Fowl River Marsh Spit Study

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Introduction. The Mobile Bay National Estuary Program's (MBNEP's) mission is to promote the wise stewardship of the quality and living resources of Alabama's estuarine waters. Alabama's estuaries are considered environmentally and economically important because of their exceptional biological diversity and productivity. These estuaries, where fresh water from rivers mixes with salt water of the Gulf of Mexico, support both freshwater and saltwater species; serve as nursery habitat for recreationally and commercially important fish and shellfish; and provide habitats essential to the annual cycles of many species of breeding, wintering, and migrating waterfowl, wading birds, shore birds, and songbirds.

The MBNEP's Comprehensive Conservation and Management Plan adopts a watershed approach to ensure that restoration efforts are based in science and fit into an overall management program. A watershed approach represents a shift in paradigm from traditional city planning, where geopolitical borders limit available actions and resources. It entails development of watershed management plans (WMPs) for areas at the U.S. Geological Survey's 12-digit-hydrologic-unit-code (HUC) scale that drain, independently of political boundaries, into common receiving waters like Fowl River. A WMP takes over a year to develop, requires intense community engagement, and focuses on informing communities about their watershed with data related to governance, demographics, socioeconomics, geography, geology, biology, ecology, hydrology, hydrography, and climate vulnerability. A WMP identifies the problems that threaten the quality and living resources of receiving waters and recommends prioritized solutions and potential funding sources to pay for them.

With funding from the National Fish and Wildlife Foundation (NFWF) Gulf Environmental Benefit Fund (GEBF), the MBNEP published the Fowl River Watershed Management Plan (WMP) in March 2016. The Fowl River Watershed (HUC 031602050206), with boundaries shown in Figure 1 below, drains an area of approximately 39,769 acres in southern Mobile County, AL. Its headwaters originate near Theodore, Alabama, and flow south and east to Bellingrath Gardens where it bifurcates into East Fowl River and West Fowl River. East Fowl River flows northeast directly into Mobile Bay, and West Fowl River flows south into Mississippi Sound. From its origin to its confluence with East Fowl River, Fowl River falls less than 150 feet. The majority of that relief occurs in the upper third of the watershed within the Southern Pine Hills physiographic district, where most of its tributaries originate. Tributary drainages are well-defined within the Southern Pine Hills district because of its greater topographic relief but become ill-defined with indeterminate channels as they cross the Coastal Lowlands district. Gentle topography and abundant rainfall create extensive floodplains and wetland areas along the tributaries and main stem of the River. The estuarine waters of Fowl River range from fresh in northern headwaters to brackish (salinities less than 20 parts per thousand [ppt]) near where East Fowl River flows into Mobile Bay.

Land use and land cover in the Fowl River Watershed are predominantly undeveloped, with 97.8% of the watershed encompassing its five greatest land uses: forests and other vegetative cover (37.1%), wetlands (29.6%), agriculture (17.4%), and urban (13.7%). The river and its tributaries comprise some of the most pristine waterways assessed by the Geological Survey of Alabama (GSA), due in large part to the extensive presence of wetlands that store and retain flood waters, filter pollutants, recycle nutrients, recharge groundwater, and enhance biodiversity. Relatively rural, this Watershed is dominated by forests and wetlands that limit erosion and the transport of sediment downstream towards Mobile Bay and Mississippi Sound.

In 2012 and prior to watershed planning, GSA mapped and classified types and lengths of shorelines and shoreline protection types along northern reaches of Fowl River (Jones and Tidwell, 2012). Organic shorelines are the dominate northern Fowl River shoreline type, comprising

121,700 feet (23 miles) or about 60.2 percent of the total mapped, with most classified as marsh, followed by swamp forest, and then open, vegetated fringe. Vegetated banks comprise 74,325 feet (14.1 miles) or about 36.7 percent of northern Fowl River shorelines, and sediment bank shorelines account for 2,811 feet, or about 1.3 percent

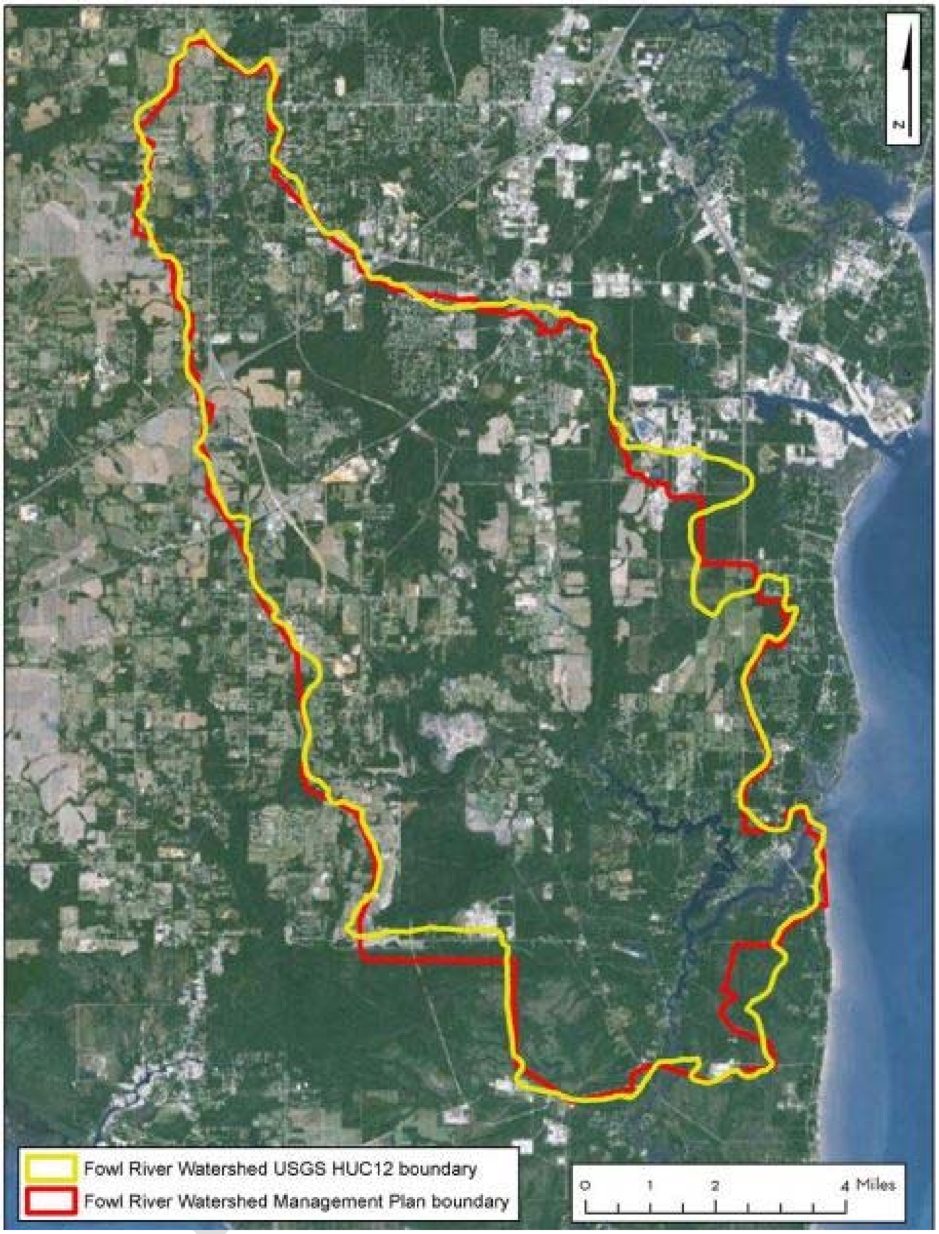

Figure 1 The Fowl River Watershed with USGS HUC 12 and WMP boundaries.

of total. The GSA also mapped northern Fowl River shore protection subtypes. Its shorelines are largely natural and unretained, accounting for 147,326 feet (27.9 miles) or about 72.9 percent of the total mapped. Among armored shorelines, bulkheads represent the second largest shore protection subtype, with 46,143 feet (8.7 miles) or about 22.7 percent of the total mapped. Three percent, or about 1,230 feet (1.2 miles) of the total shoreline is protected with rubble/riprap subtypes.

Fowl River carries the Alabama Department of Environmental Management's (ADEM's) water use classification of *Swimming and Other Whole Body Contact Water Sports* and *Fish and Wildlife* along its entire course, including both East Fowl River and West Fowl River. Although the WMP characterizes the overall health of the Watershed to be in good condition, several issues impacting ecosystem health require further monitoring and corrective actions, including mercury impairments, sediment (or a lack thereof), nutrient loading, stormwater runoff, invasive species, habitat loss, and land use change.

Of these issues, degraded marshes and spits in the transitional zone between fresh and brackish water were identified as a top priority by members of the Watershed Planning Team, the Fowl River WMP Steering Committee, and stakeholders who participated in the WMP-development process. The narrowing and breaching of habitat-rich, marsh-covered point bars (or spits), along with other river shoreline changes, are evident in imagery dating back to 1938, documented in Google Earth's timeline feature, and further supported by community input and recollections. Figure 2 shows annotated aerial imagery provided with interpretation by Fowl River resident Sam St. John (and confirmed by South Coast Engineers) of lost (yellow) or breaching (red) shorelines, spits, and islands along the River.

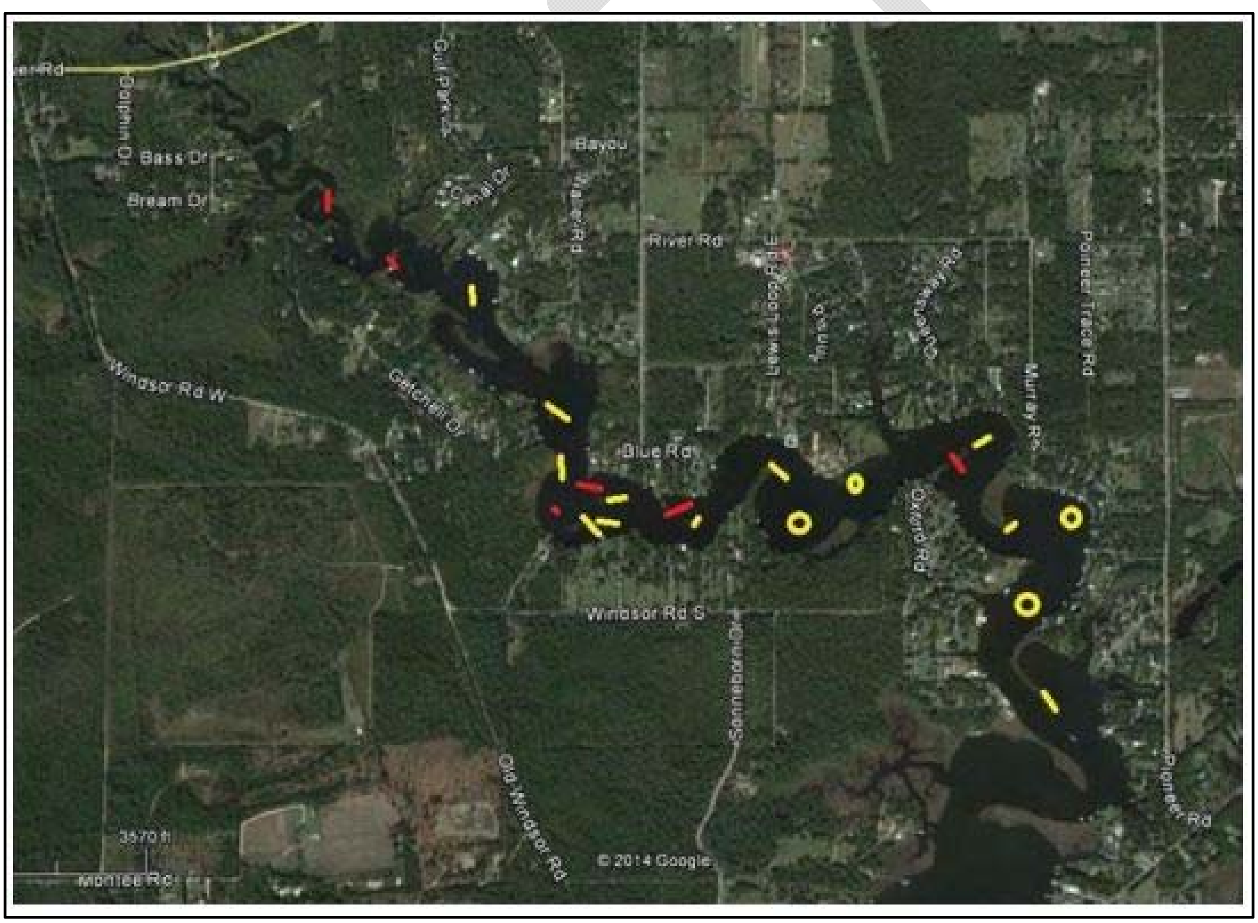

Figure 2. Annotated aerial imagery of lost (yellow) or breaching (red) shorelines, spits and islands along Fowl River. (Aerial imagery and initial interpretation by Sam St. John, confirmed by South Coast Engineers through comparison of historical and current photographs.

In 2016, the MBNEP applied for and secured a $1,127,000 award from the NFWF GEBF for the Fowl River Watershed Restoration: Coastal Spits and Wetland project for engineering and design studies to develop a solution to stabilize and protect four priority, in-river, wetland spits and restore marshland throughout intertidal portions of Fowl River. Additionally, this grant funded hydrologic modeling and a marsh health and recovery study to guide engineering and design efforts and prioritize future Fowl River Watershed restoration projects. Hydro-Engineering Solutions was contracted to undertake the hydrologic modeling effort.

The MBNEP's Science Advisory Committee (SAC), comprising scientists and government agency experts interested in developing mechanisms for measuring ecosystem health, is charged with oversight of trends and stressor assessments, monitoring frameworks and protocols, scientific review, and project planning and implementation. At the quarterly meeting of the SAC in January 2017, discussions were initiated about the marsh health study, considered necessary to determine the causes of marsh degradation on the spits, and experiments that might provide solutions. With improved understanding, a Fowl River Marsh Health and Recovery Study (Marsh Study) would inform how to best effect marsh health, guiding future restoration activities in the Fowl River Watershed and in similar riverine systems. Additionally, the study and ensuing restoration efforts will benefit two priority natural resources in coastal Alabama: water and fish. Improving water quality and maintaining healthy populations of fish and shellfish are among values identified in the MBNEP's Comprehensive Conservation and Management Plan as most important to people living along the Gulf coast: access to waters; beaches and shorelines; abundant fish and wildlife; protection of heritage and culture; environmental health and resilience; and fishable, swimmable, and drinkable waters. The spirited conversation stimulated subsequent meetings to thoroughly discuss and plan the project, and individual SAC members were invited to submit proposals for different aspects of the study related to vegetation, sediments, and hydrology.

Research Questions: Two research questions were generated to guide the Study: 1.) What is the general marsh health status in the project areas, and 2.) What are the factors that influence the health of marshes in the transition zone where fresh and brackish waters mix in Fowl River?

Problem Statement: A case for the environmental and economic importance of these estuarine habitat features, as well as stakeholder priority, was expressed in the introduction. To improve understanding of marsh health in Fowl River and inform future management decisions and restoration activities, thorough characterizations of elevation, sediment, vegetation, salinity, and hydrology are needed to address the following questions: What is the marsh health status, and how does it vary along the salinity gradient studied? Is the diversity, distribution, and density of plant species changing? Is the elevation of the marshes stable or shifting, and what impacts can be expected from future sea level rise (SLR)? Are the marshes accreting, stable, or eroding? Is the sedimentation pattern and/or composition changing? Is the salinity regime shifting? How is the natural hydrology being affected by SLR, boat wakes, and/or storm surge? A summation of the comprehensive marsh characterizations above will be used to identify potential anthropogenic stressors to marsh health.

Purpose, Goals, and Objectives: The **purpose** of the Marsh Study is to preserve an important component of what people value most about living on the Alabama coast. The **goal** of this project is to understand and improve the health and ecosystem function of intertidal marshes and flats in the transitional zone of Fowl River. To achieve this goal, the following **objective** has been developed: Prepare a comprehensive characterization of health of emergent marshes in the transitional zone of Fowl River, including an examination of factors influencing marsh health and underlying its degradation.

Scope of Work

This study will focus on fringing marshes (i.e. plant communities at the interface between the land and river and influenced by tidal forces and river flooding) throughout the brackish transitional zone (Region 2 of Figure 3) between the saltier and the fresher portions of Fowl River. A series of metrics indicative of marsh health will be monitored along the course of Fowl River. The stations will be distributed from the mouth of Fowl River (Region 3) to the extent of its tidal influence at the bridge on Fowl River Road (Region 1) to include the range of salinities affecting Fowl River marshes. These metrics will include:

- Plant distribution, diversity, and density;
- Above and below-ground plant biomass;
- Plant growth rates;
- Sediment grain size;
- Sediment accrual and erosion rates;
- Sediment composition;
- Salinity dynamics;
- Water quality;
- Hydrologic variables;
- Wave/boat wakes energy
- Marsh elevation profiles, and
- Sediment core isotope analysis.

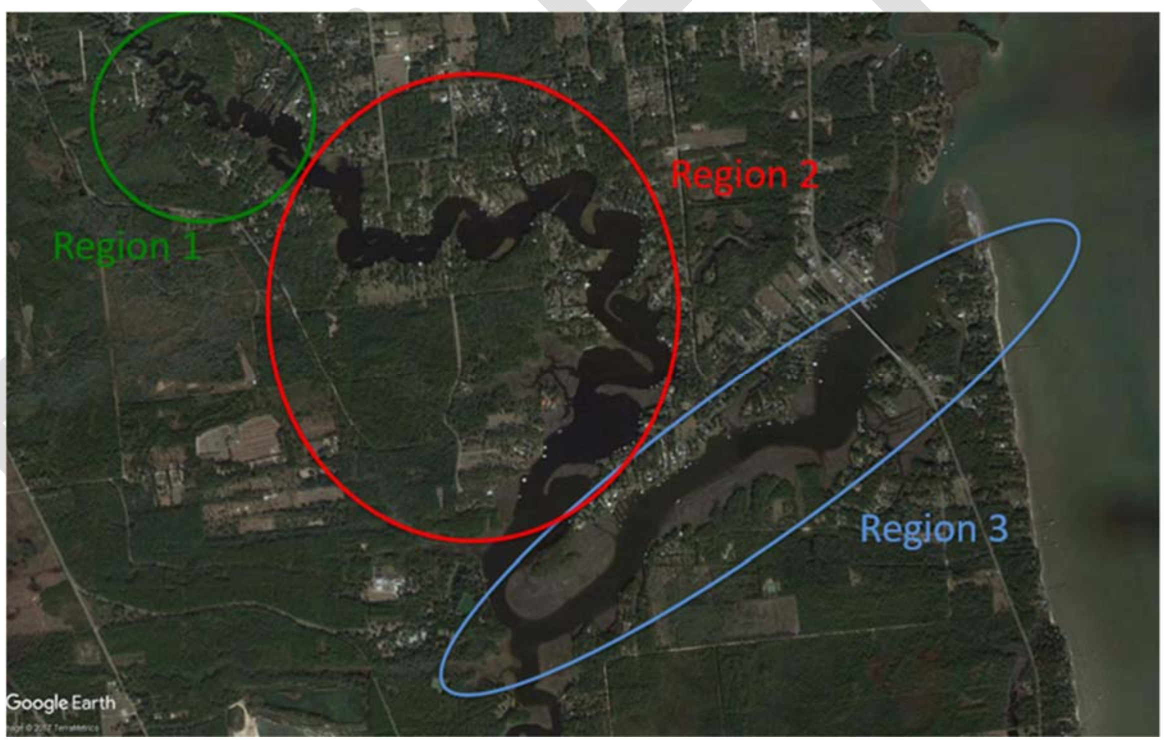

Figure 3 Fowl River Marsh Study Regions

Methodology.
At the beginning of the project, SAC members identified three potential factors likely contributing to the degradation of the marsh spits: changing vegetation patterns, changing sedimentation patterns, and changing hydrologic patterns. Intensive examinations of Fowl River vegetation, sediment, and hydrology components by three subgroups will include a coordinated comprehensive characterization of salt marshes in Region 3, the transitional zone of Fowl River. Specific methodologies and associated linkages for each subgroup are provided in their respective sections

below. The work of each subgroup will be coordinated with other subgroups and participating investigators.

Vegetation Component. A vegetation study was undertaken to quantify marsh spit plant species diversity and abundance, indices of wetland community health, and associations between marsh elevation, porewater salinity, and wetland characteristics. The Vegetation Subgroup includes Tim Thibaut, Senior Program Manager and National Environmental Policy Act Specialist at Barry A. Vittor and Associates; Just Cebrian, Ph.D., Research Professor and Associate Director, Northern Gulf Institute, Mississippi State University; and Jared Goff, Laboratory Manager, Dauphin Island Seas Lab.

Sediment Component. A sedimentation study was performed to assess sources and sinks of sediment material in the spits and surrounding estuary. The Sediment Subgroup includes Marlon Cook, Cook Hydrogeology; Dr. Alex Beebe, Ph.D., Assistant Professor of Geology, University of South Alabama; and Ruth Carmichael, Ph.D., Professor, Department of Marine Sciences, University of South Alabama, and Senior Marine Scientist III, Dauphin Island Sea Lab.

Hydrologic and Hydrographic Component. A hydrologic and hydrographic study examined the processes controlling water surface elevation, salinity, and nutrients in the estuary and how these processes are related to marsh spits. The Hydrology and Hydrography Subgroup includes Dr. Bret Webb, PhD., PE, Professor of Civil and Coastal Engineering, University of South Alabama, Dr. Stephanie Smallegan, PhD., PE, Assistant Professor of Civil and Coastal Engineering, University of South Alabama; Dr. John Lehrter, PhD., Associate Professor, Department of Marine Sciences, University of South Alabama, and Senior Marine Scientist I, Dauphin Island Sea Lab; Alexis Hagemeyer, Central Methodist University; Dr. Brian Dzwonkowski, PhD., Assistant Professor, Department of Marine Sciences, University of South Alabama, and Senior Marine Scientist I, Dauphin Island Sea Lab, and Jeff Coogan, Dauphin Island Sea Lab.

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Vegetation Component

The vegetation study quantified marsh spit plant species diversity and abundance, indices of wetland community health, and associations between marsh elevation, porewater salinity, and wetland characteristics. Work performed by Tim Thibaut, Dr. Just Cebrian, and Jared Goff were synthesized into a single report, Final Vegetation Report Fowl River Marsh Study, by Tim Thibaut. The report contains appendices, which include maps of study sites and transcript locations, a species list and data summaries, and Hydrogeomorphic Model Assessment Methods and Worksheets

FINAL VEGETATION REPORT FOWL RIVER MARSH HEALTH STUDY

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1.0 Introduction

This report presents the results and conclusions of the vegetation component of the Fowl River Marsh Health Study, funded by the Mobile Bay National Estuary Program (MBNEP) through an award by the National Fish and Wildlife Foundation's Gulf Environmental Benefit Fund. A top priority identified by members of the Fowl River Watershed Planning Team, Fowl River WMP Steering Committee, and stakeholders who participated in the WMP development process is the potential restoration and preservation of degraded marshes and spits in the transition zone of East Fowl River.

The goal of this project is to understand the habitat quality and level of ecosystem function of these tidal wetlands. To achieve this goal, objectives were developed as follows:

(1) What is the general marsh health status, and
(2) What are the factors that influence the health of marsh in the brackish transitional zone where fresh and salt waters mix in Fowl River?

This assessment was performed to provide a thorough characterization of plant community composition and condition along land margins of the Fowl River study area. The results will help inform how to maintain marsh health and function though potential future restoration activities.

