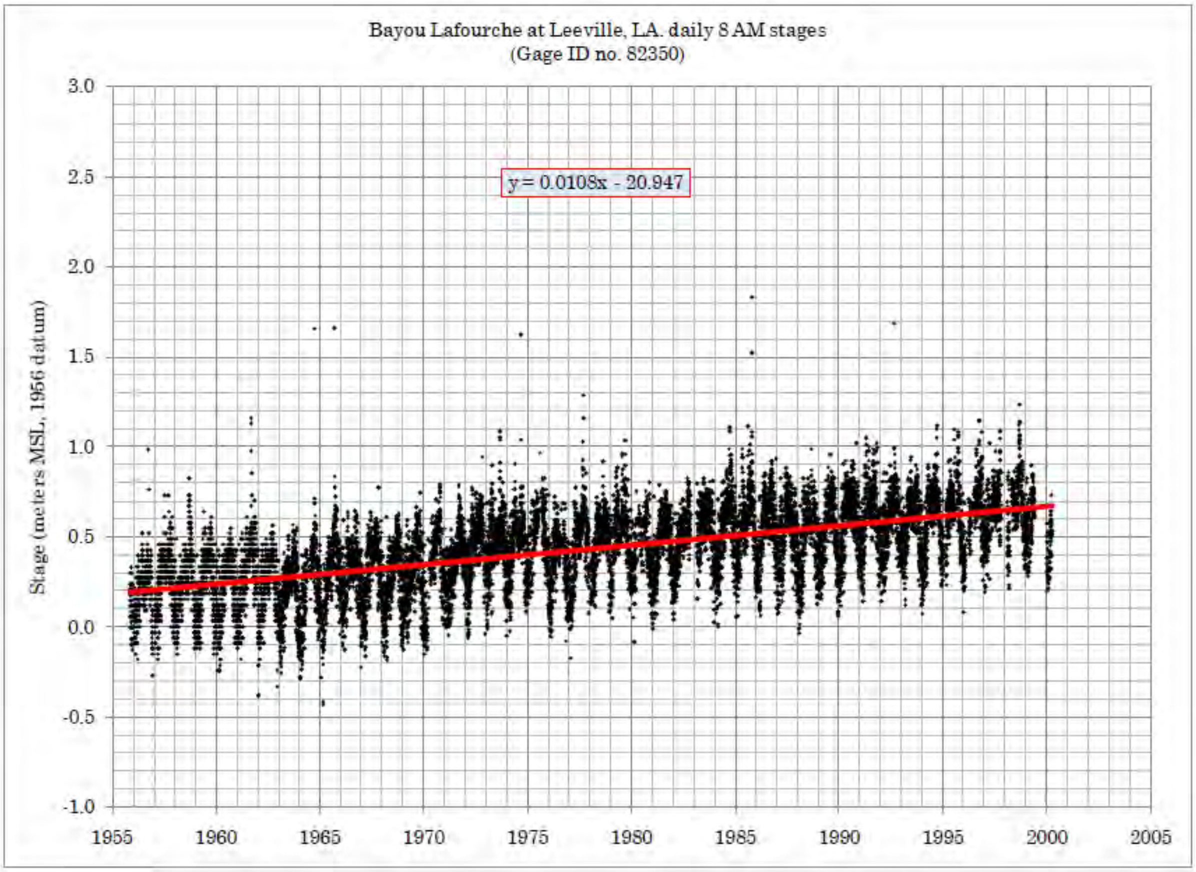


Figure 12. Relative sea level rise calculated from the Leeville tide gauge. Linear regression on daily stage measurements yield the long term relative sea level rise rate at this location. Reproduced from U.S. Army Corps of Engineers, New Orleans District (2010).

4.4. COASTWIDE REFERENCE MONITORING STATIONS (CRMS)

CRMS sites are a set of almost 400 locations across Louisiana that are used as reference stations to evaluate restoration efforts as well as monitor important coastal health and change metrics. All measurements of a specific type are taken according to a strict methodology at every CRMS site (Folse et al., 2014). Data types that are relevant to this subsidence study are rod-surface elevation (RSET) tables (Cahoon et al., 2002), feldspar accretion horizons, and marsh class characterizations. RSET tables quantify changes in the land surface elevation relative to the base of a foundation rod using measurements from pins held by an arm attached to the top of the rod, while feldspar accretion horizons measure the amount of new sediment (organic + mineral) deposited on top of the land surface. Together these two measurements allow estimates of shallow subsidence to be made (Cahoon et al., 1995; Jankowski et al., 2017). This is listed as shallow subsidence as the RSET's only integrate subsidence over the interval from the sediment surface to the depth of foundation, and each CRMS site has a different depth of RSET foundation (most are in the Holocene section). Marsh class characterizations track changes in marsh type according to plant type; they are an indirect measure of salinity conditions at the site through time.

Recent studies of subsidence in Louisiana have used CRMS data to look at subsidence rates and marsh health (Jankowski et al., 2017; Nienhuis et al., 2017). The present report builds on Jankowski et. al (2017) by adding four sites (319, 338, 387, 3296), using the same methodology, that have only recently been operating long enough to be used in subsidence calculations. The observation length for the CRMS sites used in this study ranges from 6.5 years to 11.4 years. Two CRMS stations (190, 312) in the area were excluded from the analysis because they do not have land surface data; these CRMS sites are located in floating marsh, the elevation of which changes significantly with water level. Shallow subsidence rates are shown in Figure 13 for 23 sites.

The shallow subsidence rate is the difference between the vertical accretion rate and the surface elevation change rate from RSET tables. Deep subsidence is the subsidence that occurs in the sediments below about 15 - 20 m (49 – 66 ft). Karegar et al. (2015) used GPS sites that are anchored at depths greater than about 15 m (49 ft) to capture the deep component of subsidence. They found that deep subsidence shows an approximately linear trend with latitude. This relationship was used to estimate deep subsidence at the CRMS sites (Jankowski et al., 2017; Nienhuis et al., 2017).

$$Deep\ Subsidence = -1 * \left((3.7147 * latitude) - 114.26\right)$$

CRMS sites in the study area show shallow subsidence between 1 mm/yr and 23.6 mm/yr (0.04 and 0.63 in/yr) (Figure 13). Four of the sites show increases in surface elevation that are greater than accretion, giving negative values for shallow subsidence (uplift). Deep subsidence rates range from 4.4 mm/yr to 6 mm/yr (0.17 to 0.24 in/yr). Combining the estimates for deep and shallow subsidence yields total subsidence which ranges from 2.5 mm/yr to 28.9 mm/yr (0.10 to 1.14 in/yr) (Figure 13). Eustatic sea level rise for the Gulf of Mexico has been estimated to be approximately 2.0 mm/yr (0.08 in/yr) (Letetrel et al., 2015), which results in relative seal level rise (RSLR) rates of 4.5 mm/yr to 30.9 mm/yr (0.18 to 1.22 in/yr).

A recent interpolated map of subsidence across the Louisiana coast based on the results of Jankowski et al (2017) and Karegar (2015), estimates that subsidence rates in the Fourchon area are approximately 9 mm/yr with a standard deviation around 7 mm/yr (0.28 in/yr) (Nienhuis et al., 2017). This rate is similar to the average rate for coastal Louisiana.

Because these combined deep plus shallow CRMS station methods eliminate the foundation depth determination issue relevant to tide gauges and leveling surveys, they are among the most comprehensive ground measurements of total subsidence in the study area. However, they may suffer from a distinct issue. Elevation change at the RSET pins is only measured twice annually. Studies of the organic-rich layer of LA marshes (where most CRMS sites are located) have shown elevation swelling-contraction cycles associated with tidal and meteorological flooding of the marsh surface (Cahoon et al., 1995). This likely induces significant error in the resulting elevation measurements.

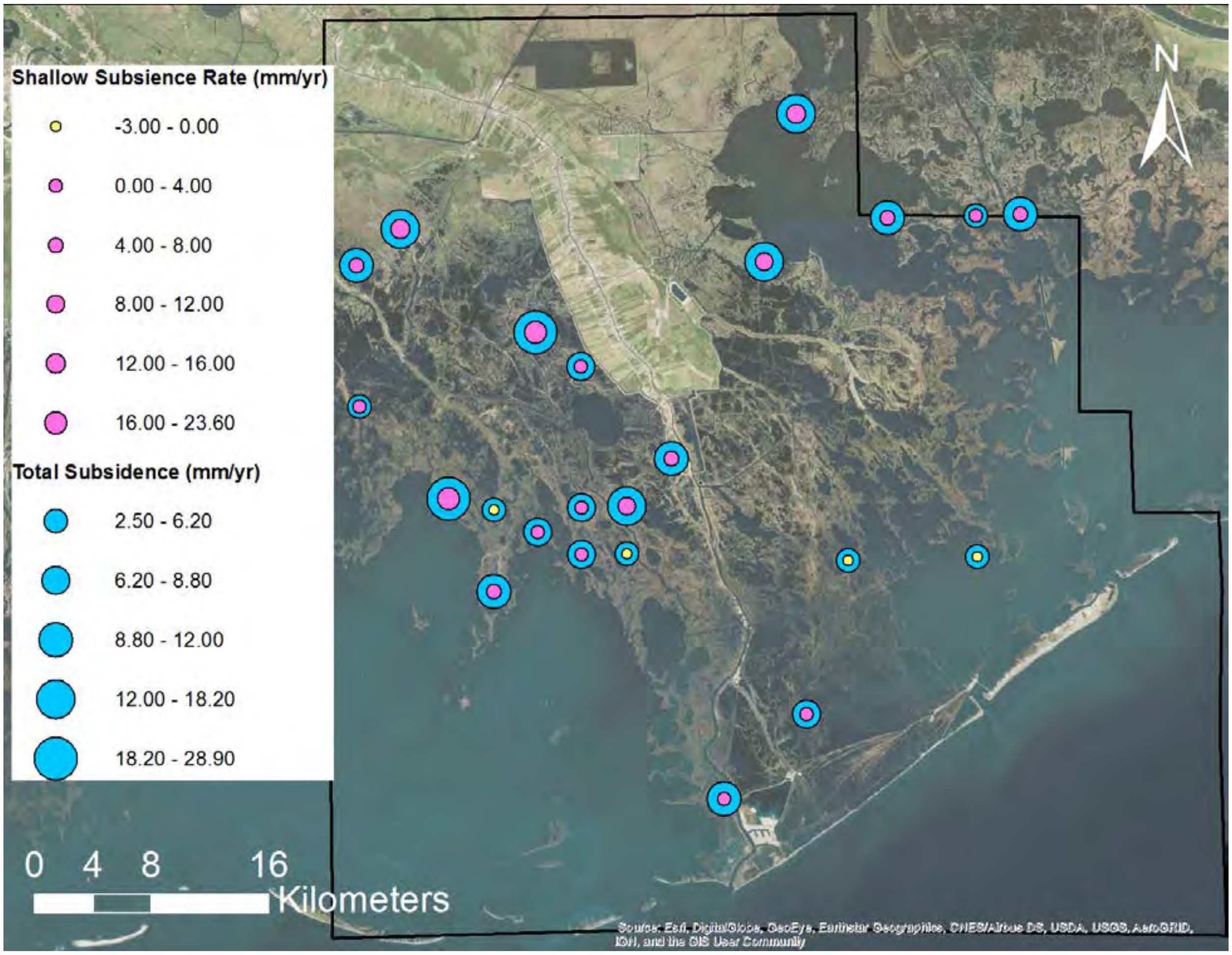


Figure 13. Shallow subsidence and total subsidence rates calculated for CRMS sites within the study area using the methodology of Jankowski et al. (2017). Shallow subsidence is the difference between vertical accretion and surface elevation change. Total subsidence is a combination of shallow subsidence and deep subsidence. The circles are scaled to the subsidence rate. The four sites that show shallow uplift (negative subsidence rate) are shown by yellow circles.

4.5. CONTINUOUSLY OPERATING REFERENCE STATIONS (CORS)

The Continuously Operating Reference Stations (CORS) are a network of Global Navigation Satellite System (GNSS) data managed by the National Geodetic Survey (NGS). GNSS GPS data can be accessed and downloaded through the CORS website (https://geodesy.noaa.gov/CORS/). There is one CORS site in the study area (referred to as the 'GRIS' station) at Grand Isle (Figure 14). This CORS site is located on top of a concrete building that is pile driven to an unknown depth. GRIS has near continuous vertical position data from 2005 through 2018. For this study, the elevation data for a 24-hour period on January 1st (or within 24 hours of January 1st) from 2006 through 2018 (with the exception of 2007 for which data was not available) was downloaded for the GRIS CORS site. A linear regression through the orthometric height through time yields a subsidence rate of 5.9 mm/yr (0.23 in/yr) with an r^2 value of 0.98 for the line (Figure 15). Based on the CORS data, subsidence at this site has had a constant rate since at least 2006.

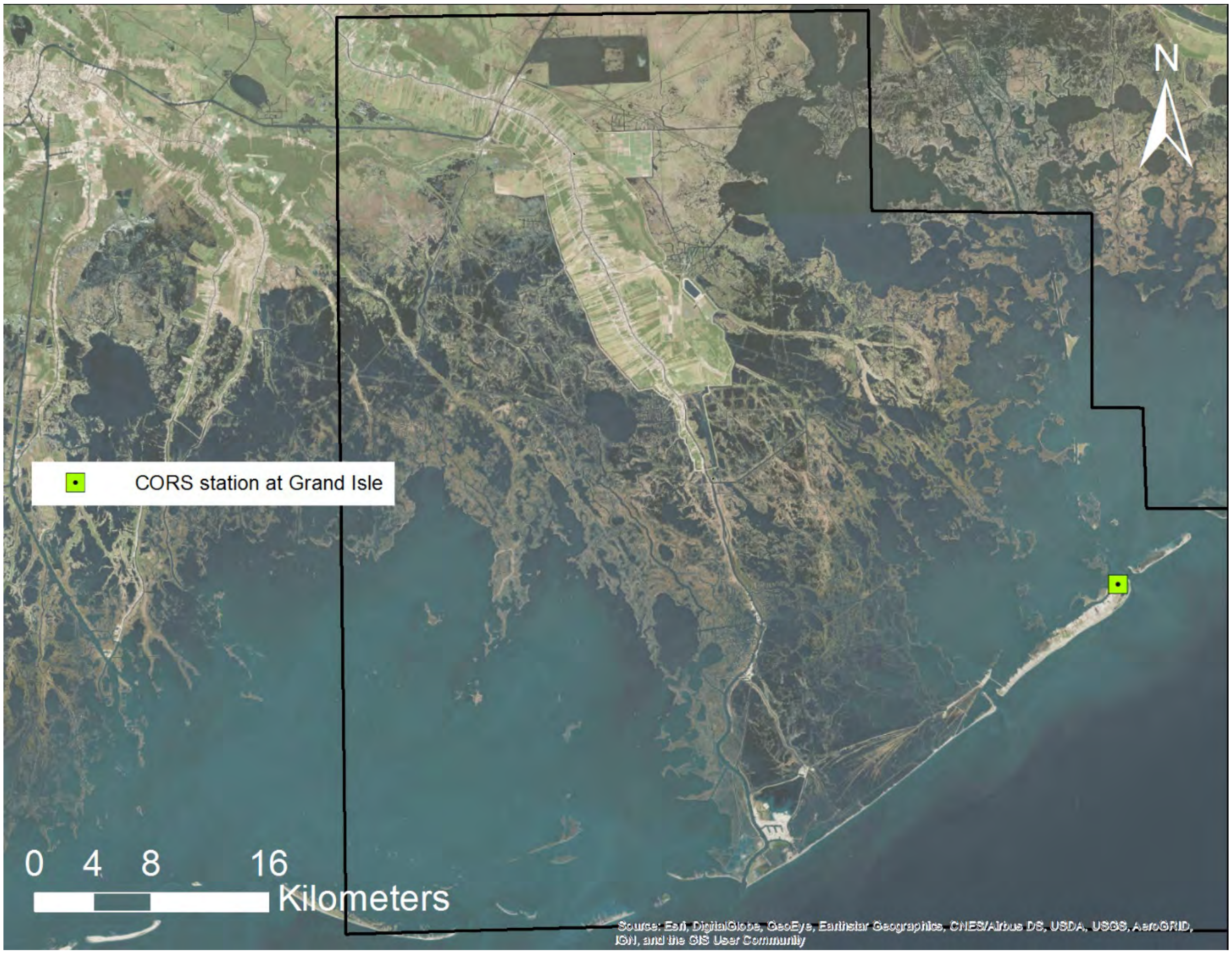


Figure 14. Location of Grand Isle CORS site. This CORS site is located on top of a concrete building that is pile driven to an unknown depth. It has been recording vertical position data nearly continuously since 2005.

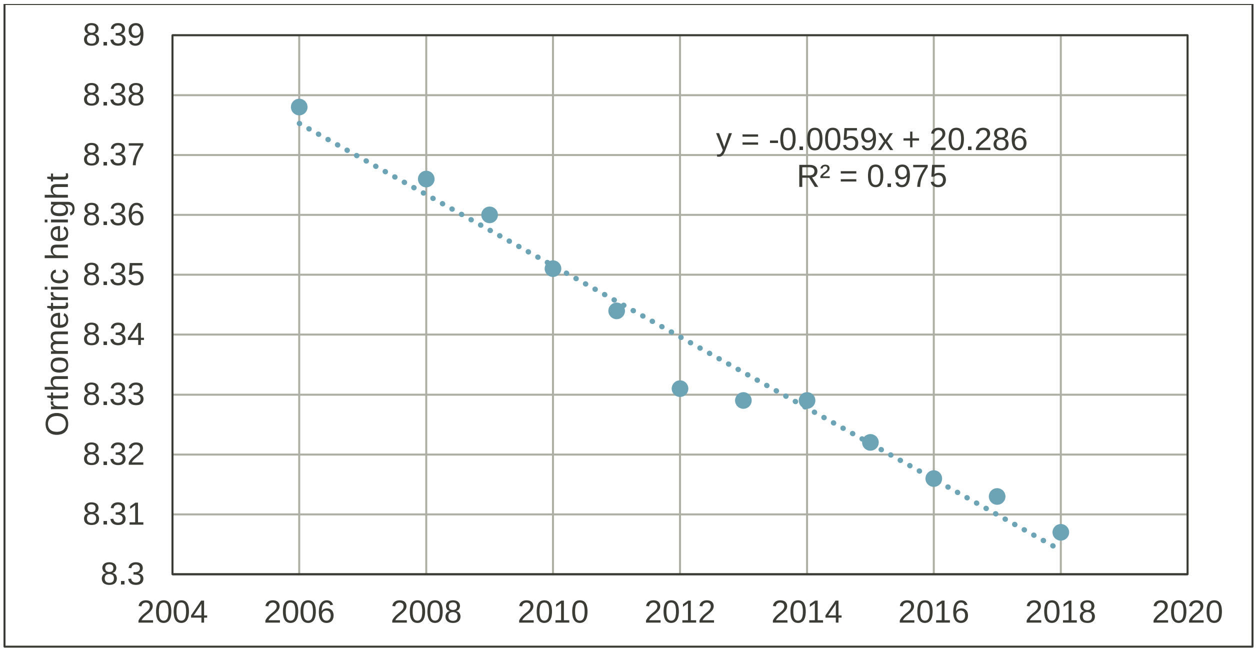


Figure 15. Subsidence rate calculated from the Grand Isle CORS data. The orthometric height is measured in meters and referenced to Geoid 12B.

4.6. LIGHT DETECTION AND RANGING (LIDAR) LAND ELEVATION SURVEYS

Light Detection and Ranging (LiDAR) is a high precision, airborne method using lasers to measure elevations of a large geographic area. Because of the nature of the methodology, it cannot provide accurate measurements for points inundated by water. Multiple LiDAR surveys of the subaerial portion of the study area have been completed between 1998 and 2013 with varying coverage and resolution. To allow comparison of elevation data between different surveys, all surveys for the present analysis were transformed into a Geoid 12A, NAD 83 UTM Zone 15N (meters) coordinate system using the NGS program VDatum. All elevations were converted to meters, if necessary.

The first LiDAR data set in the study area was collected during the Fall of 1998 and covered only a small area near the coastline (extent shown in Figure 16). The data was obtained from the National Oceanic and Atmospheric Administration (NOAA) Digital Coast website (https://coast.noaa.gov/digitalcoast/) and was part of the Airborne LiDAR Assessment of Coastal Erosion (ALACE) Project for the U.S. Coastline. The horizontal resolution is 3 m. It was provided in Geoid 12A, NAD 83 UTM Zone 15N (meters) coordinates. This dataset has not been processed to remove measurements of the water surface and vegetation.

The next LiDAR collection in the study area was part of the Louisiana Statewide Lidar Project and was obtained through Atlas: Louisiana GIS (https://atlas.ga.lsu.edu/) (Figure 17). The majority of the data was collected in March 2003. The northwest section was collected in February 2002. The data were provided in Geoid 99, NAD 83 UTM Zone 15N (meters) coordinates. Elevations were originally provided in feet and converted to meters for use in the GIS. The horizontal and vertical coordinates were converted from Geoid 99 to Geoid 12A using VDatum. These data cover the majority of the study area at a horizontal resolution of 5 m (16.4 ft). This dataset is a processed digital elevation model.

In April 2010 the U.S. Army Corps of Engineers (USACE) Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) collected LiDAR data over the coastline of the study area as part of an effort to collect topographic LiDAR across the Louisiana coast, Lake Pontchartrain, and the Mississippi barrier islands (extent shown in Figure 16). The data have a 1 m (3.3 ft) horizontal resolution. The data were provided in Geoid 12A, NAD 83 UTM Zone 15N (meters) coordinates. The data was accessed through NOAA Digital Coast. This dataset is a processed digital elevation model containing only points classified as ground.

Additional LiDAR data were collected over the majority of the study area in 2011 and 2013 as part of the U.S. Geological Survey (USGS) Coastal National Elevation Database (CoNED) (https://topotools.cr.usgs.gov/coned/) (Figure 18). The western part of the study area was collected in 2011, and the eastern part was collected in 2013. The horizontal resolution of the data is 2-3 m (6.6 – 9.9 ft). The data were provided in Geoid 09, NAD 83 UTM Zone 15N (meters) coordinates. Elevations were provided in meters. The horizontal and vertical coordinates were converted from Geoid 09 to Geoid 12A using VDatum. The data was accessed through NOAA Digital Coast. This dataset is a processed digital elevation model.

Because elevation change is a complex combination of subsidence, accretion, and erosion, LiDAR elevation data is not a direct measure of subsidence rate. However, rapid and/or persistent elevation change is an indicator of areas that should be investigated for subsidence.

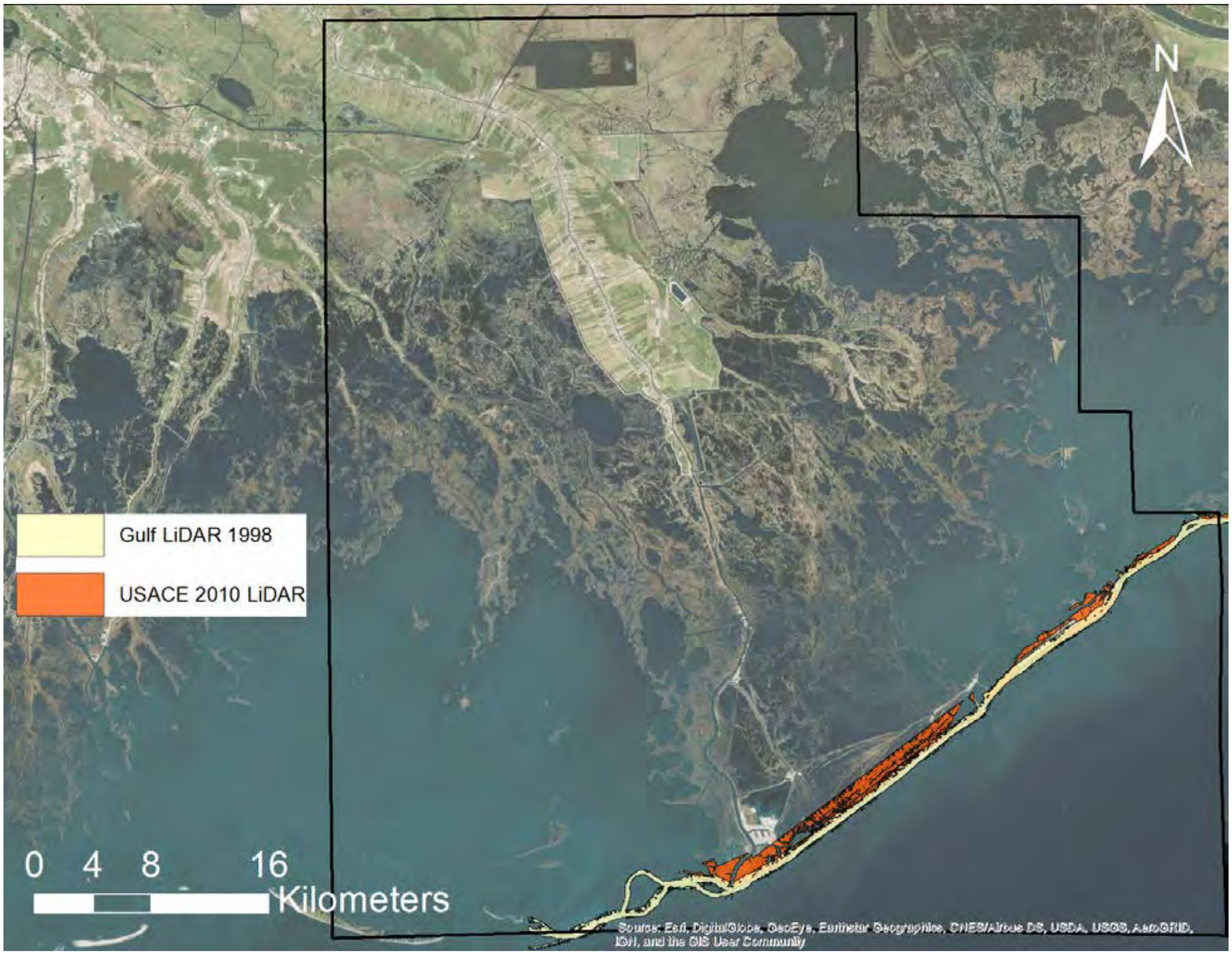


Figure 16. Extent map of Gulf 1998 and USACE 2010 LiDAR elevation data.

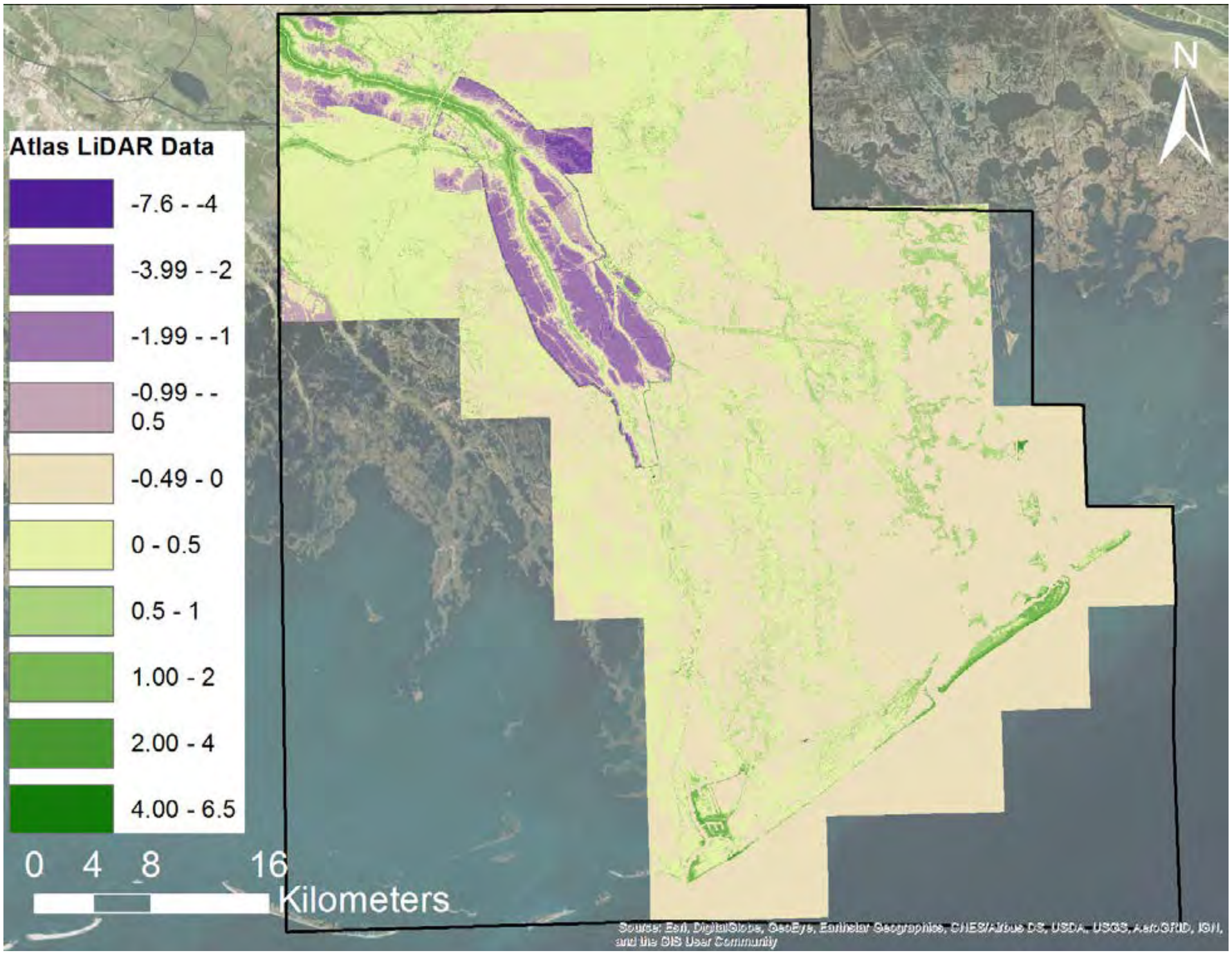
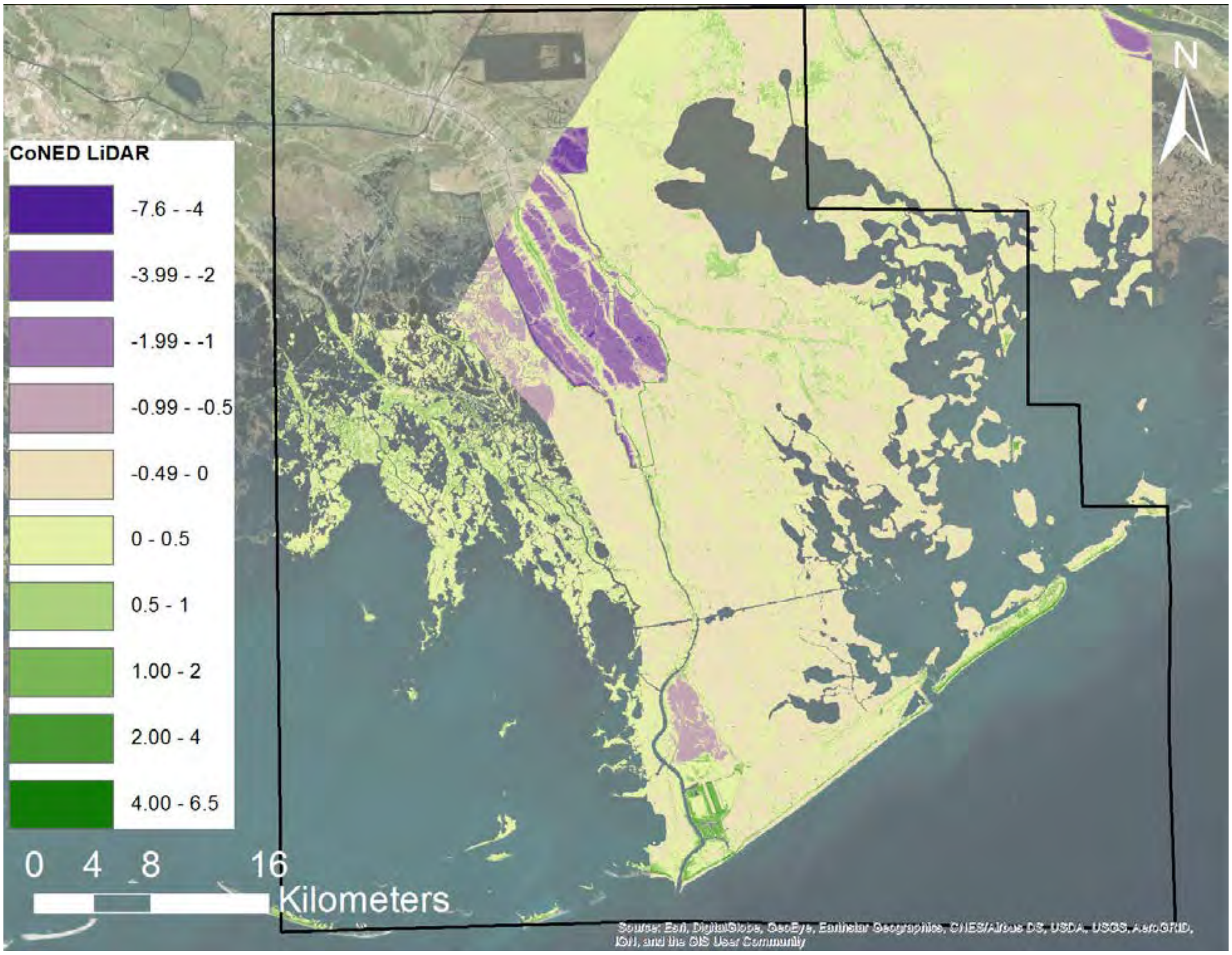


Figure 17. Louisiana Atlas LiDAR elevation data from 2002 and 2003.



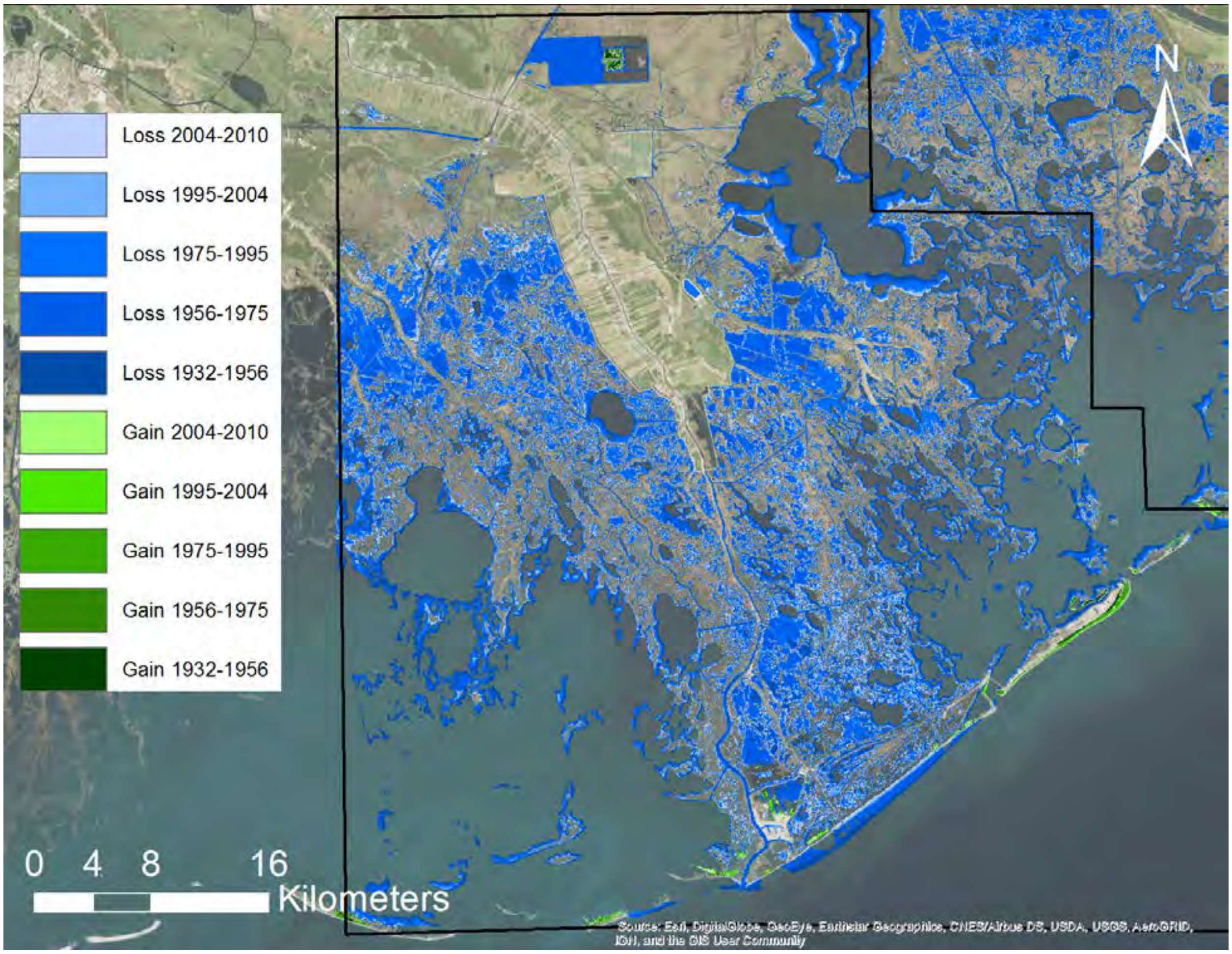
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 18. U.S. CoNED LiDAR elevation data from 2011 and 2013.

4.7. WETLAND LOSS

Subsidence contributes to wetland loss in Louisiana when marshes cannot maintain rates of vertical accretion (organic + mineral) high enough to compensate for land sinking and eustatic sea level rise, effectively drowning in place. This process has been described in many publications, forming features such as subsidence ponds that then expand outward exacerbated by wave attack of the wetland edges (Bencaz, 1988; Day et al., 2011; DeLaune et al., 1994; Ortiz et al., 2017). Because the loss of wetlands is a complex combination of acute effects like storm waves, as well as elevation loss caused by subsidence and/or reductions in sediment accretion, they are not a direct indicator of subsidence rate. However, rapid loss of wetlands by internal collapse and ponding is a key proxy for rapid subsidence (Bencaz, 1988; DeLaune et al., 1994; Day et al., 2011; Ortiz et al., 2017). Using historical land surveys, aerial imagery, and satellite data the United States Geological Survey (USGS) have tracked coastal land changes from 1932 to 2010 in Louisiana (Couvillion et al., 2011). Louisiana has lost approximately 1,883 mi^2 of land from 1932 to 2010. Land loss in the Barataria and Terrebonne basins was 421.71 mi^2 and 459.99 mi^2 over the study time period, respectively.

Figure 19 shows the combination of wetland extent maps for five time periods in the study area. Strong land-sea edge effects can be observed in Barataria and Terrebonne Bay marshes and along the sea-facing barrier islands; these are related directly to edge erosion or retreat. However, large areas of wetland loss have occurred "from the inside" on both sides of Bayou Lafourche, both in the northern section opposite the storm protection back levees in the Larose to Golden Meadow corridor, and further south to Port Fourchon. This can be strongly linked to subsidence and shows a trend of higher land loss rates in the periods prior to 1995.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 19. Wetland loss map from USGS. Changes are grouped into approximately 10-year intervals.

5.0 Data Mining Conclusions

There are 109 subsidence rates that have been calculated from data in the Port Fourchon area during the past 15 years (Figure 20). These data come from a wide variety of measurement types, each with their own strengths and weaknesses. This report has also shown that subsidence rates are highly variable in time and space. Figure 21 shows all the locations where data that can be used to calculate subsidence rates is currently being collected. Future work in the present project will utilize this data to construct subsidence and elevation loss "hazard maps" which can be used to assess the timing at which elevation loss will generate subsidence below mean sea level for various parts of the study area.

A summary of the main conclusion for each type of data set is as follows:

- Holocene thicknesses in the study area (the Lafourche delta) range from 35 m (115 ft) to more than 65 m (213 ft) and are generally greater to the south.
- Sediments in this area are composed largely of interbedded layers of organic soils and peats and mixtures of clay, silt, and sand. A detailed spatial analysis of stratigraphic trends of individual layers and their geotechnical properties is possible based on existing datasets but would require a significant future effort.
- Salt domes are known to exist in the study area, but little information about 3D extent is publicly available.
- Faults are also known to exist in the study area, but, compared to other data sources explored in this report, relatively little information is publicly available. This is an area of active research.
- Subsidence rates from geodetic levelling varied spatially and temporally. Calculated subsidence rates for the 1982 to 1993 interval of the study for Grand Isle range from 4 to 6 mm/yr (0.16 to 0.24 in/yr), while rates near Leeville range from 12 to 15.5 mm/yr (0.47 to 0.61 in/yr). Mean subsidence rates from geodetic levelling for the Raceland to Grand Isle corridor were 7.67 mm/yr (0.30 in/yr) from 1965 to 1982 and 11.09 mm/yr (0.44 in/yr) from 1982 to 1993.
- Subsidence rates have also been calculated from tide gauges in the study area. The subsidence rate calculated from 1955 to 2000 at the Leeville gauge is 8.8 mm/yr (0.35 in/yr). At Grand Isle from 1948 to 1958, the subsidence rate at was 3.16 +/- 1 mm/yr (0.12 +/- 0.04 in/yr). From 1958 to 1991, a time period of peak subsurface fluid withdrawal in the area, the subsidence rate increased to 9.82 +/- 0.33 mm/yr (0.39 +/- 0.01 in/yr). From 1992 to 2006, the subsidence rate decreased to 1.04 +/- 0.97 mm/yr (0.04 +/- 0.04 in/yr).
- The total subsidence rates calculated at the CRMS sites in the study area ranged from 2.5 mm/yr to 28.9 mm/yr (0.01 to 1.14 in/yr).
- At the Grand Isle CORS, a subsidence rate from 2006 to 2018 of 5.9 mm/yr (0.23 in/yr) was calculated.
- LiDAR elevation data and wetland loss maps provide indirect evidence that subsidence is occurring in the area.