2.0 Methodology

Field sampling was performed at ten study sites across three regions, encompassing the priority spits and marshes upstream and downstream (Figure 1). Region 1 is the farthest upstream of three regions, represented by a single study site (R1S1). Region 2 has seven target landforms in the middle portions of the study area (R2S1 through R2S7), including the priority spits. Region 3 includes two sites in the farthest downstream region near the confluence of the East Fowl River and West Fowl River (R3S1 and R3S2). Appendix A contains maps presenting vegetation transect locations at each study site.

Station locations were determined *a priori* using ArcGIS. Using these locations, transects were placed at 25-m intervals perpendicular to the shoreline across each study site. Dauphin Island Sea Lab personnel measured horizontal position and elevation (NAVD88) at 3-m intervals along each transect using a real-time Kinematic GPS (RTK GPS) unit.

Vegetation sampling was performed within m^2 quadrats placed every 3 m along transects. In all, 895 quadrats were sampled across 74 transects during August and September 2018. Measurements included plant height (cm), species-specific cover of native emergent wetland plant species, nativity status (exotic vs. native; Keener et al. 2018, Kartesz 2015), percent cover of woody plant species (Godfrey 1988), and wetland indicator status (Lichver 2016). Unknown plants were collected for identification in the lab. Plant taxonomy follows primarily Weakley (2015), Flora of North America series (FNA; 1993 onward), Wunderlin and Hansen (2011), and Godfrey and Wooten (1979, 1981).

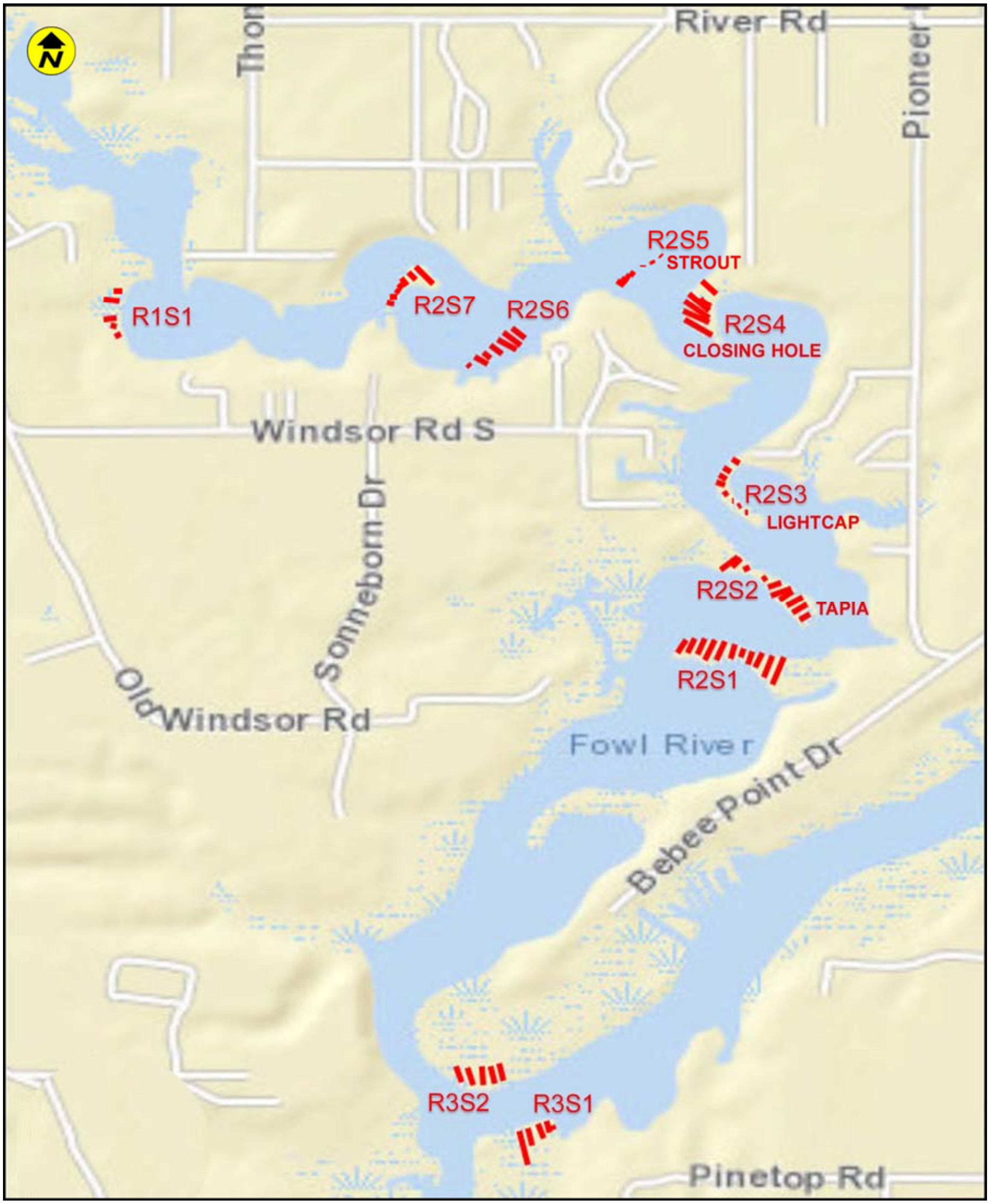

Figure 1. Fowl River sampling sites.

Wetland ecosystem function was evaluated using a hydrogeomorphic (HGM) assessment protocol developed for tidal fringe wetlands occurring along the Alabama and Mississippi Gulf coast (Shafer et al. 2007). Field data were combined with landscape variables (e.g., wetland patch size) in HGM mathematical expressions to estimate levels of five major ecosystem functions attributed to tidal wetlands in the AL/MS Gulf coast reference domain: **1)** wave attenuation; **2)** biogeochemical cycling; **3)** nekton utilization; **4)** provide habitat for tidal marsh dependent wildlife; and **5)** maintain characteristic plant community structure. As wetland condition deviates from that observed in reference wetlands, a variable subindex is assigned based on the observed relationship between model variable condition and functional capacity (on a scale of 0.0 to 1.0). A Microsoft Excel file provided by the USACE-Engineer Research and Development Center facilitated data entry and calculation of Functional Capacity Indices (FCI) for the five ecosystem functions. A description of the HGM method is contained in Appendix C, along with the HGM worksheets. Each study site was evaluated as a separate assessment area.

A Floristic Quality Index (FQI) was also used to measure the vegetative quality of the study sites. FQI employs a measure of conservatism (Coefficient of Conservatism) along with richness of a plant community to derive an estimate of habitat quality (Wilhelm & Ladd 1988, Lopez & Fennessy 2002). Coefficients of Conservatism (C values) for each plant species follow the wetland FQI for the Southeastern U.S. developed by the Southeast Wetlands Workgroup (Gianopulos 2014). A C value ranging from 0 to 10 is assigned *a priori* to individual wetland plant species by the Southeast Wetlands Workgroup to reflect tolerance to disturbance and fidelity to a particular habitat type or range of conditions. Native obligate wetland species are generally assigned higher C values, whereas plants with broad tolerances have lower values. Invasive species are assigned a C value of 0. Appendix B includes C values for plant species identified during field surveys. FQI scores were weighted according to percent cover of the individual species.

3.0 Results

Seventy-three plant species were recorded in the sampling quadrats. An additional 41 species were identified in supplemental floristic inventory surveys and incidental observations made during field sampling, for an overall total of 114 species documented in the study area. Appendix B has a complete list of vascular plants recorded during the survey.

Rare species documented in the study area include bright green spikerush (*Eleocharis olivacea*), classified as critically imperiled by the Alabama Natural Heritage Program due to its rarity and low number of known occurrences. The species was found to be widespread across the study area, including at the Closing Hole, Lightcap, and Tapia sites.

A small population of climbing fetterbush (*Pieris phillyreifolia*) was found along the east shoreline of Fowl River near R2S6 and R2S7. The occurrence of climbing fetterbush represents the first documented specimen of the species from Mobile County since the late 1800s. In addition, a single individual of climbing aster (*Ampelaster carolinianus*) was found along the shoreline margin of R2S6, and its occurrence represents the first record of the species in Alabama.

Laurel wilt is a vascular disease responsible for high mortality of American tree species in the family Lauraceae, particularly redbay (*Persea borbonia*) and swampbay (*P. palustris*).
In recent years the disease has been spreading throughout the Southeastern U.S. (Kendra et al. 2013). Nearly all of the swampbay in the study area were observed to be dead or dying from laurel wilt disease.

The three most frequently recorded species were bulltongue arrowhead (*Sagittaria lancifolia*) (70% of sampled quadrats), black needlerush (*Juncus roemerianus*) (61%), and sawgrass (*Cladium jamaicense*) (50%). Bulltongue arrowhead was present at all sites, primarily along low elevation margins of emergent vegetation. Sawgrass was the most common species in the uppermost portion of the study area, whereas black needlerush dominates the southernmost marshes, reflecting a gradient from freshwater conditions upstream and increasing salinity through the transition zone and into Region 3. Both species were common in the transition area of Region 2 (Table 1).

Table 1. Percent cover of sawgrass and black needlerush by study site.

Site	Sawgrass	Black needlerush
R1S1	47.7	0.0
R2S7	9.3	0.0
R2S6	2.8	0.0
R2S5 (Strout)	7.6	0.9
R2S4 (Closing Hole)	28.9	5.1
R2S3 (Lightcap)	15.6	19.3
R2S2 (Tapia)	18.8	13.9
R2S1	0.8	34.3
R3S2	0.0	23.9
R3S1	2.1	38.8

Table 2 presents plant community statistics. Sites in Regions 1 and 2 generally had greater species diversity than Region 3 sites. Among the target spits, the Closing Hole (R2S1), Tapia (R2S2), and Lightcap (R2S3) sites had mean cover of 52.2%, 52.0%, and 51.5%, respectively, while the Strout site (R2S5) had 38.0%. Average plant cover across all study sites was 53.8%.

Table 2. Plant community statistics.

Site	Total No. Spp.	Mean No. Spp./quadrat	Mean % Cover
R1S1	29	2.6	59.7
R2S7	32	5.5	44.2
R2S6	35	7.5	55.8
R2S5 (Strout)	29	5.3	38.0
R2S4 (Closing Hole)	41	6.3	52.2
R2S3 (Lightcap)	30	5.0	51.5
R2S2 (Tapia)	38	5.0	52.0
R2S1	21	3.9	43.8
R3S2	9	2.3	30.6
R3S1	13	2.2	44.0

Table 3 presents the scores for the HGM assessment. HGM scores representing an average of the five FCI values range from 0.83 at R2S6 to 0.42 at the Strout site (R2S5). The Strout feature is largely wooded with small patches of tidal marsh vegetation along its margins, accounting for the low quality score. HGM scores mostly deviate from reference conditions due to moderate densities of herbaceous plant cover.

Table 3. HGM and FQI scores.

Site	HGM Mean FCI	FQI
R1S1	0.76	6.8
R2S7	0.58	5.3
R2S6	0.83	5.2
R2S5 (Strout)	0.42	4.7
R2S4 (Closing Hole)	0.73	6.4
R2S3 (Lightcap)	0.68	6.8
R2S2 (Tapia)	0.71	6.5
R2S1	0.67	7.3
R3S2	0.60	7.3
R3S1	0.68	7.7

FQI scores range from 7.7 at R3S1 to 4.7 at the Strout site (R2S5). The low score at Strout is due to more generalist woody plants and invasive species, primarily torpedo grass (*Panicum repens*). The Closing Hole (FQI=6.4), Lightcap (6.8), and Tapia (6.5) scores are in line with C values for the most common transition zone species, primarily sawgrass (C value= 7), black needlerush (8), and bulltongue arrowhead (4). Site R2S1 and the two Region 3 sites have the highest FQI scores in the study area, due to their nearly monotypic stands of black needlerush.

A summary of the RTK elevation data is presented in Table 4. Maximum transect elevations range from 0.65 m at Closing Hole (R2S4) to 0.20 m at R3S1. At the target spits, highest elevations mostly align with berms on the upstream sides that support woody plants such as wax myrtle (*Morella cerifera*) and eastern baccharis (*Baccharis halimifolia*). Herbaceous marsh vegetation dominates lower elevations across the relatively broad and flat spit surfaces. A representative marsh profile is presented in Figure 2. Mean elevation on the target spits ranges from 0.20 to 0.29 m.

Table 4. Transect elevations (m, NAVD88).

Site	Min.	Max.	Mean (±SD)
R1S1	-0.08	0.50	0.21 (0.10)
R2S7	-0.23	0.38	0.13 (0.14)
R2S6	-0.16	0.34	0.19 (0.09)
R2S5 (Strout)	-0.20	0.56	0.20 (0.20)
R2S4 (Closing Hole)	-0.01	0.65	0.29 (0.08)
R2S3 (Lightcap)	-0.13	0.48	0.20 (0.14)
R2S2 (Tapia)	-0.23	0.56	0.24 (0.16)
R2S1	-0.31	0.32	0.12 (0.11)
R3S2	-0.19	0.26	0.15 (0.10)
R3S1	-0.36	0.20	0.10 (0.08)

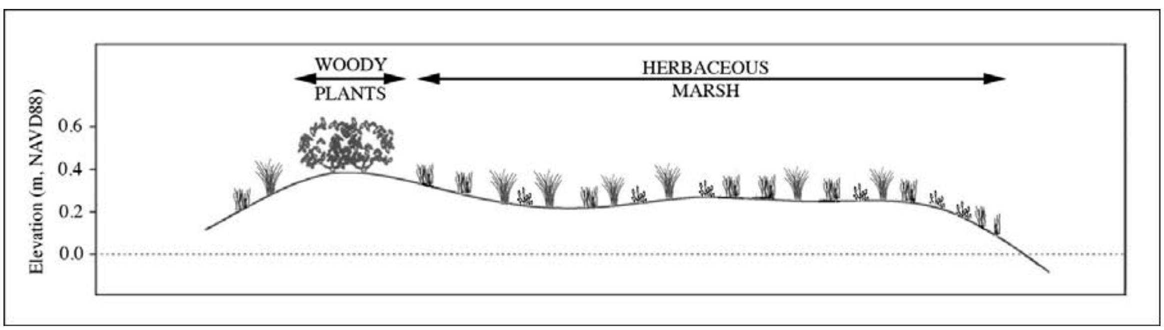

Figure 2. Representative marsh profile at the Lightcap (R2S3) target spit.

Submerged aquatic vegetation (SAV) was mapped on the periphery of the four target spits (Figure 3). Potential restoration actions that could be taken to protect/maintain the existing marshes (for example, elevating the marsh surface through thin layer sediment nourishment, or installing wave attenuation structures to prevent or minimize shoreline erosion due to boat wakes), will be required to avoid direct and indirect impacts to SAV resources.

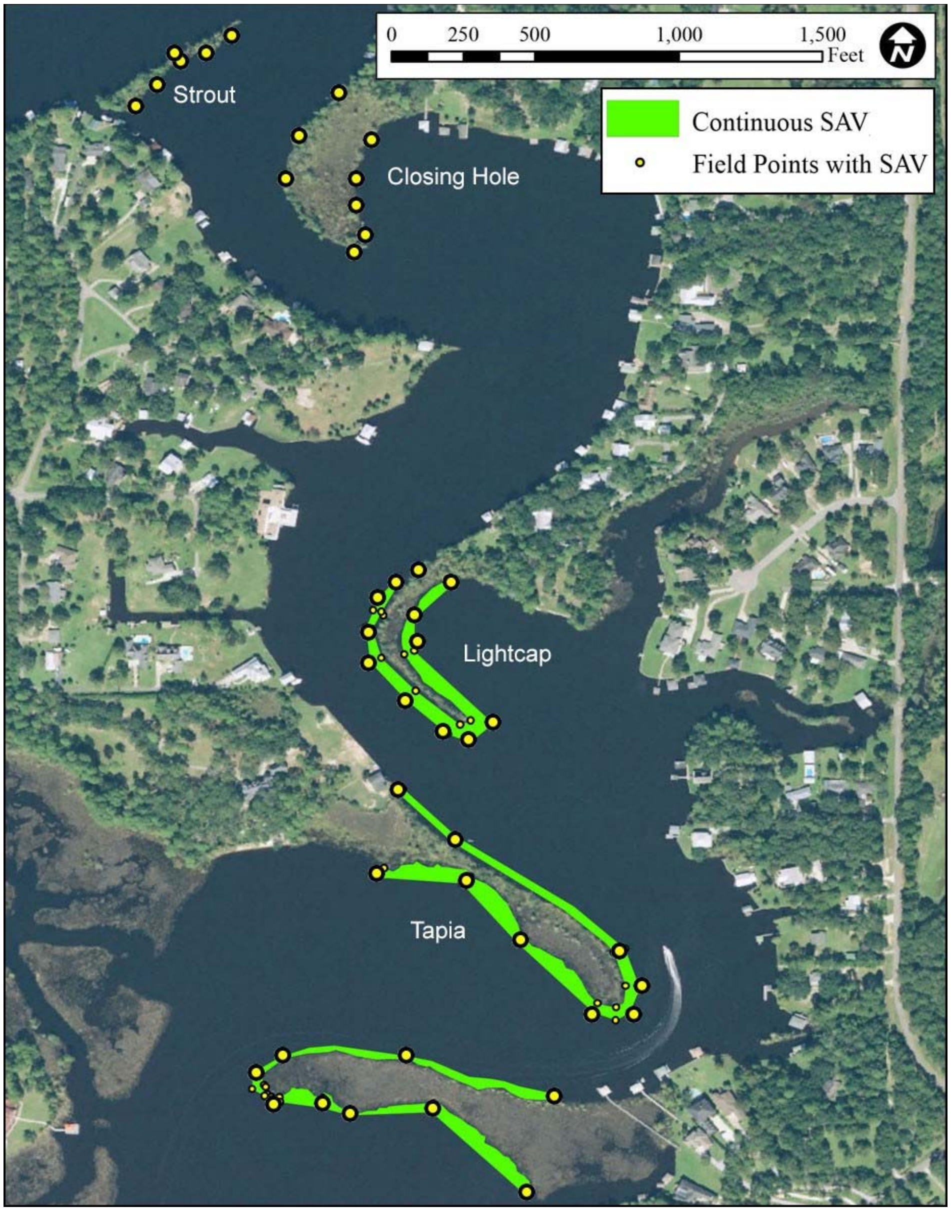

Figure 3. Submerged aquatic vegetation in the Fowl River transition zone.

4.0 Conclusions

Marsh quality is similar throughout the study area. HGM scores are within a range expected for natural marshes along the Alabama coast, though percent cover is generally lower than measured at high quality marshes in the HGM reference domain. The sites with cover dominated by sawgrass and black needlerush have the highest FQI scores.

Based on 1979 aerial imagery and field surveys, Stout and Lelong (1981) mapped the four target spits as Tupelo-Cypress Swamp. In recent decades these sites have, in whole or in part, transitioned from forested wetlands to herbaceous marsh. The spits have also lost a substantial amount of area. Changes in community composition and wetland area have coincided with recent sea level rise, and potentially increased salinity intrusion. Comparison of shoreline positions in 1940, 2002, and 2018 aerial imagery shows a progression in areal loss of wetland across all three regions of Fowl River.

The Fowl River spits are likely to continue to change in plant community composition and diminish in size due to a combination of sea level rise, subsidence, and a lack of sediment deposition. Mean elevations on the target spits are low, ranging from 0.20 to 0.29 m (8 to 12 in.). NOAA-published datums for the tide at Fowl River Bridge include mean high water at 0.23 m (9 in.) NAVD88. Much of the marsh surface at the Fowl River sites is regularly flooded, and these wetlands are highly vulnerable to further increases in sea level and tidal inundation.

With increases in relative water level, emergent marsh is likely to migrate to the higher elevation berms, and landward where adequate space allows. In much of the Fowl River transition zone, existing shoreline armor could act as a barrier to inland migration of tidal wetlands.

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Appendix A – Maps of the Study Sites and Transect Locations

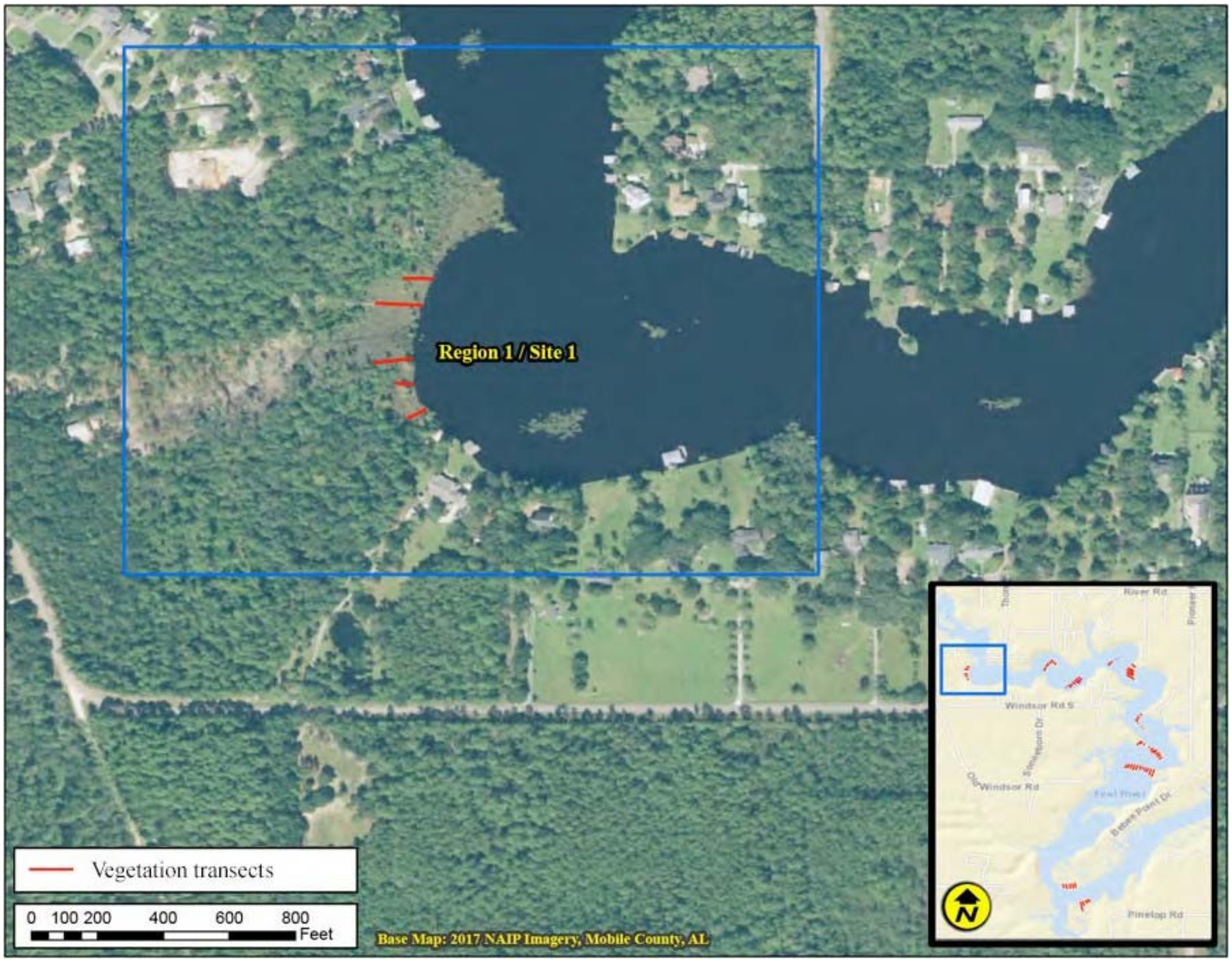

Figure A-1. Vegetation transects at Region 1 Site 1, August 2018.