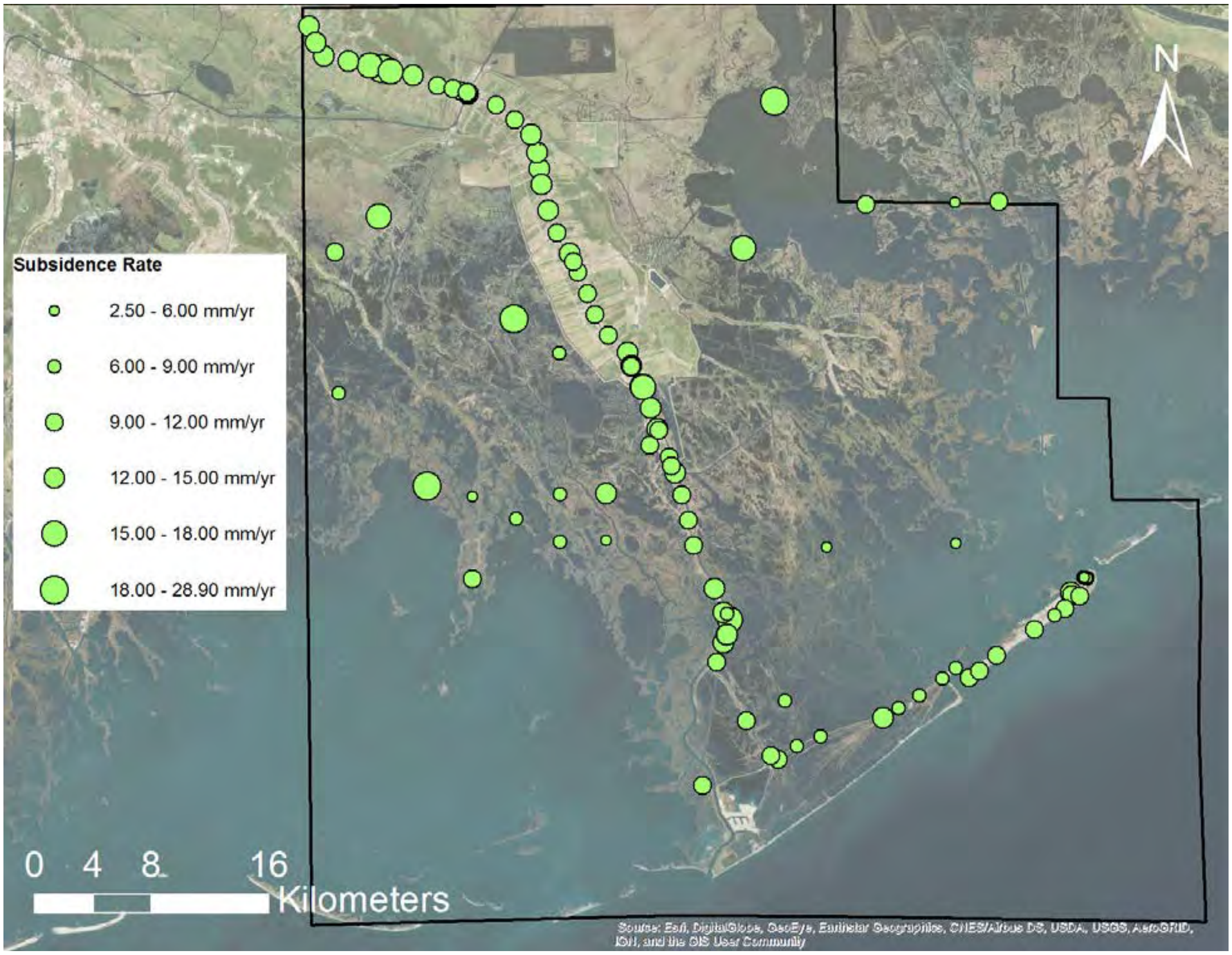


Figure 20. All subsidence data points considered in this report. Many of these locations have poorly constrained foundation depths.

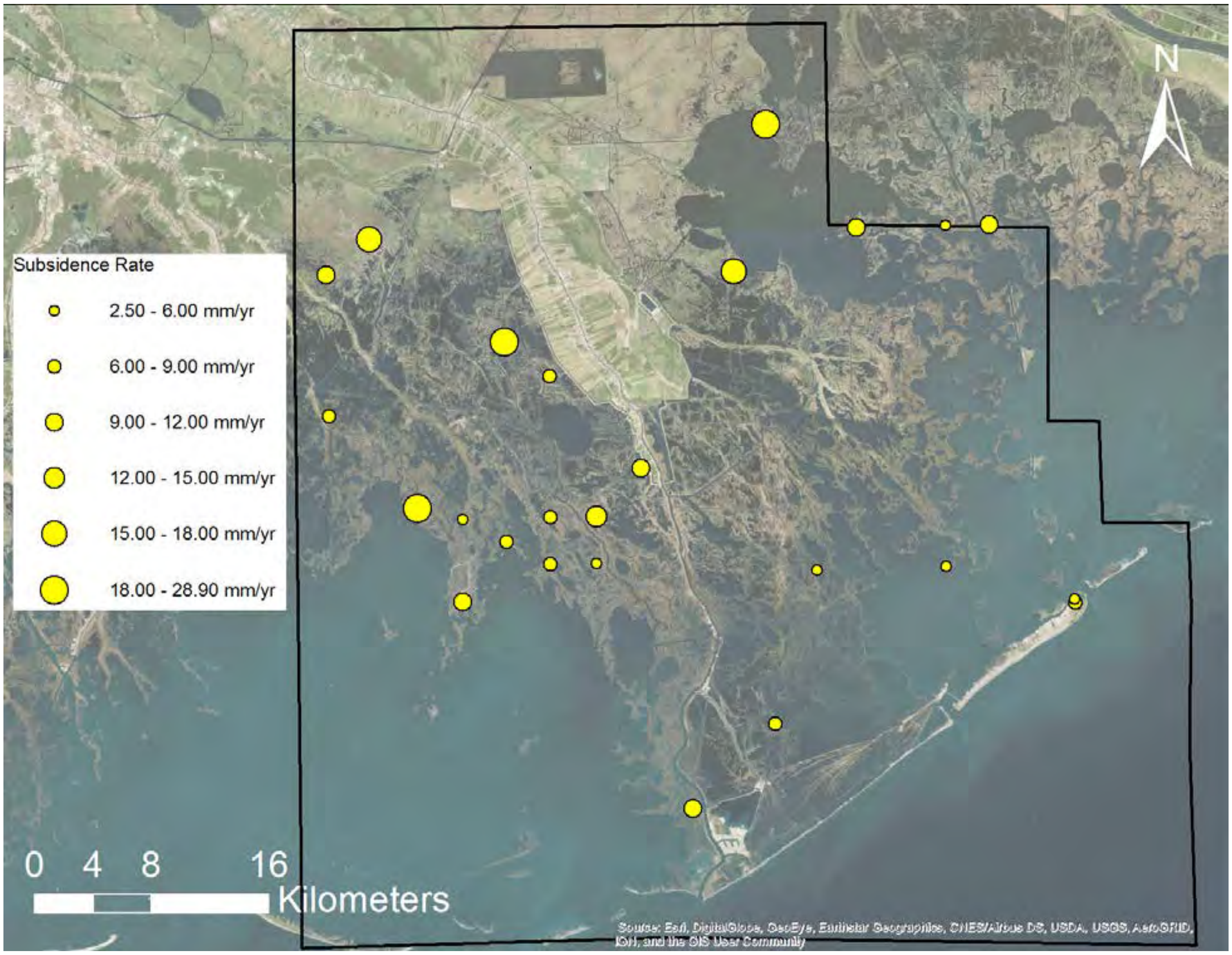


Figure 21. Locations where subsidence information is currently being collected. Note that the two locations in Grand Isle (tide gauge and CORS) have poorly constrained foundation depths.

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Partnership for Our Working Coast: Port Fourchon Phase 1 Technical Report

Chapter 3: Blue Carbon - Integrating Blue Carbon into Beneficial Use Metrics

TIM CARRUTHERS AND LELAND MOSS

Produced for and funded by: Shell, Chevron, Danos, and the Greater Lafourche Port Commission

August 20, 2018

Background

CARBON MARKETS

Blue carbon refers to the greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) sequestrated, stored, and released from seagrass, tidal wetlands, salt marshes and mangroves. At the current time, if developed as a carbon offset project, the Port Fourchon tidal wetland restoration project would be able to sell offsets only into the voluntary carbon market, as compliance markets do not currently accept offsets from tidal wetland restoration projects.

Compliance markets have been proposed at the national level but currently only exist at the regional and state levels. An example of a regional market is The Regional Greenhouse Gas Initiative (RGGI) and a state example is the California cap and trade program, both of which accept offsets, but do not currently accept blue carbon offsets. Voluntary markets are primarily made up of consumer-facing industries looking to voluntarily become more carbon neutral and help combat climate change, especially in cases where emission reductions have become cost prohibitive.

Coastal wetland restoration is among the newest project types approved to generate carbon offsets on the voluntary carbon market. This presents a new opportunity because of the high sequestration rate per hectare, as well as a unique way to incentivize increased private investment in restoration. Though not all coastal restoration activities will be appropriate as offset projects, and the potential revenue generated through offset sales generally will not cover the full cost of restoration, blue carbon offset projects can provide additional support for project components such as long-term monitoring and management and incentivize additional restoration investors. Given that Louisiana has close to 40% of the wetlands in the continental United States (Bourne, 2000), it is an appropriate location to assess the applicability of blue carbon.

CARBON STANDARDS & METHODOLOGIES

Increasing interest in carbon offsets has led to the development of standards to provide accounting and verification procedures ensuring that generated offsets represent achievable and real emission reductions. Recognized standards include the Verified Carbon Standard (Verra/VCS), American Carbon Registry, Carbon Action Reserve, and the Gold Standard. VCS is the largest issuer of land-use credits and approved methodologies relating to coastal wetland activities.

All carbon offsets generated on the voluntary carbon market must abide by rules and accounting procedures approved by recognized carbon standards. These standards certify methodologies and projects for offset generation, accreditation, and transfer on the voluntary market.

ADDITIONALITY

Additionality refers to offset projects that go above and beyond business-as-usual, ensuring that real and additional GHG reductions are being made. Under the VCS-approved restoration methodology (VM0033) all tidal wetland restoration projects located in the United States are deemed to meet the additionality requirement (due to the low penetration or occurrence of these activities) so long as they are not required by any law, statute, or other regulatory framework. Therefore, because it is located in the United States and is not required by any law, statute or regulation, the Port Fourchon tidal wetland restoration project would meet the additionality requirement.

Along the same lines, the project must show there is no leakage from the project, meaning emission reductions in one area are not relocated to another. For example, if a new wetland creation project utilizes fill or sediment material from an existing emergent wetland (reducing the area of wetland) to fill a different area, the increase in wetland area from project must show net increase in wetland area.

PERMANENCE

Project activities must show permanence by being maintained for a minimum of 30 years, and an assessment of potential loss or reversal of emission reductions over a period of 100 years must be conducted for the project.

PROPERTY OWNERSHIP

The VCS requires the project proponent (owner) to demonstrate carbon ownership by a right of use. For land use projects, a right of use can arise by virtue of land property rights in the project area, or by an enforceable and irrevocable agreement with the landowner that transfers such rights to the project proponents.

CARBON AND ACCRETION DATA OVERVIEW

There is a large spectrum of data useful both to carbon accumulation as well as assessing baseline marsh conditions in this region. Across the Louisiana coast there are Coastwide Reference Monitoring Stations (CRMS) which collected soil cores (30 cm) for bulk density and organic matter measurements approximately 10 years ago when the program was initiated (Folse et al., 2014). Elevation through a surface elevation table (SET) is measured at intervals ranging from every six months to every two or three years (Folse et al., 2014). Short-term accretion via feldspar horizon markers is taken every six months with corresponding monthly measurements of vegetation type (Folse et al., 2014). Hourly water level and salinity are also measured (Folse et al., 2014). There are CRMS stations near some of the potential restoration areas of the Port Fouchon area and in the surrounding region that can be used as reference (see Figure 1).

Total carbon accumulation rates (g TC m^{-2} yr^{-1}) are calculated by multiplying the mean carbon density (bulk density) by the accretion rates (Bernal & Mitsch, 2008, 2012; Bianchi et al., 2013). Accretion rates can be measured a variety of ways, with short-term accretion estimated by a feldspar marker horizon for assessing months to years (Bianchette et al., 2015; Cahoon & Turner, 1989). For longer accretion estimates, on a decadal or century timescale, Cesium-137 (^{137}Cs) and Lead-210 (^{210}Pb) are used (DeLaune et al., 1978; Wilson & Allison, 2008). ^{210}Pb is assumed to deposit at a constant rate and occurs naturally so the age of the soil is determined based on the 22.3 year half-life of ^{210}Pb (Appleby & Oldfield, 1978). ^{137}Cs on the other hand does not occur naturally and deposition began in the 1950s due to nuclear weapons testing, the peak quantities were in 1963 and it is that peak in the core which is used as an accretion reference (Pennington et al., 1973).

Other studies have taken these short-term accretion rates and calculated short-term total carbon (TC) accumulation rates per marsh type for the region (Baustian et al., 2017). For longer TC quantities and accumulation measurements a variety of studies have used ^{137}Cs and ^{210}Pb within this region (Baustian et al., In Prep; DeLaune & White, 2012; Hatton et al., 1983; Nyman et al., 2006; Smith et al., 1983). All of these data compiled together will provide robust estimates of carbon offset value specific to the marsh type in this region (see Table 1). Previous studies have also compared different marsh types (Baustian et al., 2017; Stagg et al., 2017a), but as blue carbon is only generated from tidal wetlands, even though the accretion rates may be higher, the fresher wetland areas cannot currently qualify for this specific crediting under existing methodologies.

To quantify these offsets, it is important to consider the short-term and long-term accumulation rates to assess the carbon captured during the life of the project. Monitoring of short-term accretion rate (cm yr^{-1}) is required and knowing the patterns of long-term accretion rate in this area will help to justify the level of carbon capture over the life of the offsets (100 years). Environmental characteristics vary in influencing these short-term and long-term accumulation rates. Salinity and inundation along with their change over time will drive both short-term and long-term accumulation rates (Baustian et al., 2017; Craft, 2007; Stagg et al., 2017a, 2017b), but many other environmental characteristics such as inorganic nutrients, mineral sediment and soil porewater are also important to short-term accretion dynamics (Marín-Spiotta et al., 2014; Morris & Bradley, 1999; Valiela et al., 1976). Production vs decomposition varies between short -term and long-term assessments with short-term accretion dominated by primary production and long term dominated by decomposition processes (Baustian et al., 2017; Choi & Wang, 2004).

To fully assess a restoration area, it is ideal to measure greenhouse gas emissions directly. This is because methane and nitrous oxide fluxes cannot be estimated from soil cores, only carbon dioxide fluxes can be estimated from soil cores (Holm et al., 2016; Krauss et al., 2016; Poffenbarger et al., 2011). However, given the continuous salinity data from the CRMS (https://lacoast.gov/crms2/) locations (as seen in Figure 1), the area remains consistently saline (>18 ppt) and therefore, the salt marshes are unlikely supporting methanogenesis (production of methane) (Poffenbarger et al., 2011). Given nitrous oxide's Global Warming Potential of 265 times that of CO_2 (Holm et al., 2016) directly measuring N_2O could benefit the projects projected GHG benefit, but given the high monitoring cost to do so, VCS's standard do provide the option of using default estimates for these quantities (Attachment 5: Feasibility Report).

Table 1. Review of short and long-term total carbon accumulation rates from coastal Louisiana.

Location	Marsh Type	Long or Short Term	Accretion Method	Accretion (cm/yr)	TC Accumulation Rates (g TC m^2 yr)	Reference
Louisiana	Saline	Short	Feldspar	0.53 - 1.01	41 - 391	(Baustian et al., 2017)
Louisiana	Saline	Short	Feldspar	1.47 - 3.03		CRMS 0292
Louisiana	Saline	Short	Feldspar	0.96 - 1.68		CRMS 0164
Louisiana	Saline	Short	Feldspar	1.44 - 2.46		CRMS 0310
Louisiana	Saline	Short	Feldspar	0.72 - 1.13		CRMS 0175
Louisiana	Saline	Short	Feldspar	1.37 - 1.87		CRMS 0318
Louisiana	Saline	Short	Feldspar	1.44 - 1.83		CRMS 0978
Louisiana	Saline	Short	Feldspar	0.92 - 1.84		CRMS 0319
Louisiana	Saline	Short	Feldspar	0.86 - 2.08		CRMS 0337
Louisiana	Saline	Short	Cs137	0.94	112 - 546	(Hansen & Nestlerode, 2014)
Louisiana	All marsh types	Long	Cs137 & Pb210	0.25 - 0.31		(Baustian et al., In Review)
Louisiana	All marsh types	Long	Cs137		72.7 - 90.1	(Baustian et al., In Review)
Louisiana	All marsh types	Long	Pb210		71.1 - 88.9	(Baustian et al., In Review)
Louisiana	All marsh types	Long	Cs137 & Pb210	0.42 - 0.92		(DeLaune et al., 1989)
Louisiana	Saline	Long	Cs137		183	(Smith et al., 1983)
Louisiana	Saline	Long	Cs137		200	(Hatton et al., 1983)
Louisiana	Saline	Long	Cs137		104 - 203	(Piazza et al., 2011)
Louisiana	Saline	Long	Cs137 & Pb210	0.18 - 0.76	31.7 - 151	(Baustian et al., In Review)
Louisiana	Saline	Long	Cs137		199	(Nyman et al., 2006)

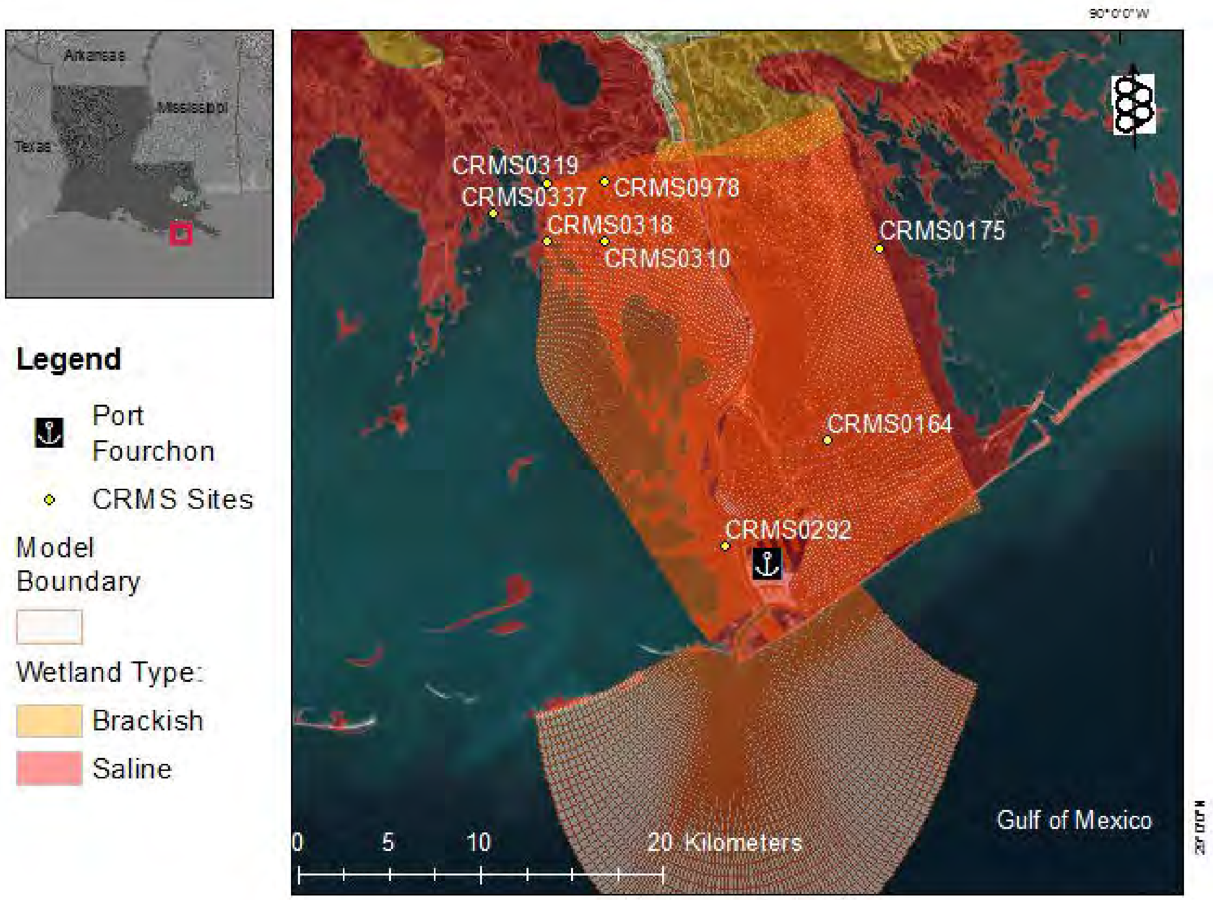

Figure 1. The locations of CRMS sites in the surrounding region. The red represents saline wetland and orange represents brackish marsh.

Results

Prior to developing a blue carbon project, a feasibility assessment should be first completed that examines the technical and financial feasibility for the project to generate carbon credits. The study is meant to guide project developers in the decision of whether or not to pursue carbon project development. The information presented below can be found in more detail in the appendix of this report (Attachment 5 : Feasibility Study). This chapter will give a broad overview of considerations for the site, which would need to be addressed in more detail when the specifics of the restoration projects are finalized post permitting, such as restoration type and design, location, and size.

PER ACRE CARBON STORAGE

The initial feasibility study found that for the full 30 year project the net GHG emission reductions vary depending on the wetland vegetation type (Figure 2). Mangrove, mangrove/marsh, and marsh can reduce the net GHG emissions by 225, 185, and 146 tons of CO_2e (Carbon Dioxide Equivalent) per hectare respectively (91, 74, and 59 tons of CO_2e per acre). Yearly, that is 7.5, 6.2, 4.9 tons of CO_2e per hectare for mangrove, mangrove/marsh, and marsh respectively (3, 2.5, 2 tons of CO_2e per acre).

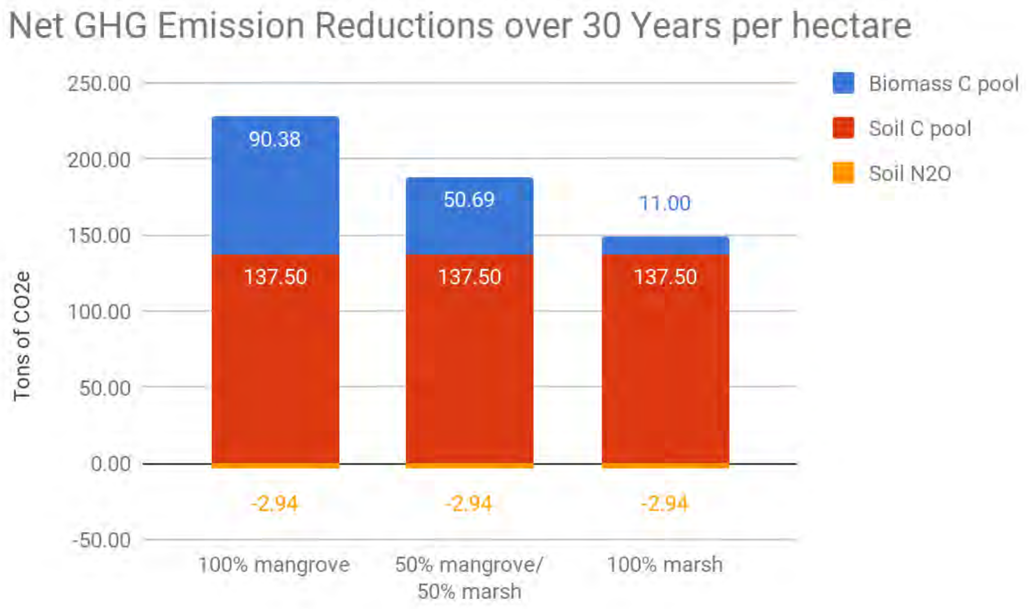

Figure 2. Carbon Dioxide Equivalent (CO_2e) per hectare for saline wetlands with three vegetation types, showing GHG sequestration and emission.

PER TON DOLLAR VALUE

As with any market the price of carbon is driven by supply and demand. Green carbon or forest carbon credits which are likely the most similar to blue carbon have fluctuated around \$5 per ton ('Price' in Figure 3). This means the value per year for mangrove, mangrove/ marsh, and marsh is approximately \$38, \$31, \$24 per hectare respectively (\$15, \$12 and \$10 per acre).

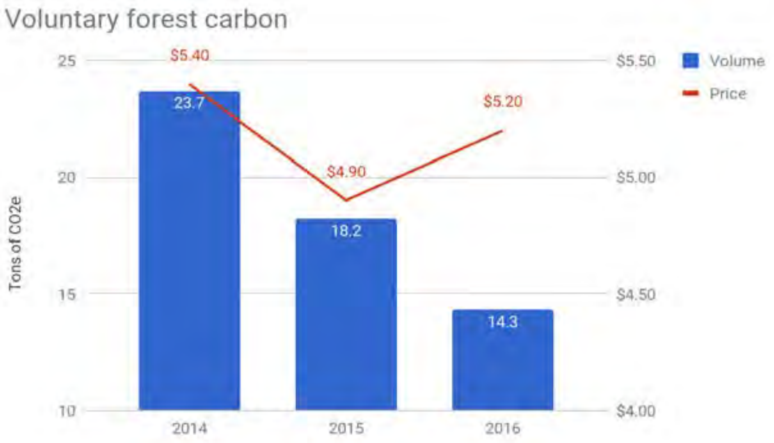

Figure 3. Market value of green carbon offsets in red and the volume of offsets created in blue

PERMANENCE

In order to be counted for carbon offsets the project is monitored for 30 years and needs to show permanence through 100 years. Relative sea-level rise (SLR) as well as subsidence are significant drivers in assessing the permanence of these potential restoration locations. Estimates of SLR used for coastwide restoration planning in the State of Louisiana's Coastal Master Plan increased between 2012 and 2017 (Coastal Protection and Restoration Authority of Louisiana, 2017), so the future impacts of relative SLR are not well known, creating uncertainty in estimating permanence. This high risk will translate into requiring more credits to be put in a risk pool, driving down the per hectare value. Potential options and solutions to address permanence are discussed later in this chapter.

COST OF MONITORING

Monitoring comes in a series of stages and varies depending upon how offsets are being used. The following monitoring costs assume the offsets are being put up for sale in the voluntary market as opposed to being used for internal company offsets. There is an initial one-time upfront development and validation cost of approximated $150,000. Every five years for the 30 year project there is monitoring and verification costs of roughly $60,000. This means the total costs for the entire project over 30 years will be roughly $510,000. However, as blue carbon is a novel approach to conservation finance, this has the potential to attract funding from donors as an opportunity to facilitate the development of blue carbon restoration projects, potentially supporting some of this validation and verification cost. This overall cost and assessment of potential additional funding partners is crucial to an assessment of the viability of the project. As shown in Figure 4, the area of land and vegetation type created heavily drive the net income from the project.

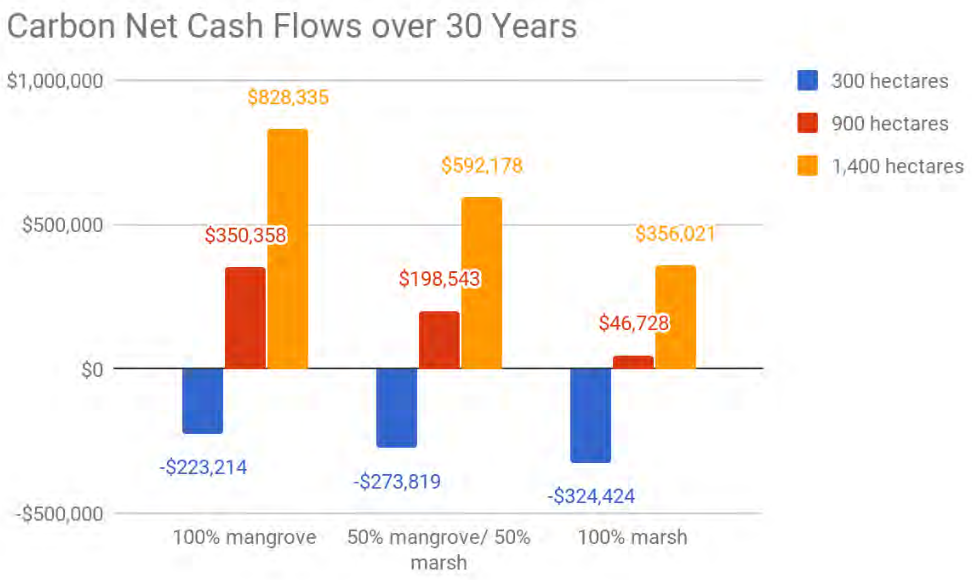

Figure 4. Net cash flow (income from offsets minus project monitoring costs) for the various project areas and for each of the saline wetland vegetation types.

Considerations for Blue Carbon in Port Fourchon

LOCATION OF RESTORATION SITE

There are multiple alternatives on where the dredge material could be placed with differing potential benefits of these alternatives. From a solely project cost perspective the cheapest method would be to create marshes through sediment deposition in the nearest possible location to the source. Additionally, deep sites were prioritized due to the Wetland Value Assessment protocol for the environmental cost/benefit approach, due to minimizing impact on currently wetlands and shallow water habitat. Both from a carbon standpoint and a larger ecosystem benefit standpoint (i.e. storm surge and wave erosion protection) this may not provide the greatest range of benefits to the ecosystem, community, and protection of infrastructure. If the sediment was placed in shallower areas (<1 meter) the same quantity of sediment would create a much greater area of wetland, with a resulting greater blue carbon value, and potentially higher amounts of other ecological, community, and protection benefits.

As seen in chapter 2, the average depth of the dumping area is 1.3 meters, ranging up to almost 2 meters. If the dredge dumping areas were prioritized to shallower habitat it would potentially provide greater coastal protection and subsequently larger carbon offset potential. Currently, the total marsh creation areas in 2030 are between 447 hectares (1,104 acres) and 481 hectares (1,189 acres) and by 2050 reach between 802 hectares (1,981 acres) and 893 hectares (2,208 acres) depending on if the basic plan or locally preferred plan is used. The maximum marsh created is estimated in year 2070 under the local preferred plan as 1,338 hectares (3,306 acres). These estimates are based on only the functional marsh created as described in chapter 2, using the middle (1 meter) SLR scenario. Comparing these to the different area categories in Figure 5 shows how varying land area created impacts net emission reductions.

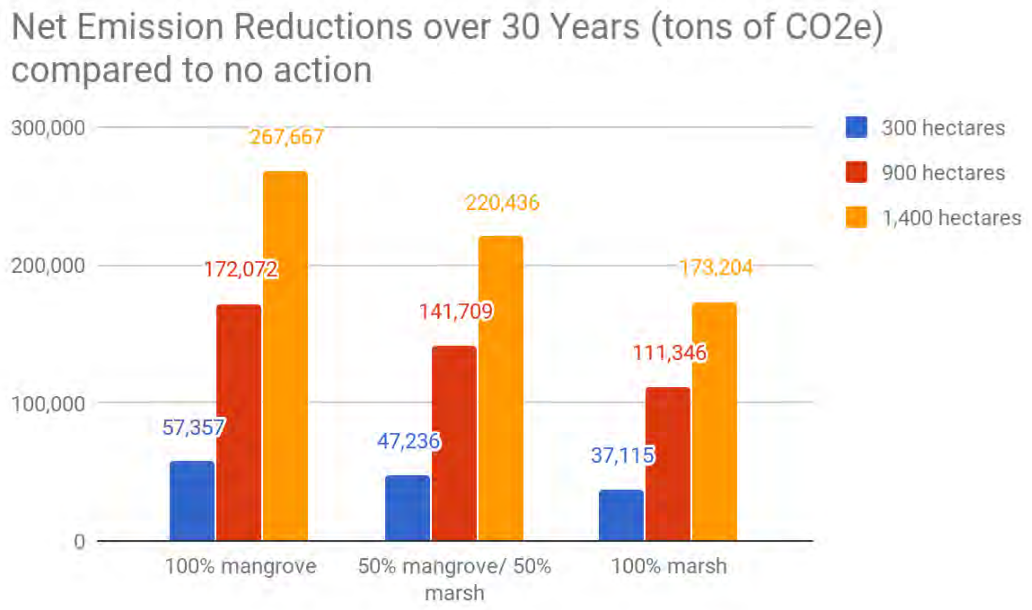

Figure 5. Net emission reduction or offset potential for the restoration projects at various project areas and for each of the saline wetland types.

TEMPORAL BUILD OUT

Project implementation is still in the planning and design stage, however presuming each phase of dredging would be used to create some type of new land area, each of these smaller areas on their own would not sequester enough carbon to justify the cost of carbon monitoring, but the aggregation of all phases over time likely would justify the cost of required monitoring.

Currently the plan is to start building wetland areas in 2020 and continue building roughly 400 hectares (1,000 acres) in the first 10 years and then roughly 200 hectares (500 acres) each decade following. These created areas are impacted by other factors such as SLR and subsidence and that will be discussed further in future sections.

Each phase of dredging does not need to trigger a whole new carbon project. Under the 'grouped project approach' (Simpson, 2016) it is acceptable to set up and validate an initial baseline for the project area. The full extent of all the proposed project phases would be needed at the commencement, and would be validated as a whole, this would minimize the cost for blue carbon assessment at each individual phase of the project. As long as new project phases meet the criteria including: occurring within the geographic area defined in the project description, compliance with the eligibility criteria, are included into future monitoring reports, have a clear property right of use, and are validated at the time of initial verification, then they can be included within the overall project (Simpson, 2016). Restoration projects do not necessarily immediately start sequestering carbon, so the sooner the larger areas of marsh can be built, the sooner offsets can start to be generated.

SEA LEVEL RISE AND LAND LOSS

Subsidence and SLR will have substantial impacts on coastal restoration in Louisiana. For SLR, the three different scenario levels used by the Coastal Master Plan (Coastal Protection and Restoration Authority of Louisiana, 2017) and USACE were incorporated. These are 0.3 meter (0.98 feet), 1 meter (3.28 feet), and 1.5 meter (4.92 feet) increases by 2100 (Coastal Protection and Restoration Authority of Louisiana, 2017). The marsh creation projects are all proposed to be located outside the direct influence of Bayou Lafourche. This allows for it to be counted as a carbon project because there will be limited allochthonous carbon (Carbon from outside of the project area), but also makes the longevity of the marsh areas less predictable.

Elevation of different salt marshes can vary, especially when including both natural and man-made marshes. Edwards and Proffitt (2003) suggest natural marshes in their study range in elevation from 0.25-0.35m, but measurements on created marshes ranged from as low as 0.15m to outlying points up to almost 0.7m. Shafer and Streever (2000) estimated natural marshes ranging from an average of 0.2m to 0.6m and dredged marshes ranging up to 1m of elevation. Dredged marshes are not necessarily always a higher elevation than nearby natural marshes, but they do tend to have a higher variation of elevations (Shafer & Streever, 2000).

Post construction settlement of the created area will occur and can vary depending on the type of dredge material used (Hymel, 2017). Various benefits, such as bird and nekton habitat (Rozas & Minello, 2007; Streever, 2000), begin to be sacrificed as the marsh is constructed higher and so project priorities need to be established early on if the goal is to make it like a natural marsh or if the main goals are to protect against storm surge and generate carbon. If the latter, it just has to be built to the extent that appropriate marsh vegetation will grow (Hymel, 2017; Streever, 2000). Optimal construction height will vary between areas and studies, some find that with higher elevations (around 1 meter) and siltier sediments that the plants grow poorly (Hymel, 2017; Mendelssohn et al., 2015), while other studies report the opposite (Mendelssohn & Kuhn, 2003; Reimold et al., 1978). Depending on the location, a higher dredged area will not necessarily lead to fresh or high marsh vegetation (Mendelssohn & Kuhn, 2003; Slocum et al., 2005), if species surrounding the project site are saline such as *Spartina alterniflora* (marsh grass) or *Avicennia germinans* (mangrove) there can be 'volunteer' colonization of a newly constructed area via rhizomes or seeds.

There is a point where too much inundation of an area will lead to marsh collapse, for salt marshes, this estimate is roughly 0.17-0.24m below mean water level (Couvillion & Beck, 2013). Once the marsh is lost there are no more offsets being generated (coupled with the loss of other ecosystem and community benefits such fisheries habitat or increased resiliency) and if those offsets have been sold they need to be pulled from the risk pool. This means that, for the project to meet the standards of permanence, it must not reach this point of no return for the period of time of the offset crediting.

MAINTENANCE DREDGING

In order to be counted for carbon offsets the project is monitored for 30 years and needs to show permanence through 100 years. Marshes in these areas that have sediment input and moderate levels of SLR have a better chance of keeping up with rising water (VIMS, 2014). Given the limited sediment input and with coastal erosion rates and relative SLR being high in coastal Louisiana, some of these projects may need sediment inputs via a different source. One option for maintaining the beneficial use marsh areas could be sediment input through thin-layer sediment addition or thin-layer dredging (Ray, 2007; VIMS, 2014).

Thin-layer dredging is not defined by a specific habitat or specific equipment, instead it should be thought of as the application of a thin layer of sediment which will not cause an elevation induced habitat change and should be applied evenly across the target area (Wilber, 1992). Commonly, thin layer dredging involves either spray dredging (Ford et al., 1999), which can be deposited up to 80 m away, or slurry dredging which is made up of about 85% water allowing the material to be spread over long distances, potentially up to 1,000 m from the point of discharge (Mendelssohn & Kuhn, 2003; Slocum et al., 2005). The thickness of this 'thin-layer' can vary from project to project, ranging from 1 cm to 1 m (Wilber, 1992). An optimal depth can be highly variable based on sites; Schrift et al. (2008) found that 0.14 to 0.2 m above ambient marsh had the best level of vegetation recruitment, but when it increased to 0.21-0.3 m there was less recovery. Other studies found that although much above 0.2 m the vegetation already growing on the marsh was not able to survive. Those studies also found that seedling establishment and recruitment led to some of the highest vegetation densities and plant heights with sediment addition up to 0.9 m (Mendelssohn & Kuhn, 2003; Reimold et al., 1978).

The content of the sediment that will be dredged is also important in predicting project success, with higher percentages of mineral sediment providing with low sulfide concentrations or high nutrients potentially resulting in increased growth (Mendelssohn & Kuhn, 2003). The nutrient benefits are likely a short-term benefit (1-3 years) whereas the elevation increase is a potentially longer benefit to the marsh (Slocum et al., 2005; Streever, 2000). Additionally the soil texture, or particle size plays a large role, with the optimal sediment having a high amount of silt and not dominated by either clay or sand (Mendelssohn & Kuhn, 2003).

The technology behind thin layer dredging is not new (Wilber, 1992), versions of this slurry method have existed for decades (Cahoon & Cowan, 1988). Although the spraying does tend to kill a large portion of the vegetation, it has been found that it is recolonized in less than a year, but estimated to take three years for full vegetation density compared to reference conditions (Cahoon & Cowan, 1988). The impacts on the vegetation are crucial from a blue carbon standpoint as the vegetation and associated organic accumulation drives the carbon capture and offset. Ideally, the depth of the thin-layer dredge material would not kill the vegetation and the timing of the dredging would best be at the beginning of the growing season (late winter or early spring) to ensure the highest degree of recovery (Ford et al., 1999). The amount and carbon content of the added sediment also needs to be monitored as the carbon content of dredged sediment does not count toward generated offsets. Only emission reductions occurring in-situ (e.g. carbon captured and stored through plant growth and stop-loss of ongoing emissions at project site) are eligible to generate carbon offsets.

RESTORATION APPROACH

There are a variety of restoration options available to Port Fouchon including wetland creation and terrace creation. The exact combination of different restoration options would be decided in the project planning and design phase.   Each of these options also has the potential to not only sequester carbon in the current area but decrease or prevent carbon from being lost in surrounding areas.

Some types of restoration may not be built to directly count towards carbon sequestration, such as marsh terraces, but instead can be used as protection for much larger areas of created marsh that are being counted towards carbon sequestration that would otherwise erode rapidly (Brasher, 2016; McGinnis & Guidry, 2011). Terraces provide this protection by reducing wave height, water level variability and fetch, sometimes themselves being sacrificed for the protection of other areas (Brasher, 2016; McGinnis & Guidry, 2011). The design and size of the terraces both impacts their protection potential as well as their cost, with smaller grids potentially providing the most benefits, while more open grids or chevrons still provide some protection while costing less to build (Brasher, 2016; Rozas & Minello, 2007). Planting the created marshes with *S. alterniflora* and *A. germinans* would not only assist in the carbon capture but also help to ensure that other species do not seed there (Shafer & Streever, 2000; Streever & Genders, 1997) only to be killed later by salt water inundation. Considerations of alternative placement of dredged material for Port Fourchon are listed in Table 2 to maximize their blue carbon credits.

Table 2. Summary of Port Fourchon default preference for placement of dredged material and suggested improvements to maximize blue carbon credits.