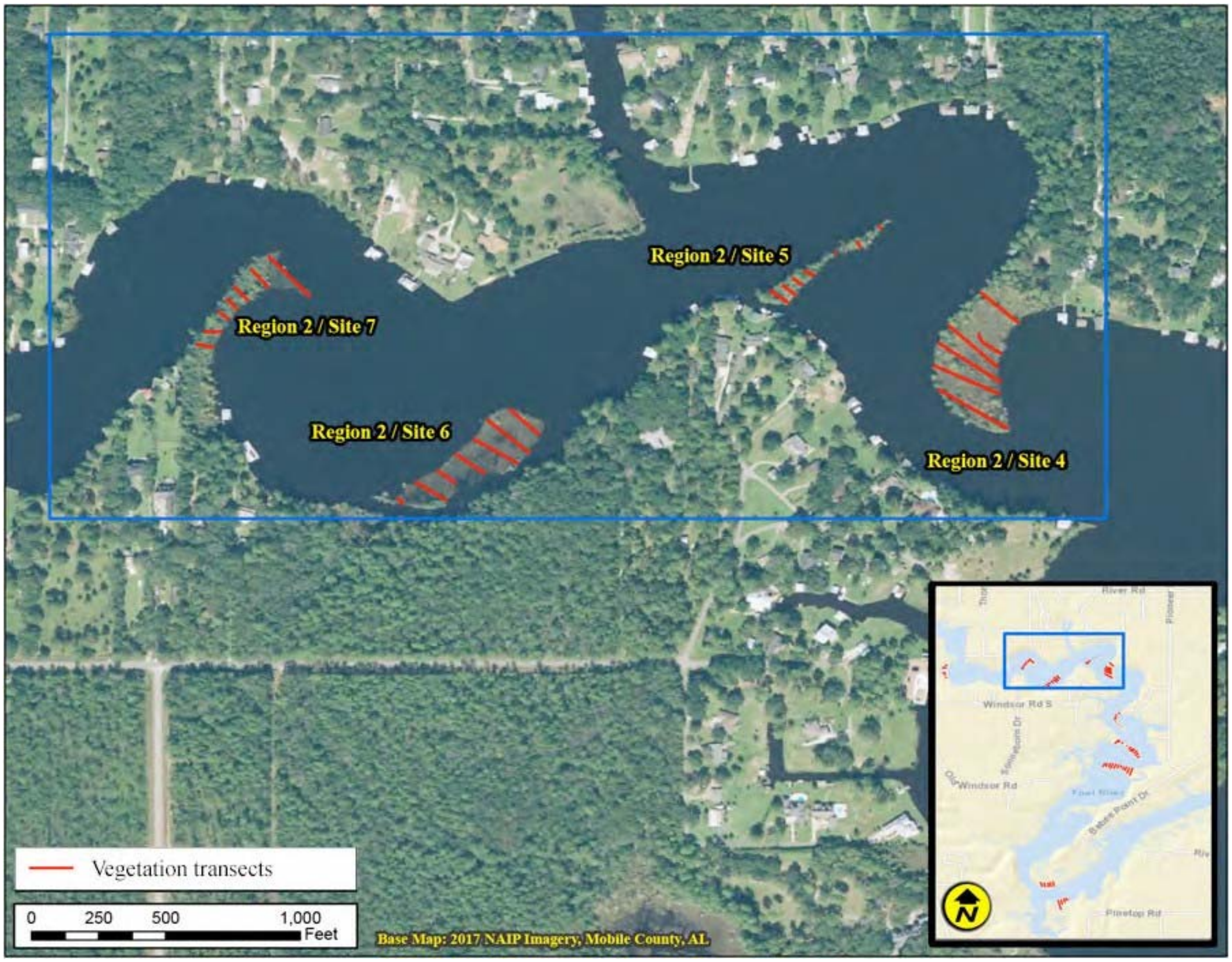

Figure A-2. Vegetation transects at Region 2 Sites 4 through 7, August 2018.

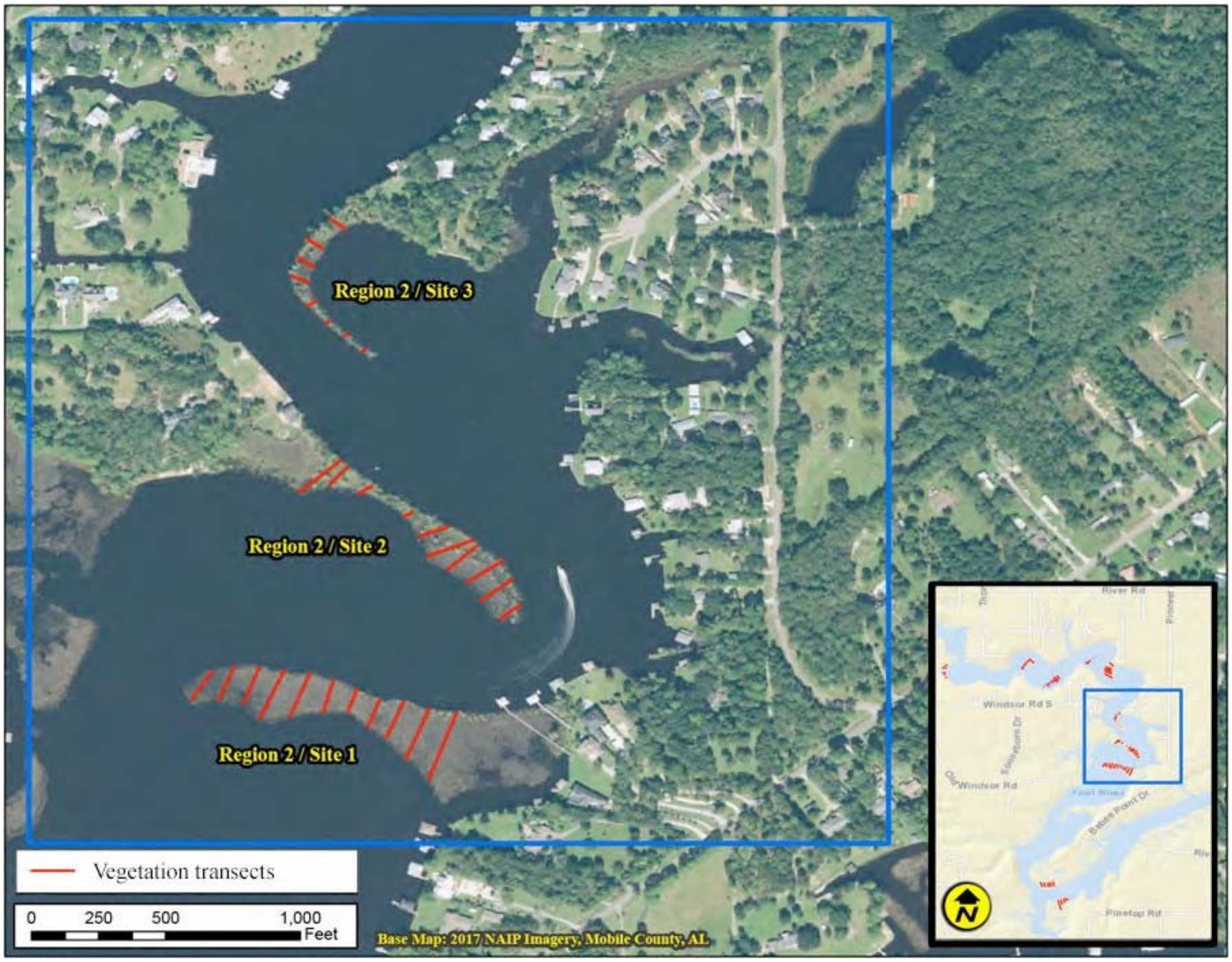

Figure A-3. Vegetation transects at Region 2 Sites 1 through 3, August 2018.

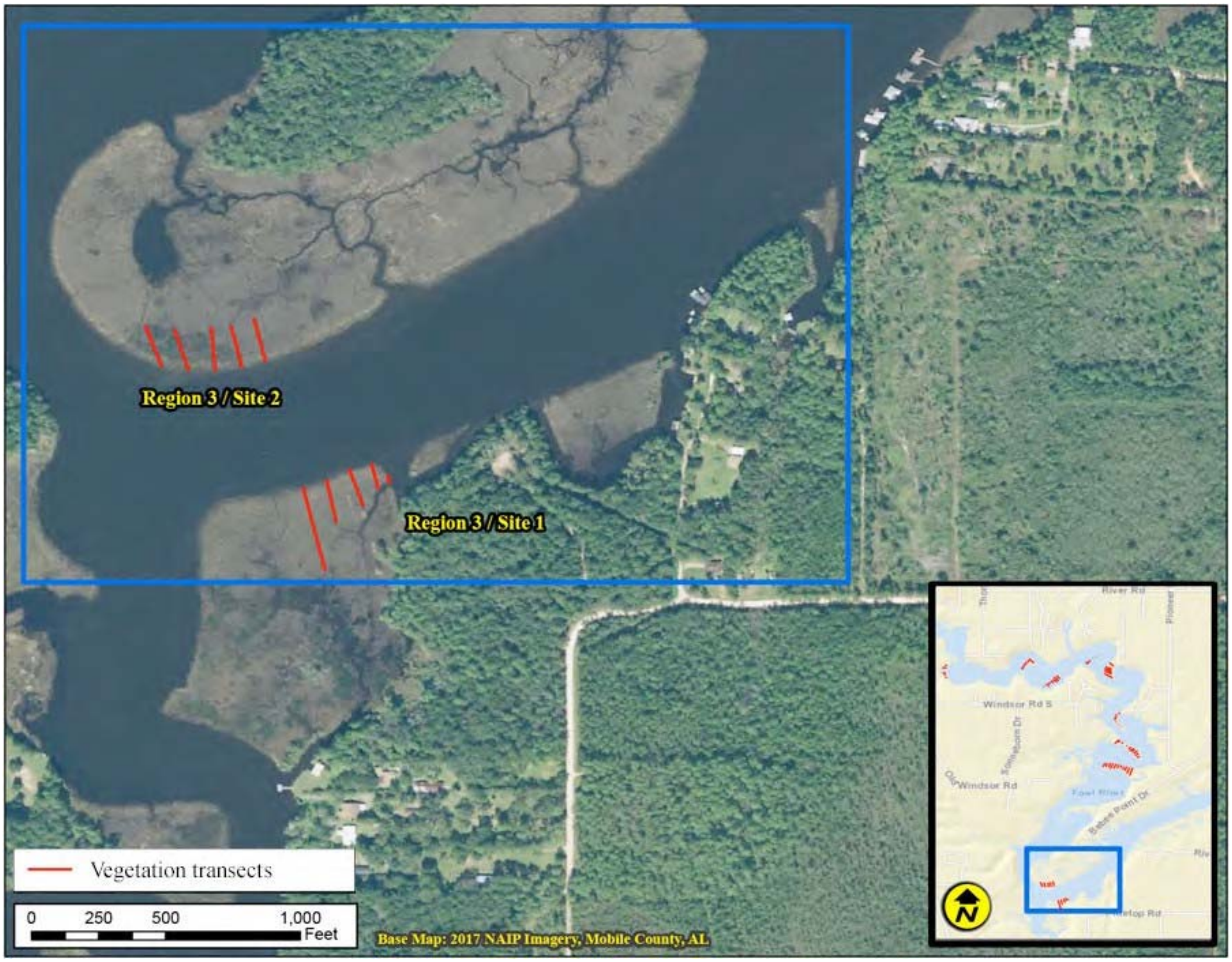

Figure A-3. Vegetation transects at Region 3 Sites 1 and 2, August 2018.

Appendix B – Species List and Data Summaries

Plant Species List (**†** = non-native, invasive exotic**)**

Order	Family	Species (FQI C value)
Osmundales	Osmundaceae	*Osmunda spectabilis* - American royal fern (7)
Osmundales	Osmundaceae	*Osmundastrum cinnamomeum* - cinnamon fern (6)
Polypodiales	Dennstaedtiaceae	*Pteridium latiusculum* - bracken fern
Polypodiales	Polypodiaceae	*Pleopeltis michauxiana* - resurrection fern (6)
Pinales	Pinaceae	*Pinus elliottii* - slash pine (3)
Pinales	Cupressaceae	*Chamaecyparis thyoides* - Atlantic white cedar (8)
Pinales	Cupressaceae	*Taxodium distichum* - bald cypress (6)
Magnoliales	Magnoliaceae	*Magnolia grandiflora* - southern magnolia (5)
Magnoliales	Magnoliaceae	*Magnolia virginiana* - southern sweetbay (7)
Laurales	Lauraceae	†*Camphora officinarum* - camphor tree (0)
Laurales	Lauraceae	*Persea palustris* - swamp bay (6)
Alismatales	Araceae	*Orontium aquaticum* - golden-club (8)
Alismatales	Araceae	*Peltandra virginica* - green arrow arum (8)
Alismatales	Alismataceae	*Sagittaria lancifolia* - bulltongue arrowhead (4)
Alismatales	Hydrocharitaceae	*Najas guadalupensis* - southern naiad (4)
Alismatales	Hydrocharitaceae	*Vallisneria neotropicalis* - large eel grass (8)
Alismatales	Cymodoceaceae	*Ruppia maritima* - widgeon grass (5)
Liliales	Smilacaceae	*Smilax laurifolia* - laurel greenbrier (6)
Liliales	Smilacaceae	*Smilax walteri* - coral greenbrier (6)
Asparagales	Iridaceae	*Iris × flexicaulis* - hybrid iris
Asparagales	Amaryllidaceae	*Crinum americanum* - swamp lily (7)
Arecales	Arecaceae	*Sabal minor* - dwarf palmetto (7)
Arecales	Arecaceae	*Sabal palmetto* - cabbage palm (5)
Arecales	Arecaceae	*Serenoa repens* - saw palmetto
Commelinales	Pontederiaceae	*Pontederia cordata* - pickerelweed (5)
Poales	Typhaceae	*Typha domingensis* - southern cattail (2)
Poales	Xyridaceae	*Xyris iridifolia* - yellow-eyed grass (7)
Poales	Mayacaceae	*Mayaca fluviatilis* - stream bog moss (7)
Poales	Juncaceae	*Juncus roemerianus* - black needlerush (8)
Poales	Juncaceae	*Juncus trigonocarpus* - red-pod rush (7)
Poales	Cyperaceae	*Bolboschoenus* sp. - bulrush
Poales	Cyperaceae	*Carex glaucescens* - southernwaxy sedge (7)
Poales	Cyperaceae	*Carex stipata* - large stalk-grain sedge (5)
Poales	Cyperaceae	*Cladium jamaicense* - sawgrass (7)
Poales	Cyperaceae	*Cyperus haspan* - haspan flat sedge (5)
Poales	Cyperaceae	*Cyperus virens* - green flatsedge (5)
Poales	Cyperaceae	*Eleocharis cellulosa* - Gulf coast spikerush (7)
Poales	Cyperaceae	*Eleocharis olivacea* - olive spikerush (6)
Poales	Cyperaceae	*Fimbristylis castanea* - marsh frimby (7)
Poales	Cyperaceae	*Fuirena breviseta* - saltmarsh umbrella sedge (5)
Poales	Cyperaceae	*Fuirena scirpoidea* - southern umbrella sedge (4)
Poales	Poaceae	*Dichanthelium scabriusculum* - woolly rosette grass (5)

Poales	Poaceae	*Distichlis spicatum* -saltgrass (6)
Poales	Poaceae	*Echinochloa muricata* - rough barnyard grass (2)
Poales	Poaceae	*Echinochloa walteri* - coast cock's spur grass (3)
Poales	Poaceae	†*Panicum repens* - torpedo grass (0)
Poales	Poaceae	*Panicum virgatum* - switchgrass (5)
Poales	Poaceae	*Phragmites mauritianus* - mauritius reed (0)
Poales	Poaceae	*Sacciolepis striata* - American cupscale (4)
Ceratophyllales	Ceratophyllaceae	*Ceratophyllum demersum* - coon's tail (4)
Saxifragales	Iteaceae	*Itea virginica* - Virgina willow (7)
Saxifragales	Haloragaceae	†*Myriophyllum spicatum* - Eurasian watermilfoil (0)
Vitales	Vitaceae	*Muscadinia rotundifolia* - muscadine (3)
Vitales	Vitaceae	*Nekemias arborea* - peppervine (3)
Rosales	Rosaceae	*Aronia arbutifolia* - red chokeberry (6)
Rosales	Rosaceae	*Prunus serotina* - black cherry
Rosales	Rosaceae	†*Rosa laevigata* - cherokee rose (0)
Rosales	Rosaceae	*Rubus pensilvanicus* - Pennsylvania blackberry (3)
Rosales	Rosaceae	*Rubus trivialis* - southern dewberry
Rosales	Urticaceae	*Boehmeria cylindrica* - small-spike false nettle (5)
Fagales	Fagaceae	*Quercus geminata* - sand live oak
Fagales	Fagaceae	*Quercus nigra* - water oak (4)
Fagales	Myricaceae	*Morella cerifera* - wax myrtle (4)
Malpighiales	Euphorbiaceae	†*Triadica sebifera* - Chinese tallowtree (0)
Malpighiales	Hypericaceae	*Hypericum fasciculatum* - narrowleaf St. John's wort (6)
Malpighiales	Hypericaceae	*Hypericum walteri* - Walter's marsh St. John's wort (4)
Myrtales	Lythraceae	*Lythrum lineare* - narrowleaf loosestrife (5)
Myrtales	Onagraceae	*Ludwigia alata* - winged seedbox (6)
Sapindales	Anacardiaceae	*Rhus copallinum* - winged sumac
Sapindales	Anacardiaceae	*Toxicodendron radicans* - eastern poison ivy (3)
Sapindales	Sapindaceae	*Acer rubrum* - red maple (4)
Malvales	Malvaceae	*Kosteletzkya pentacarpos* - saltmarsh mallow (6)
Caryophyllales	Polygonaceae	*Persicaria hydropiperoides* - water pepper (4)
Caryophyllales	Amaranthaceae	†*Alternanthera philoxeroides* - alligatorweed (0)
Caryophyllales	Amaranthaceae	*Amaranthus australis* - southern water hemp (2)
Cornales	Nyssaceae	*Nyssa biflora* - swamp tupelo (7)
Ericales	Primulaceae	†*Ardisia crenata* - coral ardisia (0)
Ericales	Primulaceae	*Samolus parviflorus* - American water pimpernel (5)
Ericales	Sarraceniaceae	*Sarracenia alata* - pale pitcher plant (8)
Ericales	Cyrillaceae	*Cliftonia monophylla* - buckwheat tree (6)
Ericales	Cyrillaceae	*Cyrilla racemiflora* - titi (6)
Ericales	Ericaceae	*Eubotrys racemosa* - swamp dog hobble (7)
Ericales	Ericaceae	*Lyonia lucida* - fetterbush (6)
Ericales	Ericaceae	*Pieris phillyreifolia* - climbing fetterbush (8)
Ericales	Ericaceae	*Rhododendron viscosum* - swamp azalea (7)
Gentianales	Rubiaceae	*Galium tinctorium - southern three-lobed bedstraw (4)*

Gentianales	Gentianaceae	*Sabatia calycina* - coastal rose gentian (7)
Gentianales	Gelsemiaceae	*Gelsemium rankinii* - swamp jessamine (6)
Solanales	Convolvulaceae	*Convolvulus limnophilus* - coastal plain bindweed (2)
Solanales	Convolvulaceae	*Ipomoea sagittata* - saltmarsh morning glory (5)
Lamiales	Oleaceae	*Cartrema americana* - devilwood (7)
Lamiales	Oleaceae	†*Ligustrum japonicum* - Japanese privet (0)
Lamiales	Plantaginaceae	*Bacopa monnieri* - herb of grace (4)
Aquifoliales	Aquifoliaceae	*Ilex coriacea* - big gallberry (7)
Aquifoliales	Aquifoliaceae	*Ilex glabra* - gallberry (5)
Aquifoliales	Aquifoliaceae	*Ilex vomitoria* - yaupon (6)
Asterales	Campanulaceae	*Lobelia cardinalis* - cardinal flower (5)
Asterales	Asteraceae	*Ampelaster carolinianus* - climbing aster (7)
Asterales	Asteraceae	*Baccharis angustifolia* - false willow (5)
Asterales	Asteraceae	*Baccharis halimifolia* - eastern baccharis (2)
Asterales	Asteraceae	*Bidens mitis* - small fruit beggar ticks (5)
Asterales	Asteraceae	*Boltonia diffusa* - small-head doll's daisy (4)
Asterales	Asteraceae	*Mikania scandens* - climbing hempvine (5)
Asterales	Asteraceae	*Pluchea odorata* - sweetscent (5)
Asterales	Asteraceae	*Solidago mexicana* - southern seaside goldenrod (6)
Asterales	Asteraceae	*Symphyotrichum racemosum* - smallwhite aster (4)
Asterales	Asteraceae	*Symphyotrichum subulatum* - eastern salt marsh aster (4)
Asterales	Asteraceae	*Symphyotrichum tenuifolium* - perennial salt marsh aster (7)
Dipsacales	Adoxaceae	*Viburnum nudum* - possum haw viburnum (7)
Dipsacales	Caprifoliaceae	†*Lonicera japonica* - Japanese honeysuckle (0)
Apiales	Araliaceae	*Hydrocotyle umbellata* - many-flowered pennywort (3)
Apiales	Apiaceae	*Centella asiatica* - coinleaf (3)
Apiales	Apiaceae	*Lilaeopsis chinensis* - eastern grasswort (7)
Apiales	Apiaceae	*Ptilimnium capillaceum* - mock bishopweed (4)
Apiales	Apiaceae	*Tiedemannia filiformis* - water cowbane (6)

Percent cover by species in quadrats and No. of quadrats - September 2018

Site R1S1

Species	% Cover	Occurrence	% Occurrence
Cladium jamaicense	47.7	47	97.9
Osmunda spectabilis	4.5	17	35.4
Taxodium distichum	1.3	2	4.2
Nyssa biflora	1.0	3	6.3
Hypericum fasciculatum	1.0	7	14.6
Sagittaria lancifolia	0.9	7	14.6
Pontederia cordata	0.7	6	12.5
Rubus trivialis	0.3	3	6.3
Mikania scandens	0.3	2	4.2
Peltandra virginica	0.3	4	8.3
Lythrum lineare	0.2	1	2.1
Persicaria hydropiperoides	0.2	3	6.3
Ilex glabra	0.2	1	2.1
Persea palustris	0.2	2	4.2
Magnolia virginiana	0.1	1	2.1
Smilax walteri	0.1	5	10.4
Morella cerifera	0.1	2	4.2
Ipomoea sagittata	0.1	3	6.3
Bidens mitis	0.0	1	2.1
Crinum americanum	0.0	1	2.1
Cyperus haspan	0.0	1	2.1
Rubus pensilvanicus	0.0	1	2.1
Boltonia diffusa	0.0	1	2.1
Sabatia calycina	0.0	1	2.1
Alternanthera philoxeroides	0.0	1	2.1
Fuirena scirpoidea	0.0	1	2.1
Galium tinctorium	0.0	1	2.1
Pinus elliottii	0.0	1	2.1
Xyris iridifolia	0.0	1	2.1

Site R2S7

Species	% Cover	Occurrence	% Occurrence
Cladium jamaicense	9.3	18	40.9
Pontederia cordata	6.2	31	70.5
Sagittaria lancifolia	6.2	26	59.1
Lythrum lineare	5.6	20	45.5
Boltonia diffusa	2.3	19	43.2
Osmunda spectabilis	2.1	11	25.0
Mikania scandens	2.0	13	29.5
Morella cerifera	1.7	7	15.9
Magnolia virginiana	1.3	3	6.8
Crinum americanum	1.2	9	20.5
Baccharis halimifolia	1.1	6	13.6
Cyperus haspan	1.1	15	34.1
Rubus pensilvanicus	0.9	4	9.1
Pluchea odorata	0.6	5	11.4
Persicaria hydropiperoides	0.5	12	27.3
Ludwigia alata	0.5	7	15.9
Nyssa biflora	0.4	2	4.5
Echinochloa walteri	0.3	4	9.1
Ipomoea sagittata	0.2	8	18.2
Solidago mexicana	0.1	4	9.1
Panicum virgatum	0.1	1	2.3
Symphyotrichum tenuifolium	0.1	3	6.8
Rosa laevigata	0.1	2	4.5
Sacciolepis striata	0.1	2	4.5
Fuirena scirpoidea	0.0	1	2.3
Rubus trivialis	0.0	1	2.3
Smilax walteri	0.0	1	2.3
Typha domingensis	0.0	1	2.3
Bidens mitis	0.0	1	2.3
Ligustrum japonicum	0.0	1	2.3
Nekemias arborea	0.0	1	2.3
Sabatia calycina	0.0	1	2.3

Site R2S6

Species	% Cover	Occurrence	% Occurrence
Sagittaria lancifolia	9.8	88	95.7
Eleocharis olivacea	9.7	23	25.0
Cyperus haspan	8.4	80	87.0
Ludwigia alata	4.9	44	47.8
Lythrum lineare	4.1	72	78.3
Eleocharis cellulosa	3.1	34	37.0
Boltonia diffusa	2.9	71	77.2
Cladium jamaicense	2.8	41	44.6
Pontederia cordata	1.8	50	54.3
Baccharis halimifolia	1.4	6	6.5
Osmunda spectabilis	1.3	7	7.6
Fuirena scirpoidea	1.0	14	15.2
Xyris iridifolia	1.0	22	23.9
Lobelia cardinalis	0.7	32	34.8
Morella cerifera	0.5	2	2.2
Symphyotrichum tenuifolium	0.5	29	31.5
Mikania scandens	0.4	8	8.7
Persicaria hydropiperoides	0.2	8	8.7
Typha domingensis	0.2	8	8.7
Hypericum fasciculatum	0.2	2	2.2
Carex glaucescens	0.2	1	1.1
Sacciolepis striata	0.2	4	4.3
Ipomoea sagittata	0.1	9	9.8
Pluchea odorata	0.1	5	5.4
Taxodium distichum	0.1	4	4.3
Panicum repens	0.1	5	5.4
Solidago mexicana	0.1	3	3.3
Fuirena breviseta	0.0	4	4.3
Juncus roemerianus	0.0	2	2.2
Galium tinctorium	0.0	2	2.2
Lilaeopsis chinensis	0.0	2	2.2
Peltandra virginica	0.0	1	1.1
Bidens mitis	0.0	1	1.1
Centella asiatica	0.0	1	1.1
Echinochloa walteri	0.0	1	1.1

Site R2S5

Species	% Cover	Occurrence	% Occurrence
Cladium jamaicense	7.6	17	85.0
Morella cerifera	6.7	7	35.0
Boltonia diffusa	3.3	8	40.0
Panicum repens	3.2	7	35.0
Solidago mexicana	3.2	7	35.0
Persea palustris	2.1	3	15.0
Sagittaria lancifolia	1.8	8	40.0
Baccharis halimifolia	1.7	4	20.0
Crinum americanum	1.4	4	20.0
Panicum virgatum	1.1	2	10.0
Juncus roemerianus	0.9	2	10.0
Mikania scandens	0.9	5	25.0
Magnolia virginiana	0.6	2	10.0
Phragmites mauritianus	0.5	3	15.0
Ipomoea sagittata	0.5	5	25.0
Pluchea odorata	0.5	2	10.0
Lythrum lineare	0.4	3	15.0
Acer rubrum	0.3	1	5.0
Muscadinia rotundifolia	0.3	1	5.0
Taxodium distichum	0.3	2	10.0
Sabatia calycina	0.3	3	15.0
Alternanthera philoxeroides	0.2	2	10.0
Rosa laevigata	0.2	1	5.0
Rubus pensilvanicus	0.2	1	5.0
Kosteletzkya pentacarpos	0.1	1	5.0
Persicaria hydropiperoides	0.1	1	5.0
Symphyotrichum racemosum	0.1	1	5.0
Camphora officinarum	0.1	1	5.0
Juncus trigonocarpus	0.1	1	5.0

Site R2S4

Species	% Cover	Occurrence	% Occurrence
Cladium jamaicense	28.9	142	91.6
Juncus roemerianus	5.1	74	47.7
Sagittaria lancifolia	3.6	135	87.1
Cyperus haspan	1.6	78	50.3
Morella cerifera	1.6	13	8.4
Taxodium distichum	1.0	8	5.2
Symphyotrichum tenuifolium	1.0	87	56.1
Lythrum lineare	1.0	61	39.4
Baccharis halimifolia	0.9	15	9.7
Mikania scandens	0.9	27	17.4
Eleocharis cellulosa	0.9	50	32.3
Eleocharis olivacea	0.7	17	11.0
Solidago mexicana	0.6	29	18.7
Kosteletzkya pentacarpos	0.6	27	17.4
Boltonia diffusa	0.5	23	14.8
Ipomoea sagittata	0.4	37	23.9
Osmunda spectabilis	0.3	14	9.0
Magnolia virginiana	0.3	5	3.2
Crinum americanum	0.3	14	9.0
Pluchea odorata	0.3	22	14.2
Smilax walteri	0.2	15	9.7
Panicum repens	0.2	10	6.5
Persea palustris	0.2	6	3.9
Toxicodendron radicans	0.2	3	1.9
Typha domingensis	0.2	11	7.1
Pontederia cordata	0.2	15	9.7
Ilex vomitoria	0.1	3	1.9
Amaranthus australis	0.1	4	2.6
Rubus pensilvanicus	0.1	3	1.9
Persicaria hydropiperoides	0.1	9	5.8
Sacciolepis striata	0.0	5	3.2
Echinochloa walteri	0.0	4	2.6
Triadica sebifera	0.0	2	1.3
Smilax laurifolia	0.0	2	1.3
Bacopa monnieri	0.0	1	0.6
Fuirena scirpoidea	0.0	2	1.3
Lilaeopsis chinensis	0.0	2	1.3
Osmundastrum cinnamomeum	0.0	2	1.3

Alternanthera philoxeroides	0.0	2	1.3
Quercus nigra	0.0	1	0.6
Rubus trivialis	0.0	1	0.6

R2S3

Species	% Cover	Occurrence	% Occurrence
Juncus roemerianus	19.3	34	73.9
Cladium jamaicense	15.6	30	65.2
Crinum americanum	2.4	22	47.8
Sagittaria lancifolia	2.4	29	63.0
Baccharis halimifolia	2.0	5	10.9
Eleocharis cellulosa	1.8	11	23.9
Lythrum lineare	1.2	17	37.0
Symphyotrichum tenuifolium	1.0	18	39.1
Mikania scandens	0.9	5	10.9
Morella cerifera	0.8	2	4.3
Vallisneria neotropicalis	0.8	2	4.3
Solidago mexicana	0.7	11	23.9
Acer rubrum	0.4	1	2.2
Boltonia diffusa	0.2	7	15.2
Toxicodendron radicans	0.2	1	2.2
Alternanthera philoxeroides	0.2	2	4.3
Ipomoea sagittata	0.2	5	10.9
Magnolia virginiana	0.2	2	4.3
Pontederia cordata	0.2	2	4.3
Persicaria hydropiperoides	0.2	3	6.5
Pluchea odorata	0.2	5	10.9
Kosteletzkya pentacarpos	0.2	1	2.2
Panicum repens	0.1	5	10.9
Amaranthus australis	0.1	3	6.5
Cyperus haspan	0.1	2	4.3
Echinochloa walteri	0.1	2	4.3
Bacopa monnieri	0.0	1	2.2
Bolboschoenus sp.	0.0	1	2.2
Convolvulus limnophilus	0.0	1	2.2
Osmunda spectabilis	0.0	1	2.2

R2S2

Species	% Cover	Occurrence	% Occurrence
Cladium jamaicense	18.8	91	67.9
Juncus roemerianus	13.9	91	67.9
Eleocharis cellulosa	3.7	36	26.9
Sagittaria lancifolia	2.6	88	65.7
Morella cerifera	2.4	15	11.2
Lythrum lineare	1.2	47	35.1
Rubus pensilvanicus	1.1	13	9.7
Pluchea odorata	1.0	33	24.6
Solidago mexicana	0.9	46	34.3
Mikania scandens	0.8	19	14.2
Persicaria hydropiperoides	0.7	19	14.2
Crinum americanum	0.6	19	14.2
Baccharis halimifolia	0.5	7	5.2
Symphyotrichum tenuifolium	0.5	44	32.8
Taxodium distichum	0.5	12	9.0
Amaranthus australis	0.4	8	6.0
Persea palustris	0.3	5	3.7
Vallisneria neotropicalis	0.3	3	2.2
Triadica sebifera	0.2	1	0.7
Ruppia maritima	0.2	3	2.2
Ipomoea sagittata	0.2	16	11.9
Najas guadalupensis	0.2	3	2.2
Boltonia diffusa	0.2	12	9.0
Eleocharis olivacea	0.1	3	2.2
Ilex vomitoria	0.1	5	3.7
Acer rubrum	0.1	1	0.7
Toxicodendron radicans	0.1	4	3.0
Fimbristylis castanea	0.1	1	0.7
Osmunda spectabilis	0.1	5	3.7
Symphyotrichum subulatum	0.0	4	3.0
Kosteletzkya pentacarpos	0.0	1	0.7
Smilax walteri	0.0	1	0.7
Bidens mitis	0.0	2	1.5
Bolboschoenus sp.	0.0	1	0.7
Lilaeopsis chinensis	0.0	2	1.5
Nekemias arborea	0.0	1	0.7
Echinochloa walteri	0.0	1	0.7

Sacciolepis striata	0.0	1	0.7
Juncus trigonocarpus	0.0	0	0.0

R2S1

Species	% Cover	Occurrence	% Occurrence
Juncus roemerianus	34.3	192	97.0
Sagittaria lancifolia	3.6	167	84.3
Pluchea odorata	1.1	63	31.8
Boltonia diffusa	0.9	65	32.8
Lythrum lineare	0.9	82	41.4
Cladium jamaicense	0.8	29	14.6
Symphyotrichum tenuifolium	0.6	75	37.9
Mikania scandens	0.5	4	2.0
Vallisneria neotropicalis	0.3	6	3.0
Echinochloa walteri	0.2	13	6.6
Eleocharis cellulosa	0.2	16	8.1
Amaranthus australis	0.1	6	3.0
Crinum americanum	0.1	13	6.6
Solidago mexicana	0.1	7	3.5
Lobelia cardinalis	0.0	5	2.5
Ipomoea sagittata	0.0	2	1.0
Taxodium distichum	0.0	1	0.5
Pontederia cordata	0.0	2	1.0
Typha domingensis	0.0	1	0.5

R3S2

Species	% Cover	Occurrence	% Occurrence
Juncus roemerianus	23.9	85	94.4
Sagittaria lancifolia	2.9	50	55.6
Lythrum lineare	1.4	18	20.0
Pluchea odorata	0.9	22	24.4
Eleocharis olivacea	0.7	6	6.7
Symphyotrichum tenuifolium	0.3	14	15.6
Vallisneria neotropicalis	0.2	1	1.1
Boltonia diffusa	0.2	3	3.3
Persicaria hydropiperoides	0.1	2	2.2
Amaranthus australis	0.0	2	2.2
Ruppia maritima	0.0	2	2.2
Distichlis spicatum	0.0	2	2.2
Myriophyllum spicatum	0.0	2	2.2

R3S1

Species	% Cover	Occurrence	% Occurrence
Juncus roemerianus	38.8	68	100.0
Cladium jamaicense	2.1	30	44.1
Sagittaria lancifolia	1.7	25	36.8
Pluchea odorata	0.6	10	14.7
Lythrum lineare	0.3	8	11.8
Ruppia maritima	0.3	4	5.9
Myriophyllum spicatum	0.2	4	5.9
Boltonia diffusa	0.0	2	2.9
Symphyotrichum tenuifolium	0.0	1	1.5

Appendix C – HGM Model Assessment Methods and Worksheets

Hydrogeomorphic (HGM) Model Analysis

Background

The Hydrogeomorphic (HGM) Approach is a collection of concepts and methods that uses mathematically derived indices to assess the capacity of a wetland to perform specific ecological, geochemical, and hydrological functions in comparison to similar wetlands within a geographic region. The HGM approach was originally developed to be used within the framework of the Federal Section 404 regulatory program permit review process to evaluate project alternatives, minimize project impacts, and determine compensatory mitigation requirements (Smith et al., 1995). Additional applications include the planning design and monitoring of habitat restoration projects outside the context of the Section 404 program.

The development of the HGM approach involves: 1) classification of wetlands within a defined region; 2) development of functional assessment models and indices; and 3) development and application of assessment protocols. The advantage of the HGM approach is that an individual site may be assessed for a suite of functions or a subset of functions, as determined by project management objectives. HGM is a rapid-assessment procedure designed to be implemented in a relatively short period of time at minimal expense (Shafer et al., 2007).

Classification

HGM classifies wetlands based on three separate criteria; geomorphic setting, water source, and hydrodynamics (Brinson, 1993). The classification criteria are used to group wetlands into five basic geomorphic classes at a continental scale (depressional, flat, slope, riverine and fringe wetlands). Flats can be further subdivided into organic and mineral flats, and fringe wetlands into lacustrine and tidal fringe. At a finer geographic scale, the three classification criteria are applied to identify regional wetland subclasses, which typically corresponds to existing, commonly recognized wetland types; for example oligohaline salt marsh along the Gulf of Mexico coastline (Shafer and Yozzo, 1998).

Reference Wetlands

In HGM, reference wetlands are sites selected to represent the variability that occurs within a regional wetland subclass. The reference domain is the geographic area represented by the reference wetlands. Ideally, the reference domain will mirror the geographic area encompassed by the regional wetland subclass; however, constraints on time, personnel, and fiscal resources, as well as agency jurisdictional boundaries often limit the size of a regional reference domain.

Reference wetlands establish the range and variability of conditions expressed by HGM model variables and provide data needed to calibrate HGM assessment models. Reference wetlands exhibiting the highest sustainable level of function across a suite of observed or documented functions are referred to as reference standard wetlands. When a model variable is within the range of conditions observed in reference standard wetlands a variable sub-index value of 1.0 is assigned. As the condition deviates from that observed in reference standard wetlands, the variable sub-index is assigned based on the observed relationship between model variable condition and functional capacity (on a scale of 0.0 to 1.0).

Assessment Protocol

The HGM assessment protocol is a series of tasks that allow the user to assess the functions of a particular wetland using the functional indices presented in a published Regional Guidebook. The first task in an HGM assessment is characterization, which involves describing the wetland and it's surrounding landscape, describing the proposed project and it's potential impacts, and identifying the wetland assessment areas (WAAs). The second task is collection of field data for model variables. The final task is analysis, which involves calculation of functional indices and units.

Models and Indices

An HGM assessment model is a simple representation of a wetland function. It defines the relationship among one or more wetland characteristics or processes (variables). Functional capacity is the ability of the wetland to perform a function relative the level of performance observed or measured in reference standard wetlands.

Variables are combined mathematically in a functional assessment model to produce a functional capacity index (FCI). The mathematical expressions used vary, depending on the type of interaction to be represented (e.g. fully or partially compensatory, cumulative, limiting, controlling, etc.). A complete discussion of variable interactions and model development is presented in Smith and Wakeley (2001). FCIs are multiplied by the wetland assessment area (typically in hectares) to produce functional capacity units (FCUs), which represent the "currency" used to determine mitigation ratios within the context of the Federal Section 404 regulatory program.

Mississippi/Alabama HGM Guidebook

The methodology employed in the data collection and HGM assessment generally follows the protocol described in the Mississippi/Alabama HGM Guidebook (Schafer et al., 2007). http://el.erdc.usace.army.mil/wetlands/guidebooks.cfm)

METHODS

Field Data Collection

Field assessment of the Mon Louis Island site was conducted in September 2018. Transects were generally aligned perpendicular to the shoreline edge along the hydrologic gradient of decreasing elevation (following Schafer et al., 2007).

Vegetation metrics used in the HGM assessment were collected within meter-squared quadrats. Data recorded included the average height of vegetation (recorded in centimeters up to one meter), and the combined overall percent cover of native wetland vegetation occurring within the quadrat. Estimates of percent cover were made using cover class categories presented in **Table B-2** (modified from Schafer et al., 2007).

Table B-2. Cover classes and midpoint values for percent cover estimates in quadrats.

Class	Percent Cover Estimate	Midpoint Value Assigned
1	< 5%	2.5%
2	5 – 25%	15.0%
3	26 – 50 %	37.5%
4	51 – 75%	62.5%
5	> 76%	87.5%

Desktop/GIS Assessment Variables

The HGM assessment procedure is twofold. First, site information is gathered and assessed in a GIS during the "desktop" component of the procedure. Wetland assessment areas (WAAs) are identified from maps and aerial photos (color infra-red is preferred, but high-quality true color air photos are acceptable, and were used in the current evaluations). A standardized scale is critical, and the methodology requires that all air photo work be conducted using a scale of 1:4800 (1 in. = 400 ft.). The following HGM variables were assessed during the desktop procedure:

V_{SIZE} (Wetland Patch Size): The size of the contiguous wetland patch within which the WAA occurs.

$V_{LANDUSE}$ (Adjacent Land Use): The proportion of the wetland perimeter occupied by various land use types.

V_{WIDTH} (Mean Marsh Width): The distance (m) that wind and vessel-generated waves must travel across intervening tidal fringe wetland (distance from the shoreline)

V_{EXPOSE} (Wave Energy Exposure): A qualitative classification of the potential for a wetland to attenuate wind and vessel-generated wave energy based on geomorphic setting and fetch distance – unitless.

V_{EDGE} (Aquatic Edge): The length (m) of vegetated tidally connected marsh/water interface or edge expressed as a proportion of total WAA area (ha).

V_{HYDRO} (Hydrologic Regime): The degree of alteration to the normal tidal hydrology typical of the subclass – unitless.

Field Assessment Variables

The HGM approach also incorporates site-specific information on vegetation metrics and habitat diversity collected in the field. The field assessments generated data on the following HGM variables:

V_{NHD} (Nekton Habitat Diversity): A measure of the heterogeneity of the site, based on comparison of the number of habitats actually present at a site relative to the number of possible habitats known to occur in the regional subclass.

V_{WHD} (Wildlife Habitat Diversity): A measure of the occurrence of habitat types known to support selected marsh-dependent wildlife species within the WAA.

V_{COVER} (Mean Percent Cover Emergent Marsh Vegetation): The mean total percent cover of native non-woody plant species with a wetland indicator status of OBL or FACW

V_{HEIGHT} (Vegetation Height): The most frequently occurring height of the plants within the tallest zone of the emergent marsh plant community.

V_{EXOTIC} (Percent Cover of Invasive or Exotic Species): The proportion of the site that is covered by non-native or invasive plant species.

V_{WOODY} (Percent Cover by Woody Plant Species): The proportion of the site that is covered by shrub-scrub or other woody plant species.

V_{WIS} (Wetland Indicator Status): The ratio of percent cover of FAC and FACU plants to the cover of emergent herbaceous wetland (OBL or FACW) plants.

Ecosystem Functions (FCIs and FCUs)

The data collected during the desktop and field assessments (i.e., the thirteen variables listed above) are combined using various mathematical expressions to estimate five ecosystem functions attributed to tidal fringe wetlands in the AL/MS Gulf coast reference domain (Schafer et al., 2007):

Wave Attenuation: Ability of a wetland to attenuate wind and vessel-generated wave energy based on geomorphic setting and fetch distance

Biogeochemical Cycling: The ability of a tidal wetland to receive, transform, and export various elements and compounds through natural biogeochemical processes.

Nekton Utilization: The potential utilization of a marsh by resident and seasonally occurring non- resident adult or juvenile fish and macrocrustacean species.

Provide Habitat for Tidal Marsh Dependant Wildlife: The capacity of a tidal marsh to provide critical life requisites to selected components of the vertebrate wildlife community.

Maintain Characteristic Plant Community Structure: The ability of a tidal marsh to support a native plant community of characteristic species composition and structure.