Blue Carbon Considerations	Port Fourchon Default Preference	Slight Improvement over Default Preference	Large Improvement	Optimal
Land Area	Fill deeper areas (>1 meter deep) and create smaller amount of land	A few shallow water projects (<1 meter deep) instead of only deeper areas	Majority shallow water locations (<1 meter deep) for dredge material, some deeper	Use dredge material in only shallow water areas (<1 meter deep) creating the most land
Dredge Type	Fill to dredge height of 1.2 meters (consolidate to 0.6 meters).	Create higher elevation areas (2 meters, consolidate to 1 meter)	Create higher elevation areas (2 meters, consolidate to 1 meter) areas and use thin layer dredging to maintain marsh areas	Fill to optimal restoration growth height of 1.2 meters (consolidate to 0.6 meters) and do thin layer dredging when channel is dredged
Restoration Type & Project Construction Timeframe	All marsh creation, large portion in the first 10 years, slower additions following	All marsh creation, large portion in the first 10 years, slower additions following. When marsh drowns convert to terraces	Initial dredging marsh creation and maintenance dredging to thin layer dredge. Some terraces constructed early	Initial dredging marsh creation and maintenance dredging to thin layer dredge. Marsh creation sites all surrounded by terraces
Permanence	Most land areas will start to erode around 50 years due to erosion and SLR	At least half of the marsh areas are maintained and justified to 100 years	Terraces are sacrificial, marsh areas are justified to 100 years	All marsh and terrace areas maintained through vegetation planting and thin layer dredging and justified to 100 years

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Conclusions and Path Forward

Thanks to the vision and forward thinking of the Greater Lafourche Port Commission and industry partners Shell, Chevron, and Danos, what was primarily an economic expansion opportunity for the port now has the opportunity to be one of the largest and most important nature-based solution projects in the country. As the permit process for the port's planned navigation channel deepening and facility expansion continues to move forward, the Partnership for Our Working Coast has taken the additional steps to make sure the best science is used to inform decision on how this dredged material should be used to provide maximum benefits to the port, industry, communities, and the environment.

This first round of technical reports lays the foundation for work that will not only better clarify the current situation around Port Fourchon but will also lay out a path forward for ultimate construction of coastal features that will provide better protection and resilience for all stakeholders.

The science and engineering laid out in the preceding technical reports shows the Institute's preliminary efforts in science and engineering to answer what is known, and unknown, about subsidence, potential options for optimal placement of dredged material for creation of nature-based defenses, and the potential for blue carbon capture.

This initial work included mining data that has already been collected, collecting new field data, and analyzing trends that will need to be considered as more detailed plans and ultimately construction designs are formed.

Within these technical reports, the Institute showed how variable subsidence can be throughout the area both in how much and how fast the land is sinking. It is vital to understand this factor more completely to avoid building critical land features in areas where subsidence rates make maintenance difficult over time.

In analyzing potential locations for where future dredged material should be placed, these reports look at what is being considered as part of the port's EIS process. After multiple considerations, the list of potential sites was narrowed considerably, but there is potential for additional sites to be considered in the future.

Blue carbon opportunities vary depending on the projects that are built, the types, and the timing, but overall there is real potential that these projects could generate carbon credits on the voluntary carbon market. While unlikely to fund the construction of coastal features themselves, these carbon credits could be instrumental in funding the necessary maintenance and monitoring the projects will require.

Multiple partners have made this first phase possible, from industry to students at Nicholls State University who helped in field work. It will take similar, and expanded, partner effort as the work moves to a more refined second phase in the path forward.

Phase two of the work will allow the Institute to make progress in the following sectors, all of which build toward providing the information necessary for the design, construction, and operation of the nature-based defenses being considered.

Building on the phase one subsidence work would involve establishing a subsidence monitoring program near the port to refine both the quality and spatial resolution done in phase 1.

Phase 2 of the beneficial use of dredged material work would use numerical models to look at performance of projects and potential dredge placement sites as far as their ability to improve infrastructure protection from storms and relative sea level rise. In addition, this work would provide a better understanding of the location, orientation, and elevation needed for marsh creation and ridge restoration/creation projects.

For phase 2 of the blue carbon work, the Institute team proposes to build on the analysis done in phase 1 with the goal of guiding design of features to be built with dredged material, ensuring the projects are assessed for carbon capture. In addition, this work can help guide the certification process either for internal company offsets or for bringing them to the voluntary carbon market. This phase will also move beyond marsh creation and terrace building to look at the potential value of mangrove habitat.

The vision for the Partnership for our Working Coast encompasses much more than providing benefits to industry and the port. Recognizing that the sustainability of the working coast is reliant upon improving the resilience and well-being of coastal communities, phase 2 will analyze the co-benefits of each of the planned nature-based defenses for local residents, including the protection of vulnerable populations, provision of ecosystem services, benefits to recreation and fisheries, and increased educational value.

The Institute team will use a Social Return on Investment framework to integrate community-based qualitative research, ecological site assessments, and economic valuation to calculate the social value of restoration project that includes current and future projects. Summing up the estimated values across all stakeholder groups will allow the team to estimate the overall societal value created by each of the proposed projects.

Attachments

Attachment 1: Modeling technical memo: Screening Alternatives of the Port Fourchon Channel Deepening Feasibility Project

Attachment 2: Wetland Value Assessment Data for Base Plan (400-ft wide, 50-ft deep) Channel Construction and 50-yr Maintenance Under Three Sea Level Rise Scenarios

Attachment 3: Wetland Value Assessment Data for Locally Preferred Plan (475-ft wide, 50-ft deep) Channel Construction and 50-yr Maintenance Under Three Sea Level Rise Scenarios

Attachment 4: Initial Deposition Sites – Pumping Distances from Each Dredge Station

Attachment 5: Carbon Project Feasibility Report

Attachment 6: The Institute and Nicholls State University Collaboration

Attachment 1:

Modeling Technical Memo: Screening Alternatives of the Port Fourchon Channel Deepening Feasibility Project

THE WATER INSTITUTE
OF THE GULF®

Screening Alternatives of the Port Fourchon Channel Deepening Feasibility Project

TECHNICAL MEMORANDUM

2/28/2018

To: GIS
From: The Water Institute of the Gulf
Dr. Brendan Yuill, Hoonshin Jung, MS, Dr. Ehab Meselhe, Dr. Melissa Baustian, Dr. Mead Allison, Andrea Jerabek, MS.
Date: February 28th, 2018
Re: Port Fourchon Channel Deepening

Preliminary Notes

This document describes the development and assumptions of the numerical model employed to support the Port Fourchon channel deepening feasibility project.

The full datasets of numerical model output referenced in this document were previously delivered to GIS, INC. and may have been excluded in this document in favor of summary tables for brevity. To obtain copies of the full datasets not included in this document, please contact Brendan Yuill at byuill@thewaterinstitute.org.

Please note the model was developed using metric units and, therefore, the model description uses metric units for continuity. Modeling results are reported in Imperial units as per standard U.S. engineering convention.

Contents

Overview

This Technical Memorandum summarizes numerical modeling conducted by the Water Institute of the Gulf in support of on-going environmental assessments related to planned Port Fourchon (the Port) improvements. The primary improvements of interest to this study includes expansion of the navigation channel (i.e., maintaining a deeper channel bed and width) and construction of a deep-water loading hole. This document contains brief overviews of the study area, numerical model set up and calibration, and model results. The overview of Port Fourchon offers environmental and economic context for this study. The description of the model set up and calibration describes the key physical and numerical properties of the numerical models employed by this study, as well as the working assumptions that guided model development and interpretation of output. The description of the model results focuses on summarizing the most important findings derived from the raw output in regard to addressing the study objectives.

Objectives

The objective of this analysis was to utilize numerical modeling to investigate the potential effect of alternative dredging scenarios on regional flow, geomorphology, and water quality properties for Bayou Lafourche Waterway Federal Navigation Channel and surrounding waters in Port Fourchon, Louisiana. The research questions addressed by this study are:

[1] How will increasing the maintenance dredge depths affect navigation channel sedimentation rates at the annual time scale in terms of magnitude and spatial distribution?

[2] How will increasing the maintenance dredge depths affect flow velocities and water level in the Port waterways?

[3] How will increasing the maintenance dredge depths affect water quality parameters (i.e., salinity and dissolved oxygen) in the Port waterways, with special focus on the proposed deep-water loading hole?

[4] How might jetty expansion alter the predicted navigation channel sedimentation rates?

Field Site

Port Fourchon is a large multi-use facility that services the Gulf Coast oil and gas production industry and provides deep-water access to Bayou Lafourche (Figure 1). Bayou Lafourche, approximately a 110-mile bayou, delineates the barrier between two major basins, Terrebonne and Barataria, and ultimately drains into the Gulf of Mexico through Port Fourchon. Bayou Lafourche was originally a Mississippi River distributary, but was dammed at Donaldsonville in 1905 (Henry & Twilley, 2013). The Mississippi River Deltaic Plain was constructed by a series of major delta-building events (over 1,000- 2,000 years) leading to six delta complexes, Maringouin, Teche, St. Bernard, Lafourche, Balize, and Atchafalaya, which each produced roughly 15,000 km^2 of marshlands (Roberts, 1997). However, the natural delta building cycle was interrupted by hydrological alterations (i.e., channelization, leveeing of waterways, and canal dredging) of the Mississippi River by the U.S. Army Corps of Engineers after the flood of 1927 (Barry, 1998).

Figure 1 Map of the study area showing the A) location of important Port Fourchon waterways including the proposed deep-water loading hole. Inset map B) shows the regional location of the site.

Currently, coastal Louisiana contains approximately 37% of the estuarine herbaceous marshes in the contiguous United States that supports regional key ecosystem services such as recreation, fisheries, carbon sequestration, wave attenuation, and surge reduction (Batker et al., 2014; Couvillion et al., 2011; Visser et al., 2012). Bayou Lafourche, divides two of the major river basins, Terrebonne and Barataria basins, which together contain approximately 5,858 km^2 of Louisiana wetlands (Sasser et al., 2014). Barataria Basin is dominated by bottomland hardwoods and fresh to brackish marshes, with saline marshes present on the fringes of the basin. In Terrebonne Basin the marsh habitats include a range from fresh to saline (LDWF, 2005). However, coastal Louisiana is currently experiencing drastic rates of disaggregation (i.e., fragmentation) and wetland loss due to factors such as sea level rise, subsidence, saltwater intrusion, and reduced sediment inflow (Day et al., 2011; Scavia et al., 2002). An estimated 5,000 km^2 of wetlands were lost between 1932 and 2010, and Louisiana is predicted to lose an additional 2,000-4,600 km^2 over the next 50 years (Couvillion et al., 2011). Specifically, the saline marshes in Barataria and Terrebonne basins have the second and third highest rates of disaggregation in Louisiana (Couvillion et al., 2016). Due to the combination of key ecosystem services provided and the high disaggregation rates of coastal wetlands, it is important to understand the potential effects that deepening of the navigation channel can have on the environment.

DESCRIPTION OF PORT FOURCHON

The legislation to establish the Greater Lafourche Port Commission passed in 1960, ultimately created the economically, environmentally, and geographically ideal location for what is now the prime multi-use port facility for logistic support and services for the Gulf of Mexico domestic deep-water oil and gas industry (Port Fourchon Operations Center, 2018b). Specifically, the Louisiana Offshore Oil Port (LOOP) uses Port Fourchon as its home base and handles 10-15% of the nation’s domestic and foreign oil and serves as a connection to 50% of the United States reefing capacity (Port Fourchon Operations Center, 2018a). In addition to LOOP, Port Fourchon is an operations base for more than 250 companies. As a result, 400 large supply vessels and 1,200 trucks traverse the Port, while 1.5 million barrels of crude oil are transported (via pipelines) through the Port on a daily basis (Port Fourchon Operations Center, 2018a).

A major component of the contemporary Port expansion plans is the development of a ‘deep-water loading hole’ along the left descending bank, downstream of station 130+00 (see Figure 1). This feature is planned to consist of a ~2000-acre basin maintained at a bed depth of -50 ft NAVD88 with a ~333-acre sub-basin maintained at a bed depth of -85 ft NAVD88. This feature would house facilities to repair and refurbish the deepwater oil and gas rigs that are currently serviced from the Port.

Methods

OVERVIEW

Numerical modeling was used to predict the impact of different dredging scenarios on regional flow, geomorphology, and water quality properties in and around Port Fourchon, Louisiana. This modeling employed the Delft3D software suite (www.oss.deltares.nl) and included the hydrodynamics and morphology (D-FLOW-SED-ONLINE), wave (D-WAVE, which is an interface for the SWAN model), and water quality (D-WAQ) modules. Delft3D is an open-source multidimensional sediment and hydrodynamics modeling package (Lesser et al., 2004). Delft3D computes flow using the Navier-Stokes equations of fluid motion and sediment transport by solving the continuity and transport equations on a two- or three-dimensional curvilinear finite-difference grid. Turbulence is simulated using a range of possible closure schemes (e.g., k-Epsilon). The Delft3D code is well documented (Deltares, 2014), and it is routinely used by The Water Institute of the Gulf to model river morphodynamics for a range of peer-reviewed studies (Meselhe et al., 2016; Yuill et al., 2016)

To predict the hydrodynamic, sediment transport, and morphodynamic response of the Port Fourchon channel system to modifications of the maintenance dredge depth, a regional-scale two-dimension (2D) model was created. To predict the evolution of water quality constituents due to alternations of the maintenance dredge depth, a three-dimensional (3D) water quality model of the lower Port Fourchon channel system and near-shore area was created. It was necessary to employ a 3D water quality model to simulate water quality dynamics to resolve the potential influence of vertical stratification within the flow depth profile.

The water quality model (D-WAQ) can simulate the evolution of a wide variety of water quality constituents in the water column and sediment/soil layers. D-WAQ solves the mass transport equations to calculate the advection and diffusion transport of mass with internal/external sources and sinks (i.e., loads and biogeochemical reaction processes) for each water quality state variable:

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y} - w\frac{\partial C}{\partial z} + \frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right) + S + P$$

where,

C : mass concentration (g/m^3),
t: time (sec),
x, y, z: coordinates in three spatial dimension (m),
u, v, w: velocity (m/sec) in x, y, z directions,
D_x, D_y, D_z: dispersion coefficients in x, y, z directions,
S: source and sinks of mass due to loads and boundaries (g/m^3/sec), and
P: source and sinks of mass due to biogeochemical processes (g/m^3/sec).

The horizontal and vertical advection and diffusion transport information used by D-WAQ are provided by Delft3D hydrodynamics module~~.~~ For sediment layers, zero horizontal advection and diffusion transport was assumed because of relatively slow transport to the horizontal direction. The vertical mass transports in sediment/soil layers and between bottom water and sediment top layer are caused by settling, resuspension, dispersion, and seepage processes (Smits, 2013; Smits & van Beek, 2013). The last term of the equation above, P, contains many biogeochemical and ecological processes in the Delft3D library, which are related to the dynamics for dissolved nutrients (e.g., nitrogen, phosphorus, silicon, and sulfur), marine and freshwater phytoplankton species biomass, organic matter/detritus, and dissolved oxygen.

During model development a paucity of field (in-situ) measurements for the Port Fourchon channel network was available to provide observational data for calibration and validation testing. Some regional monitoring instrumentation were identified to parameterize model boundary conditions (Table 1; Figure 2); these include Coastwide Reference Monitoring System (CRMS) stations, National Oceanic and Atmospheric Administration (NOAA) tide gauges, and Louisiana Department of Environmental Quality (LDEQ) stations. However, because the estuarine environment surrounding Port Fourchon contains very complex hydrodynamics (highly variable in time and space, multi-dimensional flows), it is unclear if the monitoring instrumentation can capture the full range of hydro-morphodynamic influences affecting the Port. To mitigate potential problems that might arise from the lack of available field verification observations, the model was developed with reduced complexity in mind, relying on conservative assumptions and generalized relationships derived from previous theoretical research.

Table 1: Monitoring instrumentation used in model development. Instrumentation locations are shown in Figure 2.

Map ID	Type	Station ID	Parameters Acquired
A	CRMS	318	Water level, salinity, temperature
B	CRMS	292	Water level, salinity, temperature
C	CRMS	175	Water level, salinity, temperature
D	CRMS	164	Water level, salinity, temperature
E	NOAA Tide Gauge	8761724	Water level, astronomic /tidal constituents
F	NOAA Tide Gauge	8762075	Water level
G	Weather	KXPY	Wind
H	LDEQ	021102	Salinity, dissolved oxygen
I	LDEQ	020403	Salinity, dissolved oxygen
J	LDEQ	020905	Salinity, dissolved oxygen
K	LDEQ	020402	Salinity, dissolved oxygen

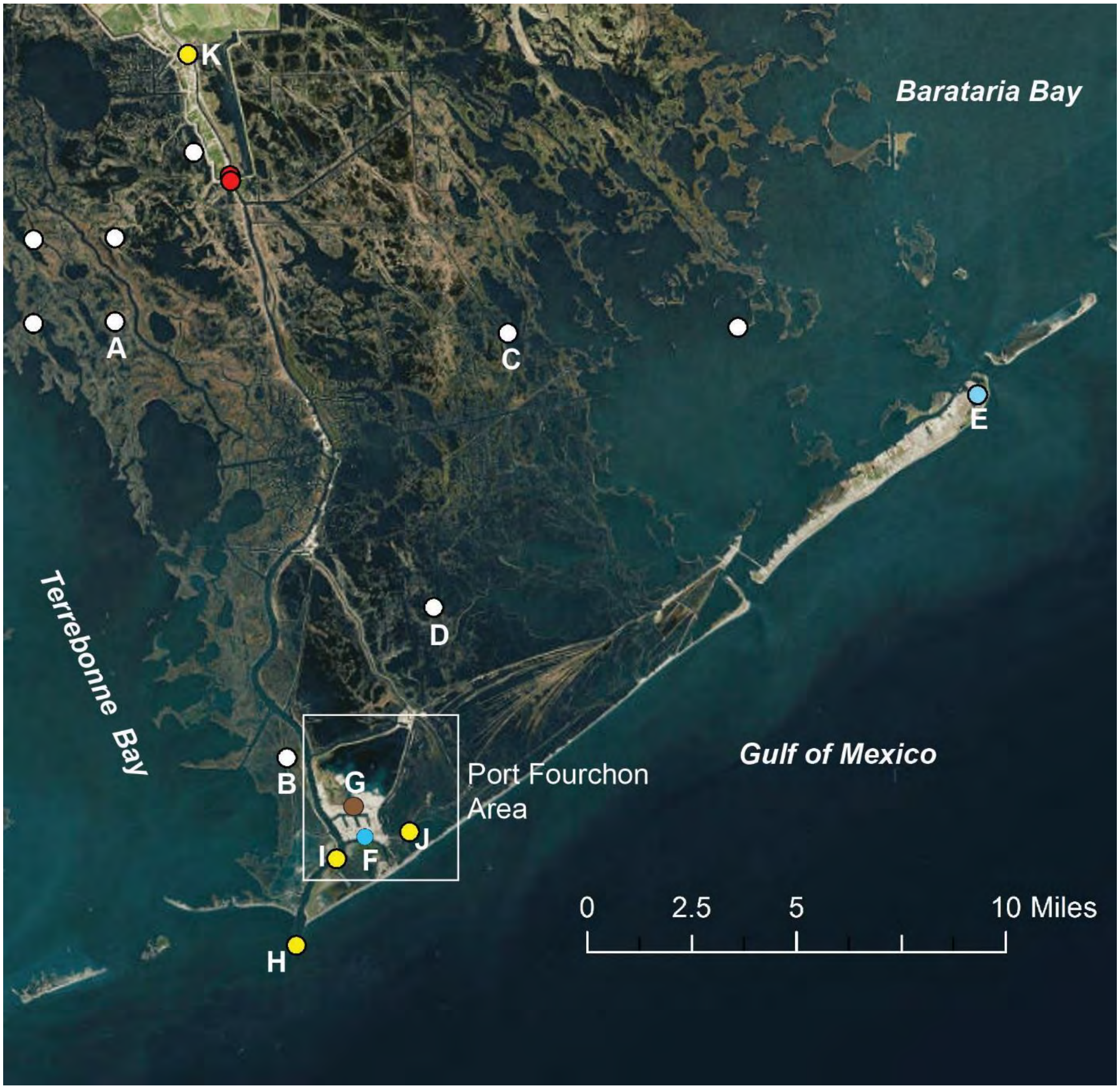

Figure 2: Locations of long-term monitoring instrumentation in the greater Port Fourchon area. White circles are CRMS stations; blue circles are NOAA tide gauges; red circles are USACE stage gauges; the brown circle is the location of a weather station associated with the Port Fourchon heliport; yellow circles are LDEQ water quality sampling stations. Lettered circles were used in model development and are referenced in Table 1.

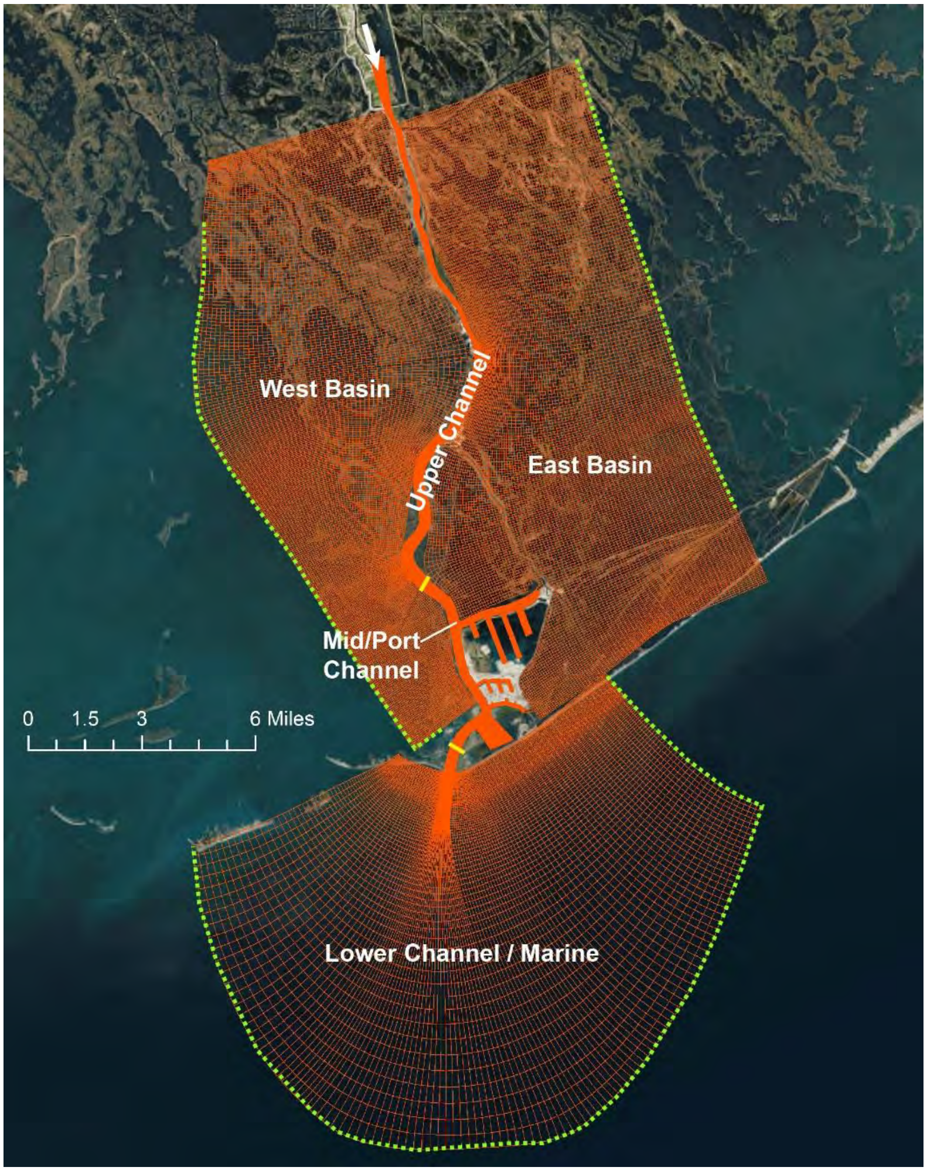

Figure 3: Map of the 5 model sub-domains: Upper Channel, Mid channel, Lower Channel/Marine, West Basin, and East Basin. The yellow lines show the connections of the channel sub-domains. The dashed orange lines show the open water-level boundaries. The downward facing white arrow shows the discharge boundary at the Upper Channel inlet boundary.

To simulate flow and sediment transport processes through Port Fourchon, a computational grid network was created to encompass the surrounding influential water bodies (Figure 3). To optimally fit the geometry of these water bodies, five separate sub-domain grids were created; the extent of each was set to include long-term hydrodynamic monitoring stations that could provide boundary condition parameterization (if available) and to provide spatial separation between areas of interest (the Port Fourchon channel system) and domain boundaries. Three sub-domains were created along Bayou Lafourche, an Upper Channel domain that reached the Golden Meadow flood gates, the Mid Channel (Port Fourchon area) domain, and a Lower Channel/Marine domain that included a large (120 mi^2) near-shore expanse of the Gulf of Mexico. It was necessary to include the Lower Channel/Marine domain into the model because the Port Fourchon navigation channel may span up to 8 mi below the outlet of Bayou Lafourche/Belle Pass depending on the maintenance dredge depth. The proximal basins to the east and west of the modeled Bayou Lafourche channel were also included as subdomains (~90 and 70 mi^2 in area, respectively) due to their significant hydrologic connectivity to Bayou Lafourche and the Port channels (17 passes were incorporated into the model). Figure 4 shows how passes were modeled in the immediate Port vicinity. Delft3D employs a technique called domain decomposition to connect the sub-domains into a master model.

Figure 4: Map diagram of the hydrologic connections between Bayou Lafourche and the proximal basins in the Port Fourchon area. The connections are identified by double-arrow lines.

The resolution of the three channel domains comprising the port area were adjusted to size cell widths comprising the Port area of approximately 13 m (43 ft), which ensured that the main channel cross sections were resolved by at least 20 cells, side channels were resolved by at least 8 cells, and all significant slips were resolved by greater than 1 cell. These resolutions were adequate to simulate the typical effects of secondary currents in river channels based on the previous experience of the modeling team. Cell resolution in the marine area decreased with distance away from Belle Pass (up to cell lengths of 322 m/1056 ft). Cell resolution in the basin sub-domains were typically 3-5 times that in the proximal channel domains.

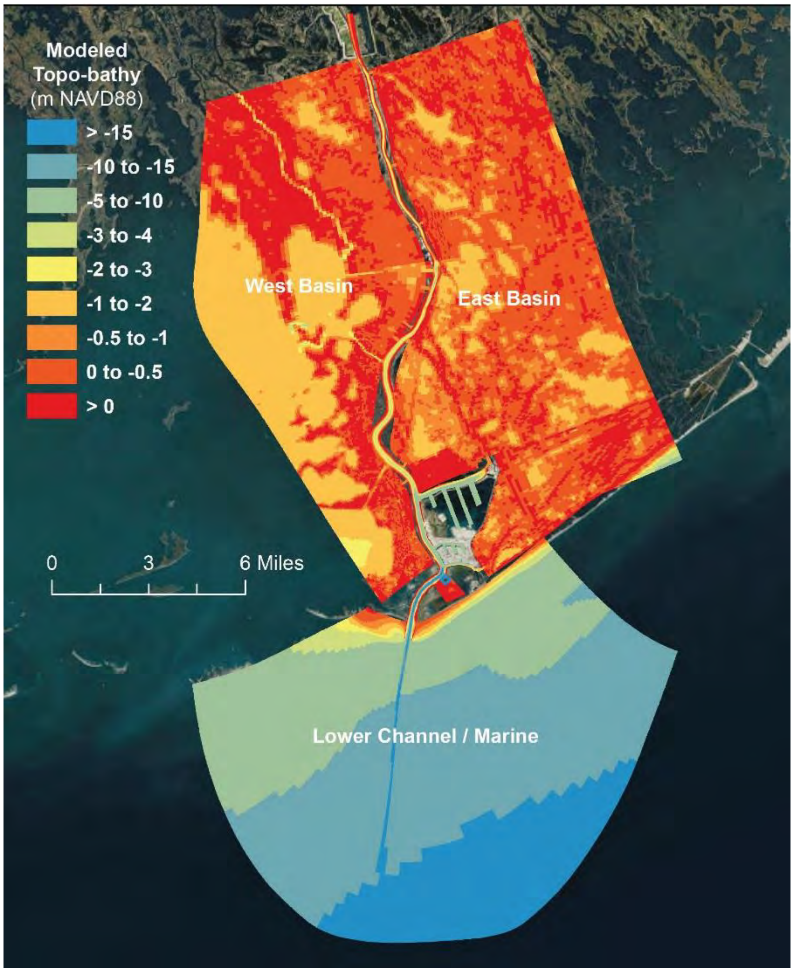

Figure 5: Map of the modeled bathymetry as incorporated into the -50 ft dredge depth scenario.

The initial model topography and bathymetry was parameterized using a modified version of the CoNED (Coastal National Elevation Database; lta.cr.usgs.gov/coned_tbdem) topobathy dataset. This dataset provides continuous 3 m^2 raster coverage of coastal U.S. areas using a synthesis of sources. The modified version used in this study was created to support Louisiana's 2017 Coastal Master Plan modeling effort and included localized corrections for Louisiana. Figure 5 shows the model bathymetry for the -50 ft dredge scenario (discussed later in this section) as an example.

The model was set up with four primary open boundaries (upstream of Bayou Lafourche, West Basin, East Basin, Lower Channel/Marine) that required boundary condition data for the modeled processes (shown in Figure 3). The upstream boundary of Bayou Lafourche was set as a total discharge inlet and was parameterized using predicted discharge data for the Golden Meadow flood gates provided by the Integrated-Compartment Model (ICM) developed for Louisiana's 2017 Coastal Master Plan. The downstream marine boundary for the Lower Channel/Marine sub-domain was set as a water-level boundary parameterized using astronomical constituents. The astronomical constituents were derived from historical records of regional tidal records using the Delft Dashboard software (publicwiki.deltares.nl/display/DDB/Delft+Dashboard). This type of water-level boundary may resolve sub-diurnal tidal fluctuations. The open boundaries at the outer margins of the East and West basins were parameterized using time series water-level data derived from CRMS (coastwide reference monitoring system) data (Coastal Protection and Restoration Authority (CPRA) of Louisiana, 2017; Folse et al., 2014).

Sediment dynamics were simulated using two representative grain-size fractions, one fraction to represent the dynamics of non-cohesive sediment (sand) and the other fraction to represent the dynamics of cohesive sediment (silt and clay). The 2004 Van Rijn formula (van Rijn, 2007) was used to simulate the transport of the sand grain size fraction. Based on geotechnical measurements of bed sediment in the region, the sand fraction was assumed to have a median grain size diameter of 0.065 mm (GeoEngineers LLC, 2017). The cohesive sediment transport was modeled using the Partheniades-Krone formulations (Partheniades, 1965) ,which required parameterization of an indicative critical shear stress, erosion parameter, and a grain-settling velocity and were set as 0.5 Pa, 0.001 $kg/m^2/s$, and 0.1 mm/s, respectively. These values were derived from previous morphodynamic models of Barataria Basin (e.g., Meselhe et al., 2015A; 2015B) that received robust calibration and validation testing and are representative of bay bottom silts. The relative abundance and spatial distribution of sands, silts, and muds within the soil and sediment layers are not well documented for the study area and were modeled as spatially uniform for simplicity.

Delft3D automatically calculates cumulative sedimentation depth (negative values equal net erosion, positive values equal net aggradation) for each model cell through a simulation. To derive sedimentation values for the navigation channel, cumulative sedimentation depth was extracted down the navigation center line and averaged over 1000 ft intervals. To calculate sedimentation volumes over the 1000 ft intervals, the averaged cumulative sedimentation depths were multiplied by the interval length (1000 ft) and assumed channel width (400 ft for the entrance channel, 300 ft for the upper Port channels). To calculate the mean sedimentation rates for the Port side channels, the cumulative sedimentation depths for the grid cells that compose each side channel were averaged.

Waves were simulated in the marine domain to resolve their effect on sediment transport and currents. Delft3D allows simultaneous coupling of the hydro-morphodynamic model (D-FLOW-SED-ONLINE) and wave model (D-WAVE) using the 'online Delft3D-wave' switch, which was employed. The wave model generated a uniform wave climate at the Lower Channel/Marine boundaries which evolved with respect to the currents generated by the hydrodynamic model and wind field as they moved landward

(Figure 3). The boundary wave climate included a 0.25 m significant wave height, 5 s peak period, 160° initial direction, and a directional spreading factor of 10. The wave model used a computation grid with the same approximate extent as the Mid Channel (Port Fourchon) and Lower Channel/Marine sub-domains with a resolution reduced by a factor of 2.

The primary model parameters employed by this study that are not discussed above are summarized in Table 2.

Table 2: Miscellaneous Delft3D model parameters for hydrodynamics, sediment, morphology, and waves; primary parameters are defined in the text.

Model Component	Parameter	Employed Value or Setting
Hydrodynamics	Roughness (Chezy coefficient)	65 $m^{0.5}/s$
	Background horizontal eddy viscosity/diffusivity	10 m^2/s
	Threshold (wetting) depth	0.1 m
	Advection scheme for momentum and transport	cyclic
Sediment	Initial sediment thickness	10 m uniform
	Sand dry bed density	1600 kg/m^3
	Silt dry bed density	500 kg/m^3
Morphology	Morphological scale factor	1 (MorFac off)
	Factor of erosion for dry cells	0 (no dry cell erosion)
	Transport multiplication factor	1 (no multiplication)
Waves	Stress formulation due to waves	Fredsoe
	Generation mode for physics	3rd generation
	Depth-induced breaking	Alpha: 1; Gamma: 0.73
	Bottom friction	JONSWAP; coefficient: 0.038 m^2/s^3
3D Model	Turbulence model	k-Epsilon
Temperature	Heat flux model	Ocean
Timesteps	2D model	0.25 min
	3D model	0.20 min

SCENARIOS

Six primary model scenarios were simulated, “As-Is” (also referred to as ‘pre-construction’), “-30 ft”, “-35 ft”, “-40 ft”, “-45 ft”, and “–50 ft”. The scenarios are named after the value used to parameterize the initial bed elevation of the entrance channel (> station 130+00). See Figure 6 for a map showing the Port and navigation channel stationing convention used in this report. This figure also shows the downstream extent of dredging for each scenario, which equates to the existing sea bed elevation contour. The “As-Is” scenario used an elevation value of -24 ft for the entrance channel and the upper Port channels (station 0+00 to station 130+00). The other five scenarios (i.e., the alternative post-construction scenarios) assumed an initial bed elevation of -30 ft for the upper Port channels. These elevations approximately correspond with the current (-24 to -27 ft) and planned (-30 ft) maintenance dredge depths investigated in this report. The only difference between these primary scenarios was the initial bed elevations of the entrance and upper Port channels.

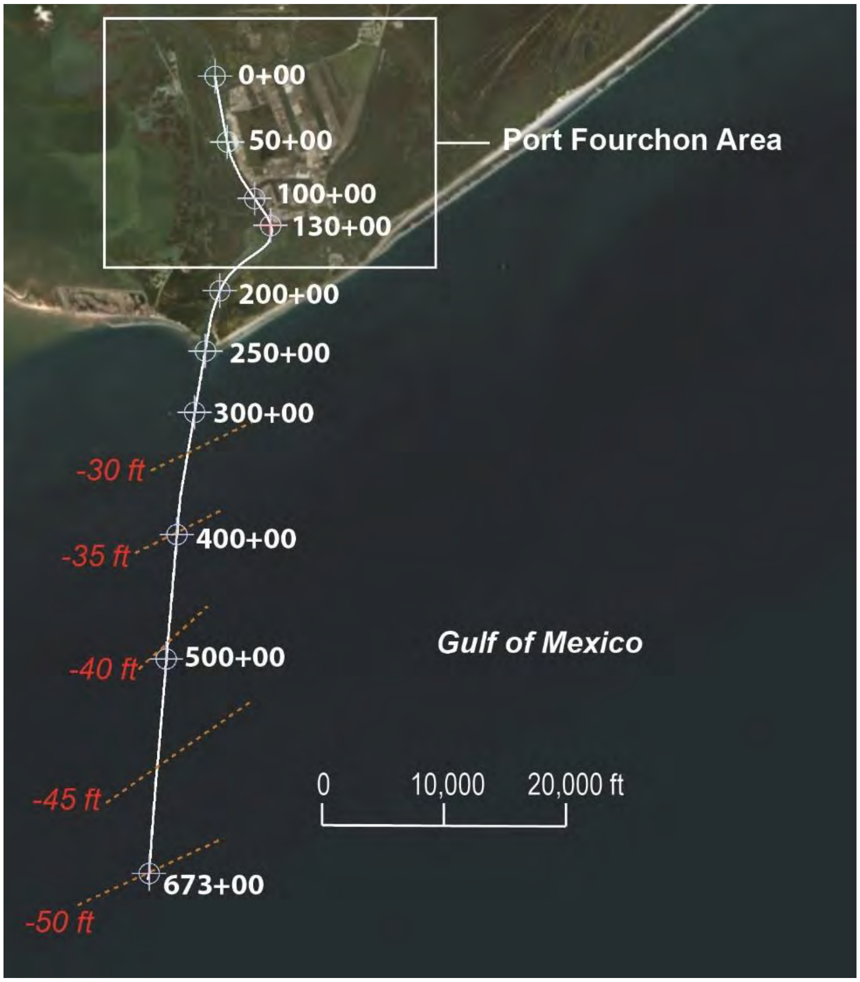

Figure 6: Map diagram of the channel stationing referenced by this study and represents the typical stationing used on previous Port Fourchon projects.

The scenarios are parameterized to simulate a design hydrograph. As opposed to simulation of an observed time period, the design hydrograph was constructed to simulate a simple, well-constrained period of typical flow conditions. The typical flow conditions were computed from a 4-year (2010-2013) time series of observed hydrologic measurements. For this study the typical flow conditions were defined as the values that fall between the 1st and 3rd quartiles (i.e., the middle 50 % of the observed distributions) (Figure 7). This design hydrograph approach was selected because it is hypothesized that the typical flow conditions are responsible for driving channel sedimentation over long time scales (> 1 year). A benefit of this approach is that the results are scalable (providing that sedimentation thicknesses << flow depths), i.e., the predicted sedimentation rates can be multiplied by a factor of 2 to calculate sedimentation for a period 2 times that simulated without invalidating the study assumptions. One of the shortcomings of this approach is that sedimentation due to low-frequency, high-magnitude hydrological events (e.g., floods or hurricanes) are not considered.

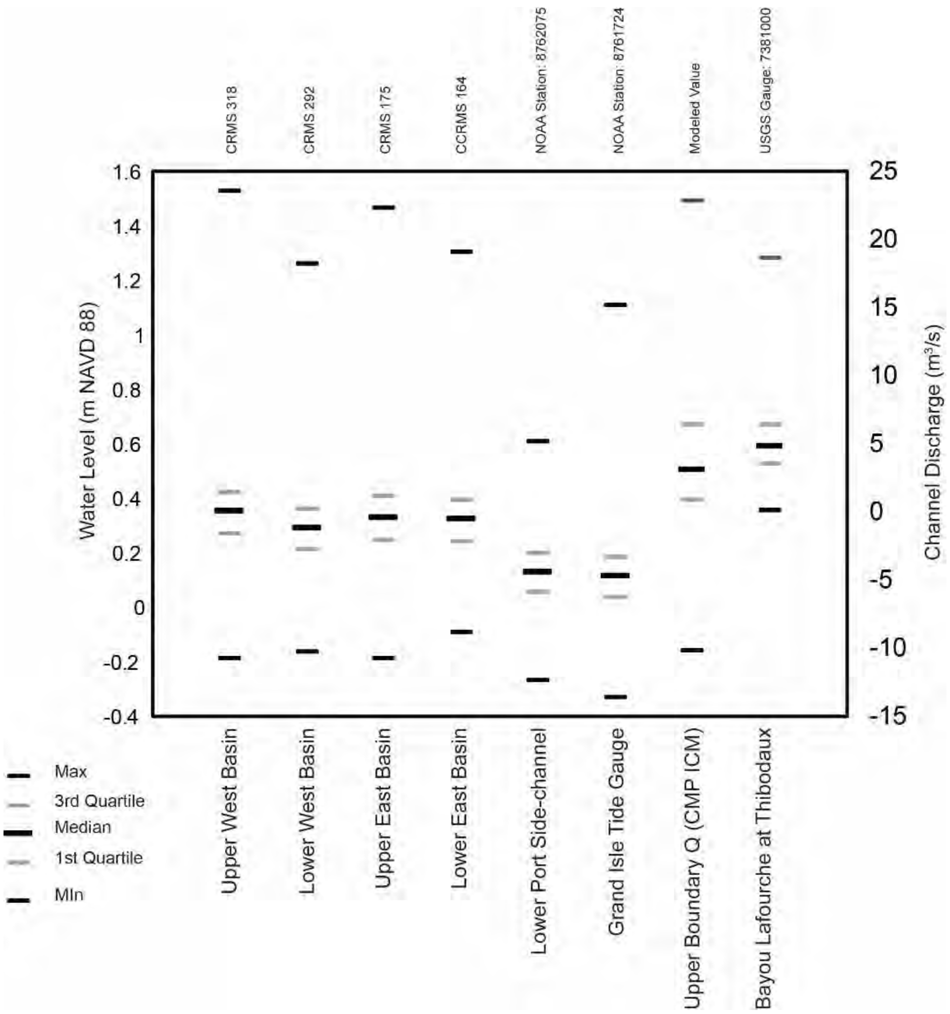

Figure 7: Summary statistics for the distribution of daily values (2010-2013) recorded at each site.

Each scenario consisted of a 100-day period. During the first 50 days of this period, [1] the inlet discharge of Bayou Lafourche was linearly increased from the 1st quartile to the 3rd quartile value and [2] the water level at the outer boundaries of the East and West basins were linearly increased from the 1st quartile to the 3rd quartile value. During the second 50 days, [1] the inlet discharge was lowered linearly from the 3rd quartile to the 1st quartile value and [2] basin boundary water levels were decreased from the 3rd quartile to the 1st quartile value. The water-level at the Lower Channel/Marine boundary had a non-time varying mean value that fluctuated in response to parameterized astronomic constituents (introducing high-resolution tidal signals).

The scenarios employed a time-varying, spatially-uniform design wind field at a 2-hr interval, which was used as an input to the hydrodynamic (D-FLOW) and wave (D-WAVE) models. The design wind field was schematized to increase wind magnitude from 12:00 midnight to 12:00 midday and decrease wind magnitude from 12:00 midday to 12:00 midnight. Wind direction revolved in either a clockwise or counter-clockwise direction each day beginning at midnight; the revolution direction for each day was randomly assigned. The design wind field values were generated to have the same frequency distribution as the measured wind field at the Port Fourchon heliport weather station (KXPY) from 2010 to 2013 (Table 1).

Two additional and secondary scenarios were tested for this study. The objective of these scenarios was to quantify the impact of the Belle Pass/ Bayou Lafourche outlet jetty extension on the predicted sedimentation rate in the Port Fourchon entrance channel (see Figure 5). These scenarios consisted of modification of the “-50 ft” scenario. For one scenario, the bathymetry was altered to simulate the extension of the jetty to channel station 275+00 (referred to as scenario “J275”). For another scenario, the bathymetry was altered to simulate the extension of the jetty to channel station 290+00 (referred to as scenario “J290”). The current jetty configuration extends to approximately station 265+00/270+00; contemporary high-resolution aerial imagery was used to define the footprint of the current jetty system.

CALIBRATION

Model hydrodynamics were calibrated against the observed water-levels measured at the NOAA Port Fourchon tide gauge for the year 2010. Calibration tests included systematic alteration of bed roughness values or downstream boundary water level values to optimize reproduction of the observed time series (Figure 8). The calibration tests resulted in adding a +0.07 m offset to the astronomical constituents employed by the downstream marine boundary; this value likely reflects the difference in mean water elevation between the Grand Isle Tide gauge (from which the astronomical constituents were derived, in part) and the marine boundary of the model.

In the absence of additional observational datasets available for calibration, the model performance was also assessed using qualitative methods. Patterns of modeled salinity gradients, which reflect the model’s ability to simulate the flux and mixture of upstream freshwater with downstream ocean water, were assessed relative to observed salinity gradients in Barataria Basin (assessed from USGS fixed instrumentation). While the magnitude of the salinity gradients would not be expected to be the same, patterns of mixing should be similar.

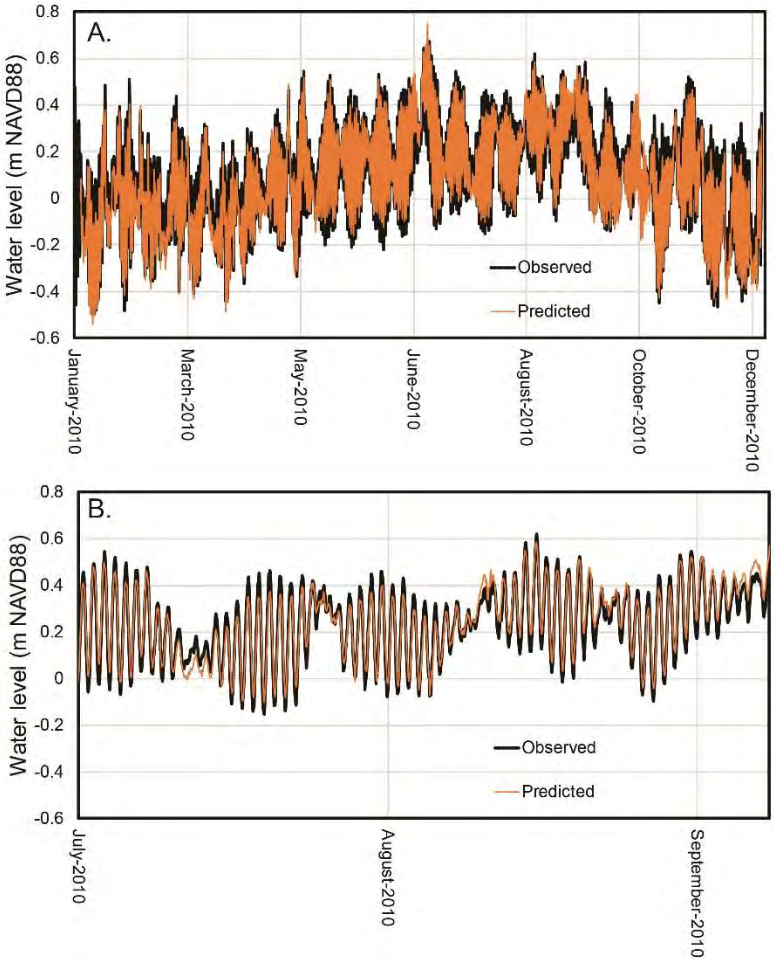

Figure 8: Results from calibration testing. The black ('observed') values are from NOAA tide gauge at Port Fourchon, the orange predicted values are from the 'As-Is' scenario.

Model sediment transport processes were calibrated by comparing predicted sedimentation rates for the As-Is scenario against historical dredging records (e.g., Table 3). The primary variables analyzed during calibration tests were the cohesive sediment settling velocity, erosion parameter, and critical shear stress for erosion. Tests indicated that the predicted sedimentation rates were very sensitive to the plausible range of critical shear stress values (e.g., increasing the critical shear stress value from 0.3 Pa to 1.0 Pa reduced total entrance channel sedimentation by 75 %). Previous environmental studies of Port Fourchon shoaling rates (e.g., the 1994 US Army Corp of Engineers (USACE) Feasibility Engineering Appendix; the 2015 Federal Assumption of Maintenance Feasibility Study) calculated mean values of 0.5 to 1.125 ft/yr for the upper Port channels and 2 to 4 ft/yr for the entrance channel. These rates compare favorably to the mean sedimentation rates predicted by the final 2D model of 0.6 ft/yr for the upper Port Channel and 2.00 ft/yr for the entrance channel (4.70 ft/yr averaged over the channel area immediately around the jetty sedimentation hotspot).

Table 3: Dredging data provided by the USACE. CY = cubic yards.

Dredge End Date	Dredge Location	Dredged Channel Length	Dredged Channel Area	Dredged Sediment Volume	Volume/ 1000 ft Channel Length	Mean Dredged Depth (below bed elev.)
	Station	*ft*	*Y^2*	*CY*	*CY*	*ft*
12/12/2002	215+00 to 280+00	6,500	216,667	338,534	52,082	4.7
12/14/2004	200+00 to 330+00	13,000	433,333	779,798	59,984	5.4
5/13/2006	215+00 to 330+00	11,500	383,333	605,005	52,609	4.7
4/25/2007	60+00 to 215+00	15,500	516,667	472,786	30,502	2.7
11/10/2008	200+00 to 288+10	8,810	293,667	435,311	49,411	4.4
6/2/2012	200+00 to 280+00	8,000	266,667	525,986	65,748	5.9
8/18/2014	235+00 to 265+00; 215+20 to 217+15	3,195	106,500	150,141	46,992	4.2
9/12/2015	60+00 to 120+00; 235+00 to 310+00	13,500	450,000	587,046	43,485	3.9

WATER QUALITY MODELING

Water Quality Model Set Up

To estimate the hydrodynamic fields used to drive the water quality model a modified version of the 2D hydro-morphodynamic model discussed above was employed. The model was modified by adding five vertical layers to its computational grid (i.e., giving it 3D capabilities). Each layer composed of 20 % of the total flow depth at each time step. The model domain was truncated to reduce computation expense (i.e., the East Basin, West Basin, and Upper Channel sub-domains were removed). Removal of the upstream sub-domains created new open boundaries at grid cells that previously connected the existing model domain to the removed sub-domains. These new boundaries were parameterized using total discharge values extracted from the output of the 2D model.

The 3D hydrodynamic was set up to simulate the observed year 2010. Simulating 2010 required creating six new scenarios using the As-Is, -30 ft, -35 ft, -40 ft, -45 ft, and -50 ft model bathymetries and observed time series data for the discharge and water-level open boundaries. The time series data was available from the same monitoring instrumentation used to derive the design hydrograph boundary conditions (shown in Figure 2). The 3D hydrodynamic model used observed annual time series data to ensure that seasonal cycles of water temperature, which significantly influence the water quality variables of interest (e.g., dissolved oxygen), were realistically resolved.

The D-WAQ water quality model computational grids were aggregated from the 3D hydrodynamic grid. The aggregation of hydrodynamic grids was based on the characteristics and geometries of hydrodynamic grids. Water grids were aggregated separately in deep water zones and shallow water zones. The size of the model segments was determined by confirming that the minimum residence time for an entire simulation period was larger than 10 min for each segment. A total of 404 surface segments were developed for D-WAQ. Each segment has five vertical layers, resulting in 2020 segments per water column (= 404 (water surface) x 5 (water layers)). Interactions at the sediment-water interface were simulated on seven sediment/soil depth layers representing the top 40 cm of the sediment/soil layer. The upper layer was very thin (1-4 mm), and the overall thickness of the layers ranged between 1 to 200 mm. The thin upper sediment layers were designed to consider steep concentration gradients at the interface between water and sediment/soil layers. Therefore, the total number of segments including those in the water column and sediment/soil profile is 4848 (= 2020 + 404 (water surface) x 7 (sediment/soil layers)).

To aid parameterization of the D-WAQ model, monthly water quality data (salinity, total suspended sediment (TSS), dissolved oxygen (DO), ammonium (NH4), nitrate+nitrite (NO3), phosphate (PO4)) measured from 2000 to 2015 were collected from the Louisiana Department of Environmental Quality. Four LDEQ stations within the model domain were selected for use in model set up and boundary condition parameterization (see Figure 2 for the locations). Instead of considering a specific year, the collected data were averaged for each month so that the water quality data represents long-term mean behaviors in this system. For salinity and NO3 concentrations, station ST020402, which is located relatively upstream, shows different behavior as compared to other more downstream stations (Figure 9). This observation might be related to localized restrictions of freshwater inputs and to agricultural activity. Relative to that upstream location, station ST021102, which is located offshore, shows lower salinity during summer compared to station ST020402. This observation may be due to inflows of freshwater from the Mississippi River. Despite that observation, the salinity levels in both stations are similar for spring, fall, and winter.

Data from stations ST020402 and ST020905 were used for the upstream boundary and lateral boundary conditions, respectively. In the case of salinity and DO concentrations, station ST020402 was determined to be too far from the model upstream boundary, therefore, salinity and DO concentrations at the upstream boundary were defined by station ST020905. For offshore boundary conditions, ST021102 data were used; the station is located immediately downstream of Belle Pass; however, more seaward observed data were not available. Other water quality data not measured by LDEQ were estimated based on previous work (Meselhe, et al., 2015). The vertical gradient of water quality constituents at the boundaries were not considered in the model setup because there was no available information.

Initial conditions for water quality constituents were designed based on the observed data and previous work (Meselhe, et al., 2015A; 2015B). The simulation started from the spatially uniform initial conditions for water quality in the water column and in sediment/soil layers, which were derived from historical data and field measurements under different hydrodynamic conditions. It should be noted that to establish dynamic equilibrium conditions for water quality constituents, the simulation was repeated with end-of-the-year conditions used as a "hot-start" for the next iteration. The process was repeated three times until the pattern stabilized and the same seasonal variability was observed from one iteration to the next.

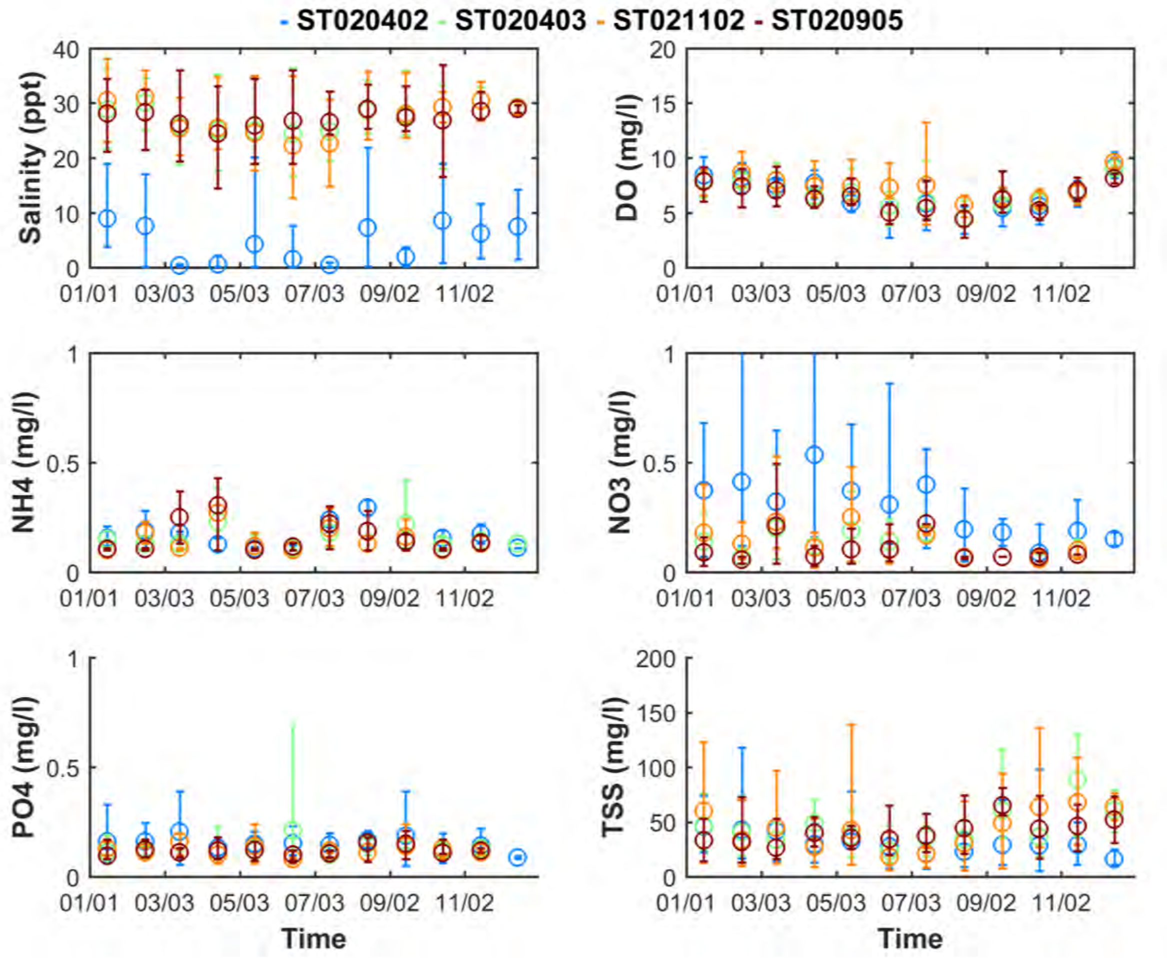

Figure 9: Water quality model performance relative to observed values measured at station ST020403 in Bayou Lafourche near Port Fourchon. Data for the five vertical layers are plotted; however, because of the absence of stratification, they are not distinguishable.

Water Quality Model Calibration

The model was set up with the same water quality model coefficients used in similar studies of analogous environments (e.g., Meselhe, et al., 2015A; 2015B) because of the relative absence of observed data sets for initial conditions, calibration, and validation. The water quality model was compared to the observed monthly mean data (see Figure 9) for salinity, DO, NH4, NO3, PO4, and TSS at ST02403 (Figure 10) and ST012203 (Figure 11).

Figure11 shows the comparison results between the model and observed data at ST020403. The model showed no vertical gradient for water quality constituents including salinity in the channel, which indicates that the system is well mixed. In the case of DO concentrations, the model results reproduced well a seasonal pattern with low DO concentrations during summer because of high decomposition rates of detritus during warm summer months. The model overestimated NO3 concentrations throughout year 2010 and the computed TSS results indicated underestimation against the observed data. Figure 12 shows a comparison between model and observed data at ST021102, which is immediately downstream of the jetty (see Figure 9 for map of location). The model output showed a similar performance to ST020403. The simulated salinity indicated some vertical stratification over the year, but salinity vertical gradients were small (less than 3 ppt). The model underestimated DO concentrations during summer compared to the observed data but captured the seasonal pattern well.

Figure 10 shows the comparison results between the model and observed data at ST020403. The model showed no vertical gradient for water quality constituents including salinity in the channel, which means that the system is well mixed. In case of DO concentrations, the model results reproduced well a seasonal pattern with low DO concentrations during summer because of high decomposition process rates throughout the year 2010 and the computed TSS results showed indicated underestimation against to the observed data. The model showed no vertical gradient for water quality constituents including salinity in the channel, which means that the system is well mixed. In case of DO, the model results reproduced well a seasonal pattern with low DO during summer because of high decomposition process of detritus. Figure 11 shows a comparison results between model and observed data at ST021102, which is immediately downstream of the jetty (see Figure 2 for map of location). The model output showed very a similar performance as shown at ST020403. The simulated salinity showed indicated some vertical stratification over the year, but salinity vertical gradients were small (less than 3ppt). The model underestimated DO concentrations during summer compared to the observed data but captured the seasonal pattern well.

Overall, the change in the concentration of water quality parameters in the channel was primarily determined by the upstream and lateral boundary conditions. Flow within the Port waterways was generally well mixed and quickly advected out of the system (e.g., high flushing rates) during the analyzed scenarios. Modeled output in year 2010 did not indicate that water volume residence times were long enough to promote significant biological/chemical reactions capable of altering the water quality condition relative to the values estimated at the model boundaries. While year 2010 was a typical year in terms of watershed hydrology and stream flow for the study area, it should be noted that it may not be representative of many other types of flow conditions from other years.

Considering there was little available field observational data for initial and boundary conditions, the model results indicate a good agreement with observed data and represent the seasonal change well in this system. The calibrated model is acceptable to evaluate the relative impact of dredging on salinity and DO changes.

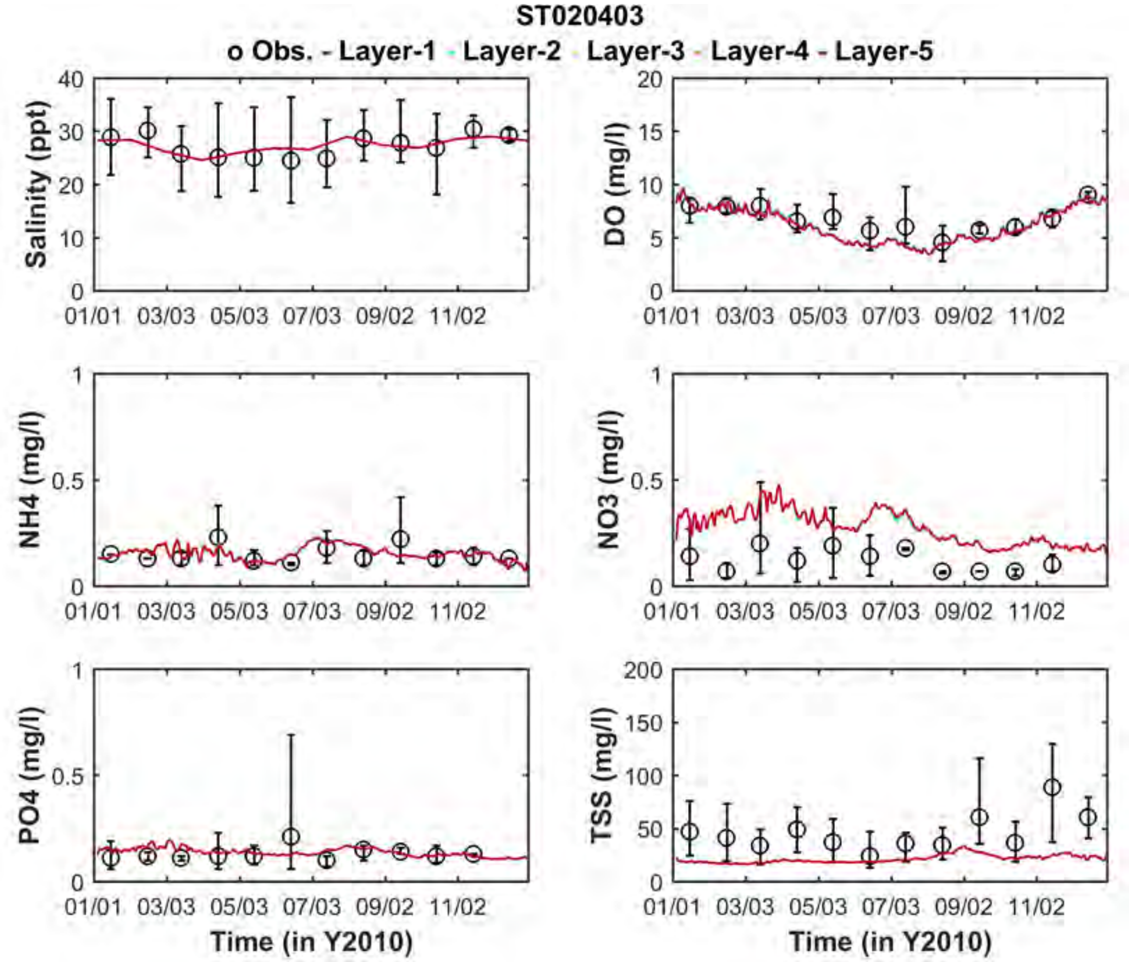

Figure 10: Water quality model performance relative to observed values measured at station ST020403 in Bayou Lafourche near Port Fourchon. Data for the five vertical layers are plotted; however, because of the absence of stratification, they are not distinguishable.

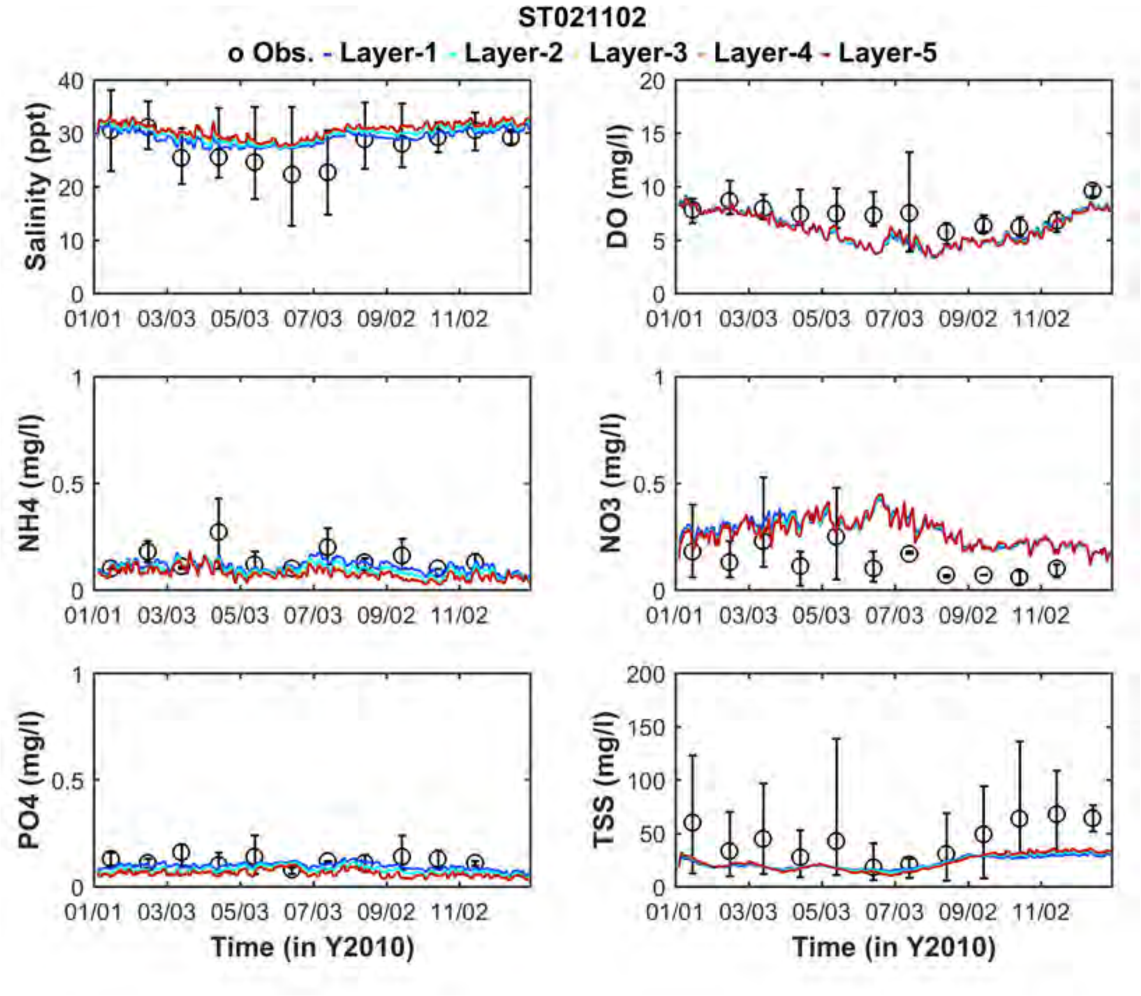

Figure 11: Water quality model performance relative to observed values measured at station ST021102. Data for the five vertical layers are plotted; however, because of the absence of stratification, they are not individually distinguishable.

Results

CHANNEL SEDIMENTATION

The predicted sedimentation values for the upper Port channel are shown in Table 4. The predicted sedimentation values for the entrance channel are shown in Table 5 (volumes) and Table 6 (thicknesses). The model predicted that the highest values of sediment occur in the entrance channel around the jetty area, approximately between station 250+00 and 300+00 (Figure 12).

The predicted spatially-averaged sedimentation rates for the Port Side Channels are shown in Table 7. In the table, the 'upper side-channel' consists of the flotation canal and slips A through D, the 'middle side-channel' consists of the E-slip, and the lower-side channel consists of the 4,300 ft western length of Pass Fourchon (these side channels are shown in Figure 1).

Table 4: Modeled sedimenation for the upper Port channel for 2 maintenance depths. CY = cubic yards.

Location Along Channel	**As-Is / Pre-construction depth**		**-30 ft Maintenance Depth**	
Starting Station	Volume	Thickness	Volume	Thickness
	CY/yr	*ft/yr*	*CY/yr*	*ft/yr*
0+00	27,213	2.45	42,741	3.85
10+00	6,144	0.55	21,374	1.92
20+00	0	0.00	14,315	1.29
30+00	0	0.00	15,816	1.42
40+00	5,632	0.51	16,926	1.52
50+00	11,429	1.03	17,225	1.55
60+00	5,313	0.48	16,549	1.49
70+00	2,097	0.19	14,399	1.30
80+00	41	0.00	13,669	1.23
90+00	8,632	0.78	16,568	1.49
100+00	10,866	0.98	17,437	1.57
110+00	7,625	0.69	17,062	1.54
120+00	2,374	0.21	14,597	1.31
Total / *mean*	**87,365**	*0.60*	**238,678**	*1.65*

Table 5: Modeled sedimentation volumes along the entrance channel for the 6 dredging scenarios.

Location Along Channel		**Predicted Sedimentation Volume** (CY/ yr per 1000 ft channel length)					
Starting Station	Feet below 130+00	**As-Is**	**-30 ft**	**-35 ft**	**-40 ft**	**-45 ft**	**-50 ft**
130+00	0	8,891	14,496	17,528	18,834	19,642	20,795
140+00	1000	4,147	16,365	17,671	18,674	19,329	20,223
150+00	2000	8,587	15,183	17,194	18,080	18,662	19,500
160+00	3000	7,804	14,365	17,271	18,312	18,652	19,362
170+00	4000	5,319	14,297	17,730	19,107	19,041	19,649
180+00	5000	7,348	16,301	19,278	20,052	19,999	20,666
190+00	6000	6,477	17,154	20,475	21,176	21,089	21,842
200+00	7000	11,033	20,418	23,021	23,453	23,104	23,546
210+00	8000	11,425	24,457	27,653	28,018	27,443	27,676
220+00	9000	4,363	29,132	36,527	38,628	36,991	37,999
230+00	10000	49,561	59,803	62,682	63,209	62,056	62,804
240+00	11000	82,374	86,286	85,349	81,657	79,449	81,996
250+00	12000	74,015	84,896	80,263	77,710	73,587	75,726
260+00	13000	77,653	94,617	91,036	88,517	84,253	85,954
270+00	14000	100,045	106,411	115,379	118,399	118,455	121,563
280+00	15000	66,118	77,451	91,069	93,297	93,001	94,251
290+00	16000	37,530	42,207	62,684	66,207	66,331	66,844
300+00	17000	29,081	26,899	45,642	48,365	48,615	49,540
310+00	18000	16,152	17,491	33,621	36,218	36,418	37,392
320+00	19000	8,499	10,274	24,929	27,158	27,701	28,706
330+00	20000	5,633	7,432	18,305	20,473	21,057	22,038
340+00	21000			14,368	16,478	16,660	16,978
350+00	22000			11,555	13,022	13,197	13,270
360+00	23000			9,413	10,668	10,864	10,896
370+00	24000			8,338	9,188	9,291	9,381
380+00	25000			7,396	8,035	8,159	8,248
390+00	26000			6,846	7,341	7,442	7,510
400+00	27000				6,821	6,922	6,983
410+00	28000				6,440	6,512	6,558
420+00	29000				6,108	6,158	6,206
430+00	30000				5,837	5,879	5,929
440+00	31000				5,593	5,645	5,691
450+00	32000				5,386	5,442	5,488
460+00	33000				5,216	5,250	5,299
470+00	34000				5,067	5,095	5,140
480+00	35000				4,946	4,980	5,014
490+00	36000					4,856	4,893

Table 5 (continued)

Location Along Channel		**Predicted Sedimentation Volume** (CY/ yr per 1000 ft channel length)					
Starting Station	Feet below 130+00	**As-Is**	**-30 ft**	**-35 ft**	**-40 ft**	**-45 ft**	**-50 ft**
500+00	37000					4,756	4,799
510+00	38000					4,694	4,735
520+00	39000					4,623	4,659
530+00	40000					4,584	4,616
540+00	41000					4,545	4,579
550+00	42000					4,526	4,555
560+00	43000					4,510	4,542
570+00	44000					4,524	4,542
580+00	45000					4,526	4,547
590+00	46000						4,571
600+00	47000						4,595
610+00	48000						4,630
620+00	49000						4,668
630+00	50000						4,716
640+00	51000						4,769
650+00	52000						4,826
660+00	53000						4,901
670+00	54000						3,840
Total		622,057	795,934	983,225	1,061,690	1,098,516	1,164,646

Table 6: Modeled sedimentation thicknesses along the entrance channel.

Location Along Channel		**Predicted Sedimentation Thickness** (ft/ yr averaged per 1000 ft channel length)					
Starting Station	Feet below 130+00	**As-Is**	**-30 ft**	**-35 ft**	**-40 ft**	**-45 ft**	**-50 ft**
130+00	0	0.60	0.98	1.18	1.27	1.33	1.40
140+00	1000	0.28	1.10	1.19	1.26	1.30	1.37
150+00	2000	0.58	1.02	1.16	1.22	1.26	1.32
160+00	3000	0.53	0.97	1.17	1.24	1.26	1.31
170+00	4000	0.36	0.97	1.20	1.29	1.29	1.33
180+00	5000	0.50	1.10	1.30	1.35	1.35	1.39
190+00	6000	0.44	1.16	1.38	1.43	1.42	1.47
200+00	7000	0.74	1.38	1.55	1.58	1.56	1.59
210+00	8000	0.77	1.65	1.87	1.89	1.85	1.87
220+00	9000	0.29	1.97	2.47	2.61	2.50	2.56
230+00	10000	3.35	4.04	4.23	4.27	4.19	4.24
240+00	11000	5.56	5.82	5.76	5.51	5.36	5.53
250+00	12000	5.00	5.73	5.42	5.25	4.97	5.11
260+00	13000	5.24	6.39	6.14	5.97	5.69	5.80
270+00	14000	6.75	7.18	7.79	7.99	8.00	8.21
280+00	15000	4.46	5.23	6.15	6.30	6.28	6.36
290+00	16000	2.53	2.85	4.23	4.47	4.48	4.51
300+00	17000	1.96	1.82	3.08	3.26	3.28	3.34
310+00	18000	1.09	1.18	2.27	2.44	2.46	2.52
320+00	19000	0.57	0.69	1.68	1.83	1.87	1.94
330+00	20000	0.38	0.50	1.24	1.38	1.42	1.49
340+00	21000			0.97	1.11	1.12	1.15
350+00	22000			0.78	0.88	0.89	0.90
360+00	23000			0.64	0.72	0.73	0.74
370+00	24000			0.56	0.62	0.63	0.63
380+00	25000			0.50	0.54	0.55	0.56
390+00	26000			0.46	0.50	0.50	0.51
400+00	27000				0.46	0.47	0.47
410+00	28000				0.43	0.44	0.44
420+00	29000				0.41	0.42	0.42
430+00	30000				0.39	0.40	0.40
440+00	31000				0.38	0.38	0.38
450+00	32000				0.36	0.37	0.37
460+00	33000				0.35	0.35	0.36
470+00	34000				0.34	0.34	0.35
480+00	35000				0.33	0.34	0.34
490+00	36000					0.33	0.33

Table 6 (continued)

Location Along Channel		**Predicted Sedimentation Volume** (CY/ yr per 1000 ft channel length)					
Starting Station	Feet below 130+00	**As-Is**	**-30 ft**	**-35 ft**	**-40 ft**	**-45 ft**	**-50 ft**
500+00	37000					0.32	0.32
510+00	38000					0.32	0.32
520+00	39000					0.31	0.31
530+00	40000					0.31	0.31
540+00	41000					0.31	0.31
550+00	42000					0.31	0.31
560+00	43000					0.30	0.31
570+00	44000					0.31	0.31
580+00	45000					0.31	0.31
590+00	46000						0.31
600+00	47000						0.31
610+00	48000						0.31
620+00	49000						0.32
630+00	50000						0.32
640+00	51000						0.32
650+00	52000						0.33
660+00	53000						0.33
670+00	54000						0.26
Mean (240+00 to 300+00)		*4.70*	*5.32*	*5.67*	*5.68*	*5.57*	*5.68*

Table 7: Modeled sedimentation thickness for the Port side-channels.

Location	**Predicted Spatially-Averaged Sedimentation Thickness** (ft/yr)					
	As-Is	-30 ft	-35 ft	-40 ft	-45 ft	-50 ft
Upper Side Channel	0.22	0.33	0.34	0.36	0.38	0.41
Middle Side Channel	0.33	0.50	0.54	0.57	0.59	0.62
Lower Side Channel	0.94	0.93	0.98	1.01	1.03	1.06
Deep-water loading hole	NA	1.02	1.08	1.13	1.18	1.24

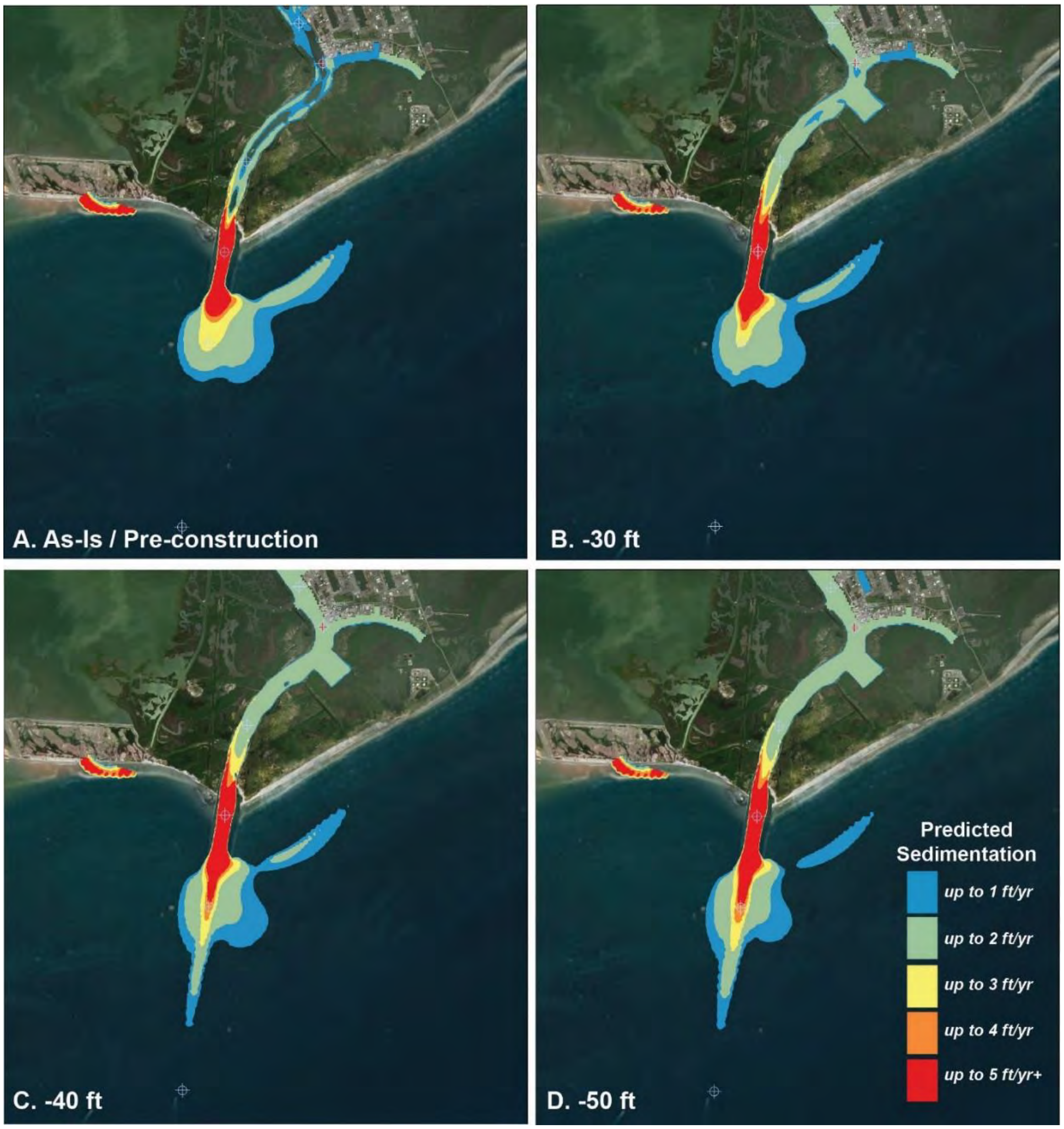

Figure 12: Maps of the predicted sedimentation near the Port Fourchon jetty complex for 4 scenarios.

AFFECTED ENVIRONMENT

Simulation of the 100-day design hydrograph scenarios resulted in the flow and sediment flux illustrated in Figure 13. The plots show predicted values for Bayou Lafourche at Port Fourchon. Mean discharges driven by the upstream boundary conditions (from the East Basin, West Basin, Upper Channel sub-domain boundaries) span 200 to 600 m^3/s (7,063 to 21,189 cfs). The tidal water level fluctuations introduced at the Marine sub-domain boundary add high-magnitude, high-frequency discharge fluctuations that exceed 100 % of the mean values and produce significant occurrences of reverse flow. Figure 13. (right plot) shows that sediment flux was highly variable and maximum fluxes can approach two orders of magnitude greater than the median rates: 229 CY/s (as-is), 410 CY/s (-30 ft), and 520 CY/s (-50 ft).

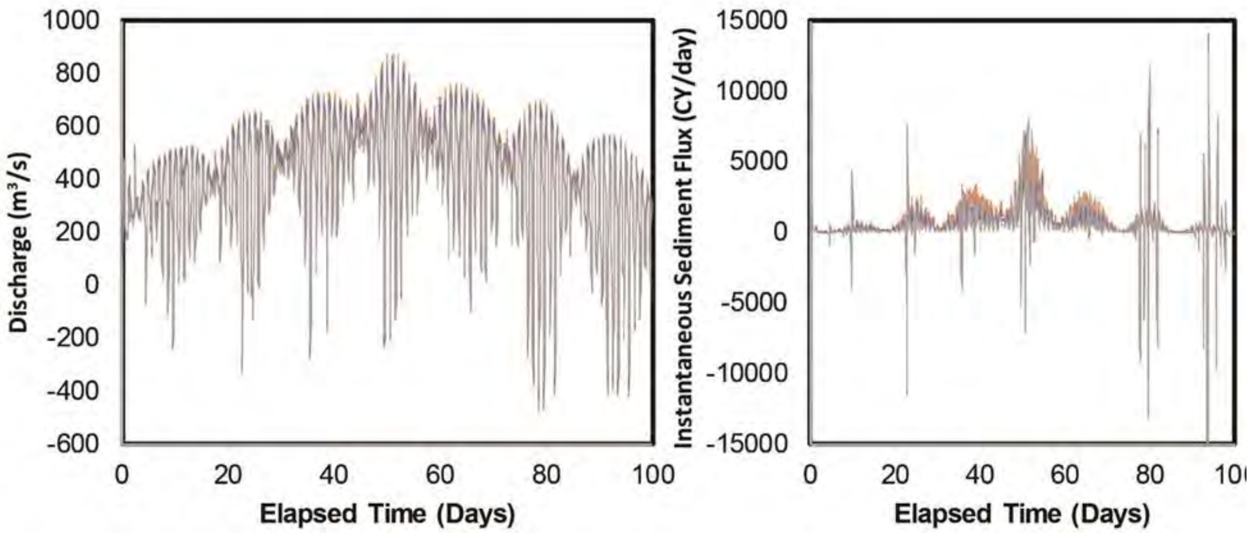

Figure 13: Flow and sediment flux predicted for Bayou Lafourche leaving the lower Port Fourchon area. The green line is from the 'as-is' channel depth; blue is for the dredged to -30 ft scenario; red is for the -50 ft scenario.

The variation in the hydrodynamic environment and water quality due to changes in the maintenance dredging depth are reported for seven distributed locations within the Port waterways (Table 8; Figure 14). These locations are widely distributed throughout the Port area and were selected so that changes reported at these locations could serve as indicators of the hydrodynamic and water quality changes that are predicted to generally occur throughout the Port waterways.

Table 8: Properties of the seven stations where hydrodynamic model results are reported. See Figure 14 for the map of locatons.

Station ID	Latitude and Longitude (decimal degrees)		Station Description
300	29.10030	-90.22050	Lower Port channel - near station 190+00
200	29.11650	-90.21140	Mid port channel - neat station 120+00
100	29.14100	-90.22120	Upper port channel - near station 10+00
PS	29.11400	-90.19970	near NOAA Ports Tide Gauge
LH	29.10640	-90.20700	Deep-water loading hole
J	29.08250	-90.22640	Jetty area - near station 260+00
C59	29.07240	-90.22840	Below jetty - near station 300+00

Figure 14: Location of the seven stations where hydrodynamic and water quality model results are reported. Further station information is listed in Table 8.

At the time of this report, the deep-water loading hole location was predominately undeveloped sub-aerial/emergent marsh (i.e., construction of the loading hole had not begun). As the numerical model was not developed to simulate physical processes in this type of environment, the model results for the 'As-Is' condition at the loading hole station (LH) were not reported.