Calculation of FCIs

A Microsoft Excel file provided by USACE-ERDC was used to facilitate data entry and to calculate FCIs for each of the functions assessed. Formulas used to calculate FCIs were:

Functional Capacity Equations	
Wave Energy Attenuation	$FCI = [(3V_{WIDTH} + V_{COVER}) / 4 \text{ X } V_{EXPOSE}]^{1/2}$
Biogeochemical Cycling	$FCI = [V_{HYDRO} \text{ X } V_{COVER} \text{ X } V_{LANDUSE}]^{1/3}$
Nekton Utilization Potential	$FCI = (V_{EDGE} + V_{HYDRO} + V_{NHD}) / 3$
Provide Habitat for Tidal Marsh Dependent Wildlife Species	$FCI = \left\{ V_{SIZE} \times \left[\frac{(V_{HEIGHT} + V_{COVER})}{2} \right] \times \left[\frac{(V_{EDGE} + V_{WHD})}{2} \right] \right\}^{1/3}$
Maintain Plant Community Composition and Structure	$FCI = (\text{Minimum } (V_{COVER} \text{ or } V_{EXOTIC} \text{ or } V_{WIS} \text{ or } V_{WOODY})$

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FCI and FCU Calculations for the Tidal Fringe HGM Regional Subclass

Project:	**Fowl River Marshes**		
WAA	**R1S1**	**Area (ha):**	**0.4**

Variable	Metric Value	Units	Subindex
V_{COVER}	56.1	%	0.60
V_{EDGE}	315	m/ha	1.00
V_{EXPOSE}	Moderate	NA	0.60
V_{EXOTIC}	0.1	%	1.00
V_{HEIGHT}	117	cm	1.00
V_{HYDRO}	Open	NA	1.00
$V_{LANDUSE}$	100%	%	1.00
V_{NHD}	4	EA	0.80
V_{SIZE}	0.65	ha	0.75
V_{WIS}	0.6	%	1.00
V_{WOODY}	5.3	%	1.00
V_{WHD}	3	EA	0.70
V_{WIDTH}	30	m	0.60

Function	Functional Capacity Index (FCI)	Functional Capacity Units (FCU)
Wave Energy Attenuation	0.60	0.24
Biogeochemical Cycling	0.84	0.34
Nekton Utilization Potential	0.93	0.37
Provide Habitat for Tidal Marsh Dependent Wildlife Species	0.80	0.32
Maintain Plant Community Composition and Structure	0.60	0.24
	FCI Ave. = 0.76	FCU Sum = 1.51

FCI and FCU Calculations for the Tidal Fringe HGM Regional Subclass

Project:	**Fowl River Marshes**		
WAA	**R2S7**	**Area (ha):**	**0.19**

Variable	Metric Value	Units	Subindex
V_{COVER}	47.1	%	0.40
V_{EDGE}	1,900	m/ha	1.00
V_{EXPOSE}	Moderate	NA	0.60
V_{EXOTIC}	0.2	%	1.00
V_{HEIGHT}	111	cm	1.00
V_{HYDRO}	Open	NA	1.00
$V_{LANDUSE}$	Undeveloped	%	1.00
V_{NHD}	3	EA	0.60
V_{SIZE}	0.2	ha	0.25
V_{WIS}	4.8	%	0.75
V_{WOODY}	6.5	%	0.80
V_{WHD}	3	EA	0.70
V_{WIDTH}	5.4	m	0.20

Function	Functional Capacity Index (FCI)	Functional Capacity Units (FCU)
Wave Energy Attenuation	0.39	0.07
Biogeochemical Cycling	0.74	0.14
Nekton Utilization Potential	0.87	0.16
Provide Habitat for Tidal Marsh Dependent Wildlife Species	0.53	0.10
Maintain Plant Community Composition and Structure	0.40	0.08
Overall Average	**FCI Ave. = 0.58**	**FCU Sum =0.55**

FCI and FCU Calculations for the Tidal Fringe HGM Regional Subclass

Project:	**Fowl River Marshes**		
WAA	**R2S6**	**Area (ha):**	**0.66**

Variable	Metric Value	Units	Subindex
V_{COVER}	63.6	%	0.80
V_{EDGE}	641	m/ha	1.00
V_{EXPOSE}	Moderate	NA	0.80
V_{EXOTIC}	0.1	%	1.00
V_{HEIGHT}	103	cm	1.00
V_{HYDRO}	Open	NA	1.00
$V_{LANDUSE}$	Undeveloped	%	1.00
V_{NHD}	5	EA	1.00
V_{SIZE}	0.66	ha	0.75
V_{WIS}	1.8	%	0.75
V_{WOODY}	2.1	%	1.00
V_{WHD}	2	EA	0.35
V_{WIDTH}	40	m	0.60

Function	Functional Capacity Index (FCI)	Functional Capacity Units (FCU)
Wave Energy Attenuation	0.72	0.48
Biogeochemical Cycling	0.93	0.61
Nekton Utilization Potential	1.00	0.66
Provide Habitat for Tidal Marsh Dependent Wildlife Species	0.77	0.51
Maintain Plant Community Composition and Structure	0.75	0.50
	FCI Ave. = 0.83	FCU Sum = 2.75

FCI and FCU Calculations for the Tidal Fringe HGM Regional Subclass

Project:	**Fowl River Marshes**		
WAA	**R2S5 (Strout)**	**Area (ha):**	**0.12**

Variable	Metric Value	Units	Subindex
V_{COVER}	27.3	%	0.100
V_{EDGE}	2,933	m/ha	1.000
V_{EXPOSE}	Moderate	NA	0.600
V_{EXOTIC}	5.4	%	1.000
V_{HEIGHT}	124	cm	1.000
V_{HYDRO}	Open	NA	1.000
$V_{LANDUSE}$	Undeveloped	%	1.000
V_{NHD}	2	EA	0.400
V_{SIZE}	0.12	ha	0.250
V_{WIS}	10.5	%	0.500
V_{WOODY}	14.4	%	0.600
V_{WHD}	0	EA	0.000
V_{WIDTH}	5.3	m	0.200

Function	Functional Capacity Index (FCI)	Functional Capacity Units (FCU)
Wave Energy Attenuation	0.32	0.04
Biogeochemical Cycling	0.46	0.06
Nekton Utilization Potential	0.80	0.10
Provide Habitat for Tidal Marsh Dependent Wildlife Species	0.41	0.05
Maintain Plant Community Composition and Structure	0.10	0.01
	FCI Ave. = 0.42	FCU Sum = 0.25

FCI and FCU Calculations for the Tidal Fringe HGM Regional Subclass

Project:	**Fowl River Marshes**		
WAA	**R2S4 (Closing Hole)**	**Area (ha):**	**0.84**

Variable	Metric Value	Units	Subindex
V_{COVER}	56.4	%	0.600
V_{EDGE}	446	m/ha	1.000
V_{EXPOSE}	Moderate	NA	0.600
V_{EXOTIC}	0.4	%	1.000
V_{HEIGHT}	127	cm	1.000
V_{HYDRO}	Minor	NA	0.750
$V_{LANDUSE}$	Undeveloped	%	1.000
V_{NHD}	4	EA	0.800
V_{SIZE}	0.9	ha	0.750
V_{WIS}	3.5	%	0.750
V_{WOODY}	5.4	%	1.000
V_{WHD}	2	EA	0.350
V_{WIDTH}	70	m	0.800

Function	Functional Capacity Index (FCI)	Functional Capacity Units (FCU)
Wave Energy Attenuation	0.67	0.56
Biogeochemical Cycling	0.77	0.64
Nekton Utilization Potential	0.85	0.71
Provide Habitat for Tidal Marsh Dependent Wildlife Species	0.74	0.62
Maintain Plant Community Composition and Structure	0.60	0.50
	FCI Ave. = 0.73	FCU Sum = 3.05

FCI and FCU Calculations for the Tidal Fringe HGM Regional Subclass

Project:	**Fowl River Marshes**		
WAA	**R2S3 (Lightcap)**	**Area (ha):**	**0.36**

Variable	Metric Value	Units	Subindex
V_{COVER}	51.5	%	0.60
V_{EDGE}	1,189	m/h	1.00
V_{EXPOSE}	Moderate	NA	0.60
V_{EXOTIC}	0.7	%	1.00
V_{HEIGHT}	119	cm	1.00
V_{HYDRO}	Minor	NA	0.75
$V_{LANDUSE}$	Undeveloped	%	1.00
V_{NHD}	4	EA	0.80
V_{SIZE}	0.36	ha	0.50
V_{WIS}	3.6	%	0.75
V_{WOODY}	4.0	%	1.00
V_{WHD}	2	EA	0.35
V_{WIDTH}	14.4	m	0.40

Function	Functional Capacity Index (FCI)	Functional Capacity Units (FCU)
Wave Energy Attenuation	0.52	0.19
Biogeochemical Cycling	0.77	0.28
Nekton Utilization Potential	0.85	0.31
Provide Habitat for Tidal Marsh Dependent Wildlife Species	0.65	0.23
Maintain Plant Community Composition and Structure	0.60	0.22
	FCI Ave. = 0.68	FCU Sum = 1.22

FCI and FCU Calculations for the Tidal Fringe HGM Regional Subclass

Project:	**Fowl River Marshes**		
WAA	**R2S2 (Tapia)**	**Area (ha):**	**0.85**

Variable	Metric Value	Units	Subindex
V_{COVER}	52.7	%	0.60
V_{EDGE}	683	m/ha	1.00
V_{EXPOSE}	Moderate	NA	0.60
V_{EXOTIC}	0.3	%	1.00
V_{HEIGHT}	131	cm	1.00
V_{HYDRO}	Minor	NA	0.75
$V_{LANDUSE}$	Undeveloped	%	1.00
V_{NHD}	4	EA	0.80
V_{SIZE}	1.25	ha	0.75
V_{WIS}	5.3	%	0.75
V_{WOODY}	6.3	%	0.80
V_{WHD}	2	EA	0.35
V_{WIDTH}	35	m	0.60

Function	Functional Capacity Index (FCI)	Functional Capacity Units (FCU)
Wave Energy Attenuation	0.60	0.51
Biogeochemical Cycling	0.77	0.65
Nekton Utilization Potential	0.85	0.72
Provide Habitat for Tidal Marsh Dependent Wildlife Species	0.74	0.63
Maintain Plant Community Composition and Structure	0.60	0.51
	FCI Ave. = 0.71	FCU Sum = 3.02

FCI and FCU Calculations for the Tidal Fringe HGM Regional Subclass

Project:	**Fowl River Marshes**		
WAA	**R2S1**	**Area (ha):**	**1.3**

Variable	Metric Value	Units	Subindex
V_{COVER}	48.8	%	0.40
V_{EDGE}	468	m/ha	1.00
V_{EXPOSE}	Moderate	NA	0.60
V_{EXOTIC}	0.0	%	1.00
V_{HEIGHT}	141	cm	1.00
V_{HYDRO}	Minor	NA	0.75
$V_{LANDUSE}$	Undeveloped	%	1.00
V_{NHD}	4	EA	0.80
V_{SIZE}	2.3	ha	1.00
V_{WIS}	0.0	%	1.00
V_{WOODY}	0.0	%	1.00
V_{WHD}	2	EA	0.35
V_{WIDTH}	50	m	0.80

Function	Functional Capacity Index (FCI)	Functional Capacity Units (FCU)
Wave Energy Attenuation	0.65	0.84
Biogeochemical Cycling	0.67	0.87
Nekton Utilization Potential	0.85	1.11
Provide Habitat for Tidal Marsh Dependent Wildlife Species	0.78	1.01
Maintain Plant Community Composition and Structure	0.40	0.52
	FCI Ave. = 0.67	FCU Sum = 4.35

FCI and FCU Calculations for the Tidal Fringe HGM Regional Subclass

Project:	**Fowl River Marshes**		
WAA	R3S1	Area (ha):	0.47

Variable	Metric Value	Units	Subindex
V_{COVER}	45.5	%	0.40
V_{EDGE}	266	nm/ha	1.00
V_{EXPOSE}	Moderate	NA	0.60
V_{EXOTIC}	0.3	%	1.00
V_{HEIGHT}	72	cm	0.31
V_{HYDRO}	Open	NA	1.00
$V_{LANDUSE}$	Undeveloped	%	1.00
V_{NHD}	6	EA	1.00
V_{SIZE}	5.8	ha	1.00
V_{WIS}	0.0	%	1.00
V_{WOODY}	0.0	%	1.00
V_{WHD}	3	EA	0.70
V_{WIDTH}	47	m	0.60

Function	Functional Capacity Index (FCI)	Functional Capacity Units (FCU)
Wave Energy Attenuation	0.57	0.27
Biogeochemical Cycling	0.74	0.35
Nekton Utilization Potential	1.00	0.47
Provide Habitat for Tidal Marsh Dependent Wildlife Species	0.67	0.31
Maintain Plant Community Composition and Structure	0.40	0.19
	FCI Ave. = 0.68	FCU Sum = 1.59

FCI and FCU Calculations for the Tidal Fringe HGM Regional Subclass

Project:	**Fowl River Marshes**		
WAA	R3S2	Area (ha):	0.62

Variable	Metric Value	Units	Subindex
V_{COVER}	33.8	%	0.20
V_{EDGE}	238	nm/ha	1.00
V_{EXPOSE}	Moderate	NA	0.60
V_{EXOTIC}	0.1	%	1.00
V_{HEIGHT}	81	cm	0.53
V_{HYDRO}	Open	NA	1.00
$V_{LANDUSE}$	Undeveloped	%	1.00
V_{NHD}	4	EA	0.80
V_{SIZE}	14.1	ha	1.00
V_{WIS}	0.0	%	1.00
V_{WOODY}	0.0	%	1.00
V_{WHD}	3	EA	0.70
V_{WIDTH}	50	m	0.80

Function	Functional Capacity Index (FCI)	Functional Capacity Units (FCU)
Wave Energy Attenuation	0.62	0.39
Biogeochemical Cycling	0.58	0.36
Nekton Utilization Potential	0.93	0.58
Provide Habitat for Tidal Marsh Dependent Wildlife Species	0.68	0.42
Maintain Plant Community Composition and Structure	0.20	0.12
	FCI Ave. = 0.60	FCU Sum = 1.87

Sediment Component

A sedimentation study was performed to assess sources and sinks of sediment material in the spits and surrounding estuary. In the first of three reports, Marlon Cook performed an assessment of pre-restoration analysis of discharge, sediment transport rates, water quality, and land-use impacts. Next, Dr. Alex Beebe established a detailed recent geologic history of the priority spits and nearby channel through sedimentological and geochronological analyses of replicate piston core samples. In the third report, Dr. Ruth Carmichael investigated whether changes in nutrient and hydrological regimes were associated with anthropogenic land-use changes by analyzing core samples and measuring organic nitrogen and carbon content and stable isotope ratios that reflect inputs from human wastewater sources and to distinguish marine from freshwater influences.

PRE-RESTORATION ANALYSIS OF DISCHARGE, SEDIMENT TRANSPORT RATES, WATER QUALITY, AND LAND-USE IMPACTS IN THE FOWL RIVER WATERSHED, MOBILE COUNTY, ALABAMA

By

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Poly, Inc.

April 2019

Project Description and Methodology

The assessment of dynamic sediment transport rates and water quality in the Fowl River estuary is part of a multi-faceted approach to characterize current health of marshes in there and to predict the fate of marshes in the future. The purpose of this investigation is to assess general hydrogeologic and water-quality conditions and to estimate sediment loads for the Fowl River Watershed to determine if adequate sediment is available to sustain these estuarine marshes.

Field parameters were measured and water samples were collected at three sites for selected discharge events and tide levels from March to September 2018 (Figure 1). Field parameters included: pH, temperature, turbidity, dissolved oxygen, conductivity, and salinity. Monitored stations were established at regular intervals from 25 to 75 ft apart at right angles to shore. Field parameters and water samples were collected at vertical intervals from about one ft above the bottom, one to two ft from the surface, and at mid-levels for deeper stations.

This investigation was combined with elements of a 2014-15 Geological Survey of Alabama assessment of water quality and sediment transport rates in the upstream, freshwater, fluvial parts of the Fowl River Watershed in 2014 and 2015 to comprehensively evaluate sediment transport conditions in the Fowl River Watershed.

Figure 1. Monitoring sites in the Fowl River

Results and Findings

Land use/cover

Dominant land cover in the Fowl River Watershed is woody and herbaceous wetlands and evergreen and mixed forests in the upstream, freshwater, fluvial part of the Watershed and woody and herbaceous wetlands, saltwater marsh, and evergreen and mixed forest in the estuarine part of the Watershed. These land cover categories account for more than 50% of the Watershed area.

Stream flow

Stream flows in Fowl River and its tributaries are relatively unimpacted by man and are primarily influenced by relatively low topographic relief, extensive wetlands, vegetation (anastomosing conditions), and tidal effects. Relatively small gradients for Fowl River streams are reflected in flow velocities, that average 0.7 ft/s. Minimum discharge measured at the U.S. Geological Survey (USGS) stream gaging site 02471078, Fowl River at Half Mile Road near Laurendine, Alabama, during the 2014-15 study was 18 cfs (September 28, 2014) and the maximum was 2,040 cfs, measured during an overbank flood on April 13, 2015. Average daily discharge was 33.5 cfs. Minimum discharge during the 2018 assessment was 11.4 cfs (November 12, 2018) and maximum was 421cfs (August 17, 2018). Average daily discharge was 42.0 cfs.

Field parameters

All field parameters were highly variable, depending on discharge and temperature. Values of pH were significantly higher during low flow when salinity levels were increased. Average temperature at site FR1 (lower estuary) was 16.8°C in March 2018 and 29.7°C in August 2018. Average conductivity at site FR2 (mid-estuary) was 90 mS/cm during a high flow event in July 2018 and 4781 mS/cm during a low flow event in August 2018. Average salinity at site FR1 in August 2018 for the near surface stations was 3.9 parts/thousand (ppt) and 8.7 ppt for near bottoms stations, indicating the presence of a salt water wedge and stratification caused by tidal influx of brackish water from Mobile Bay moving upstream through the estuary (Figure 2).

Turbidity

Average measured turbidity and discharge for the 2014-15 assessment, illustrates that generally watersheds with the highest average discharge have the lowest average turbidity. This suggests that the monitored Fowl River sites have limited sources of turbidity so that elevated discharge events provide dilution, resulting in relatively low turbidity. Average turbidity for Fowl River at Half Mile Road (upstream, freshwater, fluvial part of the watershed) during the 2014-15 assessment was 34 NTU.

Average turbidity for the 2018 assessment was 15 NTU for site FR3 (upper estuary), 14 NTU for site FR2 (mid-estuary), and 21 NTU at site FR1 (lower estuary). Turbidity at sites FR2 and FR1 is significantly impacted by tides and stratification of salt and fresh water that causes higher turbidities to remain near the bottom. Average turbidity for near-surface stations was 13 and 17 NTU, respectively, while the near bottom stations were 15 and 25 NTU, respectively. The impact was greater during periods of lower discharge, where average turbidity for site FR1 on August 2, 2018, for near surface stations was 7 NTU, while the near bottom stations were 22 NTU (Figure 2). Stratification of turbidity in estuarine environments has been addressed in

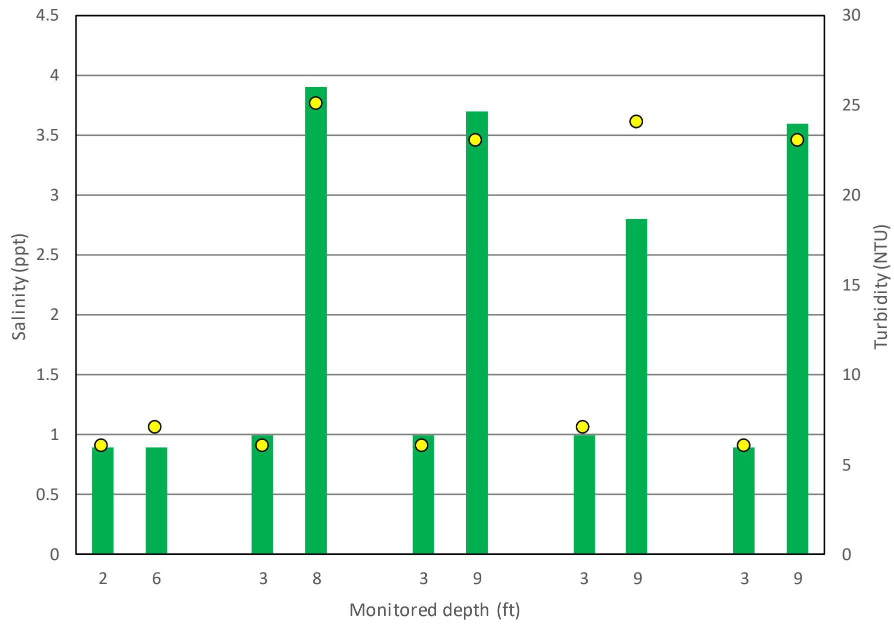

Figure 2.—Example of stratification impacting turbidity and salinity at site FR2 in the Fowl River Estuary.

numerous studies that demonstrated suppression of turbulence and vertical distribution of sediment by stratification. These studies also demonstrated that salt water intrusion in an estuary creates a trapping mechanism that reduces turbulent mixing and keeps suspended sediment near the bottom. This is an important concept that explains, at least in part, that adequate quantities of sediment are unavailable for marsh accretion in the Fowl River estuary.

Sediment transport and loading

Sediment loads in streams are composed of relatively small particles suspended in the water column (suspended sediment) and larger particles that move on or periodically near the streambed (bed sediment). A pre-monitoring assessment of sediment characteristics in the upstream, fluvial part of the watershed in 2014 indicated that relatively little bed sediment was present in the streams at selected Fowl River monitoring sites. Therefore, total sediment loads for the 2014-15 assessment were assumed to be primarily suspended. Water depth and tidal impacts prevented any attempt to quantify bed sediment transport in the estuarine part of the watershed during the 2018 assessment. Therefore, most sediment transported in the estuary was also assumed to be suspended.

Annual suspended sediment loads were estimated for Fowl River monitored sites using the computer regression model Regr_Cntr.xls (*Regression with Centering*) (Richards, 1999). The program is an Excel adaptation of the USGS seven-parameter regression model for load estimation in perennial streams. The regression with centering program requires total suspended solids (TSS) concentrations and average daily stream discharge to estimate annual loads.

Results of the 2014-15 assessment show that Fowl River at Half Mile Road had an estimated suspended sediment load of 795 t/yr. For comparison, the largest suspended sediment load in the Dog River watershed was Eslava Creek (site 10) with 10,803 t/yr. Sediment loads at monitored sites FR3, FR2, and FR1 (upstream to downstream) for the 2018 assessment were

361, 392, and 3,120 t/yr, respectively. Note that the load estimated for the Fowl River at Half Mile Road site in the 2014-15 assessment (795 t/yr) was 55% greater than the load for site FR3 (Fowl River Road), even though site FR3 is downstream and has a 61% larger drainage area. This is due to a flood event in mid-July 2014 that lasted several days and yielded a maximum average daily flow of 1,420 cfs, which was 80% higher than the maximum average daily flow at the Half Mile Road site for the 2018 assessment (289 cfs). This supports the conclusion by Cook (2015), that the vast majority of sediment transport occurs in the Fowl River Watershed during a few large discharge events.

Normalizing suspended loads to unit watershed area permits comparison of monitored watersheds and negates the influence of drainage area size and discharge on sediment loads. The Fowl River at Half Mile Road site had an estimated normalized sediment load of 52 t/mi^2/yr, determined during the 2014-15 assessment. Normalized sediment loads estimated for the 2018 assessment for estuary sites FR3, FR2, and FR1 were 9.4, 7.9, 52 t/mi^2/yr, respectively. For comparison, the largest normalized suspended sediment loads in the Dog River watershed was Spencer Branch (site 2), with an estimated normalized load of 4,332 t/mi^2/yr.

Without human impact, erosion rates in the watershed, called the geologic erosion rates, would be 64 t/mi^2/yr. Normalized sediment loads for the Fowl River at Half Mile Road site estimated during the 2014-15 assessment and all three estuary sites in the 2018 assessment were below the geologic erosion rate. This is another indication that the watershed is most likely sediment-starved, and adequate sediment for marsh accretion is not available.

Percentages of organic and inorganic material in suspended sediment provides information about the origin, composition, and depositional history of a water body. The percentage weight lost on ignition gives a crude measure of the organic content of sediment. Lost-on-ignition results document decreasing organic material from upstream to downstream in suspended sediments in the Fowl River estuary. On average, 41% of suspended sediment was lost on ignition in samples collected at site FR3 (upper estuary), 34% was lost from samples collected at site FR2 (mid estuary), and 12% was lost from samples collected at site FR1 (lower estuary). This indicates that an increasing volume of organic material settles out of the water column as water flows from the freshwater, fluvial part of Fowl River watershed to Mobile Bay, resulting in bottom sediment in the mid- and lower-estuary dominated by organic-rich clay.

The composition of bottom sediment provides information about sediment transport, depositional patterns, and the availability of sediment for marsh accretion and sustainability. Therefore, bottom sediment samples were collected at 25 locations between monitoring sites FR2 and FR1 and at site FR3. Based on general lithologic field descriptions, an upstream to downstream depositional trend is observed, characterized by decreasing grain sizes and increasing volumes of clay and organic material.

Conclusions

Conclusions derived from evaluation of data in the 2014-15 and 2018 Fowl River sediment transport assessments are that the Fowl River Watershed is relatively rural and dominated by forests, wetlands, and marsh that limit erosion and transport of sediment downstream to the estuary. Estimated sediment loads, significantly below the geologic erosion rate, confirm that the watershed is sediment-starved. Evaluation of bottom sediment samples also confirms that coarse-grained sediment is limited, with deposition in isolated areas of the upper- and mid-estuary. Therefore, adequate sediment to sustain marshes in the estuary is unavailable. Additionally, stratification caused by tidal movement of brackish water upstream along the bottom of the estuary has effectively trapped much of the suspended sediment on and near the bottom, preventing overbank deposition of sediment and limiting material for marsh accretion.

Literature Cited

Richards, R. P., 1999. Estimation of pollutant loads in rivers and streams: a guidance document for NPS programs: Heidelberg College.

Fowl River Sediment Core Analysis

Project Report

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Project Description and Methodology

Fowl River can be described geologically as a retrograding, flooded river estuary. As sea level has risen over the past several thousand years, the sinuous channel meanders and freshwater wetlands of Fowl River have been inundated by the sea and replaced by a broad basin surrounded by salt marshes in the downstream reach. As sea level has invaded inland, so too has the ecotone and river base level. Therefore, freshwater and fluvial signatures within the ecotone (point bars, freshwater vegetation, etc.) are under constant threat of succession to estuarine signatures (mud flats, saltwater vegetation, etc.). While geomorphic evolution and ecological succession are natural processes, certain anthropogenic stressors including shoreline armoring, vessel traffic, changes in land use, sea level rise, and increased stormwater runoff may accelerate succession or lead to complete ecosystem collapse and loss of valuable marshland.