Predicted Change in Hydrodynamics

The 2D hydro-morphodynamic model scenarios were used to predict at-a-station water velocity and water-level at the seven monitoring stations identified in Figure 14. Tables 9 and 10 show the median values calculated for these locations during the 100-day design hydrograph.

Table 9: Modeled depth-averaged flow velocity at seven Port waterway stations.

Location ID	**Temporally-averaged Flow Velocity** (ft/s)					
	As-Is	-30 ft	-35 ft	-40 ft	-45 ft	-50 ft
300	0.95	0.86	0.77	0.71	0.65	0.57
200	0.80	0.59	0.60	0.61	0.61	0.62
100	1.06	0.81	0.80	0.81	0.82	0.82
PS	0.09	0.07	0.07	0.07	0.07	0.07
LH	NA	0.01	0.01	0.01	0.01	0.00
Jetty	0.75	0.69	0.63	0.58	0.54	0.50
C59	0.33	0.33	0.30	0.28	0.26	0.26

Table 10: Modeled water level at seven Port waterway stations.

Location ID	**Temporally-averaged Water Level** (ft NAVD 88)					
	As-Is	-30 ft	-35 ft	-40 ft	-45 ft	-50 ft
300	0.31	0.30	0.30	0.29	0.29	0.28
200	0.42	0.40	0.38	0.36	0.35	0.33
100	0.51	0.47	0.45	0.43	0.43	0.41
PS	0.41	0.39	0.37	0.35	0.34	0.32
LH	NA	0.37	0.35	0.33	0.32	0.31
Jetty	0.24	0.24	0.24	0.24	0.24	0.24
C59	0.25	0.25	0.25	0.25	0.25	0.25

Predicted Change in Water Quality

The 3D water quality model (D-WAQ) scenarios were used to predict at-a-station water salinity and dissolved oxygen at the seven monitoring stations identified in Figure 14. Tables 11 and 12 show the median values calculated for these locations during the year 2010 hydrograph. While the 3D water quality model resolved a depth profile of output values, the values reported in Tables 11 and 12 are depth-averaged. Calibration tests predicted that little vertical stratification was present in the analyzed parameters suggesting that they could be adequately characterized by their depth-averaged values.

Table 11: Modeled median of year 2010 salinity at seven Port waterway stations.

Location ID	**Temporally-averaged Salinity** (ppt)					
	As-Is	-30 ft	-35 ft	-40 ft	-45 ft	-50 ft
300	27.3	27.3	27.3	27.3	27.3	27.3
200	27.3	27.3	27.3	27.3	27.3	27.3
100	27.3	27.3	27.3	27.3	27.3	27.3
PS	27.3	27.3	27.3	27.3	27.3	27.3
LH	NA	27.3	27.3	27.3	27.3	27.3
J	28.7	29.1	28.9	29.1	29.2	29.3
C59	31.1	31.1	31.0	31.1	31.1	31.2

Table 12: Modeled median of year 2010 dissolved oxygen (DO) concentrations at seven Port waterway stations.

Location ID	**Temporally-averaged Dissolved Oxygen**(mg/L)					
	As-Is	-30 ft	-35 ft	-40 ft	-45 ft	-50 ft
300	5.9	5.5	5.5	5.5	5.5	5.4
200	5.9	5.7	5.7	5.7	5.7	5.7
100	6.1	6.0	6.0	6.0	6.0	6.0
PS	6.1	5.9	5.9	5.9	5.9	5.9
LH	NA	5.3	5.3	5.3	5.3	5.3
J	5.7	5.4	5.5	5.4	5.4	5.3
C59	5.9	5.8	5.8	5.8	5.8	5.8

JETTY MODIFICATION ANALYSIS

Table 13 shows the predicted sedimentation for the two scenarios, J275 and J290, that simulated jetty extension. The predicted change in the annual sedimentation volume along the navigation channel (which is calculated from differencing sediment volumes from the jetty extension scenarios and the scenario reflecting the current jetty configuration) is also shown in the table (i.e., in the column entitled "Volume Change"). For the two jetty extension scenarios, sedimentation downstream of station 500+00 was approximate to that predicted from the scenario reflecting the current jetty configuration and not included in the table.

Numerical modeling predicts that jetty extension reduces total navigation channel sedimentation from 1,081,558 CY/yr (As-Is jetty configuration) to 1,035,456 CY/yr (-4.3 %) for J275, and 982,492 CY/yr (-9.2 %) for J290. Figures 15 and 16 illustrate the sedimentation patterns and the change in sedimentation patterns relative to the As-Is jetty configuration, respectively. Generally, jetty extension significantly reduced sedimentation in the immediate jetty area; however, that reduction was partially offset by increased sedimentation further downstream. Results shown in Figure 15 also indicate that the model predicted increasing risk of significant sedimentation along the outer side of the jetty due to extension. This sedimentation was due to the interruption of long-shore sediment transport and is not explicitly accounted for in Table 11, which only reports 'in-channel' sedimentation. Long-shore sediment transport processes in the current numerical were not rigorously calibrated or validated due to unavailability of observational data.

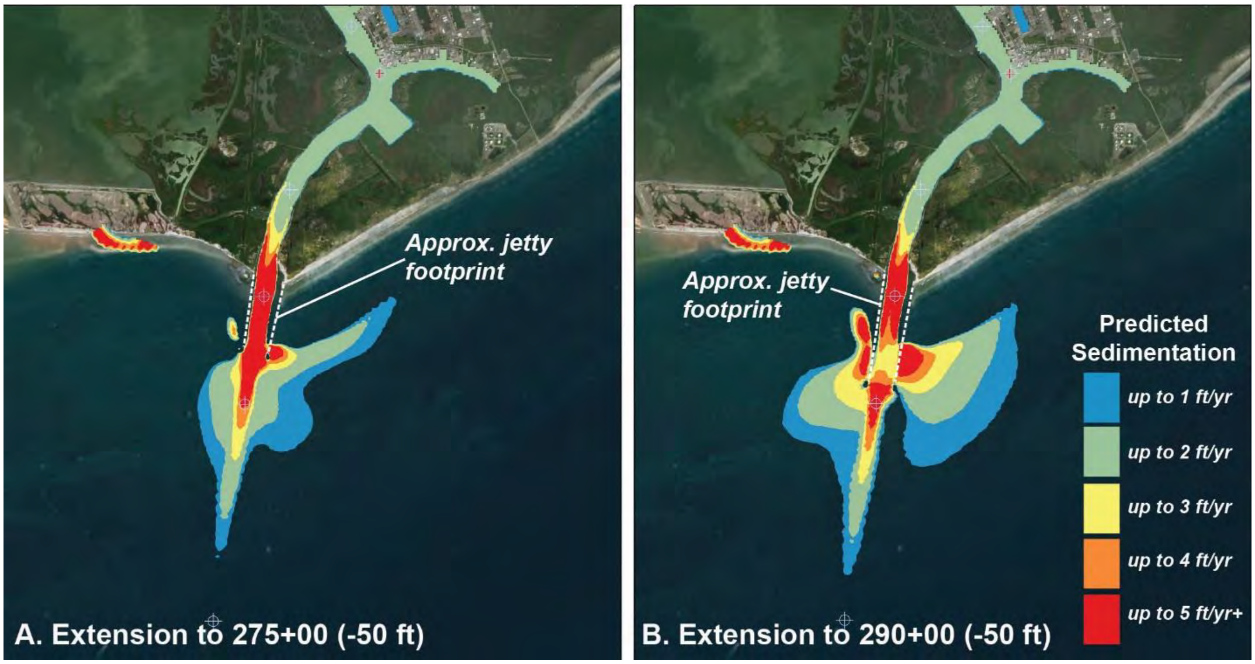

Figure 15: The predicted pattern of sedimentation around the jetty area after two jetty expansion scenarios, J275 and J290. The scenario simulations use the same model set up as the -50 ft 2D hydro-morphodynamic scenario except for new bathymetry representing new jetty dimensions.

Table 13: Modeled sedimentation thicknesses along the entrance channel.

Location Along Channel		**275+00 Extension Sedimentation/ J275**			**290+00 Extension Sedimentation/ J290**		
Starting Station	Feet below 130+00	Volume *CY/yr*	Thickness *ft/yr*	Volume Change *CY/yr*	Volume *CY/yr*	Thickness *ft/yr*	Volume Change *CY/yr*
130+00	0	20,749	1.40	-46	20,775	1.40	-21
140+00	1000	20,216	1.36	-7	20,202	1.36	-21
150+00	2000	19,433	1.31	-68	19,389	1.31	-111
160+00	3000	19,233	1.30	-130	19,160	1.29	-202
170+00	4000	19,502	1.32	-147	19,308	1.30	-340
180+00	5000	20,560	1.39	-106	20,110	1.36	-556
190+00	6000	21,589	1.46	-253	21,010	1.42	-832
200+00	7000	22,945	1.55	-600	22,179	1.50	-1,366
210+00	8000	26,595	1.80	-1,081	25,164	1.70	-2,512
220+00	9000	36,193	2.44	-1,806	34,074	2.30	-3,926
230+00	10000	58,841	3.97	-3,963	57,015	3.85	-5,789
240+00	11000	78,986	5.33	-3,011	80,350	5.42	-1,647
250+00	12000	69,513	4.69	-6,213	62,678	4.23	-13,048
260+00	13000	69,661	4.70	-16,293	55,726	3.76	-30,229
270+00	14000	85,083	5.74	-36,480	44,007	2.97	-77,556
280+00	15000	96,342	6.50	2,091	46,479	3.14	-47,771
290+00	16000	73,963	4.99	7,119	70,408	4.75	3,564
300+00	17000	54,037	3.65	4,496	70,332	4.75	20,791
310+00	18000	40,659	2.74	3,266	54,953	3.71	17,561
320+00	19000	30,896	2.09	2,189	41,301	2.79	12,594
330+00	20000	23,450	1.58	1,412	31,256	2.11	9,218
340+00	21000	17,982	1.21	1,004	23,883	1.61	6,905
350+00	22000	14,086	0.95	816	18,005	1.22	4,735
360+00	23000	11,524	0.78	628	14,173	0.96	3,277
370+00	24000	9,759	0.66	378	11,677	0.79	2,296
380+00	25000	8,464	0.57	216	9,728	0.66	1,481
390+00	26000	7,645	0.52	135	8,521	0.58	1,011
400+00	27000	7,066	0.48	83	7,692	0.52	710
410+00	28000	6,637	0.45	79	7,102	0.48	544
420+00	29000	6,261	0.42	55	6,660	0.45	454
430+00	30000	5,959	0.40	30	6,307	0.43	378
440+00	31000	5,718	0.39	27	6,000	0.40	308
450+00	32000	5,506	0.37	18	5,746	0.39	258
460+00	33000	5,313	0.36	14	5,528	0.37	229
470+00	34000	5,155	0.35	15	5,340	0.36	200
480+00	35000	5,030	0.34	16	5,200	0.35	186
490+00	36000	4,904	0.33	11	5,054	0.34	161

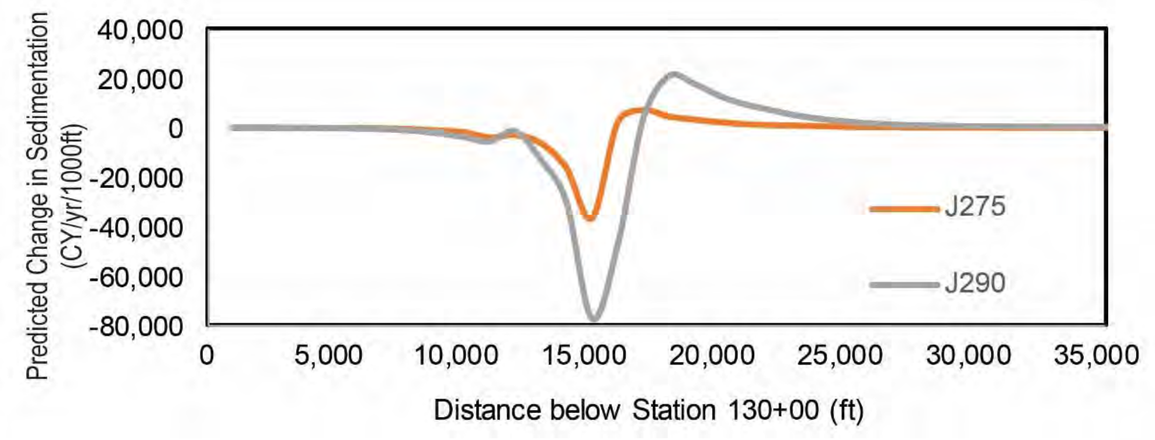

Figure 16: The predicted change in sedimentation along the entrance channel (below station 130+00) binned at 1000 ft intervals for the two jetty expansion scenarios, J275 and J290.

Summary of Key Assumptions and Conclusions

The small amount of available observational field data for the study area prevented robust calibration and validation of the numerical models. The available observational data, study results from analogous study sites, and professional judgement indicate that the predicted values were realistic estimates considering the assessed physical environment. To account for the lack of robust validation testing, model development generally favored simplified and conservative assumptions.

The 2D hydro-morphodynamic model was parameterized with mean-daily water levels that did not resolve high amplitude, tide-generated fluctuations at the East and West basin sub-domain open boundaries. However, the model used astronomical constituent data, that resolved all primary tide-generated water-level fluctuations, to predict water level along the Lower Channel/Marine sub-domain boundaries. When the model boundaries were parameterized to simulate periods of very high or low tides, this model set up would have promoted higher energy gradients in lower Bayou Lafourche than that likely observed.

This study predicts that increasing the maintenance dredge depth in the entrance channel (below station 130+00) could increase channel sedimentation from +28 % (the -30 ft scenario) to +87 % (the -50 ft scenario). Increasing the maintenance dredge depth from -24 ft to -30 ft in the upper Port channel was predicted to increase annual sedimentation from 0.6 ft/yr to 1.65 ft/yr, a 173 % increase. However, this predicted change in sedimentation is likely an overestimate because the actual current maintenance dredge depth is typically closer to -27 ft, as 3 ft over-dredge is allowed. Sedimentation was predicted to increase in the Port side-channel by approximately +50 % (-30 ft) to +87 % (-50 ft) in the upper side-channels (i.e., the slips) and remain relatively unchanged in the lower side-channels (i.e., Pass Fourchon).

Marginal increases in maintenance dredge depth did not produce a uniform response in predicted sedimentation, in terms of magnitude or spatial distribution.

Increasing maintenance dredging depths generally decreased predicted flow velocities (up to -0.4 ft/s for the -50 ft scenario) and water levels (up to -0.1 ft for the -50 ft scenario) in Port waterways.

Water quality modeling indicated that increasing maintenance dredge depths within the navigation channel would likely have an insignificant impact on the salinity and dissolved oxygen concentrations in the Port waterways. Generally, modeling predicts that the Port waters are currently, and will remain, relatively saline (> 25 ppt). Predicted values of dissolved oxygen concentrations showed significant seasonal fluctuations but were approximately spatially-uniform throughout the Port waterways due to energetic secondary currents.

A simple analysis of the impact of jetty extension on the navigation channel sedimentation indicated that extension to station 270+00 may reduce sedimentation by 4.3 % and extension to station 295+00 reduces sedimentation by 9.2 %. This analysis employed the 2D hydro-morphodynamic model developed for channel deepening study.

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Attachment 2:

Wetland Value Assessment Data for Base Plan (400-ft wide, 50-ft deep) Channel Construction and 50-yr Maintenance Under Three Sea Level Rise Scenarios

File available at:

https://thewaterinstitute-my.sharepoint.com/:x:/g/personal/rclark_thewaterinstitute_org/EUw4IpZFJlNOgtYgeGpARAoBYPoQMT8c5t-uXw9lDT4YGQ?e=BVZZbn

Attachment 3:

Wetland Value Assessment Data for Locally Preferred Plan (475-ft wide, 50-ft deep) Channel Construction and 50-yr Maintenance Under Three Sea Level Rise Scenarios

File available at:

https://thewaterinstitute-my.sharepoint.com/:x:/g/personal/rclark_thewaterinstitute_org/Ef45RnSL9tRDldpRdnG7rIEBbSPJouOOOG_dD_wZJ_n8xQ?e=0P5WX3

Attachment 4:

Initial Deposition Sites – Pumping Distances from Each Dredge Station

			Bayou Lafourche	Belle Pass	Belle Pass	Belle Pass	Pass Fourchon	Flotation Canal	Slip A	Slip B	Slip C
			Stn 0 (0 - 135)	Stn 130 (130 - 265)	Stn 270 (270 - 340)	Stn 350 (350 - end)	Stn 0 (0 - 70+)	Stn FC0 (0 - 103+)	Stn SA0 (0 - 19+)	Stn SB0 (0 - 70+)	Stn SC0 (0 - 66+)
	Pump X (UTM m)		770250	771612	769904	769491	771612	770475	771035	771687	772339
	Pump Y (UTM m)		3227324	3223678	3219998	3217595	3223678	3227058	3227168	3227497	3227624
Site	Centroid X (UTM m)	Centroid Y (UTM m)	Distance to Dredge Pump Locations (miles)								
Site 1	768610	3234629	4.65	7.06	9.13	10.60	7.06	4.84	4.87	4.83	4.93
Site 2	767153	3232491	3.74	6.14	7.95	9.37	6.14	3.96	4.09	4.19	4.42
Site 3	767003	3229062	2.29	4.40	5.91	7.29	4.40	2.49	2.77	3.07	3.43
Site 4	768843	3223828	2.34	1.72	2.47	3.89	1.72	2.25	2.48	2.88	3.21
Site 5	768120	3222703	3.16	2.25	2.01	3.29	2.25	3.08	3.31	3.71	4.03
Site 6	765639	3222156	4.30	3.83	2.97	3.71	3.83	4.28	4.58	5.01	5.37
Site 7	769811	3233507	3.85	6.21	8.39	9.89	6.21	4.03	4.01	3.91	3.98
Site 8	769874	3231393	2.54	4.91	7.08	8.58	4.91	2.72	2.72	2.67	2.80
Site 9	771249	3231007	2.37	4.56	6.89	8.41	4.56	2.50	2.39	2.20	2.21
Site 10	772568	3232199	3.35	5.33	7.76	9.27	5.33	3.45	3.27	2.97	2.85
Site 11	774129	3229837	2.87	4.13	6.65	8.13	4.13	2.85	2.54	2.10	1.77
Site 12	774978	3230145	3.42	4.53	7.05	8.51	4.53	3.39	3.07	2.62	2.27
Site 13	774217	3229378	2.78	3.89	6.42	7.89	3.89	2.74	2.41	1.96	1.60
Site 14	776817	3229100	4.23	4.67	7.10	8.48	4.67	4.14	3.79	3.34	2.93
Site 15	774614	3227352	2.71	2.95	5.43	6.85	2.95	2.58	2.23	1.82	1.42
Site 16	774052	3225468	2.63	1.88	4.27	5.65	1.88	2.43	2.15	1.94	1.71
Site 17	775325	3226249	3.22	2.81	5.14	6.49	2.81	3.06	2.73	2.39	2.04
Site 18	776881	3226307	4.17	3.66	5.85	7.10	3.66	4.01	3.67	3.31	2.94
Site 19	774775	3224221	3.41	1.99	4.01	5.27	1.99	3.20	2.96	2.80	2.60
Site 20	769296	3222105	3.30	1.74	1.36	2.81	1.74	3.16	3.33	3.67	3.92
Site 21	770057	3222319	3.11	1.28	1.45	2.96	1.28	2.96	3.07	3.37	3.59
Site 22	769566	3223594	2.36	1.27	2.24	3.73	1.27	2.23	2.40	2.76	3.04
Site 23	770325	3223641	2.29	0.80	2.28	3.79	0.80	2.13	2.24	2.54	2.77
Site 24	771034	3223677	2.32	0.36	2.39	3.90	0.36	2.13	2.17	2.41	2.58
Site 25	769607	3224948	1.53	1.47	3.08	4.57	1.47	1.42	1.64	2.04	2.38
Site 26	770236	3225224	1.30	1.29	3.25	4.76	1.29	1.15	1.31	1.68	1.98
Site 27	769025	3226025	1.11	2.17	3.78	5.25	2.17	1.11	1.44	1.89	2.29
Site 28	769800	3226589	0.54	2.13	4.10	5.59	2.13	0.51	0.85	1.30	1.70
Site 29	768498	3226924	1.12	2.79	4.39	5.83	2.79	1.23	1.58	2.01	2.43
Site 30	769232	3227779	0.69	2.95	4.85	6.33	2.95	0.89	1.18	1.54	1.93
Site 31	767577	3228146	1.74	3.74	5.27	6.66	3.74	1.92	2.23	2.59	2.98
Site 32	767843	3228764	1.74	3.93	5.60	7.01	3.93	1.95	2.22	2.51	2.88
Site 33	768235	3229047	1.65	3.94	5.72	7.16	3.94	1.86	2.10	2.35	2.70
Site 34	769984	3229212	1.18	3.58	5.73	7.22	3.58	1.37	1.43	1.50	1.76
Site 35	769395	3229602	1.51	3.93	5.98	7.46	3.93	1.72	1.82	1.93	2.20
Site 36	771263	3229687	1.60	3.74	6.08	7.59	3.74	1.71	1.57	1.39	1.45
Site 37	772259	3229900	2.03	3.89	6.32	7.84	3.89	2.09	1.86	1.53	1.42
Site 38	770484	3230111	1.74	4.06	6.29	7.80	4.06	1.90	1.86	1.79	1.93
Site 39	768895	3230122	1.93	4.35	6.32	7.79	4.35	2.14	2.27	2.38	2.64
Site 40	767163	3230228	2.63	4.92	6.58	7.98	4.92	2.85	3.07	3.28	3.60
Site 41	767876	3230392	2.41	4.77	6.58	8.01	4.77	2.63	2.80	2.97	3.26
Site 42	772580	3230551	2.47	4.31	6.76	8.28	4.31	2.53	2.31	1.98	1.82
Site 43	771608	3230724	2.27	4.38	6.75	8.26	4.38	2.38	2.24	2.01	1.98
Site 44	769794	3230797	2.18	4.57	6.71	8.21	4.57	2.36	2.38	2.36	2.53
Site 45	769374	3231221	2.48	4.89	6.98	8.47	4.89	2.68	2.72	2.72	2.90
Site 46	768335	3231491	2.85	5.26	7.21	8.66	5.26	3.06	3.17	3.24	3.46
Site 47	767355	3231565	3.19	5.57	7.36	8.78	5.57	3.41	3.56	3.69	3.95
Site 48	770738	3231762	2.77	5.05	7.33	8.84	5.05	2.93	2.86	2.72	2.76
Site 49	771949	3231889	3.03	5.11	7.50	9.01	5.11	3.14	2.99	2.73	2.66
Site 50	769970	3232460	3.20	5.55	7.74	9.24	5.55	3.37	3.35	3.26	3.35
Site 51	769354	3232945	3.54	5.93	8.05	9.54	5.93	3.72	3.74	3.68	3.79
Site 52	768411	3232955	3.68	6.10	8.10	9.57	6.10	3.88	3.95	3.96	4.11
Site 53	767808	3233079	3.88	6.30	8.23	9.68	6.30	4.09	4.18	4.22	4.41
Site 54	770995	3233360	3.78	6.03	8.33	9.84	6.03	3.93	3.85	3.67	3.66
Site 55	770234	3233933	4.11	6.43	8.66	10.16	6.43	4.27	4.23	4.10	4.13
Site 56	772075	3234184	4.41	6.53	8.92	10.43	6.53	4.54	4.41	4.16	4.08
Site 57	769652	3234214	4.30	6.66	8.84	10.33	6.66	4.48	4.46	4.36	4.42
Site 58	768621	3234407	4.52	6.92	8.99	10.46	6.92	4.71	4.74	4.70	4.81
Site 59	767791	3234428	4.67	7.09	9.06	10.51	7.09	4.87	4.94	4.94	5.09
Site 60	768305	3235512	5.23	7.64	9.69	11.16	7.64	5.42	5.46	5.41	5.51
Site 61	769570	3235526	5.11	7.47	9.65	11.14	7.47	5.29	5.27	5.16	5.20
Site 62	769118	3236734	5.89	8.26	10.41	11.89	8.26	6.07	6.06	5.96	6.00
Site 63	770218	3236813	5.90	8.21	10.45	11.95	8.21	6.06	6.01	5.86	5.86
Site 64	772035	3237186	6.23	8.40	10.76	12.28	8.40	6.37	6.26	6.02	5.94
Site 65	768832	3237815	6.58	8.95	11.09	12.57	8.95	6.76	6.76	6.65	6.70
Site 66	770329	3238002	6.64	8.94	11.19	12.69	8.94	6.80	6.75	6.58	6.57
Site 67	768741	3239007	7.32	9.69	11.83	13.31	9.69	7.50	7.49	7.38	7.42
Site 68	769992	3239325	7.46	9.77	12.01	13.51	9.77	7.63	7.58	7.42	7.42
Site 69	771422	3239701	7.73	9.96	12.28	13.79	9.96	7.88	7.79	7.59	7.53
Site 70	768644	3240039	7.96	10.33	12.48	13.96	10.33	8.15	8.13	8.02	8.05
Site 71	772301	3240129	8.06	10.23	12.60	14.11	10.23	8.20	8.09	7.86	7.77
Site 72	769699	3240490	8.19	10.51	12.73	14.23	10.51	8.36	8.32	8.17	8.16
Site 73	768412	3240975	8.56	10.93	13.07	14.54	10.93	8.74	8.73	8.62	8.65
Site 74	770922	3241018	8.52	10.78	13.08	14.58	10.78	8.68	8.61	8.41	8.37
Site 75	771793	3241277	8.72	10.94	13.27	14.78	10.94	8.87	8.78	8.56	8.49
Site 76	769191	3241381	8.76	11.10	13.29	14.78	11.10	8.94	8.91	8.77	8.77
Site 77	767853	3241850	9.15	11.53	13.64	15.11	11.53	9.33	9.34	9.23	9.27
Site 78	770294	3242057	9.15	11.45	13.71	15.21	11.45	9.32	9.26	9.09	9.06
Site 79	768761	3242275	9.34	11.69	13.86	15.34	11.69	9.52	9.49	9.36	9.37
Site 80	771386	3242430	9.41	11.65	13.97	15.48	11.65	9.57	9.49	9.28	9.22
Site 81	769918	3242952	9.71	12.02	14.26	15.76	12.02	9.88	9.83	9.67	9.64
Site 82	767453	3243009	9.90	12.29	14.38	15.84	12.29	10.09	10.09	9.99	10.03
Site 83	771092	3243404	10.01	12.26	14.56	16.07	12.26	10.16	10.09	9.89	9.84

			Bayou Lafourche	Belle Pass	Belle Pass	Belle Pass	Pass Fourchon	Flotation Canal	Slip A	Slip B	Slip C
			Stn 0 (0 - 135)	Stn 130 (130 - 265)	Stn 270 (270 - 340)	Stn 350 (350 - end)	Stn 0 (0 - 70+)	Stn FC0 (0 - 103+)	Stn SA0 (0 - 19+)	Stn SB0 (0 - 70+)	Stn SC0 (0 - 66+)
	Pump X (UTM m)		770250	771612	769904	769491	771612	770475	771035	771687	772339
	Pump Y (UTM m)		3227324	3223678	3219998	3217595	3223678	3227058	3227168	3227497	3227624
Site	Centroid X (UTM m)	Centroid Y (UTM m)	Distance to Dredge Pump Locations (miles)								
Site 84	768346	3243447	10.09	12.45	14.60	16.08	12.45	10.27	10.25	10.13	10.14
Site 85	769466	3243956	10.35	12.67	14.89	16.38	12.67	10.52	10.48	10.32	10.30
Site 86	771721	3244248	10.56	12.78	15.11	16.62	12.78	10.71	10.62	10.41	10.34
Site 87	770587	3244435	10.63	12.91	15.19	16.69	12.91	10.80	10.73	10.55	10.50
Site 88	767467	3244567	10.85	13.23	15.34	16.81	13.23	11.04	11.04	10.93	10.95
Site 89	768241	3244987	11.05	13.41	15.56	17.04	13.41	11.23	11.21	11.08	11.09
Site 90	769128	3245185	11.12	13.45	15.66	17.14	13.45	11.29	11.26	11.11	11.09
Site 91	769922	3245438	11.26	13.56	15.81	17.30	13.56	11.43	11.37	11.20	11.17
Site 92	769032	3246355	11.85	14.18	16.39	17.87	14.18	12.02	11.99	11.83	11.82
Site 93	767104	3246567	12.12	14.50	16.60	18.06	14.50	12.30	12.30	12.19	12.21
Site 94	770605	3246763	12.08	14.36	16.64	18.14	14.36	12.24	12.18	11.99	11.94
Site 95	767730	3246898	12.26	14.63	16.77	18.24	14.63	12.45	12.43	12.30	12.31
Site 96	768771	3247602	12.63	14.97	17.17	18.65	14.97	12.81	12.77	12.62	12.61
Site 97	769862	3247804	12.73	15.03	17.28	18.77	15.03	12.90	12.84	12.67	12.63
Site 98	766460	3247961	13.04	15.42	17.51	18.96	15.42	13.23	13.23	13.12	13.15
Site 99	770822	3248184	12.97	15.24	17.52	19.03	15.24	13.13	13.06	12.87	12.81
Site 100	767073	3248476	13.29	15.66	17.78	19.25	15.66	13.48	13.47	13.35	13.36
Site 101	768467	3248798	13.39	15.73	17.92	19.40	15.73	13.57	13.53	13.39	13.38
Site 102	765697	3248965	13.74	16.14	18.19	19.63	16.14	13.93	13.94	13.85	13.89
Site 103	769853	3249194	13.59	15.89	18.14	19.64	15.89	13.76	13.71	13.53	13.49
Site 104	764962	3249474	14.15	16.55	18.57	20.01	16.55	14.34	14.36	14.28	14.33
Site 105	766142	3249593	14.07	16.46	18.54	19.99	16.46	14.26	14.26	14.16	14.18
Site 106	768586	3249967	14.11	16.44	18.64	20.12	16.44	14.28	14.25	14.09	14.08
Site 107	769516	3250213	14.23	16.54	18.78	20.27	16.54	14.40	14.35	14.18	14.15
Site 108	765582	3250499	14.69	17.08	19.14	20.59	17.08	14.88	14.89	14.79	14.82
Site 109	768314	3251259	14.92	17.26	19.45	20.93	17.26	15.10	15.06	14.91	14.90
Site 110	769093	3251324	14.93	17.25	19.47	20.96	17.25	15.10	15.06	14.89	14.86
Site 111	768049	3252468	15.68	18.03	20.21	21.69	18.03	15.86	15.83	15.68	15.67
Site 112	768650	3252602	15.74	18.07	20.27	21.76	18.07	15.91	15.87	15.71	15.69
Site 113	776655	3226219	4.04	3.51	5.70	6.97	3.51	3.88	3.54	3.19	2.82
Site 114	777376	3226802	4.44	4.07	6.28	7.53	4.07	4.29	3.95	3.56	3.17
Site 115	776068	3226898	3.63	3.42	5.75	7.08	3.42	3.48	3.13	2.75	2.36
Site 116	777017	3227341	4.20	4.06	6.35	7.65	4.06	4.07	3.72	3.31	2.91
Site 117	775760	3227432	3.42	3.48	5.88	7.25	3.48	3.29	2.94	2.53	2.13
Site 118	776767	3228882	4.16	4.55	6.98	8.34	4.55	4.07	3.72	3.27	2.86
Site 119	781213	3229044	6.90	6.83	9.00	10.18	6.83	6.79	6.43	6.00	5.58
Site 120	781047	3229432	6.84	6.87	9.07	10.28	6.87	6.73	6.38	5.94	5.53
Site 121	781602	3229550	7.19	7.20	9.38	10.57	7.20	7.09	6.73	6.29	5.88
Site 122	782239	3229839	7.61	7.63	9.81	10.98	7.63	7.51	7.16	6.72	6.30
Site 123	775140	3230190	3.52	4.60	7.12	8.58	4.60	3.49	3.17	2.72	2.36
Site 124	773984	3230251	2.95	4.34	6.86	8.34	4.34	2.95	2.65	2.23	1.93
Site 125	781978	3230377	7.53	7.67	9.89	11.10	7.67	7.44	7.09	6.64	6.23
Site 126	777646	3231349	5.23	6.06	8.54	9.94	6.06	5.19	4.86	4.41	4.03
Site 127	781354	3232956	7.74	8.36	10.74	12.06	8.36	7.69	7.35	6.90	6.51
Site 128	773270	3233068	4.03	5.92	8.39	9.90	5.92	4.12	3.92	3.60	3.43
Site 129	782788	3233529	8.69	9.26	11.61	12.90	9.26	8.64	8.30	7.85	7.46
Site 130	775309	3233535	4.98	6.54	9.06	10.54	6.54	5.02	4.77	4.38	4.11
Site 131	776135	3233686	5.39	6.82	9.35	10.82	6.82	5.42	5.14	4.74	4.44
Site 132	780871	3233770	7.72	8.51	10.94	12.29	8.51	7.69	7.36	6.91	6.53
Site 133	784700	3233926	9.87	10.33	12.63	13.87	10.33	9.82	9.47	9.02	8.62
Site 134	779454	3234184	7.13	8.15	10.63	12.02	8.15	7.12	6.81	6.37	6.01
Site 135	778095	3234223	6.49	7.69	10.20	11.63	7.69	6.50	6.20	5.77	5.44
Site 136	781194	3234319	8.07	8.90	11.33	12.68	8.90	8.04	7.72	7.27	6.90
Site 137	771638	3234974	4.83	7.02	9.37	10.88	7.02	4.97	4.87	4.65	4.59
Site 138	771712	3235257	5.01	7.20	9.55	11.06	7.20	5.15	5.04	4.82	4.76
Site 139	771174	3235333	5.01	7.25	9.56	11.07	7.25	5.16	5.07	4.88	4.84
Site 140	772246	3235465	5.21	7.33	9.72	11.23	7.33	5.34	5.21	4.96	4.87
Site 141	779962	3235584	7.92	9.04	11.53	12.93	9.04	7.93	7.62	7.19	6.85
Site 142	783917	3235608	9.93	10.65	13.03	14.34	10.65	9.90	9.57	9.12	8.74
Site 143	771852	3235752	5.33	7.50	9.86	11.38	7.50	5.47	5.36	5.13	5.06
Site 144	777321	3235951	6.93	8.41	10.93	12.40	8.41	6.97	6.71	6.31	6.03
Site 145	771212	3235954	5.40	7.63	9.95	11.46	7.63	5.55	5.46	5.26	5.22
Site 146	775504	3235960	6.28	8.01	10.51	12.01	8.01	6.35	6.13	5.77	5.54
Site 147	773318	3235961	5.70	7.71	10.14	11.66	7.71	5.81	5.64	5.36	5.22
Site 148	772480	3236027	5.58	7.69	10.09	11.60	7.69	5.71	5.58	5.32	5.22
Site 149	781386	3236050	8.79	9.80	12.26	13.64	9.80	8.79	8.48	8.04	7.68
Site 150	771565	3236152	5.55	7.75	10.09	11.60	7.75	5.69	5.59	5.38	5.32
Site 151	779911	3236342	8.21	9.41	11.91	13.33	9.41	8.23	7.93	7.50	7.18
Site 152	776651	3236383	6.89	8.49	11.01	12.49	8.49	6.95	6.71	6.32	6.07
Site 153	783381	3236668	10.01	10.89	13.32	14.66	10.89	10.00	9.68	9.23	8.87
Site 154	778261	3236674	7.65	9.07	11.59	13.05	9.07	7.69	7.42	7.01	6.72
Site 155	771725	3237063	6.12	8.32	10.66	12.18	8.32	6.27	6.16	5.94	5.88
Site 156	782412	3237235	9.75	10.77	13.23	14.61	10.77	9.75	9.44	9.00	8.65
Site 157	779751	3237262	8.54	9.84	12.35	13.78	9.84	8.57	8.29	7.87	7.55
Site 158	775640	3237340	7.07	8.85	11.35	12.85	8.85	7.15	6.94	6.59	6.38
Site 159	772584	3237402	6.43	8.55	10.94	12.46	8.55	6.56	6.43	6.18	6.08
Site 160	773067	3237626	6.64	8.71	11.13	12.64	8.71	6.76	6.62	6.35	6.23
Site 161	778498	3237784	8.28	9.75	12.27	13.74	9.75	8.32	8.06	7.67	7.38
Site 162	781059	3237958	9.42	10.64	13.14	14.55	10.64	9.44	9.15	8.73	8.40
Site 163	774385	3238090	7.17	9.12	11.58	13.09	9.12	7.27	7.10	6.79	6.63
Site 164	776890	3238123	7.88	9.56	12.07	13.56	9.56	7.95	7.72	7.35	7.11
Site 165	779580	3238275	8.94	10.33	12.85	14.30	10.33	8.98	8.71	8.30	8.00

			Bayou Lafourche	Belle Pass	Belle Pass	Belle Pass	Pass Fourchon	Flotation Canal	Slip A	Slip B	Slip C
			Stn 0 (0 - 135)	Stn 130 (130 - 265)	Stn 270 (270 - 340)	Stn 350 (350 - end)	Stn 0 (0 - 70+)	Stn FC0 (0 - 103+)	Stn SA0 (0 - 19+)	Stn SB0 (0 - 70+)	Stn SC0 (0 - 66+)
	Pump X (UTM m)		770250	771612	769904	769491	771612	770475	771035	771687	772339
	Pump Y (UTM m)		3227324	3223678	3219998	3217595	3223678	3227058	3227168	3227497	3227624
Site	Centroid X (UTM m)	Centroid Y (UTM m)	Distance to Dredge Pump Locations (miles)								
Site 166	777657	3238516	8.34	9.96	12.47	13.95	9.96	8.40	8.16	7.79	7.53
Site 167	772022	3238563	7.07	9.25	11.61	13.12	9.25	7.21	7.11	6.88	6.80
Site 168	779460	3238993	9.24	10.69	13.21	14.67	10.69	9.28	9.02	8.62	8.34
Site 169	775749	3239167	8.11	9.96	12.45	13.96	9.96	8.21	8.01	7.68	7.48
Site 170	778719	3239353	9.14	10.69	13.22	14.69	10.69	9.20	8.95	8.57	8.30
Site 171	776920	3239665	8.72	10.47	12.98	14.47	10.47	8.80	8.58	8.23	8.01
Site 172	780585	3239696	10.02	11.41	13.92	15.37	11.41	10.06	9.79	9.38	9.08
Site 173	779476	3240049	9.77	11.29	13.81	15.27	11.29	9.82	9.57	9.18	8.90
Site 174	761525	3219300	7.37	6.83	5.22	5.06	6.83	7.36	7.67	8.11	8.48
Site 175	761204	3218738	7.75	7.16	5.46	5.20	7.16	7.74	8.05	8.49	8.85
Site 176	760563	3218396	8.19	7.61	5.89	5.57	7.61	8.18	8.49	8.93	9.30
Site 177	759898	3218446	8.47	7.97	6.29	5.98	7.97	8.47	8.79	9.23	9.61
Site 178	759103	3218800	8.72	8.34	6.75	6.50	8.34	8.73	9.06	9.51	9.88
Site 179	769641	3221252	3.79	1.94	0.80	2.27	1.94	3.64	3.78	4.08	4.30
Site 180	768972	3221470	3.72	2.14	1.08	2.43	2.14	3.60	3.77	4.11	4.36
Site 181	768218	3221545	3.81	2.49	1.42	2.58	2.49	3.70	3.91	4.28	4.56
Site 182	767490	3221578	3.96	2.87	1.79	2.77	2.87	3.88	4.11	4.51	4.82
Site 183	766778	3221634	4.14	3.26	2.19	3.02	3.26	4.08	4.34	4.75	5.08
Site 184	766084	3221787	4.31	3.63	2.62	3.36	3.63	4.26	4.54	4.97	5.32
Site 185	765466	3222012	4.44	3.96	3.03	3.71	3.96	4.42	4.72	5.15	5.51
Site 186	770531	3221010	3.93	1.79	0.74	2.22	1.79	3.76	3.84	4.09	4.26
Site 187	771160	3221356	3.75	1.47	1.15	2.56	1.47	3.57	3.61	3.83	3.96
Site 188	771912	3221801	3.58	1.18	1.68	3.02	1.18	3.39	3.38	3.54	3.63
Site 189	772725	3222224	3.52	1.14	2.23	3.51	1.14	3.31	3.25	3.34	3.36
Site 190	773523	3222637	3.55	1.35	2.78	4.01	1.35	3.34	3.21	3.23	3.18
Site 191	774283	3223268	3.55	1.68	3.40	4.61	1.68	3.34	3.15	3.08	2.96
Site 192	775117	3224048	3.65	2.19	4.10	5.32	2.19	3.44	3.19	3.02	2.81
Site 193	775977	3224722	3.91	2.79	4.78	5.99	2.79	3.71	3.43	3.17	2.89
Site 194	776734	3225303	4.22	3.34	5.37	6.57	3.34	4.04	3.73	3.42	3.09
Site 195	777589	3225940	4.64	3.97	6.04	7.23	3.97	4.47	4.14	3.79	3.43
Site 196	778454	3226569	5.12	4.62	6.70	7.88	4.62	4.97	4.62	4.24	3.86
Site 197	779235	3227138	5.58	5.20	7.30	8.47	5.20	5.44	5.10	4.70	4.30
Site 198	780115	3227770	6.14	5.86	7.97	9.14	5.86	6.01	5.65	5.24	4.83
Site 199	781020	3228493	6.73	6.57	8.69	9.86	6.57	6.61	6.26	5.83	5.42
Site 200	781887	3229210	7.33	7.25	9.39	10.56	7.25	7.22	6.86	6.43	6.01
Site 201	782799	3229910	7.96	7.96	10.11	11.27	7.96	7.86	7.51	7.07	6.65
Site 202	783806	3230653	8.67	8.73	10.88	12.04	8.73	8.58	8.23	7.78	7.37
Site 203	784929	3231423	9.47	9.57	11.73	12.88	9.57	9.38	9.03	8.58	8.17
Site 204	785970	3232107	10.21	10.35	12.50	13.64	10.35	10.13	9.77	9.33	8.92
Site 205	786787	3232699	10.80	10.97	13.13	14.27	10.97	10.72	10.37	9.92	9.52

Attachment 5:

Carbon Project Feasibility Report

Port Fourchon - Tidal Wetland Restoration

Carbon Project Feasibility Report

Prepared For **Restore America's Estuaries**

Authors/ S.Settelmyer, E.Swails

Date / April 24, 2018

Version / 2.0

TerraCarbon®

Acknowledgements

We are grateful to Leland Moss and Tim Caruthers of the Water Institute for guiding this work and for collecting and sharing extensive published and unpublished data on greenhouse gas fluxes on tidal wetlands in the region that have helped informed this study.