In order to understand and isolate the natural geologic factors involved in spit transition and marsh loss, a detailed recent geologic history of the priority spits and nearby channel was established through sedimentological and geochronological analyses of replicate piston core samples. A total of 16 cores were collected in and around the four priority marsh spits identified in the Fowl River Watershed Management Plan and at one downstream reference site (Figures 1 & 2). Following core collection, loss on ignition, grain size characterization, and radiocarbon/fallout radionuclide dating were employed to detect accretion changes over the past millennium. The lithological descriptions and dating enable a reconstruction of recent marsh accretion rates and channel depositional rates and provide information regarding the timing of natural depositional facies transitions.

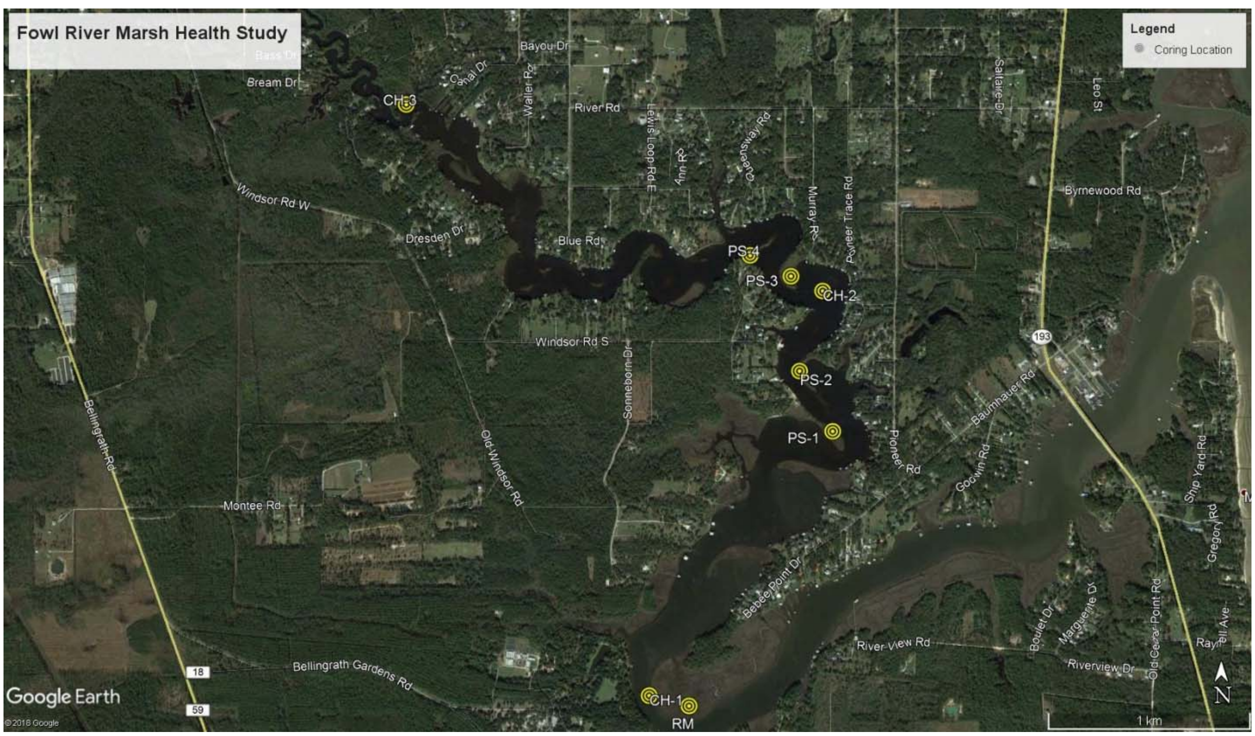

Figure 1. Site map indicating coring locations of priority marsh spits (PS-1, PS-2, PS-3, and PS-4), reference marsh spit (RM), and river channels (CH-1, CH-2, and CH-3).

Figure 2. Piston coring apparatus and undergraduate research assistants with freshly collected core from PS-1. Cores were immediately transported to the laboratory and frozen prior to sectioning and analysis.

Results and Findings

Marsh Core Lithology and Depositional Characteristics

Visual inspection of the marsh cores revealed unique and unexpected spatial differences, but very few vertical (i.e. temporal) differences. For the five pairs of cores collected from marsh spits (e.g. four priority spits and one downstream reference marsh spit), lithology was essentially dominated by either a dark brown, muddy peat with coarse, marsh plant macrofossils (PS-2, PS-3, and RM) or by a brown to black, organic rich sand with some coarse, deciduous plant litter (i.e. leaves and bark; PS-1 and PS-4). The visual lithological descriptions were further supported by grain size analyses (Figure 3) and loss on ignition (Figure 4) with the muddy peat containing higher percentages of organic carbon and lower percentages of sand and the organic sand containing lower percentages of organic carbon and higher percentages of sand. Subtle increases or "pulses" in percentages of sand were consistently observed between 5 and 10 cm below ground surface and again between 15 and 20 cm below ground surface in the majority of marsh cores. These "pulses" perhaps correspond to stochastic depositional events with tropical cyclones (e.g. Hurricane Frederic) and associated storm surges offering the most plausible explanation.

Other than subtle pulses and random fluctuations in percentages of sand and organic carbon, no apparent temporal changes or trends in lithology were noted, indicating stable depositional modes. The differences in lithology were largely spatial, suggesting that depositional modes amongst and perhaps within the spits are heterogeneous. A review of satellite imagery along with field observations recorded during coring reveals that the muddy peat sediment was associated with grassy marsh vegetation, submerged hydrosoil, and downstream banks of the marsh spits, while the organic rich sand was associated with deciduous vegetation, emergent hydrosoil, and upstream banks of the marsh spits (Figures 5 & 6). These findings provide evidence for a bi-modal depositional model for the marsh spits, with the downstream portions of the spits accreting predominantly autochthonous plant litter and the upstream portions of the spits accreting allochthonous coarse-grained sediment (i.e. sand) likely sourced as bedload from the river (Figure 7). This proposed model is in some ways similar to the more established coastal plain fluvial model with coarse-grained sand levees and deciduous vegetation located along river banks transitioning into marshy floodplains in the hinterland direction.

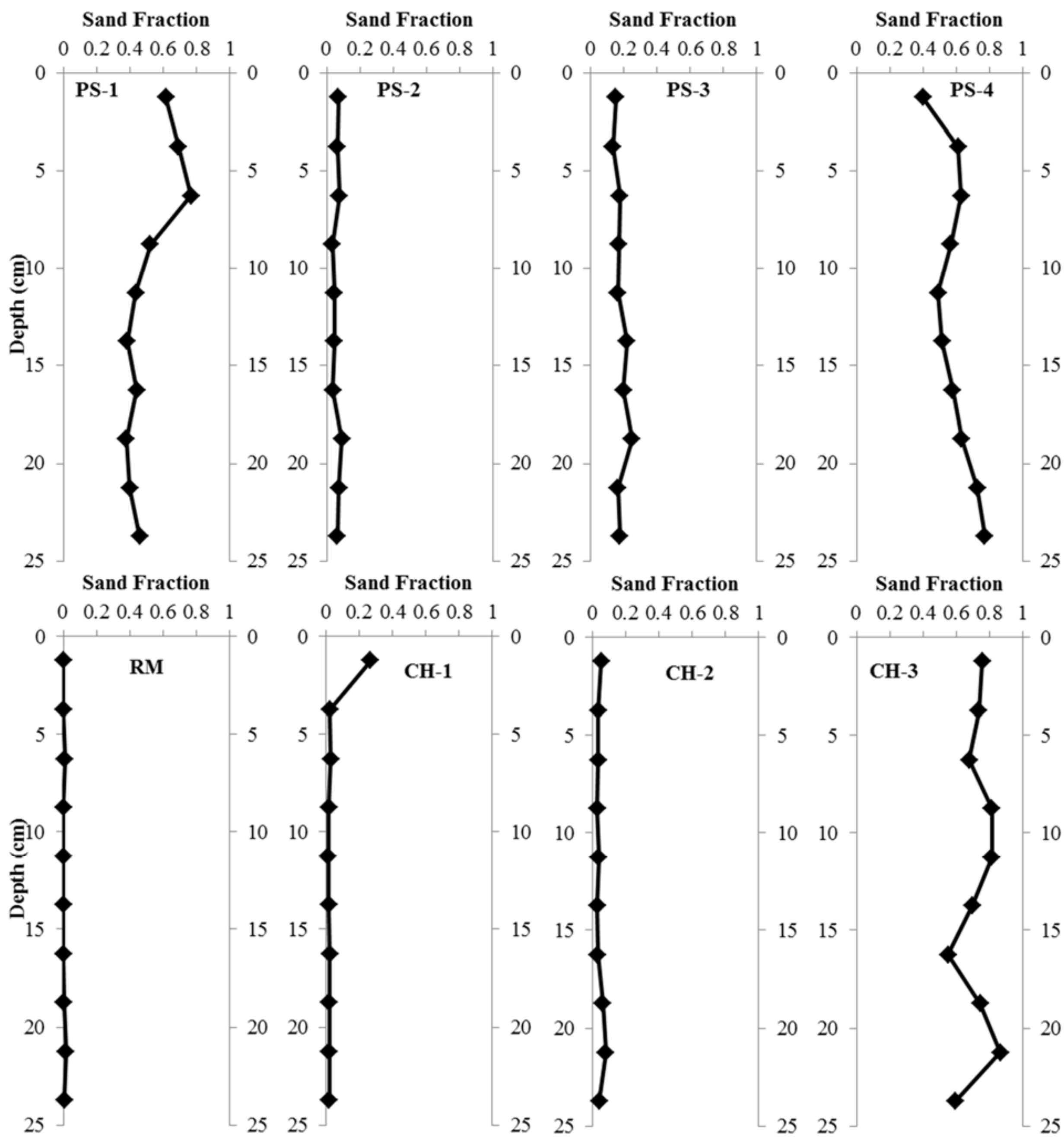

Figure 3. Sand fractions from the cores. PS-1 and PS-4 were visually described as organic rich sand and PS-2, PS-3, and RM were described as muddy peat. The channel cores (CH-1, CH-2, and CH-3) indicate a fining downstream trend, and CH-3 shows several sand "pulses" likely related to cyclones.

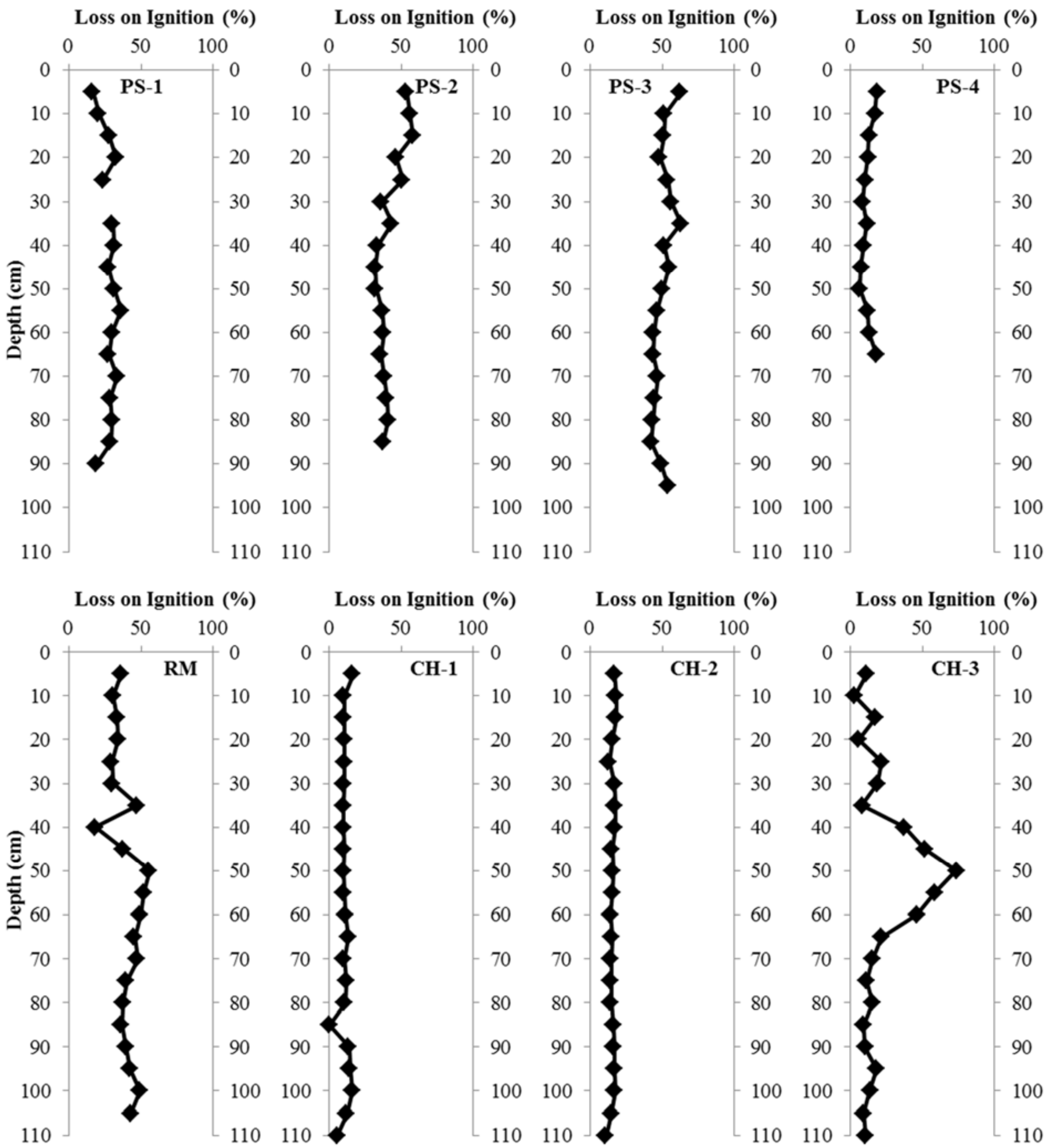

Figure 4. Loss on ignition (LOI) at 550 ºC (i.e. fraction of organic carbon) from the marsh and channel cores. PS-1 and PS-4 were visually described as organic rich sand and PS-2, PS-3, and RM were described as muddy peat. The low LOI anomaly at 85 cm in CH-1 was marked by a clean sand layer, and the high LOI anomaly from 40 to 65 cm in CH-2 was marked by an abundance of coarse wood fragments.

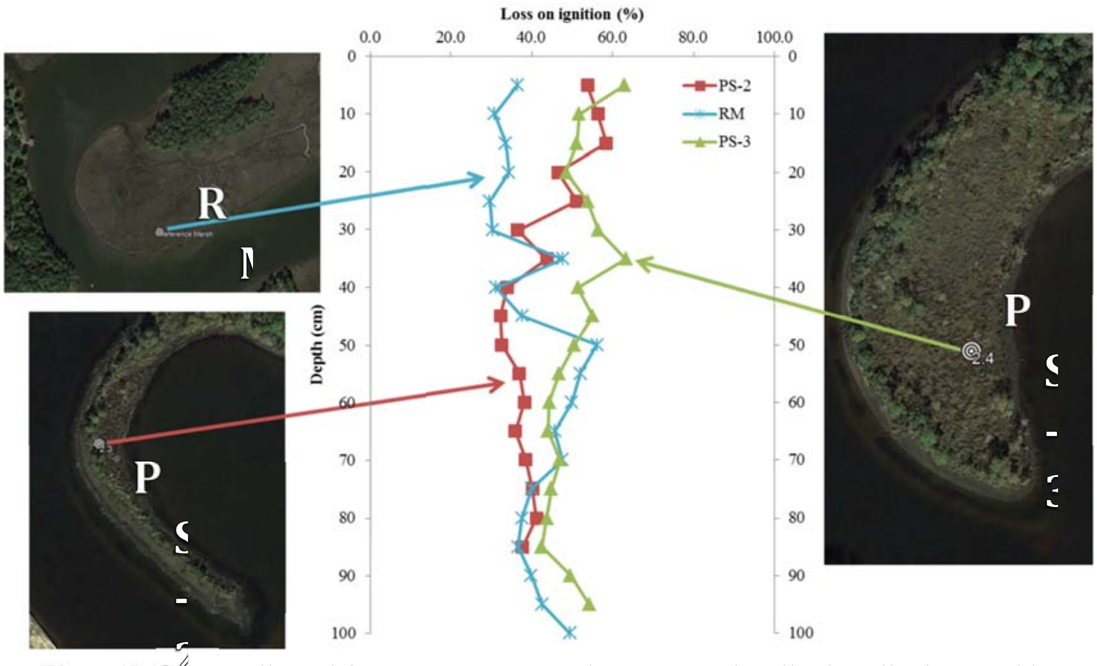

Figure 5. Cores collected from PS-2, PS-3, and RM were visually described as muddy peat and contained an abundance of organic carbon (> 30% LOI) and less than 15 % sand. Common characteristics among PS-2, PS-3, and RM were the presence of marsh vegetation, saturated and/or submerged hydrosoil, and downstream placements within the spits.

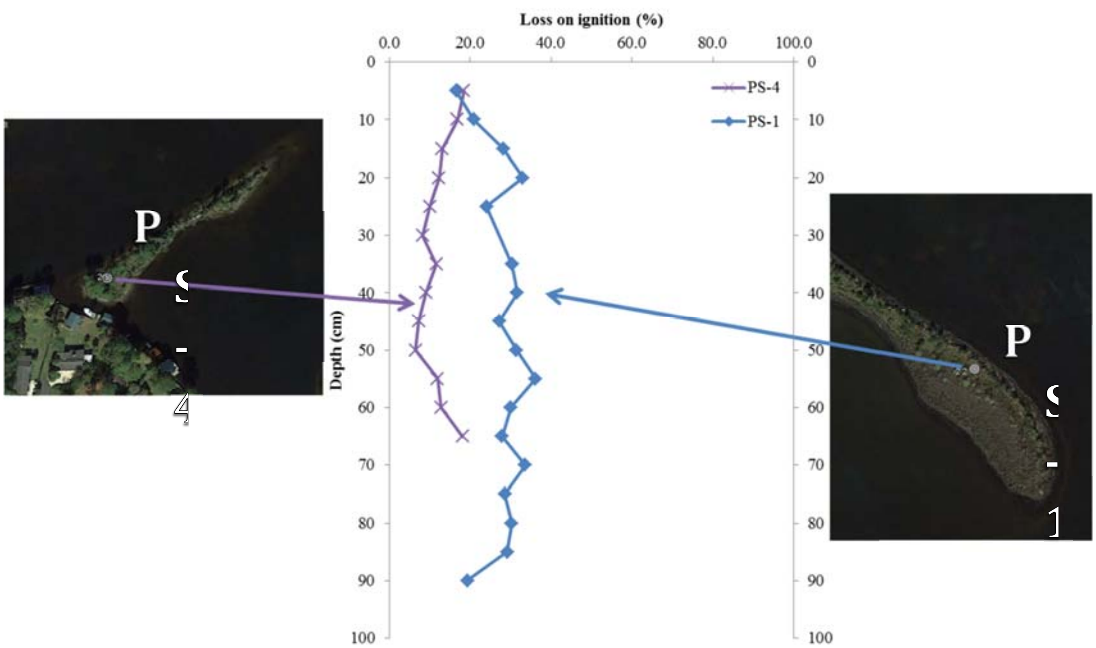

Figure 6. Cores collected from PS-1 and PS-4 were visually described as organic sand and contained an abundance of sand (> 35 %) and between 5 and 35 % LOI (i.e. organic carbon). Common characteristics among PS-1 and PS-4 were the presence of deciduous vegetation, emergent hydrosoil, and upstream placement within the spits.

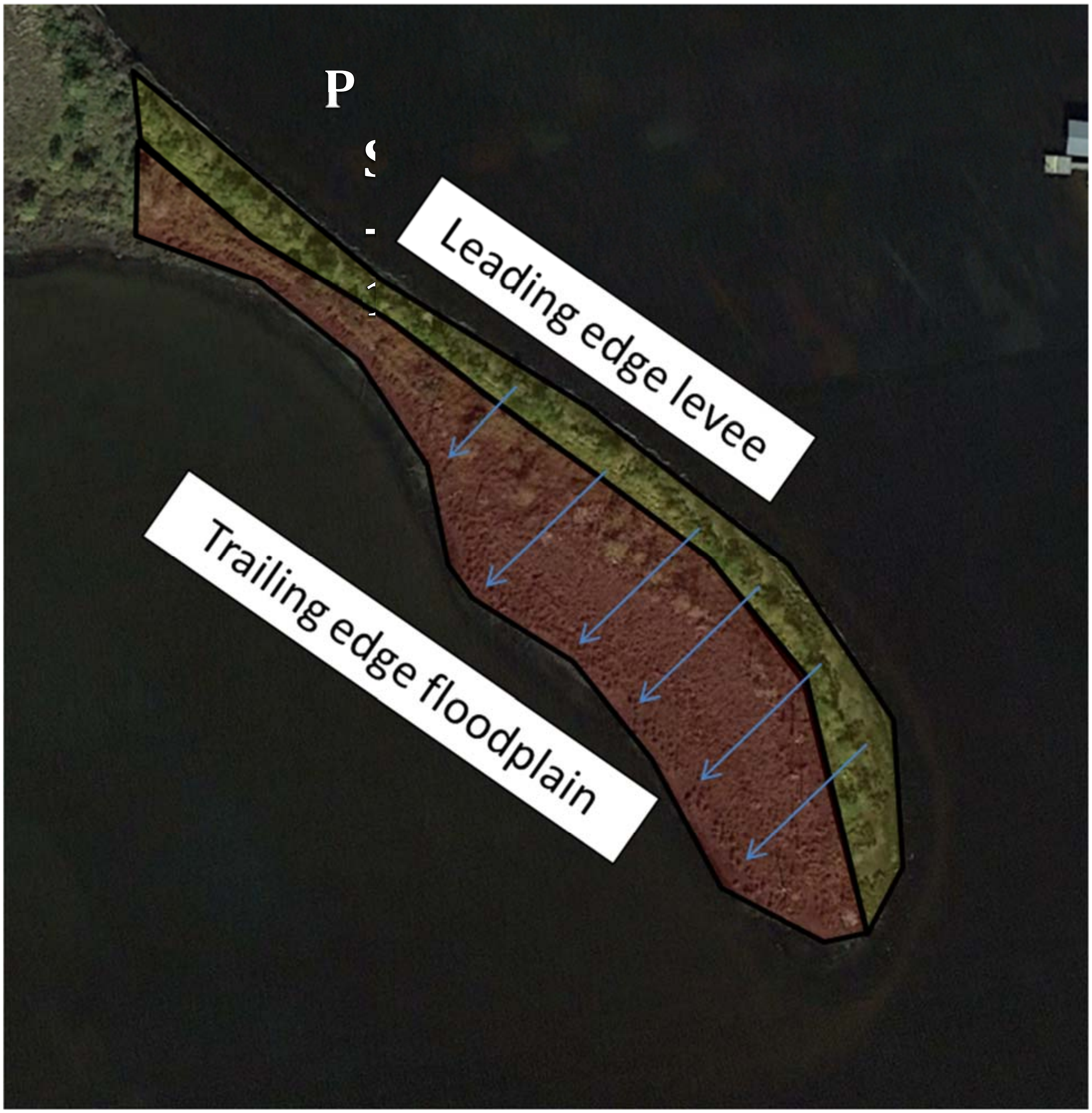

Figure 7. PS-1 with overlain proposed bi-modal depositional model for the Fowl River priority spits. The leading edge levee is characterized by emergent hydrosoil, deciduous vegetation, and organic rich sand and is similar in composition and geomorphology to a natural river levee. The trailing edge floodplain is characterized by submerged or saturated hydrosoil, marsh grass vegetation, and muddy peat and is similar in composition and geomorphology to a floodplain. With increasing sea level during transgression and resulting upstream migration of base level and deltaic deposition (i.e. retrogradation), leading edge levees will likely experience clastic sediment starvation, therefore autochthonous processes (i.e. marsh organic deposition) become increasingly more important in preventing marsh collapse (e.g. reference marsh). Furthermore, increased erosion of the leading edge levee due to anthropogenic activities will expose the trailing edge to erosional forces (e.g. boat wakes) and may disrupt fine (i.e. silt and clay) capture.

River Channel Core Lithology and Depositional Characteristics

Visual inspection of the channel cores revealed both spatial and temporal difference in lithology. In general, a fining downstream spatial pattern was observed, with an upstream brown to white, organic-rich to clean sand grading downstream to a dark brown to black, organic muck and estuarine mud (see Figure 3 for sand fraction and Figure 4 for LOI). This downstream fining trend is commonly observed from the head to the center of modern micro-tidal rivers and estuaries (Figure 8) due to decreasing depositional energy as channel area increases in addition to increasing fine organic and clastic sedimentation as rising salinity promotes flocculation and settling in the seaward (i.e. downstream) direction.

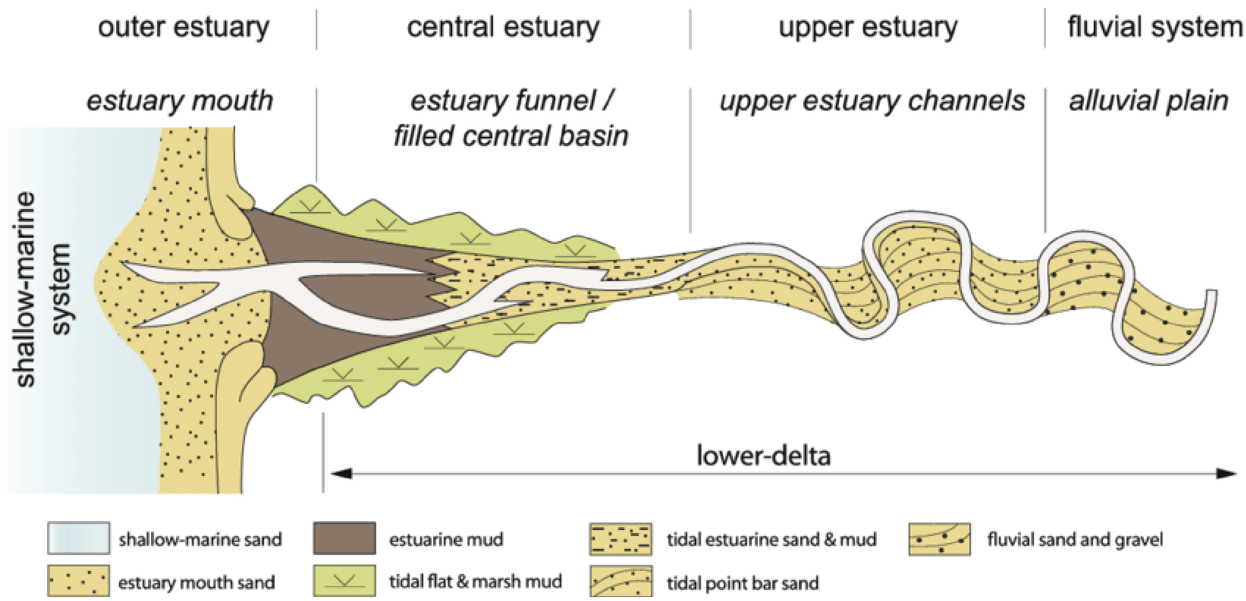

Figure 8. The Rhine estuary exemplifies commonly observed transgressive, micro-tidal estuarine geomorphology and sediment gradation from the hinterland to the sea (from Van den Berg et al., 2007). Of particular relevance to Fowl River is the downstream transition from coarse-grained fluvial sediment and sinuous point bars to a broad, relatively straight estuary dominated by estuarine mud.

Temporal changes in lithology were noted in the upstream and downstream channel cores (CH-1 and CH-3) indicating changes in depositional mode through time. Lithology of the downstream core (CH-1) consisted of brown to black organic mud to a depth of 90 cm underlain by a 2.5-cm bed of clean, coarse-grained sand (Figure 9). Underneath the sand and to the bottom of the core (110 cm), the sediment transitions into brown to black organic rich sand with some coarse, deciduous plant litter not unlike that seen in the marsh cores. Relying on observations of analogous, current depositional environments in Fowl River, these lithological changes can be interpreted as a transgressional sequence with depositional environments evolving from a deciduous environment (organic rich sand) to an unvegetated shoreline (clean, coarse-grained sand) to an estuarine mud basin (brown to black organic mud). The burial of deciduous sediment beneath estuarine mud suggests that marsh loss has occurred in the recent geologic history of Fowl River due to relative sea level rise, likely prior to human influence.

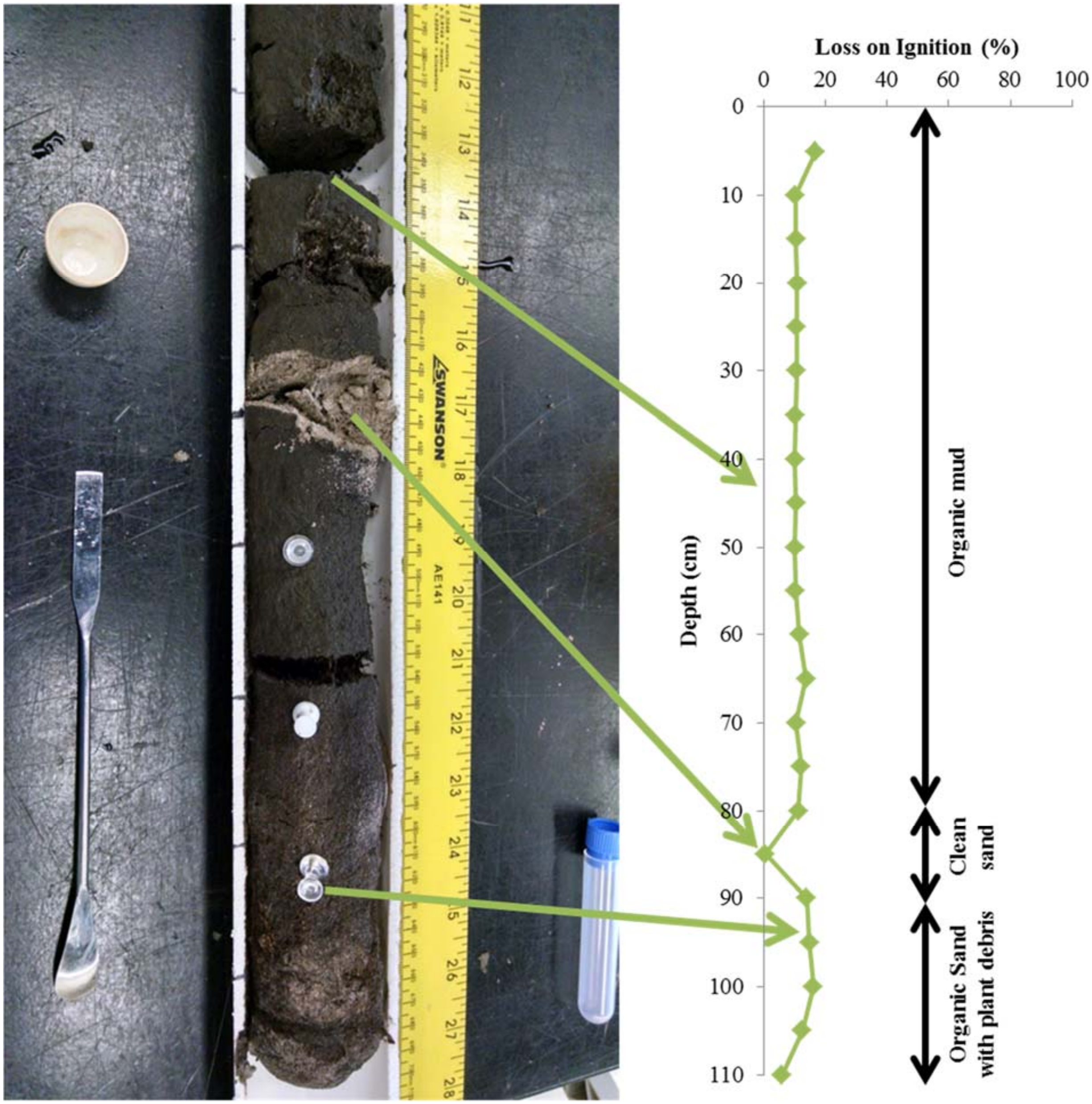

Figure 9. CH-1 core demonstrates a fining upward, transgression sequence. The bottom of the core contains organic rich sand with deciduous plant litter, not unlike sediment observed in PS-1 and PS-4. Overlying the organic sand is a clean, white sand similar in composition to the current shoreline of much of Fowl River. Above the sand is an organic mud, consistent with central estuary dynamics (Figure 8). A simple interpretation would suggest that CH-1 was once a terrestrial environment that was flooded during recent sea level rise. Radiocarbon dating of the organic sand at the base of CH-1 yields an age of 4,620 years BP (i.e. well before human development; Table 1), suggesting that marsh loss can be attributed to natural processes.

Channel core CH-3 also demonstrated temporal changes in lithology with an unusual and unexpected progressive increase in coarse, woody fragments from 35 to 75 cm below the seafloor surface (Figure 10). These coarse, woody fragments are angular in nature and nearly uniform in size, suggesting an anthropogenic source such as land clearing and development or lumber milling. A brief review of available historical maps indicates that several mills have been in operation in the Fowl River watershed since at least 1837 through the early 1900's. Although less notable in the visual inspection, a series of three anomalously clean, white sand beds lies immediately above the coarse, woody fragments (two can be observed at ~ 10 cm and 22 cm in Figure 3). These sand beds likely correspond to stochastic, rapid depositional events although the causes are uncertain. Rapid deposition may have been prompted by land development or clearing activities in the early 1960s and/or several tropical cyclones (e.g., Hurricanes Frederick and Ivan). Nevertheless, the presence of these anomalously clean sand beds suggests that depositional changes have taken place since the introduction of the coarse woody fragments, presumably post-development.

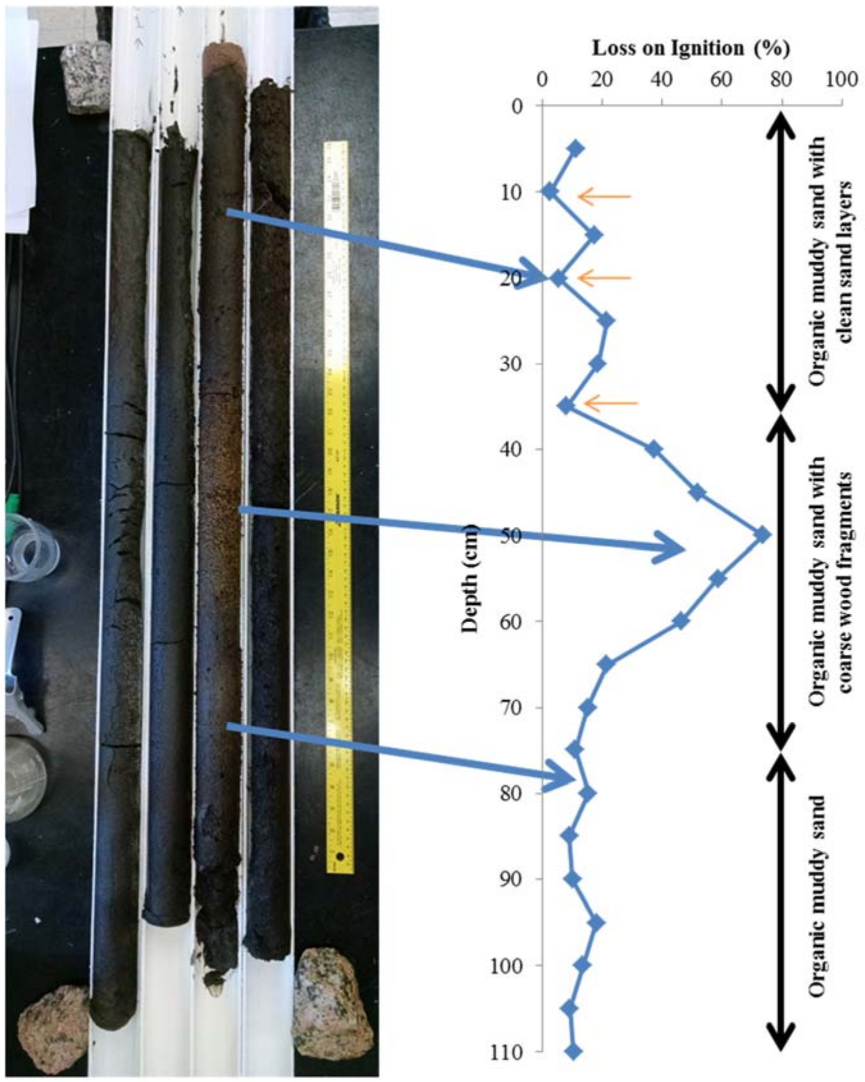

Figure 10. CH-3 shows temporal (i.e. vertical) changes in deposition. Among these changes are an abundance of coarse wood fragments from 35 to 75 cm that may be associated human activities (land clearing and/or lumber milling). Above the wood fragments, a set of three clean sand layers (arrows) suggests rapid deposition that may be related to land clearing and/or cyclone landfall (Figure 3).

Radiocarbon Geologic Net Accretion/Depositional Rates

Subsamples from the bottom core interval of each coring location were sent to Beta Analytics for plant macrofossil extraction (*i.e.*, humin fractionation) and radiocarbon dating. The results reveal marsh spit core bottom ages of up to 950 years from the time of collection, and channel core bottom ages of up to 4,690 years from time of collection (Table 1). A simple linear net accretion/deposition rate was calculated for each coring location by dividing the subsample depth by the radiocarbon date (adjust for years before 2018).

Table 1. Radiocarbon results and linear accretion/deposition rates.

Core location	Subsample depth (cm)	C^{14} age (years BP*)	2018 age (years)	Linear accretion/deposition rate (mm/yr)
PS-1	90	710	780	1.16
PS-2	85	680	750	1.14
PS-3	95	630	700	1.36
PS-4	65	590	660	0.99
RM	105	880	950	1.11
CH-1	110	4,620	4,690	0.23
CH-2	110	400	470	2.35
CH-3	90	1,220	1,290	0.70

* BP refers to years before the present carbon age (i.e. years before 1950).

Linear marsh accretion rates for the five marsh sampling locations (PS-1, PS-2, PS-3, PS-4, and RM) ranged between 0.99 and 1.36 mm/yr, averaged 1.15 mm/yr (σ = 0.13), and had a relative standard error of 5.2 %. The low relative standard error (0.052 ~ α of 0.05) demonstrates that there is very little difference between linear marsh accretion rates for the five marsh sampling locations, despite the differences in depositional mode evident in core lithology. This consistent accretion rate indicates that marsh accretion is governed by a common factor, likely the relative rate of sea level rise (i.e., the sum of eustatic sea level rise and local geologic subsidence).

Given that the rate of sea level rise has increased over the last 150 years, a linear regression through the five marsh radiocarbon ages vs. subsample depths was completed to determine pre-development, background "geologic" accretion rates (Figure 11). In essence, the regression offers a linear accretion rate between the measured subsample ages (i.e. 660 to 950 years before sample collection or between 1070 and 1360 AD) when sea level was relatively static. The accretion rate yielded by the slope of the regression (1.0 mm/yr; Figure 11) approximates the current local subsidence as indicated by the historical water surface elevation records from Dauphin Island (Figure 12). The intercept of the regression thus indicates an additional 8.5 cm of accretion in excess of subsidence that has occurred over the past 660 years. This additional 8.5 cm of accretion is likely prompted by the recent increase in sea level and suggests that the marshes are responding to sea level rise. However, eustatic sea level rise (2.74 mm/year) has exceeded 13 cm in just the last 50 years (Figure 12), suggesting that the marsh spits are not keeping pace with recent sea level rise and may be drowning in place. Observations from the field revealed that the grassy marsh portions of the spits were consistently flooded with approximately 5 to10 cm of water, further lending support to this conclusion. Given the geologic record of marsh flooding and burial observed in CH-1, the threat of marsh flooding in the priority spits is almost a certainty. However, during transgression, marsh loss along the shoreline can be offset by succession of hinterland terrestrial environments to marsh environments. In other words, the marshes should be considered dynamic ecosystems capable of migrating inland along with invading sea levels provided inland accommodation area is available.

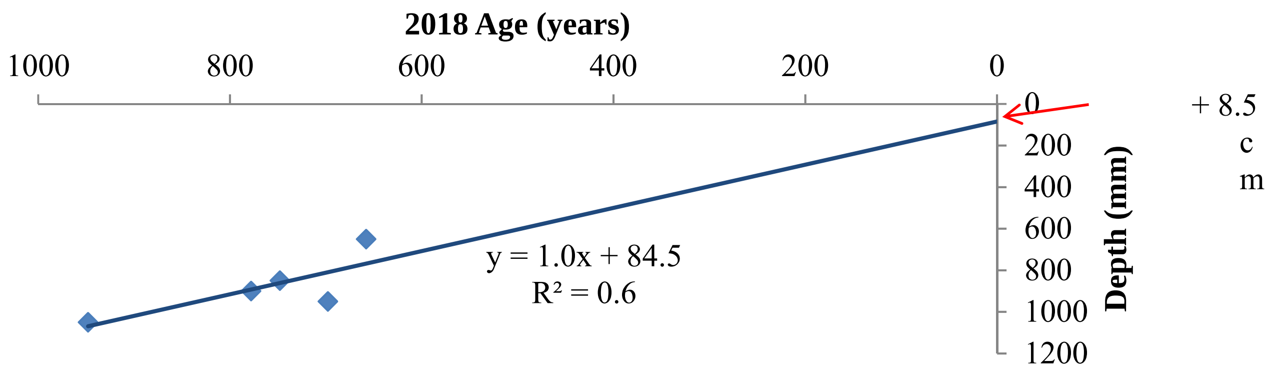

Figure 11. Regression of the marsh spit cores yields an average linear accretion rate of approximately 1.0 mm/yr between 1070 and 1360 AD when sea level was relatively static. The 1.0 mm/yr of accretion is likely necessary to keep pace with geologic subsidence. The intercept of 85 mm (8.5 cm) suggests that the marshes have accreted an additional 8.5 cm of sediment over subsidence within the last 600 years; however, eustatic sea level has risen by at least 13 cm in the past 50 years alone. This suggests that the marshes are not keeping pace with recent sea level rise.

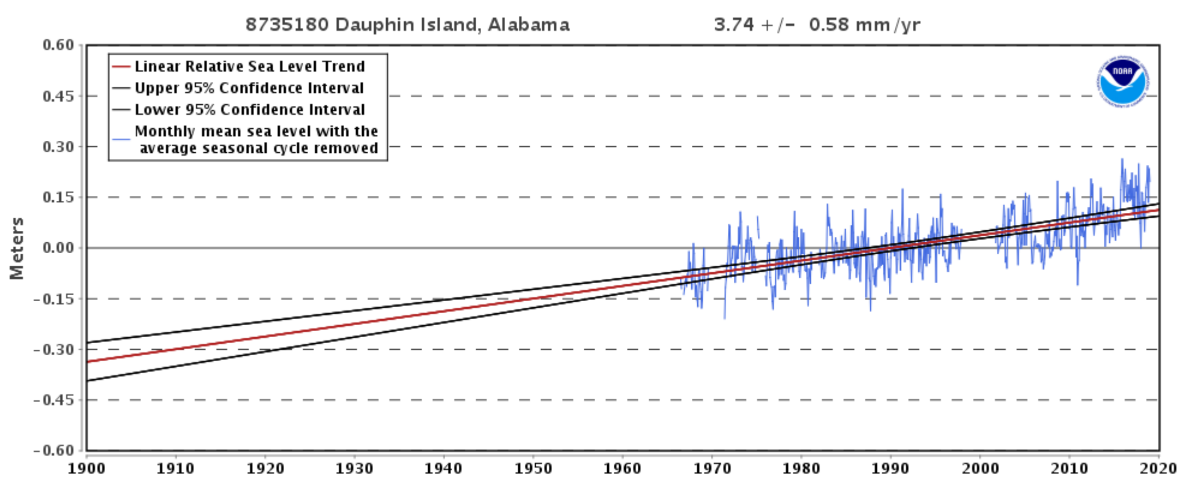

Figure 12. Relative sea level trend from Dauphin Island tide data (NOAA, 2019) indicates approximately 3.74 mm/yr of sea level from 1966 through 2019. Given a local subsidence of approximately 1.0 mm/yr (Figure 11), eustatic sea level rise is approximately 2.7 mm/yr or 13.5 cm over the past 50 years.

Fallout Radionuclide Accretion/Depositional Rates

The top 25 cm of cores PS-1, CH-2, and CH-3 were further analyzed using high purity germanium (HPGe) gamma-ray spectrometry to determine more recent rates of accretion and deposition from lead-210 (^{210}Pb) inventories assuming constant rate of supply and cesium-137 (^{137}Cs) peaks related to man-induced atmospheric releases of nuclear fission products. ^{210}Pb has a half-life of 22.3 years, making it a useful tracer for dating events up to 200 years before present, and ^{137}Cs is only replenished in the environment as a result of human activities (e.g. above ground atomic weapons testing through 1963 and the Chernobyl nuclear disaster in 1986) making it a useful anthropogenic tracer.

All three cores analyzed for fallout radionuclides demonstrate a clear exponential decay of ^{210}Pb with increasing depth (R^2 between 0.95 and 0.96; Figure 13) thus indicating limited erosion, bioturbation, and other disturbances. ^{137}Cs peaks were less useful in resolving timing, but rather serve to constrain ^{210}Pb data. The ^{210}Pb constant rate of supply model (Appleby and Oldfield, 1978) was applied to determine ages and accretion and deposition rates over the period of record (Figures 13 & 14).