We thank Stefanie Simpson at Restore America's Estuaries for coordinating this study and blue carbon efforts around the U.S., and the U.S. National Oceanic and Atmospheric Administration's Office of Habitat Conservation for their funding support for this work.

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1.0

Executive Summary

The Port Fourchon tidal wetland restoration project involves the dredging and placement of sediment to create/restore wetlands for saline coastal marsh, dominated by *Spartina patens* and the mangrove *Avecennia germinans*. The Water Institute (WI) and its partners are currently evaluating alternatives and developing recommendations to optimize the restoration and its benefits for storm protection, wildlife habitat, and climate. As part of this effort, TerraCarbon is assisting WI with assessing the feasibility of developing a carbon offset project to monetize the benefits of these restoration activities.

This report documents our evaluation and includes an assessment of market, technical, financial, and legal considerations of developing a carbon offset project around the proposed tidal wetland restoration. It serves as a “Phase 1” preliminary assessment, and should inform further analysis of the carbon benefits of the restoration alternatives. It is intended to be further developed in a “Phase 2” as specific details about the restoration (amount of dredge material, location of placement, filling further data gaps) become available, as well as further discussion with project partners.

Market Assessment
At the current time, if developed as a carbon offset project, the Port Fourchon tidal wetland restoration project would be able to sell offsets only into the voluntary markets, as compliance markets do not currently accept offsets from tidal wetland restoration projects. Buyers in the voluntary markets consist mainly of U.S. and European multinational companies in consumer facing industries such as financial services and technology. Prices for offsets from individual projects have varied widely due to differences in co-benefits. Based on the location of the project, on the Gulf of Mexico coast, and the consequent climate resiliency co-benefits, our market assessment is that offsets from the Port Fourchon project, could sell at the mid to high end of land-based offsets (2016 range was $4.20-$9.50/ton).

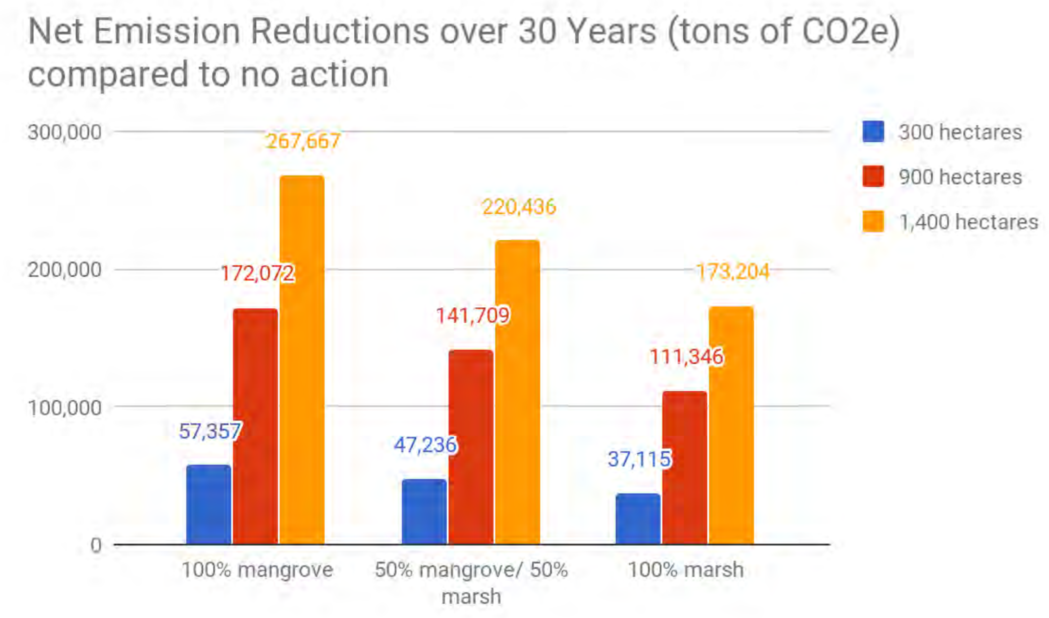
Technical Analysis
The Port Fourchon project meets the applicability and additionality requirements of the VCS Methodology for Tidal Wetland and Seagrass Restoration (VM0033) as well as the VCS Methodology for Coastal Wetland Creation (VM0024), and therefore either methodology can be used to account for the GHG benefits of the project. The key gases and pools to measure are biomass carbon stocks and soil organic carbon; methane and nitrous oxide emission will also have to be accounted, but are not expected to high as the site has salinity that remains above 18 ppt during the entire year. Biomass stocks will need to be quantified using field collected

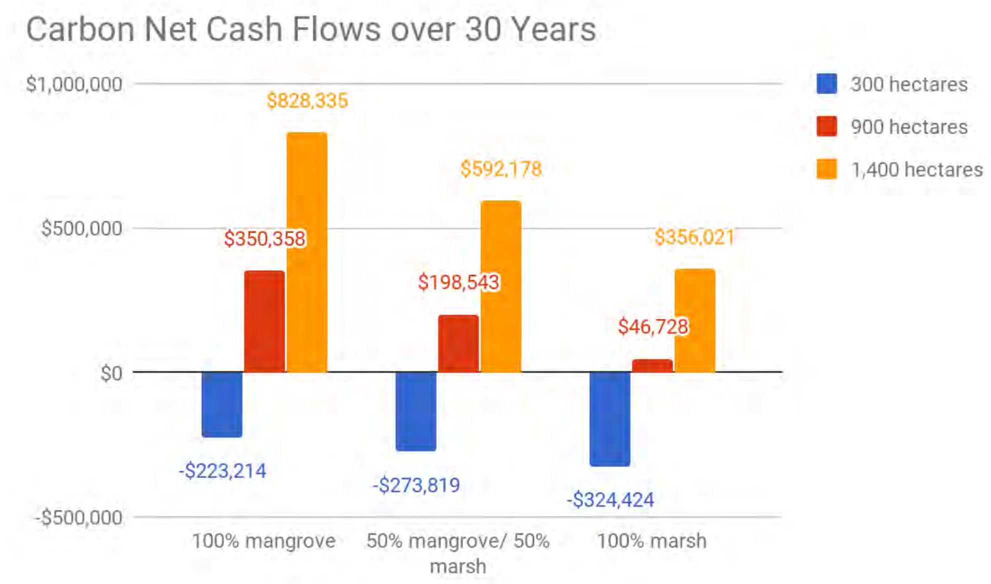
data, while soil organic carbon stock changes will need to be quantified using either field data (VM0024 and VM0033), or published values (VM0033 only).

Estimates of soil organic carbon and biomass carbon removals were developed by reference to published and unpublished data from coastal Louisiana or similar saline coastal marsh ecosystems. Methane and nitrous oxide emissions were estimated using the default values for high salinity systems from VM0033.

Financial Assessment

Estimates of potential net GHG emission reductions were developed by comparing GHG emissions/removals in the baseline (open water) and with-project (marsh creation) scenarios. Our estimates are based on GHG estimates for each carbon pool (soil organic and biomass carbon) and gas (methane and nitrous oxide emissions) and listed assumptions for new, vegetated marsh area created (“project area”) and associated vegetation coverage, comparing two potentially dominant vegetation types (*Spartina* vs. *Avicennia*).   We have also developed estimates of carbon cash flows (excludes restoration-related costs) based on $5.00/ton sales price and typical carbon project costs.





As illustrated above, net emission reductions and cash flows increase as the project area increases and as mangrove coverage increases (due to higher biomass accruals than marsh coverage during the first 30 years after restoration). Our report includes further analysis of net present values (NPVs) as well as sensitivity analysis at various carbon price assumptions and indicates that NPVs are positive for each vegetation scenario only in the 1,400 hectare project area scenario.

Legal Assessment

The VCS requires the project proponent (owner) to demonstrate carbon ownership by a right of use. For land use projects, a right of use can arises by virtue of property rights in land of the project area, or by an enforceable and irrevocable agreement with the landowner that transfers such rights to the project proponents. Louisiana statutes support this premise so long as the project is not carried out, sponsored, or funded with public resources by the Coastal Protection and Restoration Authority (CPRA) or the CPRA Board.

Next Steps

The next steps for Phase 2 with respect to refining the results in this Phase 1 report are summarized below.

Phase 2 - Next Steps for Carbon Project Development
1. Obtain updated estimates of project area and vegetation coverage based on specific location for dredge placement.
2. Update review of GHG estimates for each pool (soil organic and biomass carbon) and source (methane and nitrous oxide emissions) published and unpublished data (for new data).

3. Model sea level rise based on area, location, elevation, and expected accretion in the project area and based on relative sea level rise projections.
4. Revise emission reduction estimates accordingly based on results of #1-3.
5. Finalize methodology selection and measurement approach for each pool/source considering stakeholder preference for direct measurements vs. cost, and update cost estimates accordingly.
6. Once a specific location for dredge placement is decided, engage landowners on carbon project opportunities and considerations and engage counsel to draft appropriate agreements if decision is made to proceed.
7. Prepare and share summary information about the project and request indications of interest from potential buyers.

2.0

Introduction

2.1 Background

South Louisiana’s Port Fourchon plays a critical national economic security role by providing the U.S. with approximately 18% of its total oil supply and servicing over 90% of the Gulf of Mexico’s deepwater oil production.

As Port Fourchon continues to grow, there are plans to potentially deepen the port’s access channel which could yield more than 20 million cubic yards of sediment. This situation presents a unique opportunity as the port will need to dispose of the material while also desiring additional storm protection.

The Water Institute of the Gulf has created a Public-Private Partnership with the Port, Shell, Chevron, and Danos to determine the best, nature-based way to use the dredged material to protect the port’s critical infrastructure, improve the environment; make communities from Fourchon to Larose more resilient; and yield carbon-capture sequestration benefits.

2.2 Objectives

TerraCarbon has been asked to assist WI with an assessment of the carbon sequestration benefits of using dredge material to restore and/or create tidal wetlands at or near Port Fourchon, and specifically, to evaluate the feasibility of developing a carbon offset project to monetize the benefits of these restoration/creation activities.

This evaluation includes an assessment of market, technical, financial, and legal considerations of developing a carbon offset project around proposed tidal wetland restoration at Port Fourchon. It serves as “Phase 1” preliminary assessment, and should inform further analysis of the carbon benefits of the restoration alternatives and be updated in a “Phase 2” as specific details about the restoration (amount of dredge material, location of placement) emerge, and after further discussion with project partners.

3.0

Market Analysis

3.1 Overview

Carbon offsets may be transacted on voluntary or compliance carbon markets. In voluntary carbon markets, buyers are typically motivated by corporate social responsibility – they are concerned about climate change and have set a target to reduce their emissions, outside of or ahead of regulation. In compliance carbon markets, buyers are motivated to purchase offsets when they offer a more cost-effective way to meet their requirements to cut emissions under the law – for instance, if the price of offsets falls below the cost of allowances or the carbon tax[1].

At the current time, if developed as a carbon offset project, the Port Fourchon tidal wetland restoration project would be able to sell offsets only into the voluntary markets, as compliance markets do not currently accept offsets from tidal wetland restoration projects. However, voluntary blue carbon projects like the Port Fourchon project would help inform decisions on future eligibility by demonstrating how these types of projects could accurately quantify emission reductions.

3.2 Voluntary markets

Voluntary carbon offsets are issued to eligible projects by voluntary standards such as the Verified Carbon Standard (VCS), American Carbon Registry (ACR), and the Climate Action Reserve (CAR). Tidal wetlands restoration projects, such as the Port Fourchon tidal wetland restoration project, are currently only eligible under the VCS, which is the dominant voluntary standard in the carbon market, representing more than 50% of all transacted credits[2].

The voluntary market has been transacting certified carbon offsets from a variety of project types since the early 2000s. In that time, more than 1 billion tons have been sold at a value of $4.8 billion (see Figures 1 and 2 below)[2].

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[1] Goldstein, Allie. The Bottom Line: Taking Stock of the Role of Offsets in Corporate Carbon Strategies. Washington, DC: Forest Trends, 2015.

[2] Hamrick, Kelly. Unlocking Potential: State of the Voluntary Carbon Markets 2017. Washington, DC: Forest Trends, 2017

As illustrated in Figure 1, the volume of offsets sold in the voluntary market has fluctuated over time, with volumes in 2016 reported at 63 million tons. Over the past few years, because the supply of offsets has increased faster than demand, average prices have dropped to $3.00/ton in 2016[2] (compared to $5.00/ton in 2013).

Figure 1: Historical Market-Wide Voluntary Offset Transaction Volumes[2]

Forestry and other land use offsets continues to be one of the most popular project types in the voluntary carbon market, accounting for more than 25% of all voluntary transactions in 2016[2]. While the average voluntary carbon price in 2016 across all project types was $3.00/ton, the average price for forest and land use projects was $5.20/ton (Figure 2 below) and ranged from $4.20/ton (avoided deforestation or REDD) up to $9.50/ton (improved forest management) (see Figure 3 below).

Figure 2: Voluntary forest carbon volumes and prices[2]

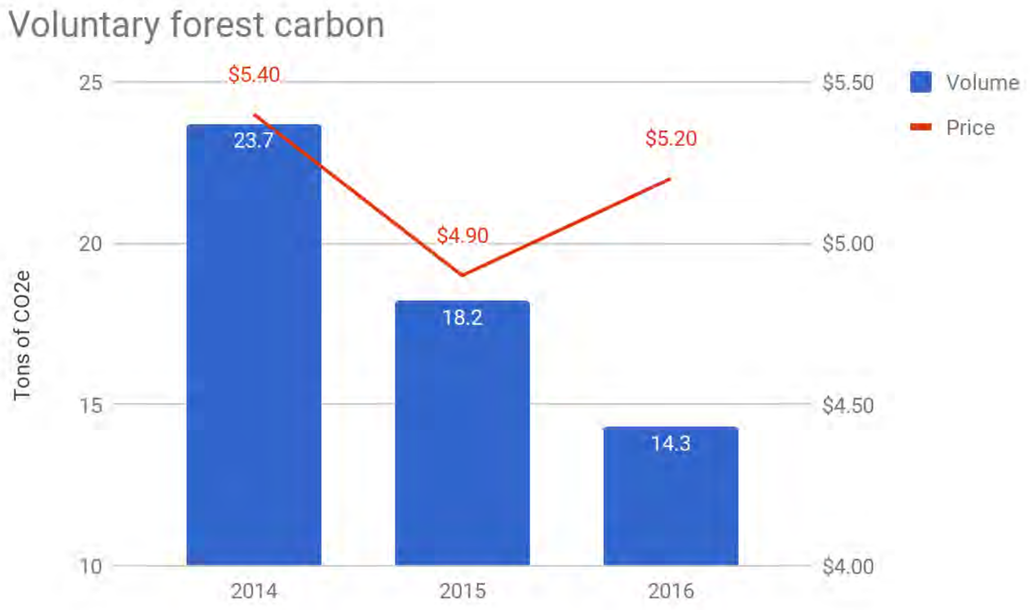
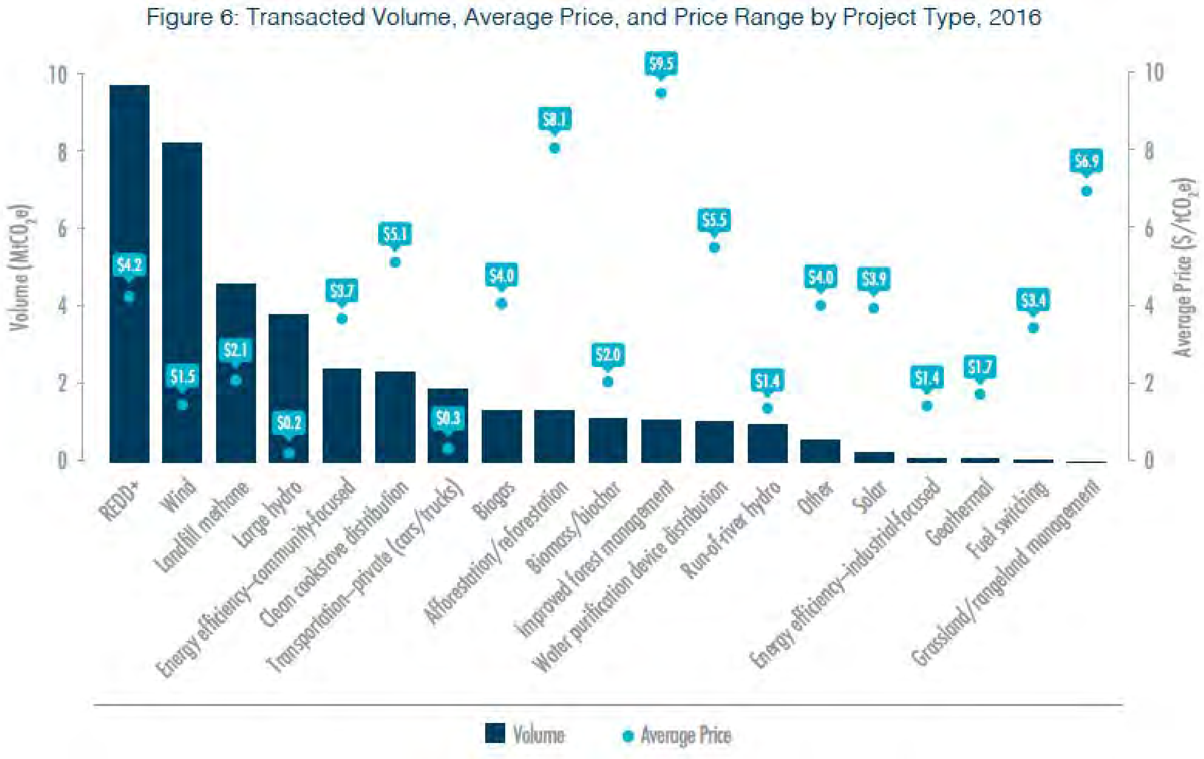


Figure 3: Average offset prices in 2016 by project type[2]



The buyers of voluntary credits are companies located mainly in North America and Europe. Most buyers come from consumer-facing industries, with companies in the energy, financial services, consumer goods, events, and transportation industries topping the list. Beyond purchasing offsets to meet emission reduction targets, buyers are interested in supporting projects with strong co-benefits (i.e., benefits in addition to greenhouse gas mitigation) and projects that are located in the same region(s) that their businesses operate[2].

Tidal wetland restoration projects, like the Port Fourchon project, should be well positioned to sell offsets to voluntary buyers as they can be expected to generate a number of co-benefits, including adaptation to climate change from increased resilience to sea level rise and storm surges. We would expect U.S.-based buyers to have the strongest interest since the co-benefits will be most appreciated by stakeholders in the United States. For reference, we have compiled a partial list of U.S.-based voluntary offset buyers (Table 4 below).

Table 1: U.S.-Based Companies in Top 100 Voluntary Offset Buyers[1]

Company	**Industry**	**HQ Location**
Biogen	Biotech	Massachusetts
Entergy	Energy	Louisiana
Capital One Financial	Financial Services	Georgia
Delta Airlines	Transportation	Georgia
Exelon	Energy	Illinois
FedEx	Transportation	Tennessee
General Motors	Transportation	Michigan
Goldman Sachs	Financial Services	New York
Hilton Worldwide	Tourism	Virginia
Google	Technology	California
Interface	Consumer goods	Georgia

Intuit	Technology	California
JP Morgan Chase	Financial Services	New York
Microsoft	Technology	Washington
Office Depot	Consumer goods	Florida
PG&E	Energy	California
Reynolds American	Consumer goods	North Carolina
SC Johnson	Consumer goods	Wisconsin
State Street	Financial Services	Massachusetts
UPS	Transportation	Georgia
Walt Disney	Tourism/Communications	California

In addition, several intermediaries, who buy from projects and resell to end-users, have expressed interest in blue carbon projects, including The Climate Trust, Natural Capital Partners, and Carbonfund Foundation.

3.3 Compliance markets

At the moment, there are no compliance markets that accept offsets from tidal wetland restoration projects. However, in Appendix 1, we review the only two compliance cap-and-trade programs in the United States, the California Cap and Trade program and the Regional Greenhouse Gas Initiative, which could be relevant to the Port Fourchon tidal wetland restoration project if future changes are made to offset rules in these programs. Development of the Port Fourchon project in the voluntary market would help inform decisions on future eligibility by demonstrating how tidal wetland restoration projects could accurately quantify emission reductions.

3.4 Market Considerations

Due to the high supply of voluntary offsets available and the long-lead time of most voluntary buyers, we recommend immediate engagement with potential buyers of offsets from the Port

Fourchon project if and when a decision to move forward with project development is made. Buyers and intermediaries that have expressed an interest in blue carbon projects in the past include Entergy, The Climate Trust, and Natural Capital Partners.

Engagement could take the form of sharing summary information (fact sheets) about the project (highlighting co-benefits) to requesting indications of interest from buyers and negotiating future sales agreements. These agreements could be structured whereby the buyer agrees to purchase an amount of credits in the future at a pre-agreed price, and to pay for these credits in the future when the credits are delivered. This type of “payment on delivery” agreement would provide the Port Fourchon project with the certainty that credits generated can be quickly monetized, while also protecting the buyer from loss of funds in the event that credit generation is smaller or slower than expected.

4.0

Technical Analysis

4.1 Methodology applicability

There are currently two approved VCS methodologies potentially applicable to the project activity: (1) the Methodology for Coastal Wetland Creation (VM0024), which was developed specifically for Louisiana, and was approved in 2014; and (2) the Methodology for Tidal Wetland and Seagrass Restoration (VM0033), which was approved in late 2015, and is a globally applicable methodology. We have assessed the potential beneficial use project in the Port Fourchon region against each applicability condition of both VM0024 and VM0033. In order for either methodology to be applied, the project must meet all applicability conditions of the methodology.

Based on our assessment, both VM0024 and VM0033 would be applicable to the proposed beneficial use project in the Port Fourchon region. Though the project area boundaries have not yet been defined, we have determined that the project area could be delineated to meet the relevant applicability criteria of both methodologies. Key aspects of the project activity must also be addressed in the project design phase to meet methodology applicability criteria. Notably, vegetation establishment must not involve the application of nitrogen fertilizers, per applicability conditions of both VM0024 and VM0033. Key methodology applicability conditions are summarized below. The detailed results of our assessment of methodology applicability are found in Appendix 1.

The Port Fourchon tidal wetland restoration project meets the following key methodology applicability conditions of VM0024:

- Project activities create new wetlands in coastal ecosystems through substrate establishment and vegetation establishment (applicability condition #1).
- Project activities do not actively lower the water table depth (applicability condition #2).
- The project area meets the definitions of tidal or estuarine, open water, and degraded wetland before project activities are implemented and would have remained open water in the absence of the project activities (applicability condition #3). USGS datasets (i.e. Couvillion 2012[3]) or the US Fish and Wildlife Service's National Wetlands Inventory should be acquired to show that the project area historically met the definition of a wetland and thus the definition of a degraded wetland. Per Section 6.1 of the methodology, if applicability condition #3 is met, the only possible baseline scenario is

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[3] Couvillion, BR, Barras, JA, Steyer, GD, Sleavin, W, Fischer, M, Beck, H, Trahan, N, Griffin, B, Heckman, D. 2011. Land area change in coastal Louisiana from 1932 to 2010:US Geological Survey Scientific Investigations Map 3164, scale 1:265,000, 12 p. pamphlet.

open water. To support the baseline scenario, the project proponent must also demonstrate that wetland creation is unlikely to occur in the project area based upon historical evidence of land accretion and loss using a published regional land use change analysis (e.g., USGS publication ‘Land Area Change in Coastal Louisiana from 1932 to 2010’, or the US Fish & Wildlife Service, National Wetlands Inventory, ‘Wetlands Status and Trends’ report series) or by conducting a spatial analysis using high-resolution satellite or aerial imagery. To support the chosen analysis method, the project proponent also must provide evidence of long-term water level changes in the project area with a minimum record length of 20 years of hydrological data to demonstrate the long-term nature of the documented pattern of wetland loss.

- The project area is entirely within tidal or estuarine areas within the coastal zone boundary, and meets the definition of Waters of the United States (applicability condition #4). The project proponent must demonstrate that the project area boundaries falls entirely within the coastal zone as defined in NOAA’s Ocean and Coastal Resource dataset, or individual coastal zone maps.
- Afforestation/Reforestation/Revegetation activities do not include commercial harvest or active peatland drainage. In addition, the project activities must not involve the application of nitrogen fertilizers (applicability condition #5).
- The project proponent must have obtained the necessary permits to demonstrate that the project will not have a significant negative impact on hydrologically connected areas. This applicability condition must be satisfied at validation or at the first verification event (applicability condition #6). The procedures for demonstrating that the project meets applicability condition #6 are set out in Section 8.3.3 of the methodology. The project proponent must demonstrate compliance with Section 404 of the Clean Water Act, and Section 10 as applicable, by providing relevant permitting issued by USACE. Likewise, any NEPA analyses and decision documents must be provided where applicable.

The Port Fourchon tidal wetland restoration project meets the following key methodology applicability conditions of VM0033:

- Project activities restore tidal wetlands. Tidal wetland restoration, as defined by the methodology, includes activities that create wetland ecological conditions within open water (applicability condition #1).
- Project activities include altering sediment supply (e.g. beneficial use of dredge material) and introduction of native plant communities (applicability condition #2).
- No productive activities are occurring in the project area that could be displaced from restoration and result in off-site emissions (applicability condition #3).
- While allowed, harvesting is not planned, and the project does not intend to request credits for fire risk reduction, since fires do not occur in the project area (open water) in the baseline scenario (applicability conditions #4 and #7 are not relevant).
- The project activity may involve prescribed burning (applicability condition #5).
- Afforestation/Reforestation/Revegetation activities will be combined with restoring hydrological conditions (condition #8).
- Project activities do not increase carbon stocks in an existing forest or protect an existing forest from degradation or conversion to non-forest (condition #9).

- Baseline conditions do not include commercial forestry (applicability condition #10).
- Project activities may not lower the water table, unless the project converts open water to tidal wetlands (applicability condition #11). The project converts open water to tidal wetlands, thus the condition is not applicable to the Port Fourchon tidal wetland restoration project.
- Converting open water to tidal wetlands will not result in increased offsite GHG emissions (applicability condition #12).
- Project activities do not involve burning of soil (applicability condition #13).
- In addition, under VM0033, the project activities must not involve the application of nitrogen fertilizers (applicability condition #14).

4.2 Additionality requirement

In addition to meeting the methodology applicability requirements, a carbon project must also satisfy an additionality requirement to ensure that the project would not have occurred in the absence of carbon market incentives or as part of “business-as-usual” activities.

In the case of the VM0033, all tidal wetland restoration projects located in the United States are deemed to meet the additionality requirement (due to the low penetration or occurrence of these activities) so long as they are not required by any law, statute, or other regulatory framework. Therefore, because it is located in the United States and is not required by any law, statute or regulation, the Port Fourchon tidal wetland restoration project would meet the additionality requirement of VM0033.

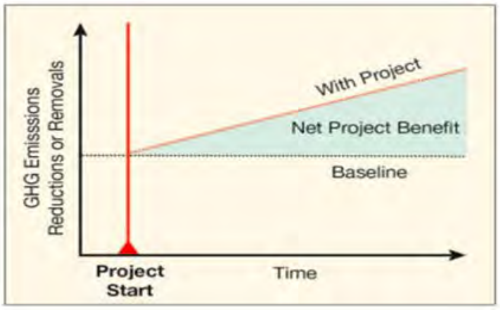
VM0024 also assesses additionality using an “activity” method. Project activities that meet the applicability conditions of the methodology and demonstrate regulatory surplus (activity is not mandated by law, statute or other regulatory framework) are deemed additional under VM0024. The Port Fourchon tidal wetland restoration project would therefore also meet the additionality requirement of VM0024.

4.3 GHG accounting approach

Carbon pools and greenhouse gas sources included in accounting
Under the accounting approaches of both methodologies, the GHG benefits of the Port Fourchon tidal wetland restoration project would be driven by increased carbon storage in biomass and the soil organic carbon pool from the conversion of open water to tidal wetland.

GHG benefits generated by the project are calculated as the difference between emissions in the “baseline” (zero, assuming no tidal wetland creation occurs) and “with-project” (net sequestration, after tidal wetland creation occurs) scenarios. Note that in addition to changes in soil and biomass carbon stocks, project accounting considers microbial emissions of CH_4 and N_2O emissions as well as emissions from the use of fossil fuels and fire if significant (>5% of GHG emission reductions from the project).

Figure 4: Likely Baseline and With Project Emission Reduction Scenarios



The approved approaches for accounting the GHG benefits of the Port Fourchon project under VM0024 and VM0033 are detailed in the following section.

Measurement approaches for selected carbon pools and GHG sources
Alternative measurement approaches for selected carbon pools and GHG sources under VM0024 and VM0033 are summarized below (Table 2).

Note that the table below does not include the allochthonous soil organic carbon pool (soil organic carbon generated and transported from offsite into the project area), gains in which are generally deducted from soil organic carbon gains attributed to the project. However,both methodologies contain exceptions to this general rule. Under VM0024, project proponents are not required to deduct allochthonous carbon imports for projects located within Louisiana that are not within the direct influence of a river diversion or river mouth. Under VM0033, project proponents may assume allochthonous carbon import is equal to zero for organic soils. For non-organic soils, allochthonous carbon imports may be measured directly, or a default value may be used. As soils in the project area are expected to be organic[4], we have excluded allochthonous soil organic carbon from the table and from our analysis in this Phase 1.

Also note that changes in soil organic carbon and biomass carbon pools are assumed to be zero in the baseline case (and therefore are also not included in the table below) where open water is expected to persist.

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[4] Organic soils are defined, as by the 2006 IPCC Guidelines (Annex 3A.5, Chapter 3 in Volume 4), as having at least 12% organic carbon when mixed to a depth of 20 cm, and 35% organic matter if never saturated with water for more than a few days, or if subject to water saturation episodes, at least 20% organic matter if the soil has no clay and at least 30% organic matter if say has 60% or more clay.

Table 2: Summary of alternative measurement approaches for selected carbon pools and GHG sources under VM0024 and VM0033

Scenario	**Carbon pool / GHG source**	**Measurement approach**	
		VM0024	**VM0033**
Baseline	CH_4 from ebullition in open water	May conservatively exclude, or Direct measurement in a reference area during the project	May conservatively exclude, or Proxies, field collected data, published values, default factors, models, or IPCC emission factors
	N_2O from nitrification / denitrification	Not included under VM0024	May conservatively exclude, or Proxies, field collected data, published values, default factors, models, or IPCC emission factors
	Fossil fuel emissions	Estimated based on energy consumption	Estimated based on energy consumption or number and type of vehicles used and duration of use
With-Project	Soil organic carbon	Direct measurement with soil cores to fixed depth, and optionally, above a marker horizon	Direct measurement with soil cores to a reference plane, which may be a feldspar surface marker horizon, a strongly contrasting soil layer within the soil profile, an installed shallow marker, or a biogeochemically identified layer Suitable literature values or suitable peer-reviewed

			models may alternatively be used Default values may be used only if suitable published values are not available.
	Biomass	Above-ground tree: Direct measurement Below-ground tree: Estimated from direct measurement of above-ground tree biomass with conversion factors Herbaceous: Direct measurement	Above-ground tree: Direct measurement Below-ground tree: Estimated from direct measurement of above-ground tree biomass with conversion factors Herbaceous: Direct measurement or default factor (3 tons C for 100% vegetation cover in first year only)
	CH_4 from anaerobic microbial respiration in project soils	Direct measurement, proxies, published values, or default factor	Direct measurement or proxies, field collected data, published values, default factors, models, or IPCC emission factors may be used If default factors are used, salinity must be monitored
	N_2O from nitrification / denitrification	Direct measurement, proxies, or default factor	Direct measurement or proxies, field collected data, published values, default factors, models, or IPCC emission factors may be used If default factors are used, salinity must be

			monitored
	Fossil fuel emissions	Direct measurement of energy consumed by the project or extrapolated from project budget and historic energy prices	Direct measurement of energy consumed by the project or the number and type of vehicles used and duration of use
	Fire from prescribed burns	Not included under VM0024	CO_2 emissions addressed in direct measurements of biomass stock changes in the project area Non-CO_2 emissions estimated with conversion factors based on reduction in tree biomass

4.4 Assumptions for estimation of project GHG benefits

To estimate the potential GHG benefit of a beneficial use project that converts open water to tidal wetland in the Port Fourchon region, we considered different scenarios for new, vegetated marsh area created by the project ("project area") as well as vegetation coverage.

We analyzed three project area scenarios of 300 hectares, 900 hectares, and 1,400 hectares to reflect a range of dredged material that could be used to create new vegetated saline marsh (being separately assessed by WI as part of the overall Phase 1 study) We also analyzed three vegetation coverage scenarios of 100% salt marsh, 100% percent mangrove, and 50-50% mangrove-salt marsh to illustrate the range of possible vegetation outcomes to reflect uncertainty in species that will be planted and future climate conditions that will affect the type of vegetation that is ultimately established. Our estimation of GHG benefits includes carbon stock changes in biomass and soils, and potential increases in CH_4 and N_2O emissions, in the project area, resulting from the creation of new tidal wetland. We assume that fossil fuel emissions from machinery are equal in the baseline and project, and prescribed burns are not part of ongoing project activities.

Biomass and soil organic carbon assumptions
Our assumptions regarding biomass and soil organic carbon stocks in the baseline and project case are summarized in Table 3 and detailed below.

Table 3: Biomass and soil organic carbon stock change assumptions

Scenario	Pool	Base Case Assumption	Justification
Baseline	Soil organic carbon stock change	0.00 tons CO2e/ha/yr	Baseline scenario is open water
	Biomass carbon stock change	0.00 tons CO2e/ha/yr	Baseline scenario is open water
With Project	Soil organic carbon stock change	4.58 tons CO2e/ha/yr[5]	4.58 tons CO2e/ha/yr (1.25 tons C/ha/yr) average C accumulation[6] (per Baustian et al. In Prep[7])
	Biomass carbon stock change	Above-ground tree: 1.80 tons of CO2e/ha/yr[8]	54.12 tons CO2e/ha (14.76 tons C/ha) stocking for mature mangrove forest (per Yando et al. 2016) over 30 year average growth cycle
		Below-ground tree: 1.21 tons of CO2e/ha/yr[9]	Root:shoot ratio of 0.67 calculated from measurements collected by USGS from *A. Germinans* dominated mangrove stands at Rookery Bay NERR, Florida Gulf Coast
		Herbaceous: 11 tons of CO2e/ha[10]	11 tons CO2e/ha (3 tons C/ha) default claimed for the first year of the project crediting period only per VM0033

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[5] 1.25 tons C/ha/yr was multiplied by 44/12 to convert from C to CO2e.

[6] (n=59 data points; saline and brack marsh)

[7] Baustian, M. M., Stagg, C. L., Perry, C. L., Moss, L. C., Carruthers, T. J. B., & Allison, M. A. (In Prep). Long-term soil carbon accumulation rates of coastal marshes in Mississippi River Deltaic Plain suggest over 300 years of carbon burial at risk to wetland loss.

[8] 14.76 tons of C/ha at maturity divided by 30 year growth cycle, multiplied by 44/12 to convert from C to CO2e.

[9] 1.80 tons of CO2e/ha/year multiplied by root:shoot ratio of 0.67.

[10] 3 tons of C/ha/year was multiplied by 44/12 to convert from C to CO2e.

Data collected within two miles of Port Fourchon from Louisiana Coastal Reference Monitoring System (CRMS) site 0292 indicated that the dominant mangrove species in the area of Port Fourchon is *Avicennia Germinans* (black mangrove). Therefore total above-ground biomass stocks in mangrove vegetation at maturity was assumed to equal 54.12 tons CO2e/ha per measurements collected on above-ground tree biomass in mature black mangrove stands in the Port Fourchon region by Yando et al. (2016)[11].

We considered using soil bulk density and organic matter content measurements from cores collected at CRMS sites 0292 (a black mangrove site) and 0164 (a salt marsh) to estimate soil organic C for mangroves in the Port Fourchon region. We decided to not use these values, as these measurements are a small sample and may not be broadly representative. Accretion data was also available for CRMS sites 0292 and 0164, but did not include measurements to estimate organic C accumulated above feldspar marker horizons (bulk density and soil organic C or loss on ignition). For these reasons, we did not develop separate marsh and mangrove soil organic C sequestration data for the Port Fourchon tidal wetland restoration project, and instead have used an average value of soil carbon accumulation in marshes calculated from accretion data compiled by the Water Institute. For reference, soil organic C sequestration in global literature analysis[12] indicates similar levels of soil organic C sequestration between marshes and mangroves (and is the reason the VCS methodology uses the same default value for both systems). Thus differences in carbon accumulation rates among the different vegetation scenarios we considered are driven by differences in carbon stocks in live biomass in mangrove and marsh ecosystems (Table 3).

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[11] Yando, E. S., Osland, M. J., Willis, J. M., Day, R. H., Krauss, K. W., Hester, M. W. (2016), Salt marsh-mangrove ecotones: using structural gradients to investigate the effects of woody plant encroachment on plant-soil interactions and ecosystem carbon pools, Journal of Ecology, 104, 1020-1031.

[12] Chmura, G. L., S. C. Anisfeld, D. R. Cahoon, and J. C. Lynch (2003), Global carbon sequestration in tidal, saline wetland soils, Global Biogeochem. Cycles, 17, 1111, doi:10.1029/2002GB001917, 4.

Soil CH_4 and N_2O emissions assumptions

The project activity may result in increased N_2O emissions from soils in the project area. CH_4 emissions may occur in the baseline (from methane bubbling in open water) and in project (from anaerobic microbial respiration in soils) but is expected to be low in saline systems. Our assumptions regarding CH_4 and N_2O emissions in the baseline and project case are summarized in Table 4 and detailed below.

Table 4: Soil CH_4 and N_2O emission assumptions

Scenario	GHG	Source	Base Case Assumption	Justification
Baseline	CH_4	Methane ebullition in open water	0.14 ton CO2e/ha/yr[13]	0.14 tons CO2e/ha/yr (0.0056 ton CH_4/ha/yr) for tidal wetlands with salinity > 20 ppt per VM0033
	N_2O	Nitrification / denitrification	0.05 ton CO2e/ha/yr	0.05 tons CO2/ha/yr (0.000157 ton N_2O/ha/yr) for open water systems with salinity > 18 ppt per VM0033
With Project	CH_4	Anaerobic microbial respiration in project soils	0.14 ton CO2e/ha/yr	0.14 ton CO2e/ha/yr (0.0056 ton CH_4/ha/yr) for tidal wetlands with salinity > 20 ppt per VM0033
	N_2O	Nitrification / denitrification	0.15 ton CO2e/ha/yr[14]	0.15 ton CO2e/ha/yr (0.000487 ton N_2O/ha/yr) for tidal wetlands with salinity > 18 ppt per VM0033

We assessed methane emissions from soil and open water reported for a salt marsh located in the Barataria basin (DeLaune et al., 1983)[15], but combined average salinity levels at CRMS sites 0292 and 0164 (22 ppt) were higher than salinity levels at the salt marsh in DeLaune et al. Therefore, we used VM0033 default values for CH_4 and N_2O appropriate for polyhaline systems with average salinity of 22 ppt.

Qualitative assessment of the impact of sea level rise on project GHG emission reductions

Sea level rise may impact GHG emission reductions from project activities that increase carbon storage in biomass and soils. As the baseline scenario is open water, sea level rise will not impact carbon stocks in the baseline. Under the current version of VM0033, carbon stocks in above-ground biomass in project strata that are submerged due to sea level rise are assumed to be immediately lost to oxidation. It is conservative to assume that all soil carbon is eroded and oxidized, or alternatively the project may justify a smaller oxidation rate based on appropriate scientific research. However, a revision to a similar methodology is currently being

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[13] 0.0056 ton CH_4/ha/yr multiplied by 25 (100 year global warming potential for CH_4 per IPCC).

[14] 0.000487 ton N_2O/ha/yr multiplied by 298 (100 year global warming potential for N_2O per IPCC).

[15] DeLaune, R. D., Smith, C. J., Patrick, W. H. (1983) Methane release from Gulf coast wetland, Tellus B: Chemical and Physical Meteorology, 35, 1, 8 - 15.

reviewed; if approved, VM0033 will likely be updated similarly such that project proponents would no longer have to assume 0% oxidation in the baseline and 100% oxidation in the with project scenarios (expected approval in 2018). Rather, the rate of soil organic carbon oxidation would be based on estuary type, and the potential project area in the Port Fourchon region would probably be considered deltaic mud or normal marine with an 80% oxidation assumption. VM0033 requires sea-level rise modeling for the next 100 years based on IPCC regional forecasts or peer-reviewed literature applicable to the region.

Under VM0024, accounting procedures for strata that are submerged are not specified, but we expect that similar to VM0033, that oxidation of stored carbon would be assumed (likely could reference rates in VM0033). Also similar to VM0033, VM0024 requires the project proponent to provide evidence that the project activity has been designed such that the created tidal wetland is expected to withstand projected sea level rise. The evidence should be documented and take into consideration current technical scientific literature relevant to the area (based on sources such as the most recent IPCC assessment report and peer-reviewed literature) and site level factors such as existing natural or constructed measures (e.g., how existing landforms or constructed features offer physical protection of the project area), and the post-construction soil surface elevation relative to mean sea level, taking into account estimated accretion, subsidence and sea level rise parameters within the project area.

4.5 Considerations

If a decision is made to pursue carbon project development, the project proponents will need to select VM00024 or VM0033 to account for the GHG benefits of the project. Based on our initial analysis and understanding of project activities, both methodologies are applicable to the Port Fourchon tidal wetlands restoration project.

Measurements approaches in both methodologies are broadly similar, but there are still differences that could affect the cost of monitoring the project. For example, VM0033 permits field data measurements, but also provides for lower-cost approaches such as use of published values (e.g., for soil organic C) and default factors (e.g., for soil methane and nitrous oxide if salinity > 18 ppt). VM00024, on the other hand, generally requires more field data measurements (e.g., only approach for soil organic C) and allows for little use of default factors (only for nitrous oxide). That said, if the project proponents prefer to collect field data to get more accurate measures of the project impacts, then the cost of monitoring under either methodology will be similar. In any event, if and when the project moves forward, published values should be reviewed again (for any new, suitable data) and the GHG emission reduction calculations (in the next section) should be revised accordingly.

As mentioned above, both methodologies also require sea level rise modeling in the project area to determine if the restored tidal wetlands would remain above water based on projections using current technical scientific literature. If this modeling is performed as part of further project analysis, then the net emission reduction estimates presented in the next section should be updated accordingly. Under VM0024, areas that convert to open water are assumed to lose 100% of their stored carbon, while under VM0033, based on proposed revisions in review, those areas are assumed to lose 80% of their stored carbon.

Finally, we have assumed soil methane and soil nitrous oxide emission in the with-project (restored scenario) would be minimal based on the high salinities expected at the selected project area. Our expectation of high salinities was informed by our assessment of salinity data from CRMS sites 0292 and 0164, the two CRMS sites closest to Port Fourchon, which indicate that the potential project area would meet the requirements for application of the lowest default values for CH_4 and N_2O emissions in the project case. However, these default could only be used if there are not published values that are suitable to the project area. Therefore, the project proponent should assess existing published values for appropriateness once the project boundaries have been determined.

5.0

Financial feasibility

5.1 Methods

We have assessed the financial feasibility of the Port Fourchon tidal wetland restoration project by estimating the net carbon cash flows and net present value of the net carbon cash flows over the first 30 years of the project. Net carbon cash flows have been estimated using emission reduction estimates that are based on the GHG assumptions described in section 4.0, and do not include any restoration-related costs.

5.2 Assumptions

The key assumptions that we used in our analysis are described below.

Net emission reductions represent the difference between the baseline and with project emissions. Our estimates of emissions (or sequestration) are based on the GHG assumptions described in section 4.0, and include changes in soil organic carbon and biomass carbon as well as emissions of methane and nitrous oxide. We have generated net emission reduction estimates for scenarios of 300 hectare, 900 hectare, and 1,400 hectare project areas and for 0%/100%, 50%/50%, and 100%/0% marsh/mangrove vegetation coverages. For further reference, we present the net emission reductions on a per hectare basis over a 30 year project crediting period in Appendix 3.

Non-permanence deductions represents the contribution of net ERs to the VCS non-permanence buffer pool. All land use projects must contribute to this pool that protects against future reversals (emissions of carbon that has been removed and previously credited) that may occur (e.g., due to hurricanes, fires, other disturbances). Contributions are determined using the VCS non-permanence risk tool. For purposes of this analysis, we have assumed a 15% buffer contribution (10% represents the lowest contribution).

Tradeable carbon offsets are the net emission reductions less non-permanence deduction and represent the amount of carbon credits that can be sold.

Carbon prices are assumed to be $5.00/ton. The carbon price of $5/ton represents a midpoint for land based carbon transactions in the voluntary market. For reference, as illustrated in Figure 3 in section 3, the average voluntary carbon price in 2016 across all project types was $3.00/ton, while prices for forest/land use projects ranged from $4.20/ton (avoided deforestation) to $9.50/ton (improved forest management). In section 5.4, we also present results at varying carbon prices.

Carbon development and validation costs are assumed to be $150,000 and relate to the third-party fees and travel expenses of installing field plots ($25,000), preparing sea level rise analysis ($25,000), and preparing ($50,000) and validating ($50,000) the Project Description to be registered with the VCS. This estimate is based on our experience for similar land use projects. These are one-time expenses that are incurred at the inception of the project.

Carbon monitoring and verification costs are assumed to be $60,000 per monitoring event assuming 5-year monitoring intervals (maximum elapsed time between verifications before VCS buffer credits are put on hold). The estimated costs include the costs of collecting field biomass data ($10,000 per event), collecting field soil organic carbon data ($10,000 per event), and preparing and verifying the VCS monitoring report ($40,000 per event).

Discount rate is the rate used to discount future cash flows back to the present. We assume a discount rate of 6.0%.

Table 5: Summary Table of Assumptions

Parameter	Assumptions
Project area	300 ha, 900 ha, 1,400 ha
Marsh/Mangrove Coverage	0%/100%, 50%/50%,100%/0%
Non-permanence deduction	15%
Carbon price (per ton)	$5.00
Annual change in Carbon Price	0.0%
Carbon development and validation costs (one-time)	$150,000
Carbon monitoring and verification costs (every 5 years)	$60,000
Discount Rate	6.0%

5.3 Results

Based on the above assumptions, we have calculated the net emission reduction, cash flows, and net present value over 30 years (see Figures below). We show detailed calculations for illustration in Appendix 4 and 5 for the 1,400 hectare project area and 50% marsh/50% mangrove scenario and have separately provided our calculation workbook. As shown below, net emission reductions, cash flows, and NPV increase as the project area increases and as mangrove coverage increases (due to higher biomass accruals than marsh coverage).

Figure 5: Net Emission Reductions over 30 Years

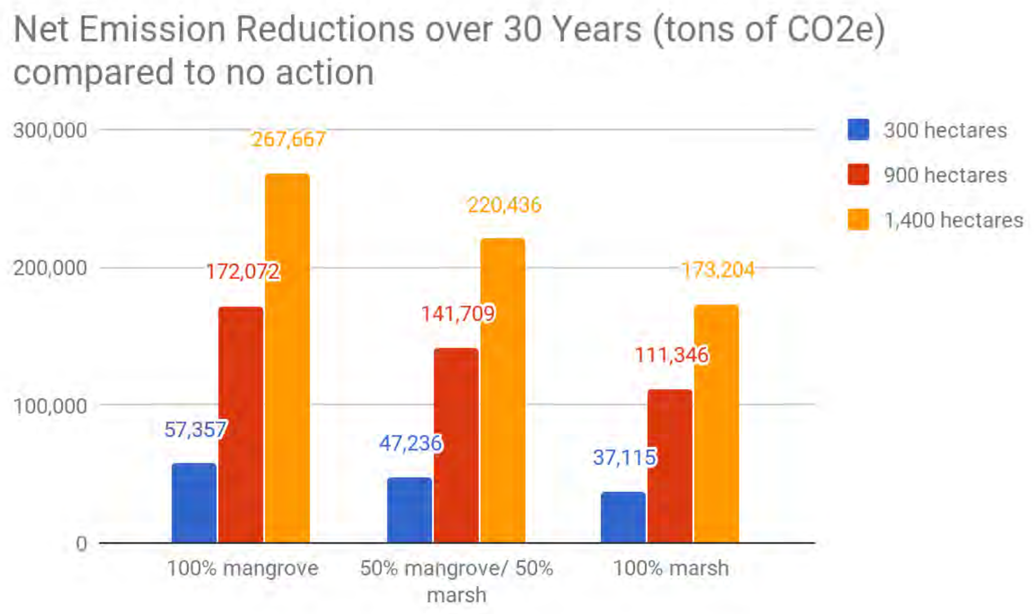


Figure 6: Carbon Net Cash Flows over 30 Years

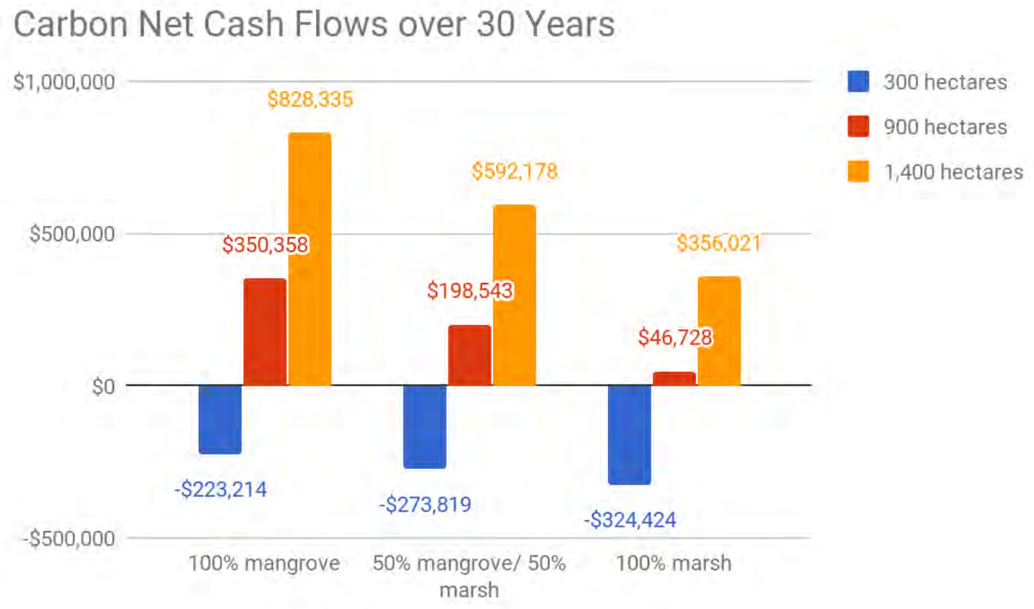
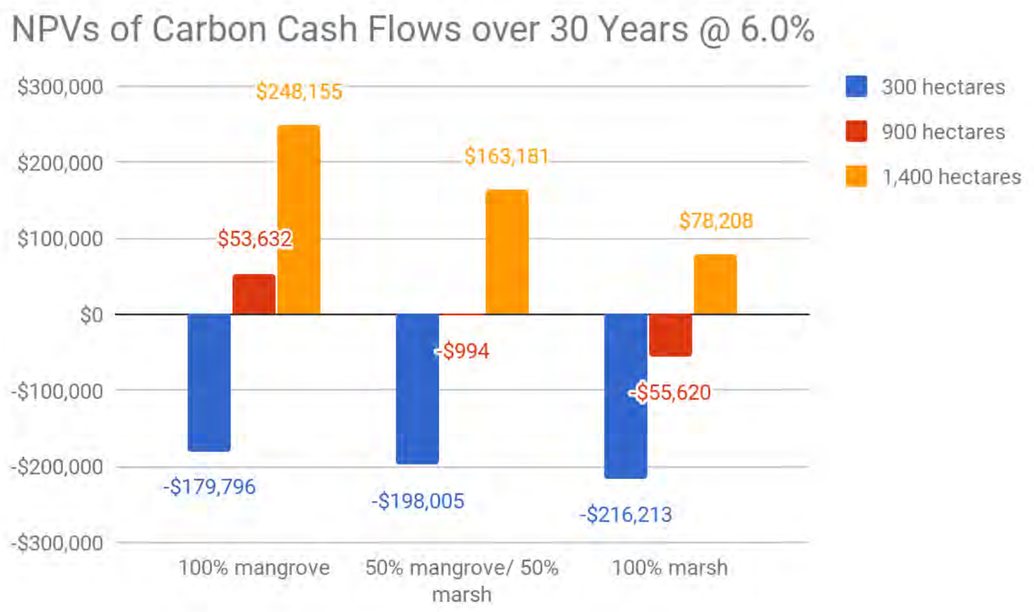


Figure 7: NPVs of Carbon Cash Flows over 30 Years



5.4 Sensitivity analysis

We have calculated the net cash flows over 30 years at carbon prices from $4.00/ton to $7.00/ton and annual carbon prices increases from -1.0% to 2.0% to illustrate the impact of varying carbon prices (Table 6). For example, as illustrated below, at $5.00/ton and 0.0% annual carbon price change, net cash flows over 30 years are estimated at $0.6 million if the project area is 1,400 hectares. At the same initial carbon price of $5.00/ton, but assuming annual price increases of 1.0%, net cash flows are estimated at $0.8 million (+$0.2 million change).

Table 6: Net Cash Flows over 30 years
(1,400 hectares and 50% marsh/50% mangrove cover)

		Carbon Price			
		$4.00	$5.00	$6.00	$7.00
Annual C Price Change	-1.00%	$235,118	$421,397	$607,677	$793,956
	0.00%	$371,742	$592,178	$812,614	$1,033,049
	1.00%	$539,495	$801,869	$1,064,243	$1,326,616
	2.00%	$746,189	$1,060,236	$1,374,283	$1,688,331

We have also calculated the net cash flows over 30 years at varying soil organic and biomass carbon assumptions (Table 7).

Table 7: Net Cash Flows over 30 years
(1,400 hectares and 50% marsh/50% mangrove cover)

		Soil C (WP) (tons C/ha/yr)		
		1.00	1.25	1.46
AG Biomass (tons C/ha in 30 yrs)	10.0	$341,840	$505,465	$642,910
	14.8	$428,553	$592,178	$729,623
	20.0	$524,010	$687,635	$825,080

In Appendix 6, we present sensitivity analysis of net carbon cash flows and net present values by varying these key assumptions along with project area assumptions.

5.5 Considerations

The largest drivers of uncertainty in our financial analysis relate to the uncertainties in our net emission reduction estimates, primarily related to our assumptions around the project area and the distribution of vegetation (marsh vs. mangrove), as well as future sea level rise (which we have not modeled).

We present the above scenarios to illustrate the impact on net cash flows of varying assumptions around project area and distribution of vegetation. If the project moves forward, additional clarity on project area should be prioritized and the net emission reduction calculations should be updated. Similarly, once the specific location of the placement for the dredge material is finalized, an assessment of surrounding vegetation types should be conducted to develop a refined estimate of likely vegetation and the net emission reduction calculations should be updated accordingly.

Sea level rise modeling, which considers impacts of relative sea level rise over the next 100 years has not yet been performed for the Port Fourchon tidal wetland restoration project. This modeling is required if the carbon project moves forward. Once completed, the net emission reduction estimates should be updated. Under VM0024, areas that convert to open water are assumed to lose 100% of their stored carbon, while under VM0033, based on proposed revisions in review, those areas are assumed to lose 80% of their stored carbon.

Our net emission reduction estimates are also driven by our GHG assumptions related to soil organic carbon and biomass carbon removals, and to a lesser extent by soil methane emissions, in the with-project (restored) scenario. Our assumptions for soil organic and biomass carbon are informed locally relevant data (see section 4) and cannot be refined any further at this point. Because actual removals may vary from our assumptions, we present the above sensitivity analysis to illustrate the impact of varying assumptions for soil organic carbon and biomass carbon removals in the with-project (restored) scenario. Because salinity is expected to be high in the restored marsh, it is expected that methane emissions should be minimal and not a big driver of net emission reductions. We have used the default values in our estimates, but as discussed in the previous section, the availability of “suitable” published values should be reassessed when the project area is finalized; and emission reduction estimates should be updated accordingly.

Our cost estimates assume soil organic carbon is measured directly with field data (and not using the published values approach allowed in VM0033). If carbon project development is pursued, these costs estimates should be re-evaluated based on the decision around monitoring approach for soil organic carbon (field data vsd. published values); if the field data approach is used, the number of field plots (based on the expected variability in soil organic carbon measurements and precision requirements of the methodology) and specific cost estimates for equipment and labor to install and monitor these plots should be obtained and the net cash flow analysis should be revised accordingly.

As discussed in section 3, if a decision is made to proceed with the development of a carbon offset project, we recommend immediate engagement with potential offset buyers. Engagement should include discussion of forward, pre-issuance sales that are settled in the future upon delivery of issued offsets (to minimize performance risk to buyers). Potential buyers in Louisiana, including companies that use Port Fourchon for oil and gas transportation and distribution and that will derive co-benefits from the project, are likely to place the highest value the offsets and should be targeted.

Finally, consideration should be given to potential grants or other forms of financial support to cover upfront and first monitoring event. As one of the first blue carbon projects, the Port Fourchon tidal wetland restoration could attract such funding from donors that would like to facilitate the development of blue carbon and carbon-based tidal wetland restoration projects.

6.0

Legal feasibility

6.1 Ownership of carbon rights

The VCS requires the project proponent (owner) to demonstrate carbon ownership by a right of use. For land use projects, a right of use can arises by virtue of property rights in land of the project area, or by an enforceable and irrevocable agreement with the landowner that transfers such rights to the project proponents.

Louisiana statutes support this premise so long as the project is not carried out, sponsored, or funded with public resources by the Coastal Protection and Restoration Authority (CPRA) or the CPRA Board:

§1103. Carbon sequestration on surface or water bottom

Any monetary compensation derived from the sequestration of carbon on the surface of land or water bottoms through biological processes, including but not limited to the growth of plants or animals or other natural or induced processes, is the property of the owner of the land or water bottom upon which such sequestration occurs, unless (a) contractually assigned to another party; or (b) the sequestration, uptake, or prevention of emission of greenhouse gases is directly related to the avoided conversion or avoided loss attributable to a project carried out or sponsored by the Coastal Protection and Restoration Authority or the Coastal Protection and Restoration Authority Board, including use of public resources as provided in R.S. 49:214.5.4. In such instance, the monetary compensation is the property of the state.

Acts 2010, No. 193, §1; Acts 2016, No. 430, §1.

We note that the above statute seems to target only projects that avoid conversion or loss, and strictly interpreted, may not be applicable to restoration projects.

It is our understanding that the Port Fourchon tidal wetland restoration project will not be carried out, sponsored, or funded with public resources by the CPRA or CPRA Board, and therefore carbon rights should accrue to the landowners where dredge material is placed and new marsh is created. At the current time, because the project area for the Port Fourchon tidal wetland restoration project has not been finalized, the landowners that would own the carbon rights from the project are not yet known. We understand, however, that the these owners are likely to be private entities and/or individuals (and not public or government entities).

6.2 Transfer of carbon rights

As mentioned above, landowners can transfer their carbon rights to another party by signing enforceable and irrevocable agreements. In many cases, when carbon offset projects are developed on land with multiple owners, agreements are signed whereby the landowners to transfer the carbon rights to a project developer who registers and monitors the project, receives the offsets, enters into sales transactions, and then distributes carbon revenues (less costs) back to the owners, typically allocated on a pro-rata basis corresponding to the area owned.

In other cases, landowners have collaborated to develop the carbon offset project and have retained their carbon rights. In these instances, a project developer typically still registers and monitors the project, but carbon offsets are issued to separate registry accounts maintained by the landowners and the project developer, and it is up to each party to enter into sales transactions with buyers. This scenario is less common as it increases the complexity of project management and sales transactions to buyers.

6.3 Considerations

In order to pursue carbon project development, it will be important to identify the specific landowners that will own new land that is created, and to enter into discussions with these landowners regarding the development of a potential carbon project.

Discussion with these landowners should include a broad discussion of the opportunity and costs, the process, and the responsibilities associated with developing and registering a project (including not to undertake activities that are prohibited by the methodology applicability conditions - e.g. application of fertilizers - or that may result in emissions of carbon that has been removed and previously credited). Consideration should be given to identifying a project developer (non-profit or for-profit organization) that could lead development and registration of the project as well ongoing monitoring and sales.

If a decision is made to pursue carbon project development, legal counsel should be engaged to draft appropriate agreements between the landowners and the project developer that specify carbon rights and roles and responsibilities of each party.

7.0

Next Steps

7.1 Summary

We summarize below the next steps for Phase 2 with respect to refining the results in this Phase 1 report if the project stakeholders decide to pursue further evaluation of carbon project development for the Port Fourchon tidal wetland restoration project.

Table 8: Phase 2 - Next Steps for Carbon Project Development

Next Steps
1. Obtain updated estimates of project area and vegetation coverage based on specific location for dredge placement.
2. Update review of GHG estimates for each pool (soil organic and biomass carbon) and source (methane and nitrous oxide emissions) published and unpublished data (for new data).
3. Model sea level rise based on area, location, elevation, and expected accretion in the project area and based on relative sea level rise projections..
4. Revise emission reduction estimates accordingly based on results of #1-3.
5. Finalize methodology selection and measurement approach for each pool/source considering stakeholder preference for direct measurements vs. cost, and update cost estimates accordingly.
6. Once a specific location for dredge placement is decided, engage landowners on carbon project opportunities and considerations, and engage counsel to draft appropriate agreements if decision is made to proceed.
7. Prepare and share summary information about the project and request indications of interest from potential buyers.

Appendices

Appendix 1 - Applicability Conditions for VM0024 and VM0033

VM0024 Applicability Condition	Port Fourchon Project

VM0024 is applicable under the following conditions:	
Project activities must include activities intended to create new wetlands in coastal ecosystems through substrate establishment, vegetation establishment, or both.	Condition met.
Project activities must not actively lower the water table depth.	Condition met.
The project area must meet the definitions of tidal or estuarine, open water, and degraded wetland before project activities are implemented and would have remained open water in the absence of the project activities	The project proponent may acquire data from USGS datasets or the US Fish and Wildlife Service's National Wetlands Inventory to show that the project area historically met the definition of a wetland and thus the definition of a degraded wetland. Per Section 6.1 of the methodology, if applicability condition #3 is met, the only possible baseline scenario is open water. The methodology uses a 10 year minimum time frame for the historic period.
The project area must be entirely within tidal or estuarine areas within the coastal zone boundary, and must meet the definition of Waters of the United States, excluding the Great Lakes.	Areas within the coastal zone boundary are defined for each state of the US by NOAA's Ocean and Coastal Resource dataset or individual coastal zone management maps. Waters of the United States is defined by the EPA to include "all waters which are subject to the ebb and flow of the tide" and thus would include the project area.
When ARR+RWE project activities are implemented and include the establishment of woody vegetation, there must not be commercial harvest activities, nitrogen fertilization or active peatland drainage.	Condition met. The project may use natural colonization, seeding or transplantation to accomplish establish woody vegetation (mangroves). The project activities do not include harvest activities or active peatland drainage. The project activities must not include the application of nitrogen fertilizers.
The project proponent must have obtained the necessary permits to demonstrate that the project will not have a significant negative impact on hydrologically connected areas (Section 8.3.3). This applicability condition must be satisfied at validation or at the first verification event.	As specified by Section 8.3.3 of the methodology, the project proponent must demonstrate compliance with Section 404 of the Clean Water Act by providing an individual or general permit issued by the USACE, prior to the completion of the first verification even. Where applicable, compliance with Section 10 of the Clean Water Act (River and Harbors Act) must also be demonstrated. Likewise, any NEPA analyses and decision documents must be provided (ie, a Finding of No Significant Impact for an Environmental Assessment or a Record of Decision for an Environmental

	Impact Statement) where applicable.

VM0033 Applicability Condition	**Port Fourchon Project**
VM0033 is applicable under the following conditions:	
1) Project activities which restore tidal wetlands (including seagrass meadows, per this methodology's definition of tidal wetland) are eligible.	Condition is met. Definition of tidal wetland restoration in the methodology: "Restoration of degraded tidal wetlands in which establishment of prior ecological conditions is not expected to occur in the absence of the project activity. For the purpose of this methodology, this definition also includes activities that create wetland ecological conditions on mudflats or within open or impounded water." Project area is open water.
2) Project activities may include any of the following, or combinations of the following: a) Creating, restoring and/or managing hydrological conditions (eg, removing tidal barriers, improving hydrological connectivity, restoring tidal flow to wetlands or lowering water levels on impounded wetlands) b) Altering sediment supply (eg, beneficial use of dredge material or diverting river sediments to sediment-starved areas) c) Changing salinity characteristics (eg, restoring tidal flow to tidally-restricted areas) d) Improving water quality (eg, reducing nutrient loads leading to improved water clarity to expand seagrass meadows, recovering tidal and other hydrologic flushing and exchange, or reducing nutrient residence time) e) Re-introducing native plant communities (eg, reseeding or replanting) f) Improving management practice(s) (eg, removing invasive species, reduced grazing)	Condition is met. Project activities primarily involve b) altering sediment supply – beneficial use of dredge materials and e) re-introducing native plant communities (eg, reseeding or replanting).
3) Prior to the project start date, the project area: a) Is free of any land use that could be	Condition is met. The project satisfies condition a) that no land uses/activities are present in the project area

displaced outside the project area, as demonstrated by at least one of the following, where relevant: (i) The project area has been abandoned for two or more years prior to the project start date; or (ii) Use of the project area for commercial purposes (ie, trade) is not profitable as a result of salinity intrusion, market forces or other factors. In addition, timber harvesting in the baseline scenario within the project area does not occur; or (iii) Degradation of additional wetlands for new agricultural sites within the country will not occur or is prohibited by enforced law. OR b) Is under a land use that could be displaced outside the project area (eg, timber harvesting), though in such case emissions from this land use shall not be accounted for. OR c) Is under a land use that will continue at a similar level of service or production during the project crediting period (eg, reed or hay harvesting, collection of fuelwood, subsistence harvesting) The project proponent must demonstrate (a), (b) or (c) above based on verifiable information such as laws and bylaws, management plans, annual reports, annual accounts, market studies, government studies or land use planning reports and documents.	that could be displaced outside the project area as evidenced by (ii) use of the project area for commercial purposes of not profitable as a result of market forces and other factors.
4) Live tree vegetation may be present in the project area, and may be subject to carbon stock changes (eg, due to harvesting) in both the baseline and project scenarios.	Condition is met. Live tree vegetation (mangrove) may be present and subject to carbon stock changes (growth/die-off) in the project scenario.
5) The prescribed burning of herbaceous and shrub aboveground biomass (cover burns) as a project activity may occur.	Condition is met. Prescribed burning may be part of vegetation management.
6) Where the project proponent intends to claim emission reductions from reduced frequency of peat fires, project activities must include a combination of rewetting and fire management.	Not applicable. Project proponent does not intend to claim emission reductions from reduced fire, since project area is not subject to fires.
7) Where the project proponent intends to	Not applicable.

claim emission reductions from reduced frequency of peat fires, it must be demonstrated that a threat of frequent on-site fires exists, and the overwhelming cause of ignition of the organic soil is anthropogenic (eg, drainage of the peat, arson).	Project proponent does not intend to claim emission reductions from reduce fire, since project area is not subject to fires.
8) In strata with organic soil, afforestation, reforestation, and revegetation (ARR) activities must be combined with rewetting.	Not applicable. The project creates wetland ecological conditions within open water.
VM0033 is not applicable under the following conditions:	
9) Project activities qualify as IFM or REDD.	Condition is met. Project activities to create wetland ecological conditions within open water do not qualify as IFM (increasing carbon stocks in an existing forest) or REDD (protecting forest from degradation or conversion to non-forest).
11) Project activities lower the water table, unless the project converts open water to tidal wetlands, or improves the hydrological connection to impounded waters.	Condition is met, i.e. not applicable. Project activity lowers the water table to convert open water to tidal wetlands.
12) Hydrological connectivity of the project area with adjacent areas leads to a significant increase in GHG emissions outside the project area.	Condition is met. No significant increases in GHG emissions outside the project area are anticipated
13) Project activities include the burning of organic soil.	Condition is met. No soils will be burned as part of the project activities.
14) Nitrogen fertilizer(s), such as chemical fertilizer or manure, are applied in the project area during the project crediting period.	Condition is met if no nitrogen fertilizers are planned to be applied in the project area during the project crediting period.

Appendix 2 - Summary of Compliance Carbon Markets in the U.S.

California Cap and Trade Program
The California cap-and-trade program started in 2013. The program, which initially consists of three compliance periods (2013-2014, 2015-2017, 2018-2020), aims to reduce California's emissions to 1990 levels by 2020. The program initially covered large emitters (>25,000 tons CO2/year) in the electricity generation sector and was expanded in 2015 to also cover transportation, residential, and commercial fuels.

The key element of the cap-and-trade program is the requirement for regulated entities to retire allowances or offsets equal to their emissions during the relevant compliance period. The program regulator, ARB, initially approved four offset protocols including forestry, urban forestry, livestock methane, and ozone depleting substances (ODS). It has subsequently approved offset protocols for rice and coal mine methane projects.

The program regulations limit the amount of offsets that an entity can use to 8% of its compliance requirement. To date, more than 92 million offsets have been issued by ARB, with more than 66 million offsets issued to forest projects.[16]

Since the program was first implemented, the California cap and trade program has faced legal challenges, most notably from businesses who argue that the program is an unconstitutional tax and did not receive the requisite two-thirds approval from the California legislature needed for new taxes.

In the summer 2017, the program was extended and new emissions caps for 2030 and preliminary caps for 2050 were passed by two-thirds vote in the California legislature insulating the program from future legal challenges. Several changes to the program will go into effect in 2021, including a change in the offset limit to 4% from 2021-2025 and to 6% from 2025-2030 (down from current 8% limit). Additional limitations were also imposed so that not more than 2% of offsets from 2021-2025 and not more than 3% of offsets from 2026-2030 (50% of the offset limit in each period) can come from projects that do not have a direct environmental benefit in California (likely interpreted as projects located outside the state of California[17]).

California offsets currently trade at $12-13/ton, which is below California allowances which are trading at around $15/ton[18]. The California cap and trade program has set a floor price for allowances that are auctioned off by the state each quarter which provides support for both

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[16] https://www.arb.ca.gov/cc/capandtrade/offsets/issuance/arb_offset_credit_issuance_table.pdf accessed on February 21, 2018.
[17] https://climatetrust.org/understanding-the-odd-language-of-the-california-offset-requirement-scorcher/
[18] http://californiacarbon.info/ accessed on February 21, 2018

allowance and offset prices (floor initially set in 2012 at $10/ton with annual increases at 5%+CPI, 2017 floor price = $14.53)[19].

Forest projects located anywhere in the U.S. are generally eligible to participate in the ARB compliance offset program. The only exclusions are projects located on federally-owned land or projects on land where a federal entity holds an easement. When ARB issued the compliance forest offset protocol, ARB stated that it excluded projects on these lands due to their additional complexity and that further study would be needed (in particular, about enforceability of ARB's rights on federal entities).[20]

At this moment, other than forestry and the recently approved rice cultivation protocol, ARB does not issue carbon offsets to other land use projects such as tidal wetland restoration. However, new offset methodologies can be developed and submitted to ARB for consideration by standards bodies such as the VCS, ACR, or CAR. In fact, two new offset methodologies have been approved (coal mine submitted by CAR and rice cultivation submitted by ACR) since the ARB offset program was first established.

While it is hard to know whether ARB would approve a tidal wetland restoration methodology in the future, it is certain that pilot blue carbon projects like the Port Fourchon project would help inform ARB's decision by demonstrating how these types of projects could accurately quantify emission reductions.

Regional Greenhouse Gas Initiative (RGGI)

RGGI is a cap and trade program that operates in nine northeastern states, including Connecticut, Delaware, Massachusetts, Maine, Maryland, New Hampshire, New York, Rhode Island, and Vermont. It started in 2009 and covers only electric utilities. Following elections in November 2017, the states of New Jersey and Virginia have now also introduced legislation or rules that would join their states in RGGI or a RGGI-like program.

Due to initial oversupply, prices for RGGI allowances fell to the floor price which had been set at around $2/ton. While the program also allowed regulated companies to use offsets from U.S.-based projects (including forestry offsets), the low prices for allowances did not provide sufficient incentives for offset developers to register projects in the RGGI program.

In 2012, due to continued oversupply of allowances, regulators lowered the emissions caps (from initial caps) in RGGI for the time period 2014-2020 by 45%. In 2017, regulators lowered the emission caps from 2021-203 by an additional 30%. Despite a lower cap, prices in RGGI have remained low ($3.80 ton in December 2017 auction[21]) and are likely still not sufficient to incentivize project developers to register offset projects with RGGI because developers can access higher prices and greater demand in the California cap-and-trade market.

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[19] https://www.arb.ca.gov/cc/capandtrade/auction/2017_annual_reserve_price_notice_joint_auction.pdf accessed on February 21, 2018

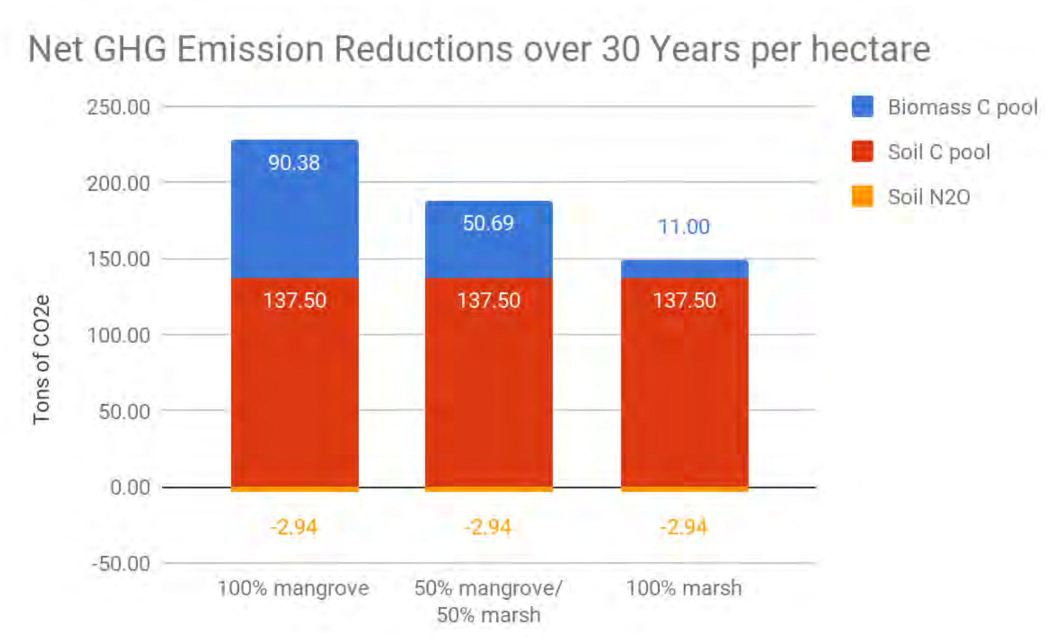
[20] http://www.arb.ca.gov/regact/2010/capandtrade10/cappt5.pdf, page 15

[21] https://www.rggi.org/auctions/auction-results accessed on February 21, 2018

That said, with new out-of-state limits in California starting in 2021, offset project development in RGGI may increase in the future. At the same time, adding tidal wetland restoration projects as an eligible offset project type in the future could be supported by many of the RGGI states that rely on tidal wetlands for their own coastal protection. Of course, as mentioned above, pilot projects like the Port Fourchon project could serve as valuable demonstration that the climate benefits of tidal wetland restoration can be reliably quantified.

Appendix 3 - Net Emission Reductions per Hectare

Please note that the net GHG emission reductions presented below do not include any buffer contributions related to non-permanence that would be deducted from offsets issued (discussed in and analyzed in section 5 and illustrated in Appendix 4).



Appendix 4 - Emission Reduction Calculations

At 1,400 hectares and 50% marsh/50% mangrove cover

	Baseline		**With Project**				
Year	**Soil**	**Biomass C**	**Soil**	**Biomass C**	**Net ERs**	**Non-Perm**	**C Offsets**
0							
1	(262)	0	6,017	9,809	16,088	-2,413	13,675
2	(262)	0	6,017	2,109	8,388	-1,258	7,130
3	(262)	0	6,017	2,109	8,388	-1,258	7,130
4	(262)	0	6,017	2,109	8,388	-1,258	7,130
5	(262)	0	6,017	2,109	8,388	-1,258	7,130
6	(262)	0	6,017	2,109	8,388	-1,258	7,130
7	(262)	0	6,017	2,109	8,388	-1,258	7,130
8	(262)	0	6,017	2,109	8,388	-1,258	7,130
9	(262)	0	6,017	2,109	8,388	-1,258	7,130
10	(262)	0	6,017	2,109	8,388	-1,258	7,130
11	(262)	0	6,017	2,109	8,388	-1,258	7,130
12	(262)	0	6,017	2,109	8,388	-1,258	7,130
13	(262)	0	6,017	2,109	8,388	-1,258	7,130
14	(262)	0	6,017	2,109	8,388	-1,258	7,130
15	(262)	0	6,017	2,109	8,388	-1,258	7,130
16	(262)	0	6,017	2,109	8,388	-1,258	7,130
17	(262)	0	6,017	2,109	8,388	-1,258	7,130
18	(262)	0	6,017	2,109	8,388	-1,258	7,130
19	(262)	0	6,017	2,109	8,388	-1,258	7,130
20	(262)	0	6,017	2,109	8,388	-1,258	7,130
21	(262)	0	6,017	2,109	8,388	-1,258	7,130
22	(262)	0	6,017	2,109	8,388	-1,258	7,130
23	(262)	0	6,017	2,109	8,388	-1,258	7,130
24	(262)	0	6,017	2,109	8,388	-1,258	7,130
25	(262)	0	6,017	2,109	8,388	-1,258	7,130
26	(262)	0	6,017	2,109	8,388	-1,258	7,130
27	(262)	0	6,017	2,109	8,388	-1,258	7,130
28	(262)	0	6,017	2,109	8,388	-1,258	7,130
29	(262)	0	6,017	2,109	8,388	-1,258	7,130
30	(262)	0	6,017	2,109	8,388	-1,258	7,130
Total	**(7,845)**	0	**180,525**	**70,966**	**259,336**	**-38,900**	**220,436**

Appendix 5 - Cash Flow Calculations

At 1,400 hectares and 50% marsh/50% mangrove cover

Year	C Offsets	Verified Offsets	C Revenues	C Costs	C Cash Flow
0				-$150,000	-$150,000
1	13,675				$0
2	7,130				$0
3	7,130				$0
4	7,130				$0
5	7,130	42,193	$210,967	-$60,000	$150,967
6	7,130				$0
7	7,130				$0
8	7,130				$0
9	7,130				$0
10	7,130	35,648	$178,242	-$60,000	$118,242
11	7,130				$0
12	7,130				$0
13	7,130				$0
14	7,130				$0
15	7,130	35,648	$178,242	-$60,000	$118,242
16	7,130				$0
17	7,130				$0
18	7,130				$0
19	7,130				$0
20	7,130	35,648	$178,242	-$60,000	$118,242
21	7,130				$0
22	7,130				$0
23	7,130				$0
24	7,130				$0
25	7,130	35,648	$178,242	-$60,000	$118,242
26	7,130				$0
27	7,130				$0
28	7,130				$0
29	7,130				$0
30	7,130	35,648	$178,242	-$60,000	$118,242
Total	**220,436**	**220,436**	**$1,102,178**	**-$510,000**	**$592,178**

Appendix 6 - Sensitivity Analyses

At 1,400 hectares and 50% marsh/50% mangrove cover

Sensitivity Analyses-C Cash Flows over 30 Years					
		Carbon Price			
		$4.00	$5.00	$6.00	$7.00
Annual C Price Change	-1.00%	$235,118	$421,397	$607,677	$793,956
	0.00%	$371,742	$592,178	$812,614	$1,033,049
	1.00%	$539,495	$801,869	$1,064,243	$1,326,616
	2.00%	$746,189	$1,060,236	$1,374,283	$1,688,331
		Area (hectares)			
		300	900	1,400	
Marsh Coverage	0.00%	-$223,214	$350,358	$828,335	
	50.00%	-$273,819	$198,543	$592,178	
	100.00%	-$324,424	$46,728	$356,021	
		Soil C (WP) (tons C/ha/yr)			
		1.00	1.25	1.46	
AG Biomass (tons C/ha in 30 yrs)	10.0	$341,840	$505,465	$642,910	
	14.8	$428,553	$592,178	$729,623	
	20.0	$524,010	$687,635	$825,080	

At 1,400 hectares and 50% marsh/50% mangrove cover

Sensitivity Analyses-NPV over 30 Years					
		Carbon Price			
		$4.00	$5.00	$6.00	$7.00
Annual C Price Change	-1.00%	$27,182	$108,105	$189,028	$269,951
	0.00%	$71,243	$163,181	$255,120	$347,058
	1.00%	$123,394	$228,370	$333,346	$438,322
	2.00%	$185,419	$305,901	$426,383	$546,865
		Area (hectares)			
		300	900	1,400	
Marsh Coverage	0.00%	-$179,796	$53,632	$248,155	
	50.00%	-$198,005	-$994	$163,181	
	100.00%	-$216,213	-$55,620	$78,208	
		Soil C (WP) (tons C/ha/yr)			
		1.00	1.25	1.46	
AG Biomass (tons C/ha in 30 yrs)	10.00	$61,301	$127,892	$183,828	
	14.76	$96,591	$163,181	$219,118	
	20.00	$135,439	$202,030	$257,966	

Attachment 6:

The Institute and Nicholls State University Collaboration

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Water Institute and Nicholls State Collaboration

August 20, 2018

An element of the Supporting the Working Coast Initiative at Port Fourchon was to engage and collaborate with students from Nicholls State to conduct field research. The Biology Department nominated three students to join two WI researchers for a multi-day research trip to Port Fourchon. The field effort involved a combination of research activities on current Water Institute projects, as well as site visits to areas related to previous work. Figure x shows data collection sites, the port, and surrounding areas, including the Caminada Headland and lower Bayou Lafourche.

The field team visited site PF-5 near Belle Pass, where several instruments had been deployed in mid-April 2018. Instruments at this station included an automated carousel water sampler (AWS), a YSI multiparameter water quality sonde, and an upward facing ADCP current meter. The ADCP was programmed to collect vertical water velocity profiles every hour. Each profile consists of velocity bins starting 0.4 m from the ADCP transducers, about 1.5 from the seabed, extending up to the surface of the ship channel at 0.25m intervals.

The YSI multiparameter water quality sonde holds probes to measure water level, salinity, temperature, and turbidity at 12-minute intervals. The turbidity measurement is a proxy for suspended sediment concentration in the water. The AWS pumps water samples from an intake installed adjacent to the YSI probes. It was set to fill 1 of 24 1 liter bottles every 72 hours. These physical samples are later filtered such that the mass of the sediment in the water can be measured to render the suspended sediment concentration (SSC) in mg/L. The SSC of the physical samples are then used to calibrate the YSI turbidity yield a continuous record of SSC in mg/L.

The first task at PF-5 was to recover the bottom sitting ADCP and replace it with a horizontal ADCP (H-ADCP) because of concerns that large, deep draft vessels may harm the ADCP. After the ADCP was top side, and with the help of the Nicholls State students, a new mount was built and installed on an existing fixed platform at the western edge of the ship channel.

The mount was designed to hold the H-ADCP at a depth of approximately 2.5m with the transducers aimed perpendicular to the channel. The instrument was set to collect hourly stream velocity in 12 cells starting at the platform, spaced 10 m apart and extending out 120m into the channel. The balance of activity at PF-5 was routine field maintenance of instrumentation. The YSI was checked and cleaned. The data was offloaded, batteries changed, and then redeployed. The AWS was checked to see if it was running properly; however, no bottles were swapped out, as there were enough empty bottles to last up until the following servicing trip.

The second field activity was to get the students involved in vessel-based data collection. At each red transect line in Figure 1, stream velocity was measured using a downward facing, vessel mounted ADCP. Each time the ADCP pings, an ensemble, or water velocity profile, is recorded at 0.25 m intervals from the surface to the seabed. As the vessel moves across the channel, a series of ensembles is generated that yields a grid of stream velocities in a plane that is normal to the channel. By integrating the velocities vertically and horizontally and then multiplying by the cross-sectional area of the channel a discharge is calculated.

An effort was made to run the 3 transects at the channel junction around PF-5 in a rapid sequence to quantify the mass flux of water coming down, leaving or entering the channel at that time. The same technique was employed at the junction near PF-4 for the same reason. The vessel based ADCP velocities and discharge are also useful to the validation and calibration process of developing numerical models that describe circulation in Bayou Lafourche.

As a compliment to the vessel based ADCP measurements, CTD (Conductivity, temperature and depth) casts were taken at the deepest portion of each transect. The CTD is essentially a multiparameter sonde like the YSI that is designed to record a vertical profile of temperature, salinity, pH, turbidity, and dissolved oxygen (DO). The turbidity parameter of these measurements is of specific interest, as, taken with the water flux, they can provide insight to sediment transport within the system. A set of vertical water samples were collected with a van Dorn water sampler at fractional depths of 0.1, 0.5, and 0.9 of the total depth at the cast site. These water samples were filtered and processed in a similar fashion to the AWS samples described above to aid in calibrating the CTD measured turbidity to SSC in mg/L.

A final aspect of the field endeavor was to visit the study locations that had been monitored by the Coastal Ecology Team for the Louisiana Sea Grant mangrove and fisheries project. These sites were of interest due to their relative abundance of mangroves and how that abundance related to elevation, salinity, etc. Figure 2 shows the students in action taking readings with the YSI at our field sites and updating and using these measurements to create a real time map in a mobile GIS on the ship board computer. We were able to look at the spatial variation in some key water quality parameters, such as temperature, salinity, and turbidity.

Figure 1. Lower Bayou Lafourche, Port Fourchon, and the Caminada Headland are shown above along with red lines that indicate locations of transects where vessel based ADCP measurements were taken to characterize and quantify flow in the channel. Orange triangles indicate sites where multiparameter water quality sondes are deployed to measure water level, sediment concentration, salinity, and water temperature.

Figure 2. Nicholls State students in action. David Bird, top left, takes a spot reading of water salinity, temperature, and turbidity with a YSI multiparameter sonde. Bottom left, Andrea Jarebek shows David Bird and Olijuwan Jimoh how to set up a data collector to take a water quality measurement with the YSI. On the right frame, Olijuwan Jimoh shares the reading from the data logger with Kellyn LaCoeur-Conant as she updates the on-board GIS map on the shipboard computer.

Attachment 7:
Subsidence and Hazard Maps Supplement

THE WATER INSTITUTE
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PARTNERSHIP FOR OUR WORKING COAST:
PORT FOURCHON PHASE 1 TECHNICAL REPORT
SUBSIDENCE AND HAZARD MAPS SUPPLEMENT

August 31, 2018

Mead Allison, Diana Di Leonardo, and Harris Bienn

Introduction

The objective of the Phase 1 report on subsidence was a data mining exercise to bring together all available information on subsidence rates in the Port Fourchon area, including relevant ancillary data (e.g., stratigraphy, salt/fault structure, etc.). The main deliverable of this effort was the data report that this memorandum supplements. While the goal of this Phase 1 effort was not an analysis of the data collected, it was deemed necessary to conduct some initial analysis as part of the conversation with the clients about a possible Phase 2 subsidence effort. The following memorandum provides a brief summary and presentation of the analysis conducted on the Port Fourchon area subsidence data. The main purpose of this supplement is to provide the map products resulting from this analysis to the clients, along with a brief explanation of how they were constructed. A more extensive explanation of the methods used to create these products will be provided in a future report.

Subsidence Maps

The subsidence data for Port Fourchon stems from four different site measurement methods. These are (1) tide gauges (2) Coastal Reference Monitoring Stations [CRMS], (3) geodetic levelling surveys, and (4) continuously operating reference GPS stations [CORS]. A detailed explanation of these data collection methods can be found in the main report. Each of these methods measures subsidence over different sections of the subsurface, defined here as the interval from the land surface to the center of the Earth. Here we attempt to unify these measurements to derive a map of subsidence rates across the entirety of the Port Fourchon area (Figure 1). The derived rates should be viewed with caution as an evaluation of the sensitivity of these rates to the described assumptions has not yet been conducted. One possible major goal of a Phase 2 subsidence effort might be placing subsidence measuring stations on the Port Fourchon landscape that measure subsidence over the entire subsurface and, simultaneously, over different subsurface depth intervals. This would provide insight into the assumptions made to convert each one of these four subsidence measurement techniques to a total, depth-integrated subsidence rate.

SUBSIDENCE MAP METHODS

Foundation Depth

Each point measurement of subsidence rate represents a different section of the subsurface based on its foundation depth. Benchmarks associated with levelling surveys, tide gauges, and CORS stations measure the subsidence occurring below their foundation depths to the center of the Earth. CRMS rod sediment elevation tables (RSETs) measure the subsidence occurring between the surface of the Earth and their foundation depths.

Significant efforts were made to find a foundation depth for every subsidence rate used in this study. The benchmark sheet for every survey monument used in the Shinkle and Dokka (2004) study was reviewed for information about the monument's foundation depth. Tide gauge records were reviewed for information on their benchmarks and foundation depths. Ultimately, it was only possible to find recorded foundation depths for 53 of the 110 subsidence measurement sites.

To assign a foundation depth to those stations where that information was absent, we estimated whether a foundation would be shallow or deep and assigned a foundation depth accordingly. Benchmarks set in a concrete block or pavement were assigned a foundation depth of 2 m. Benchmarks set in larger structures, such as bridges and seawalls, were assigned a foundation depth of 5 m. The Grand Isle (GRIS) CORS GPS station was assigned a foundation depth of 15 m because it is set on top of a larger building. The Belle Pass tide gauge is attached to dock pilings, and was assigned a foundation depth of 5 m.

Belle Pass Tide Gauge Subsidence Rate

The tide gauge at Belle Pass has been recording water levels since August 2003. We used the records of the monthly mean of the recorded mean sea level to calculate a subsidence rate. Only the records from complete years were used (2003 through 2017). The RSLR rate calculated from a linear regression through the water levels at this gauge is 15 mm/yr (Figure 2). Assuming a eustatic sea level rise rate of 2 mm/yr (Letetrel et al., 2015), produces a total subsidence rate of 13 mm/yr. This subsidence rate must be used with caution because the water level record utilized at this gauge is not long enough to capture the full variability of the 18.6 year tidal cycle.

Coastal Reference Monitoring Station Subsidence Rates

Shallow subsidence is defined herein as the subsidence occurring between the surface of the Earth and the foundation depth of a measurement location. When combined with accretion measurements from regularly (twice/year) visited feldspar plots on the sediment surface at each site, RSET measurements at CRMS stations measure subsidence between the surface of the Earth and the foundation depth of the RSET. Thus, at CRMS stations the shallow subsidence rate is the rate measured at the station's RSET minus the accretion rate at the site. The shallow subsidence rates at CRMS stations were interpolated across the study area to provide estimates of shallow subsidence for every location with any kind of subsidence measurement.

Deep subsidence is defined herein as the subsidence occurring below the foundation depth to the center of the Earth at a measurement location. At CRMS stations, a relationship between deep subsidence and latitude, derived from the geodetic data, was used to calculate the deep subsidence rate (Figure 3). This relationship relies solely on local geodetic data from the Shinkle and Dokka (2004) levelling surveys. Only benchmarks with known foundation depths greater than 15 m were used to derive this relationship (n = 29) (Figure 3). This relationship differs from others derived for Louisiana (eg. Karegar et al., 2015); however, it represents a very local relationship instead of a regional one.

Geodetic Levelling Survey Subsidence Rates

The measured subsidence at all stations, except for CRMS stations, is the subsidence rate below its foundation depth, or deep subsidence. The foundation depth for geodetic benchmarks varied from very shallow (~2 m) to very deep (>20 m). For measurement locations that are not CRMS stations and have a foundation depth less than 15 m, a fraction of the shallow subsidence from the CRMS station interpolation was added to the total subsidence rate to account for shallow subsidence above the foundation depth. For measurement locations that are not CRMS stations and have a foundation depth greater than or equal to 15 m, the shallow subsidence rate interpolated from the CRMS stations for that point was used as the shallow subsidence rate.

Grand Isle CORS Station Subsidence Rate

Similar to the geodetic benchmarks, the shallow subsidence rate for the Grand Isle CORS station (GRIS) is taken from the interpolated shallow subsidence rates from the CRMS sites. The subsidence rate measured at the station is the rate below its foundation depth; this is used as the deep subsidence rate.

Interpolation of Subsidence Rates

After calculating subsidence rates at every point where it has been measured in the Port Fourchon study area, the rates were interpolated to a surface over the extent of the LiDAR data using a natural neighbor interpolation method (Figure 1). Natural neighbor uses a weighted sample of the closest points to interpolate a smooth surface that passes through the input points. With any kind of interpolation, the edges of the interpolated area will tend to have higher errors; to minimize these edge effects contaminating the study area, we interpolated subsidence rates to an area larger than the study area using additional CRMS data (Figure 1). Because the natural neighbor method does not extrapolate beyond the input points, some manual extrapolation based on the extension of contour lines was used to extend the interpolation to the edges of the LiDAR data.

Land Elevation

To construct the hazard maps outlined below, it was necessary to determine land elevation of the study area as recently as possible. The CoNED data set from 2011 and 2013 is the most recent LiDAR data available for the study area (see main report for further explanation of the data set); however, because there is a gap in the northwest corner of the study area, the CoNED data is supplemented with Atlas LiDAR data from 2002 and 2003. A dashed line demarcates the joined section in the maps provided with this supplement. We have made no attempts to adjust the measured elevations for time and consider the combined LiDAR data as the elevations for 2018 for the purpose of calculating land elevations into the future (Figures 4-7).

Hazard Maps

Total subsidence rate information, by itself, is less useful for decision makers than total elevation change as expressed at the ground surface. Combining our derived total subsidence rates with eustatic sea level rise rates and land elevations provides a method to construct hazard maps that examines the risk of inundation for various parts of the study area. To construct the maps provided with this supplement, several assumptions were made that are outlined below.

HAZARD MAP METHODS

Mean Water and Mean Low Water Level

Because LiDAR elevation data measures only the land above the water at the time of collection, it is affected by meteorological and astronomical water level, and classifying low lying areas as land or water requires a clear definition of the water level elevation. The water level used in these hazard maps is mean low water (MLW). MLW is defined as the average water level at low tide. Hence, any LiDAR data point above MLW is classified as "land" in the present (2018) maps. The MLW levels for 2017 were obtained from the NOAA operated tide gauge at Belle Pass, Louisiana. The MLW level used in this analysis is an average of monthly mean water levels over an entire year to account for seasonal variations in water levels.

The vertical reference for the LiDAR elevation data is NAVD 88, Geoid 12A. The MLW level must be referenced to the same datum for an accurate analysis. As part of the preliminary data collection effort to support the Institute's proposed Phase 2 modelling effort in the study area, we placed YSI instruments measuring continuous water levels in the study area beginning in February 2018. The water levels from this instrument were referenced to NAVD 88, Geoid 12A using Real Time Kinematic Differential GPS (RTK-DGPS) measurements taken at the instrument location. The hourly water level measurements from February 21, 2018 through April 18, 2018 from both the Belle Pass tide gauge and The Institute's YSI have an average difference of 0.13 m. This offset was used to reference the MLW from the Belle Pass tide gauge to NAVD 88, Geoid 12A so that the water level could be applied to the LiDAR data.

Areas Within Levee Protection

For areas within protection levees, the effective elevation for a hazard map is the elevation of the levee rather than the elevation of the land. We first determined the height of the levees every 100 m along the entirety of the protected area. Then we created a 1000 m square grid across the area inside the protection levees. Each grid cell was assigned the elevation of the nearest levee. This new elevation grid was used for the hazard maps within the levee protection system.

Eustatic Sea Level Rise Rate

The eustatic sea level rise rate used in this analysis (2 mm/yr) was calculated by Letetrel et al. (2015) for the Gulf of Mexico using a combination of tide gauge and satellite altimetry data. This rate was also used by Jankowski et al. (2017). This rate was applied linearly (and equally across the entire field area) to the MLW from 2017 to calculate the water level at each time period.

Hazard Map Results

The relative sea level rise (total subsidence + eustatic) rates for every location on the map are applied linearly to the combined LiDAR data for three time steps into the future using 2018 as the base year (Figures 4-7). Land areas that have an elevation at or below MLW for the time period under consideration are colored white. The time periods considered here are 10 years (2028) (Figure 5), 25 years (2043) (Figure 6), and 50 years (2068) (Figure 7). Predicted land loss between each of the time periods is shown in Figure 8.

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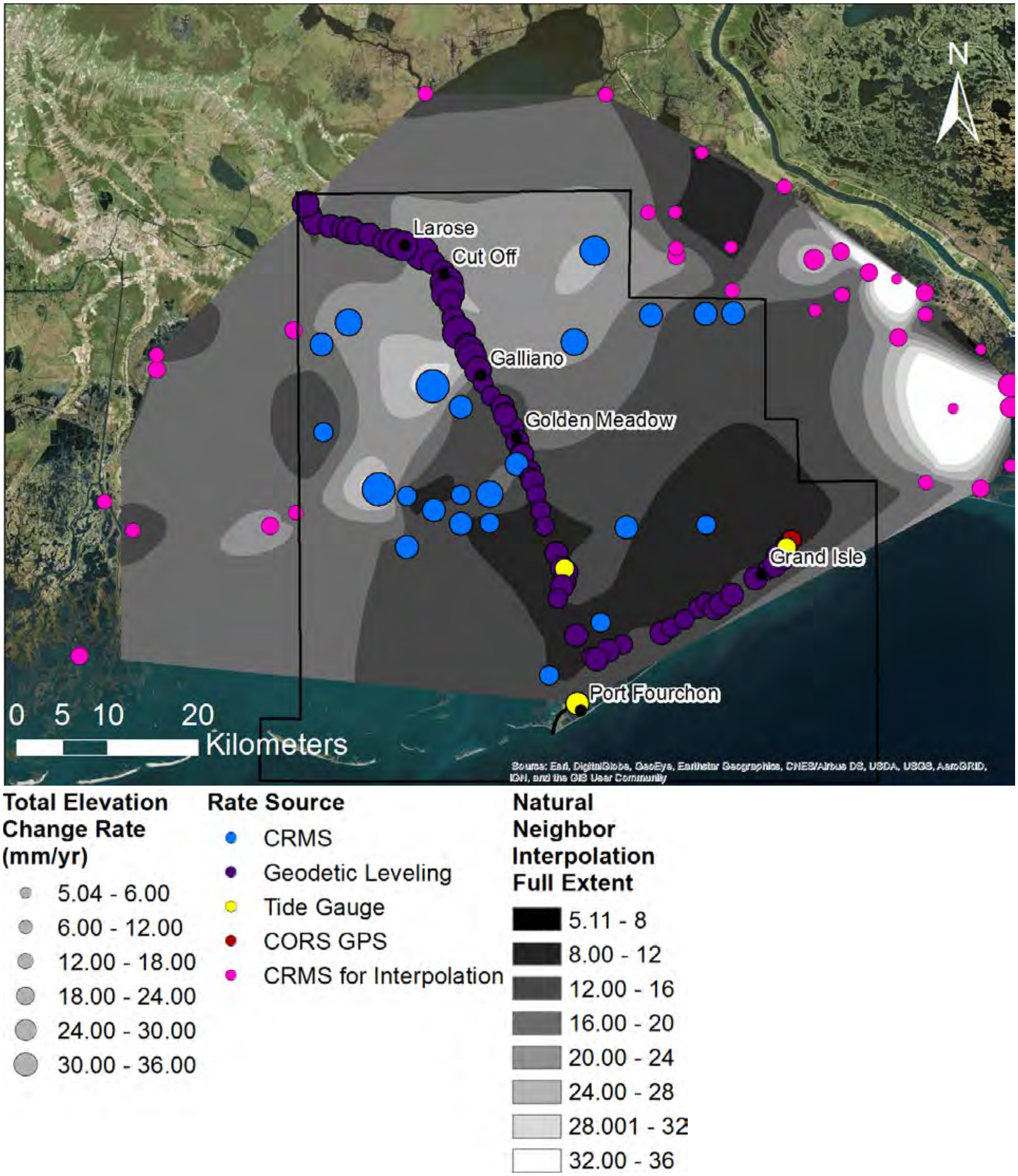
Figures



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 1. Total subsidence rates (deep + shallow) for the study area colored by type and sized by rate. The natural neighbor interpolation derived from these points is shown in gray scale.

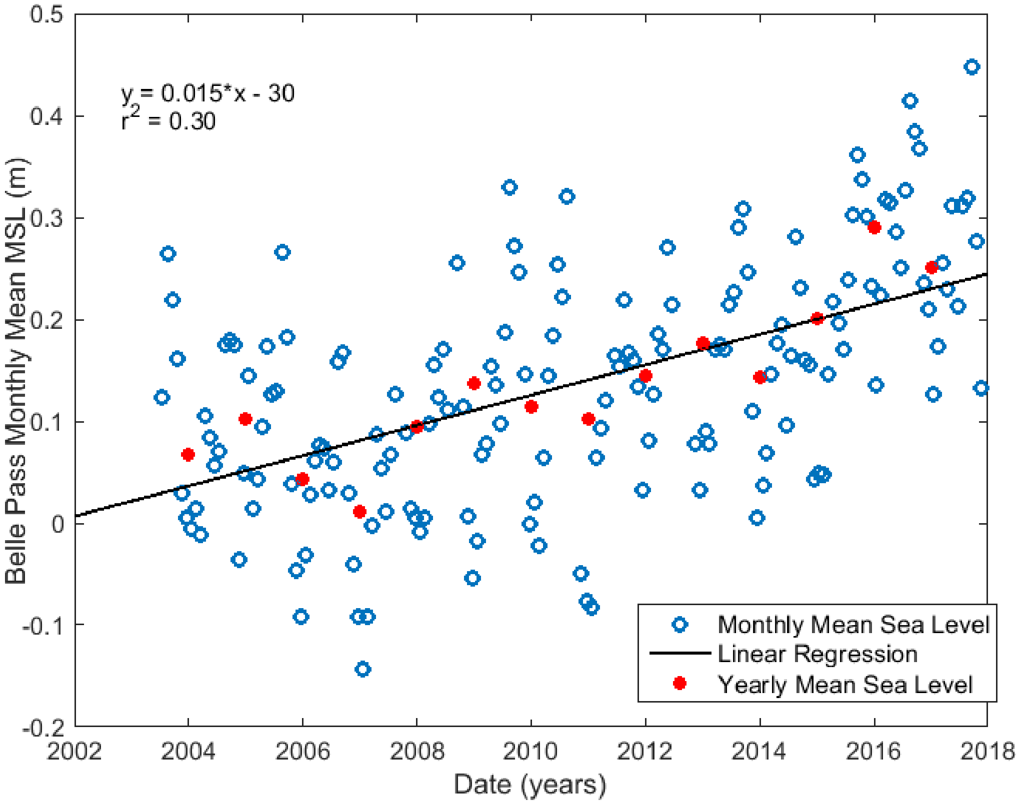


Figure 2. Monthly mean of mean sea level at Belle Pass from 2003 to 2017 used to derive subsidence rates from the GRIS CORS station at Grand Isle.

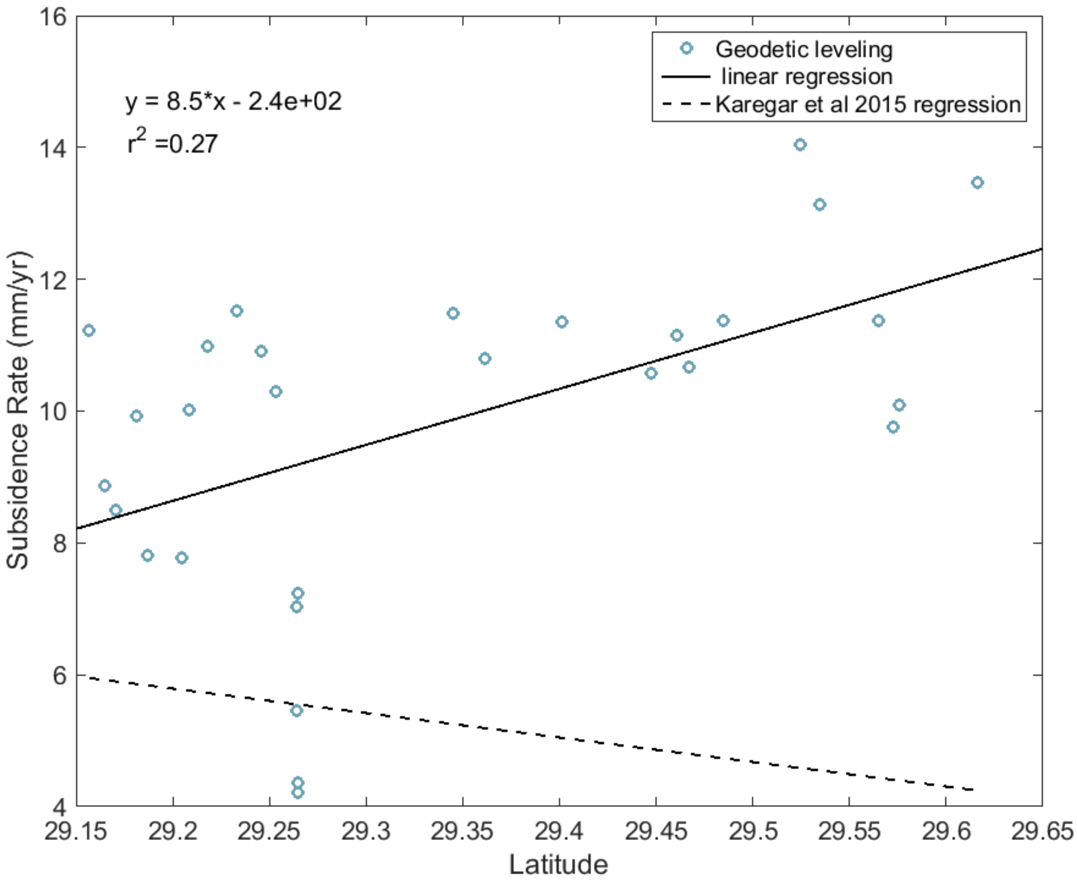


Figure 3. Deep subsidence relationship derived for the Port Fourchon area and applied to the present dataset with the Karegar et al. (2015) deep subsidence relationship (dotted line) for reference. Note that this is the primary reason that CRMS data points in the present study have rates higher than those calculated by Nienhuis et al. (2017).

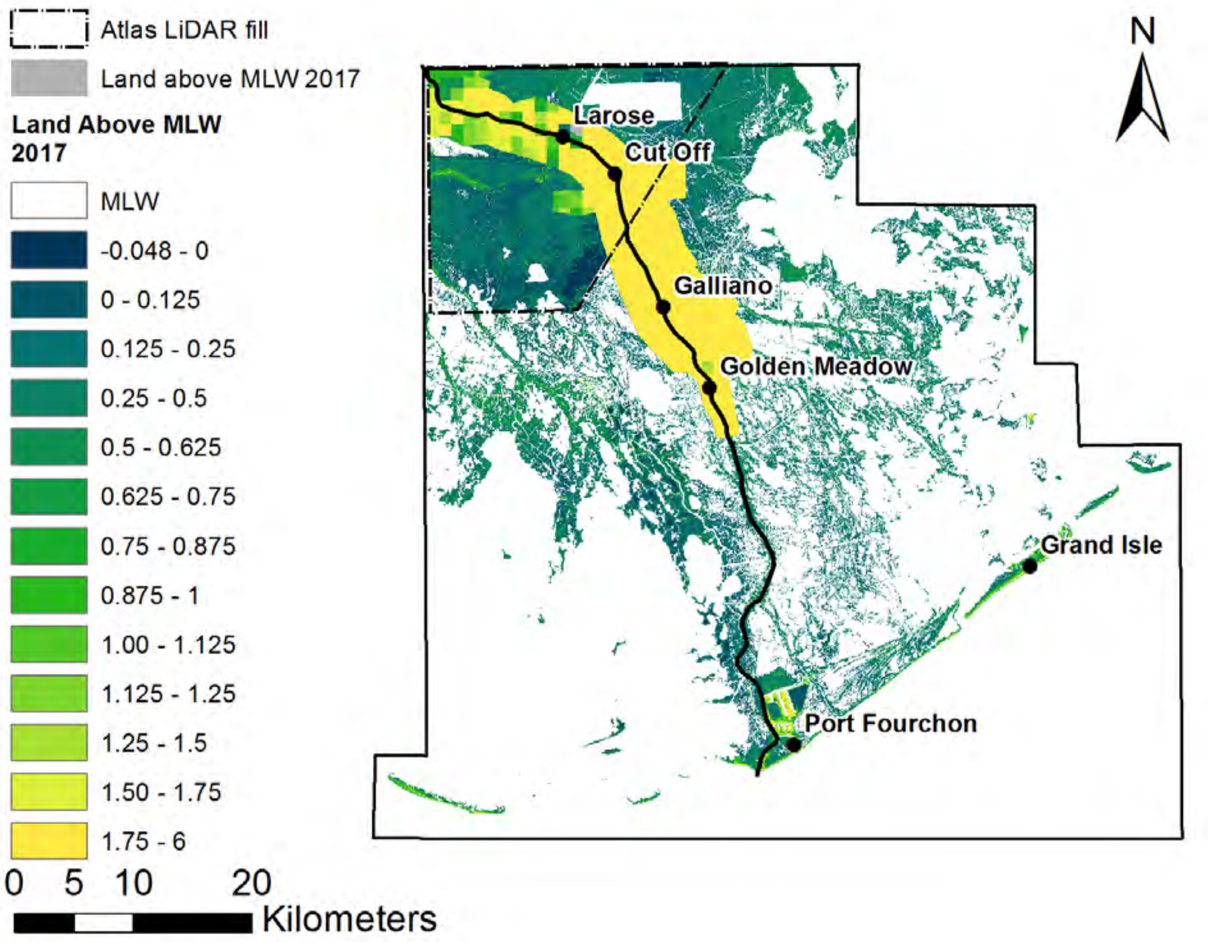


Figure 4. Hazard map showing present land elevation above MLW using 2017 water levels.

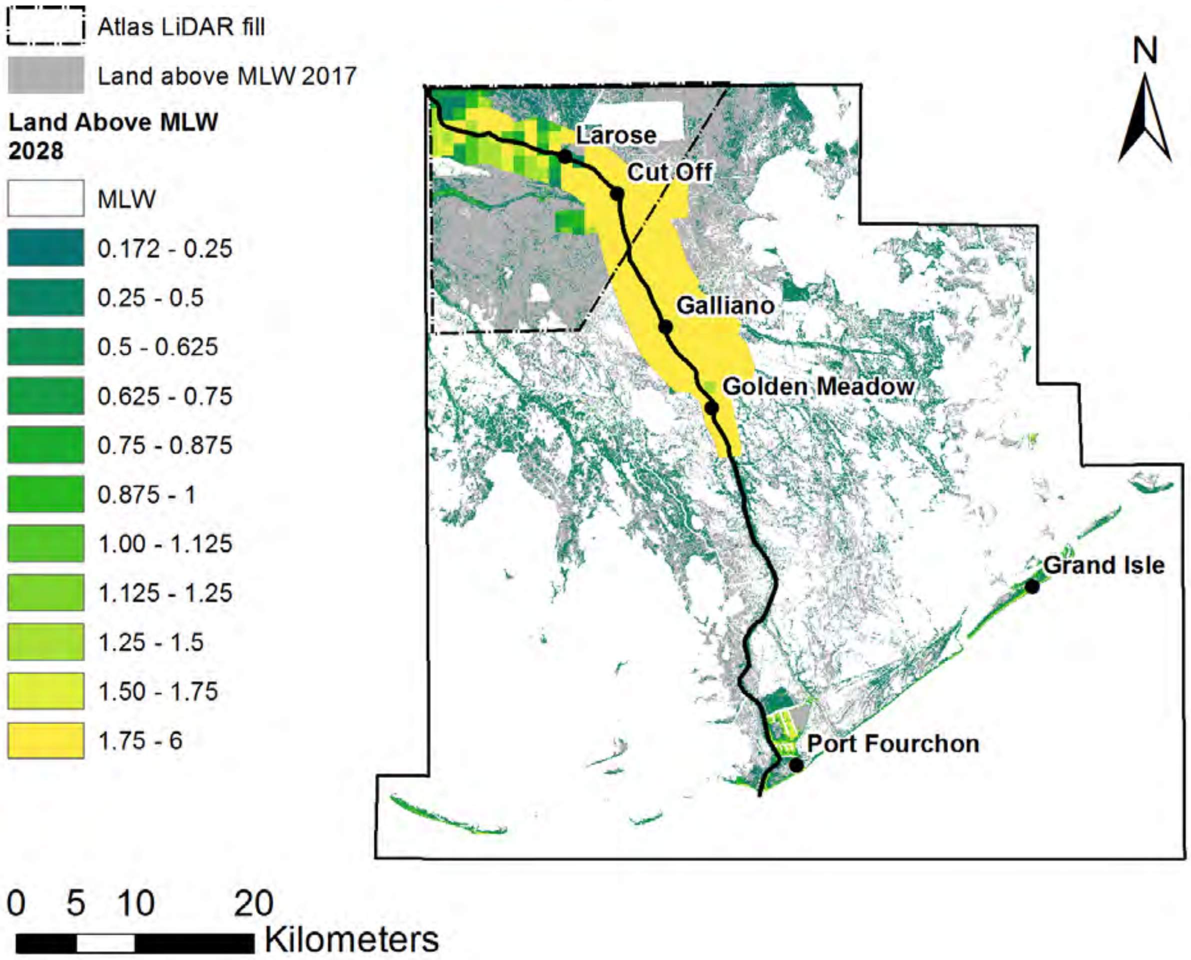


Figure 5. Hazard map showing predicted land elevation above MLW using 10 years of total subsidence rates and 2028 water levels, assuming a eustatic sea level rise rate of 2 mm/yr.

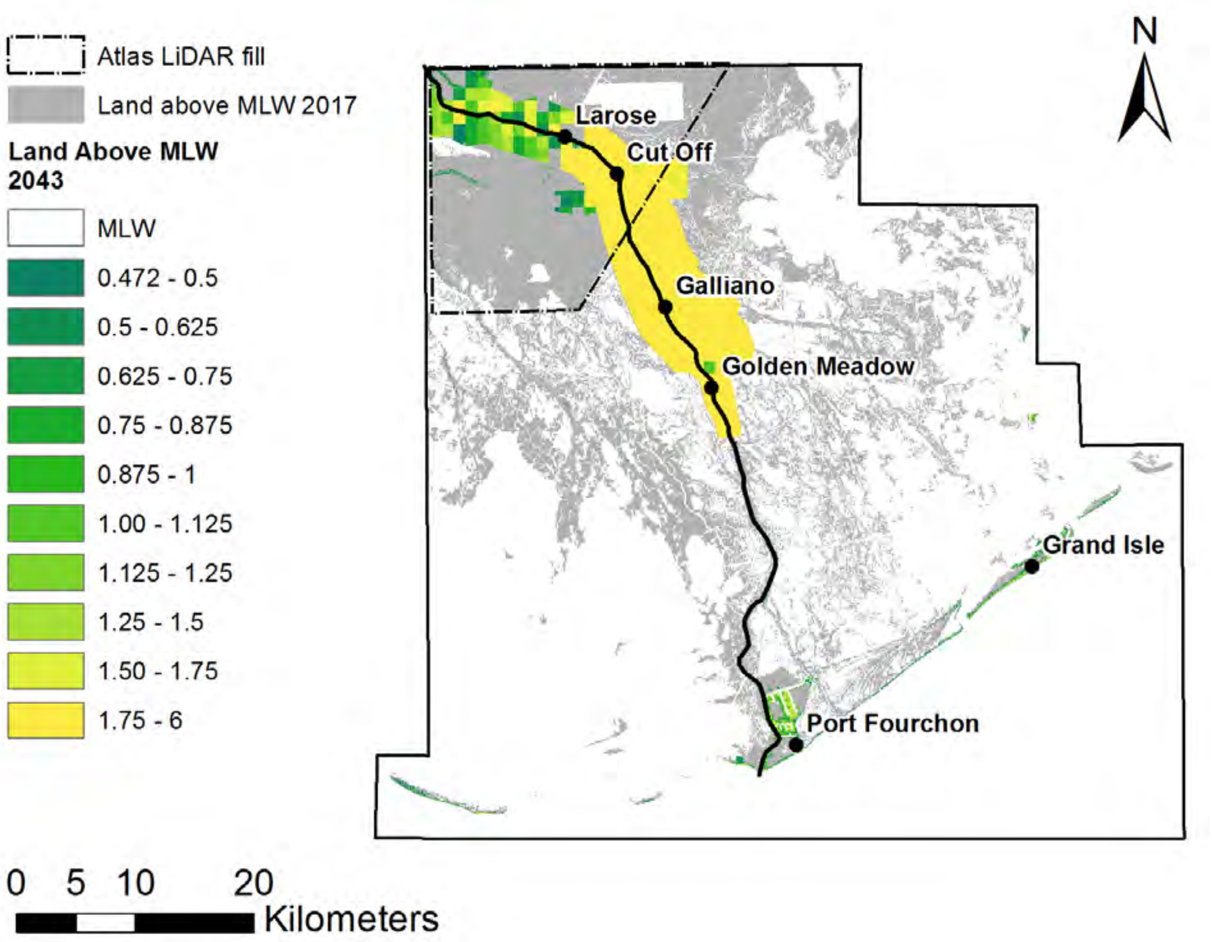


Figure 6. Hazard map showing predicted land elevation above MLW using 25 years of total subsidence rates and 2043 water levels, assuming a eustatic sea level rise rate of 2 mm/yr.

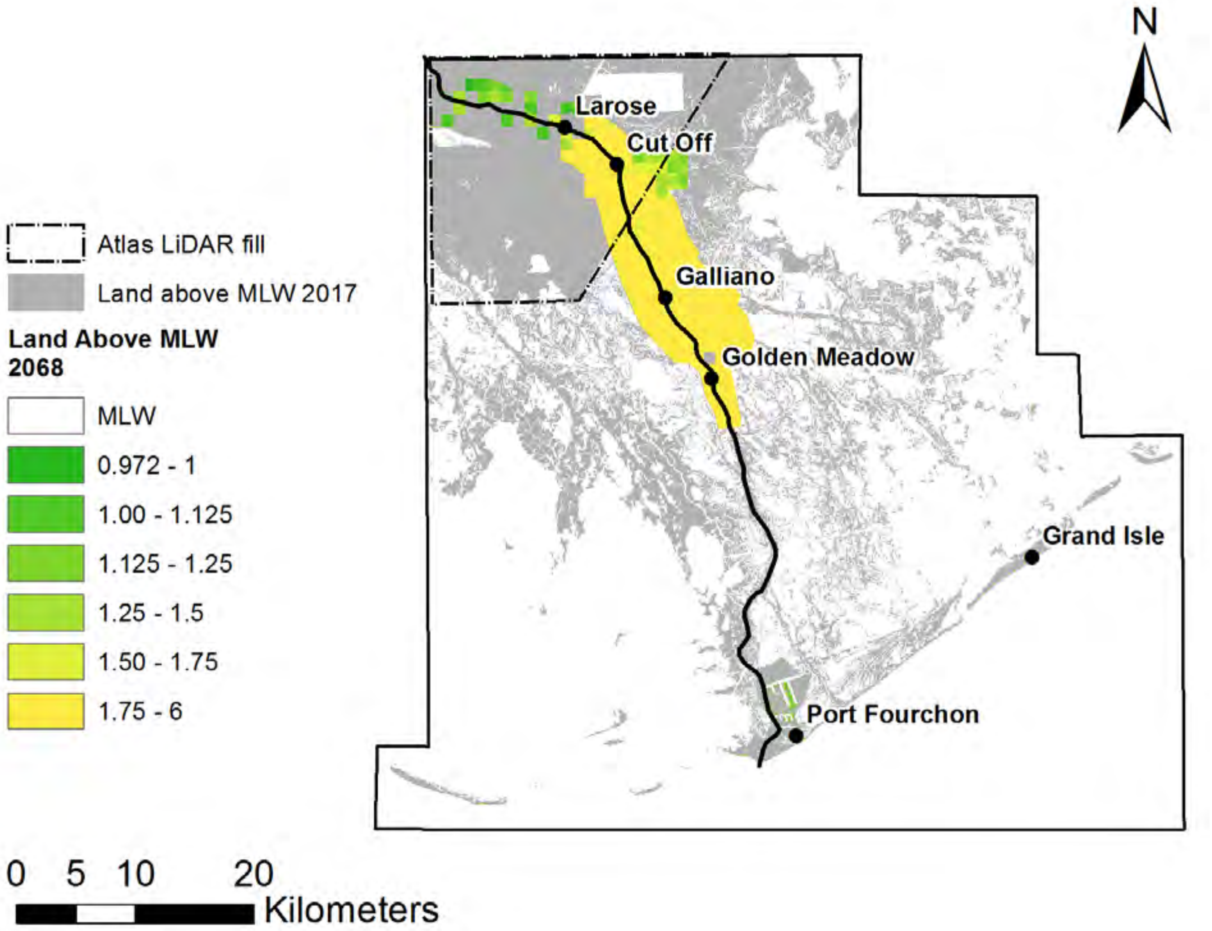


Figure 7. Hazard map showing predicted land elevation above MLW using 50 years of total subsidence rates and 2068 water levels, assuming a eustatic sea level rise rate of 2 mm/yr.

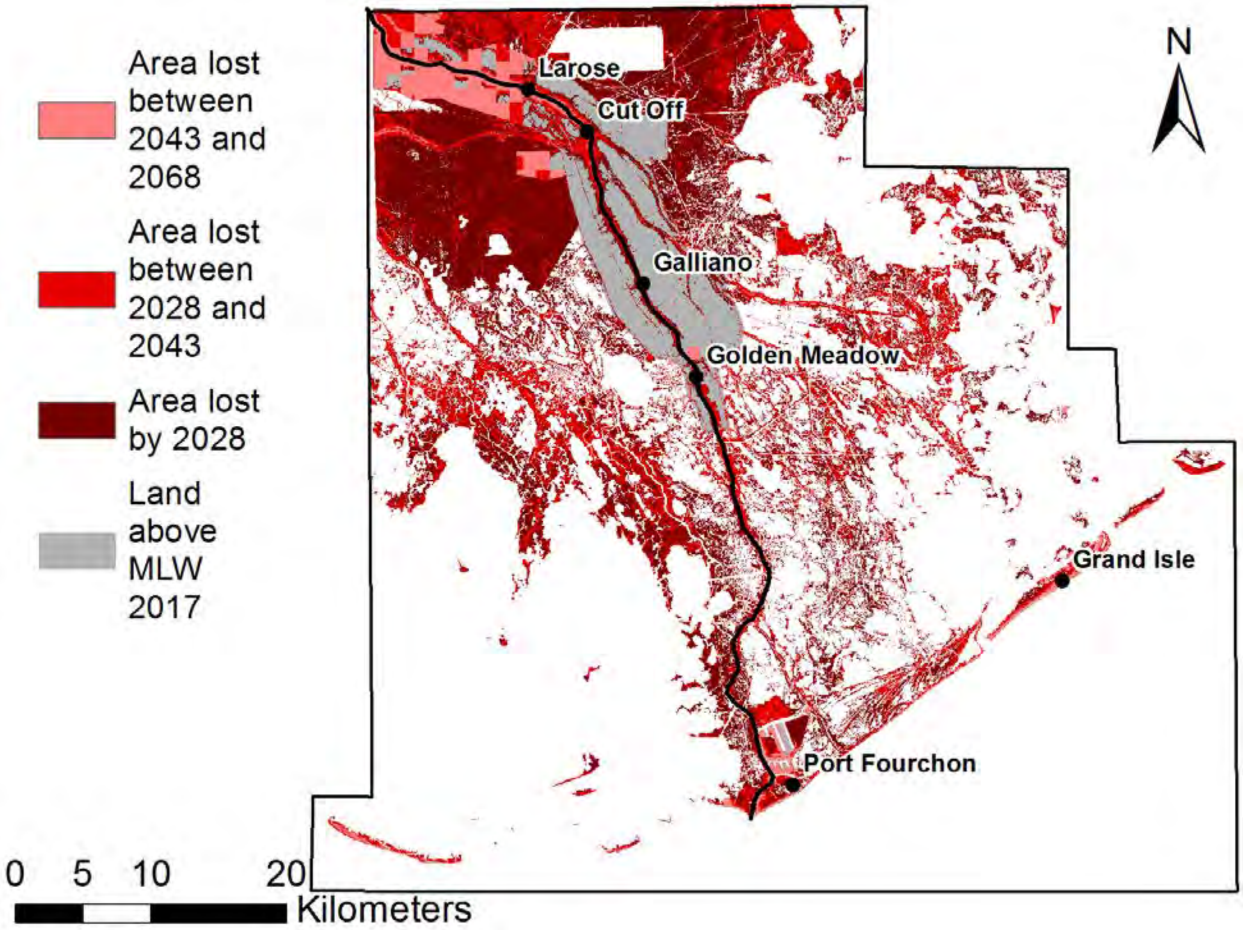


Figure 8. Predicted land loss (elevation below MLW) during each of the considered time periods.

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