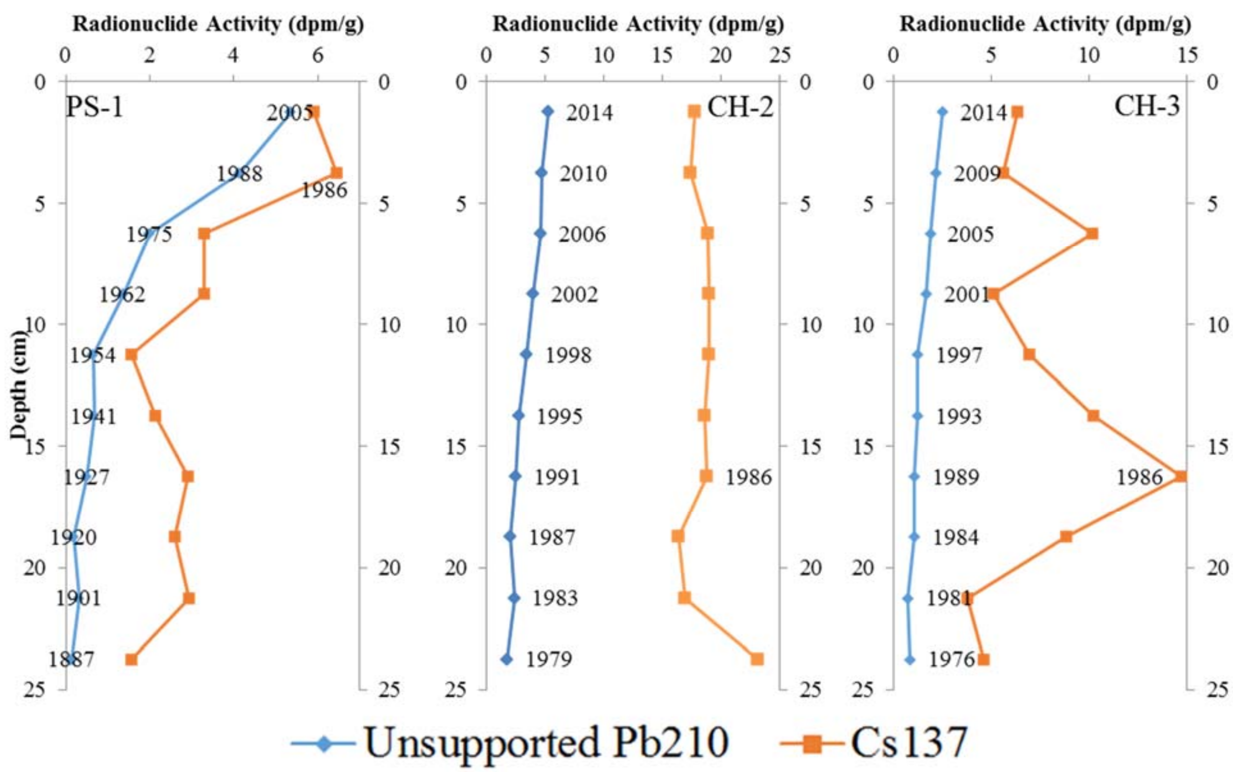

Figure 13. ^{210}Pb and ^{137}Cs activities (note different scales for activities) from cores PS-1, CH-2, and CH-3 demonstrate predictable exponential decay of ^{210}Pb and inconsistent ^{137}Cs. Dates from the constant supply rate model have been added to the ^{210}Pb data points and the qualitatively identified 1986 Chernobyl disaster peaks in ^{137}Cs provide additional constraint.

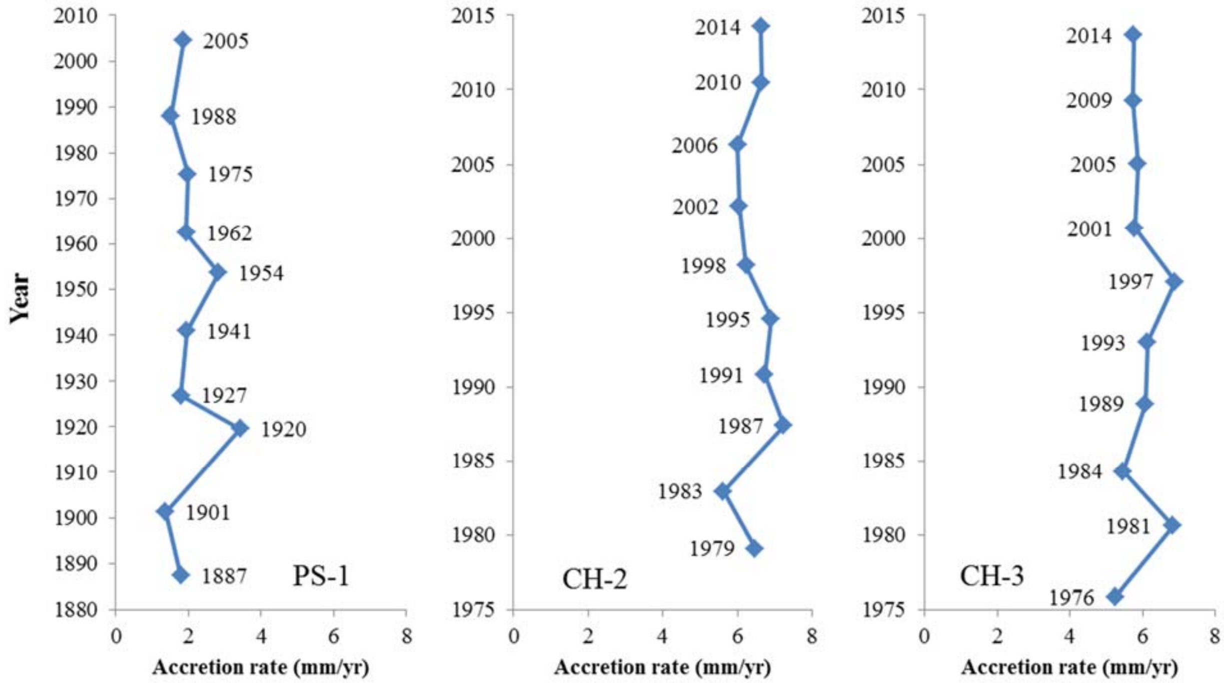

Figure 14. ^{210}Pb derived accretion and/or deposition rates for cores PS-1, CH-2, and CH-3 (note different scales for y-axis). PS-1 had a lower accretion rate and exhibited more variability than the channel core depositional rates (CH-2 and CH-3).

PS-1 had an average rate of accretion of 2.0 mm/yr over the past 131 years which is nearly twice the average marsh linear accretion rate determined from the radiocarbon ages (i.e. 1.15 mm/yr; Table 1). This suggests that PS-1 is experiencing a recent increase in accretion which may be explained by a response to the increased rate of sea level rise over the last century and a half and/or a decrease in compaction of the upper portion of the core due to more recent burial. In either case, the 2.0 mm/yr accretion rate is still below the relative rate of sea level rise of 3.74 mm/yr (Figure 12), further suggesting that the marshes are succumbing to sea level rise (i.e. sinking). The rate of accretion over the past century at PS-1 has not been constant, with two notable increases taking place in the 1920's and yet again in the 1950's (Figure 15). A likely explanation for these increases is a period of two development booms in Mobile County that would have led to increased sedimentation from land-clearing and stormwater runoff.

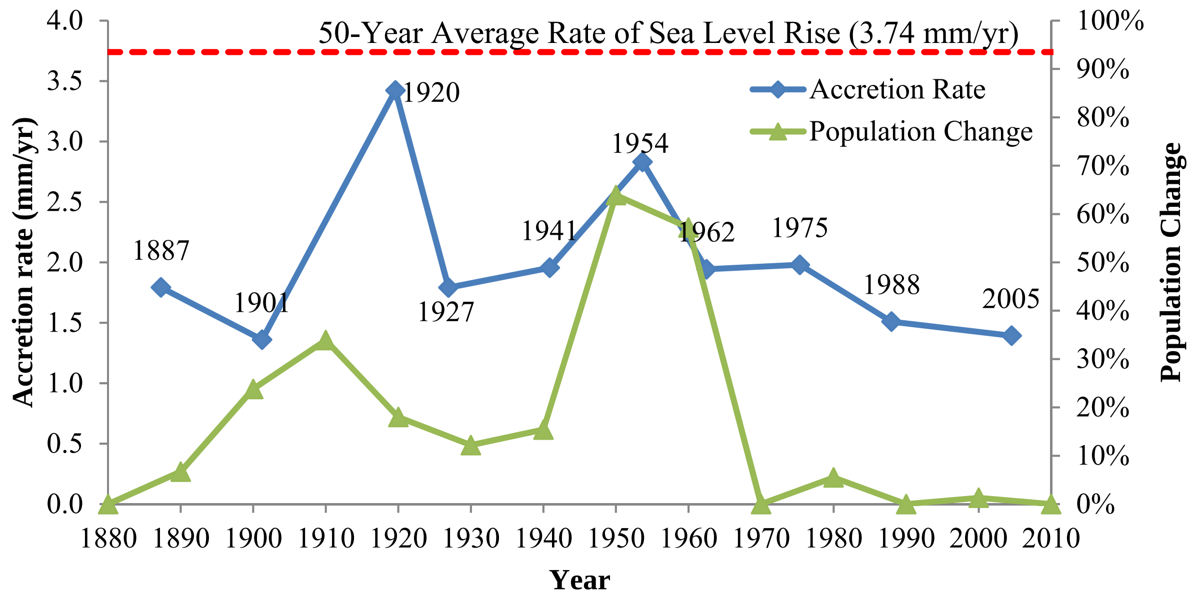

Figure 15. Accretion rates from the ^{210}Pb constant supply rate models for marsh core PS-1 dating back to the late 19th century reveal accretion below the relative rate of sea level rise. This evidence again suggests that the marshes are succumbing to the effects of accelerated sea level rise. Two periods of enhanced accretion are synchronous with large relative population increases in Mobile, suggesting that land clearing and development may affect sediment supply in the Fowl River marsh spits.

Conclusion

The results from core analyses provide evidence for a bi-modal depositional model of the Fowl River marsh spits (Figure 7). The model consists of a leading edge feature for marsh spits that is reliant upon sand for deposition, presumably sourced from river bed load. The leading edge protects the trailing marsh platform from erosive processes and is likely key for stabilizing marsh spits during transgressive geomorphic evolution and ecosystem succession. Therefore, plausible factors for marsh health decline include sediment starvation related to changes in land use, increasing erosion from boat wakes, and retrogradation associated with recent sea level rise. Furthermore, linear accretion rates derived from radiocarbon dating suggest that the marshes are not currently keeping pace with sea level rise and are essentially drowning in place (Figures 11 & 12). This is further supported by limited fallout radionuclide data which suggest that recent accretion has increased by nearly 75 %; however, the accretion rate over the last 131 years has remained well below the 50-year average relative rate of sea level rise (Figure 15).

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Fowl River Sediment Core Analysis

Project Report: Organic element analyses

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Project Description and Methodology

Fowl River can be described geologically as a retrograding, flooded river estuary. As sea level has risen during the past several thousand years, the sinuous channel meanders and freshwater wetlands of Fowl River have been inundated by the sea and replaced by a broad basin surrounded by salt marshes in the downstream reach. As sea level has invaded inland, so too has the ecotone and river base level. Therefore, freshwater and fluvial signatures within the ecotone (point bars, freshwater vegetation, etc.) are under constant threat of succession to estuarine signatures (mud flats, saltwater vegetation, etc.). While geomorphic evolution and ecological succession are natural processes, certain anthropogenic stressors including shoreline armoring, vessel traffic, changes in land use, sea level rise, and increased stormwater runoff may accelerate succession or lead to complete ecosystem collapse and loss of valuable marshland.

Changes in nutrient and hydrological regimes associated with anthropogenic land-use change often can be traced by measuring organic nitrogen (N) and carbon (C) content and stable isotope ratios that reflect inputs from human wastewater sources and distinguish marine from freshwater influences (Carmichael et al. 2005, Darrow et al. 2016). To determine if changes in Fowl River marsh structure or function may be related to changes in N and C sources associated with anthropogenic influences or variation in sea level through time, we measured N and C content in sediment core samples and suspended particular matter (SPM) in the water. A total of 16 cores were collected in and around the four priority marsh spits identified in the Fowl River Watershed Management Plan and at one downstream reference site (Figure 1). Water samples were collected monthly during January through October at eight collection sites (Figure 2) and filtered onto glass fiber filters to collect SPM. Sediments and filters were analyzed by continuous flow isotope ratio mass spectrometry at the UC Davis Stable Isotope Facility, yielding N and C stable isotope ratios and % N and C content in the samples. These data were aligned with elemental dating outputs to determine changes through time relative to land use and marsh area to help define sources and mechanisms of change.

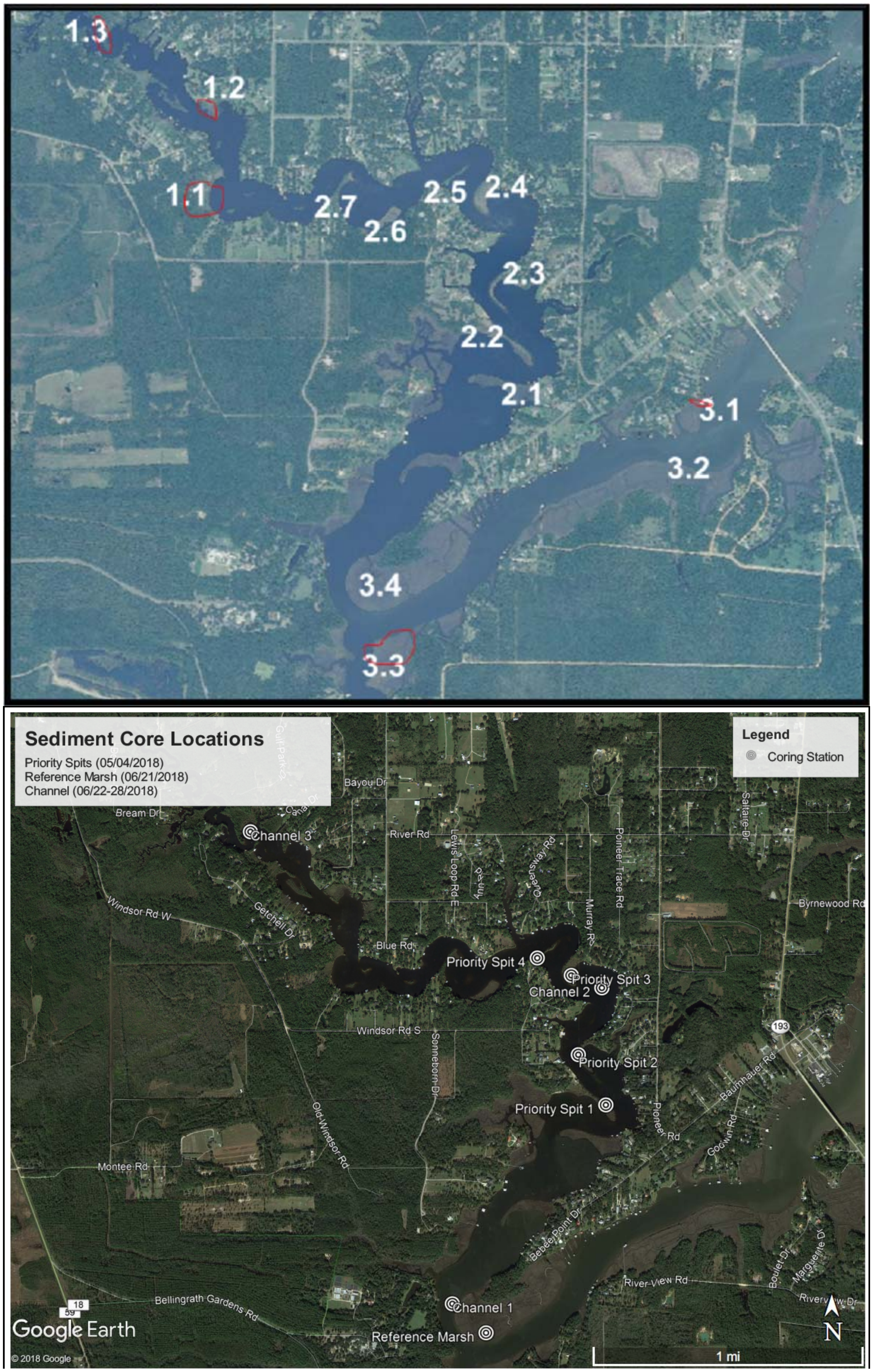

Figure 1. Project-wide sampling locations (top) and specific sediment coring locations, including priority marsh spits 1-4, reference marsh, and river channels 1-3 (bottom).

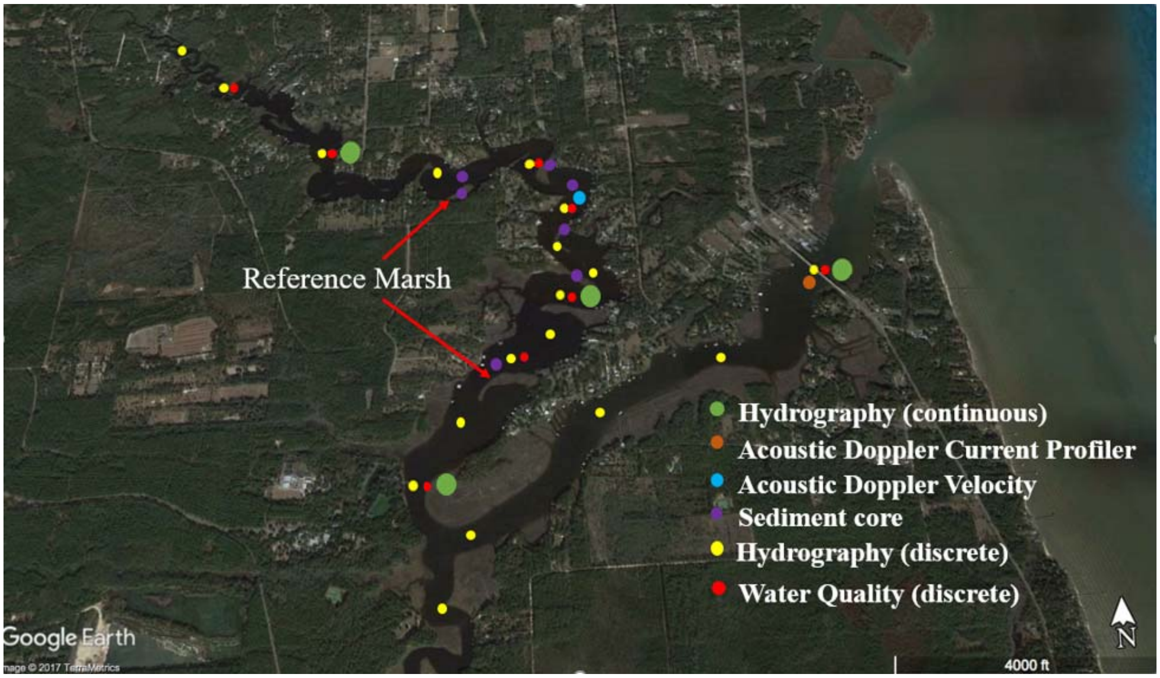

Figure 2. Water (suspended particulate matter; SPM) sampling locations (numbered sites).

Results and discussion

N and C stable isotope ratios in the reference marsh (site 3.4) and spits 2 and 3 (sites 2.3 and 2.4; Figures 1 and 3) showed distinctive changes with core depth between 20 cm depth and the surface, including an increase in N from ~1 to 5‰ and a decrease in C from -27.5 to -29‰. Assuming consistent sedimentation rates among sites, comparison to dates estimated for other sediments in this study (cf Beebe report) suggests the sediment depth of greatest change (20 to 7.5 cm) corresponds to the period from 1900 to 1960.

These findings are consistent with known changes in C and N stable isotope ratios in sediments due to increasing human influence in the Watershed, particularly shifts from primarily vegetated to residential or urbanized areas that are occurring worldwide (Carmichael and Valiela 2005, Vaalgamaa et al. 2013). Higher N stable isotope ratios are typically associated with processed human wastewater and lower carbon values are typical to terrestrial and freshwater influences. The isotopic shifts in Fowl River, therefore, are common to areas that have experienced changes from vegetated to urbanized or residential areas (with more impervious surface and channelized flow), which allow more direct delivery of terrestrial C and human wastewater and stormwater to local estuaries. Our results suggest these changes began in the early 1900s and continued most intensively through 1960 in the Fowl River watershed. These findings are consistent with results of similar studies in the Grand Bay, MS area (Darrow et al. 2016).

Unlike the reference marsh and spits 2 and 3, channels and spits 1 and 4 (Figures 1 and 4) did not show consistent or coincidental changes in C and N stable isotope ratios with sediment depth. These differences can be readily visualized as a lack of correlation between C and N stable isotope ratios at channel compared to spit sites (Figure 5). These findings suggest that channels do not intercept and retain land-derived organic matter as effectively as marsh. C:N values showed no clear pattern relative between channel and spit sites (Fig. 6).

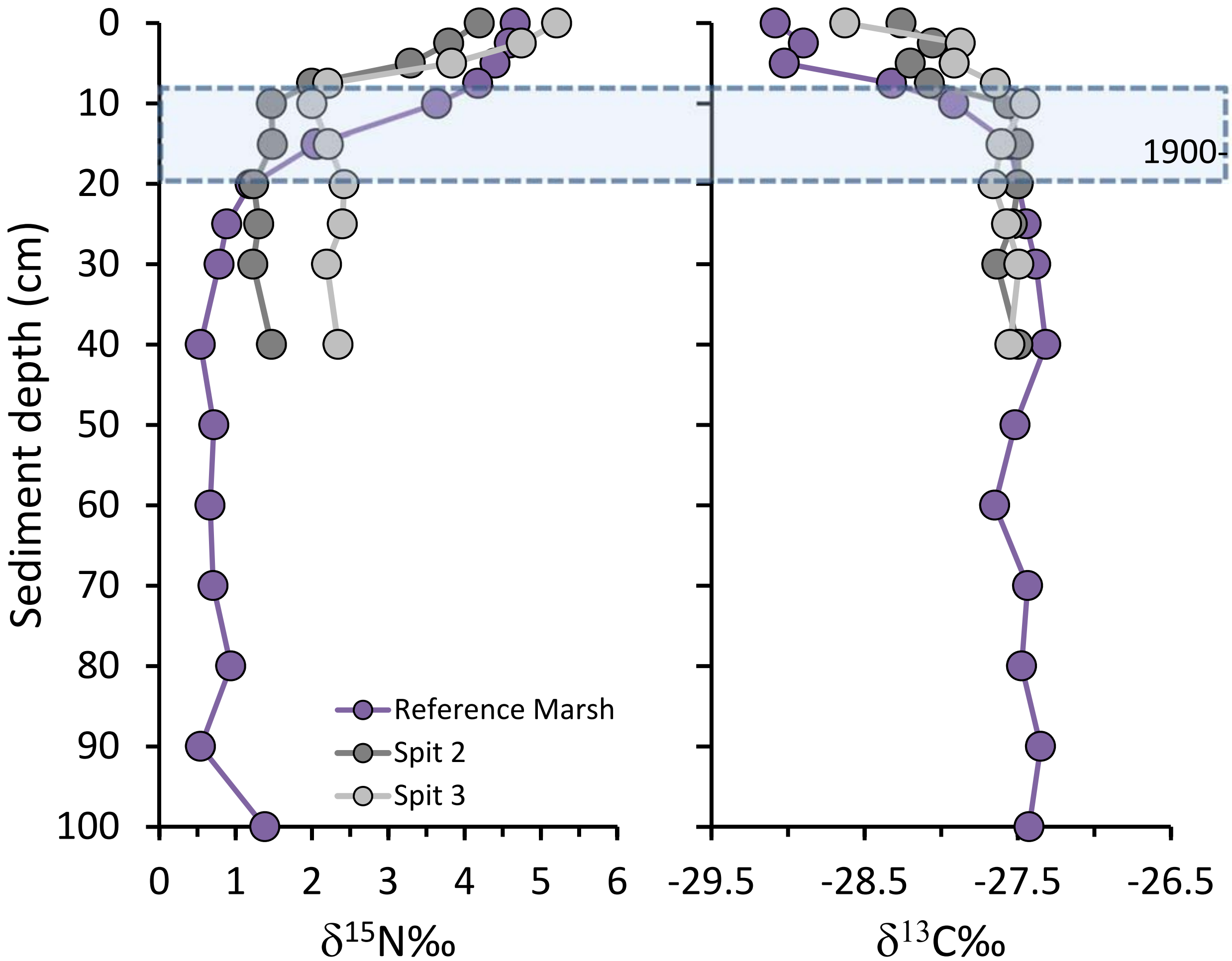

Figure 3. C and N stable isotope ratios in sediment core samples from the reference marsh and spits 2 and 3 (locations shown in Fig.1). Dashed box indicates the core depth likely to reflect organic material deposited from 1900 (~20 cm) to 1960 (~7.5 cm) based on dating data from this study (cf Beebe report).

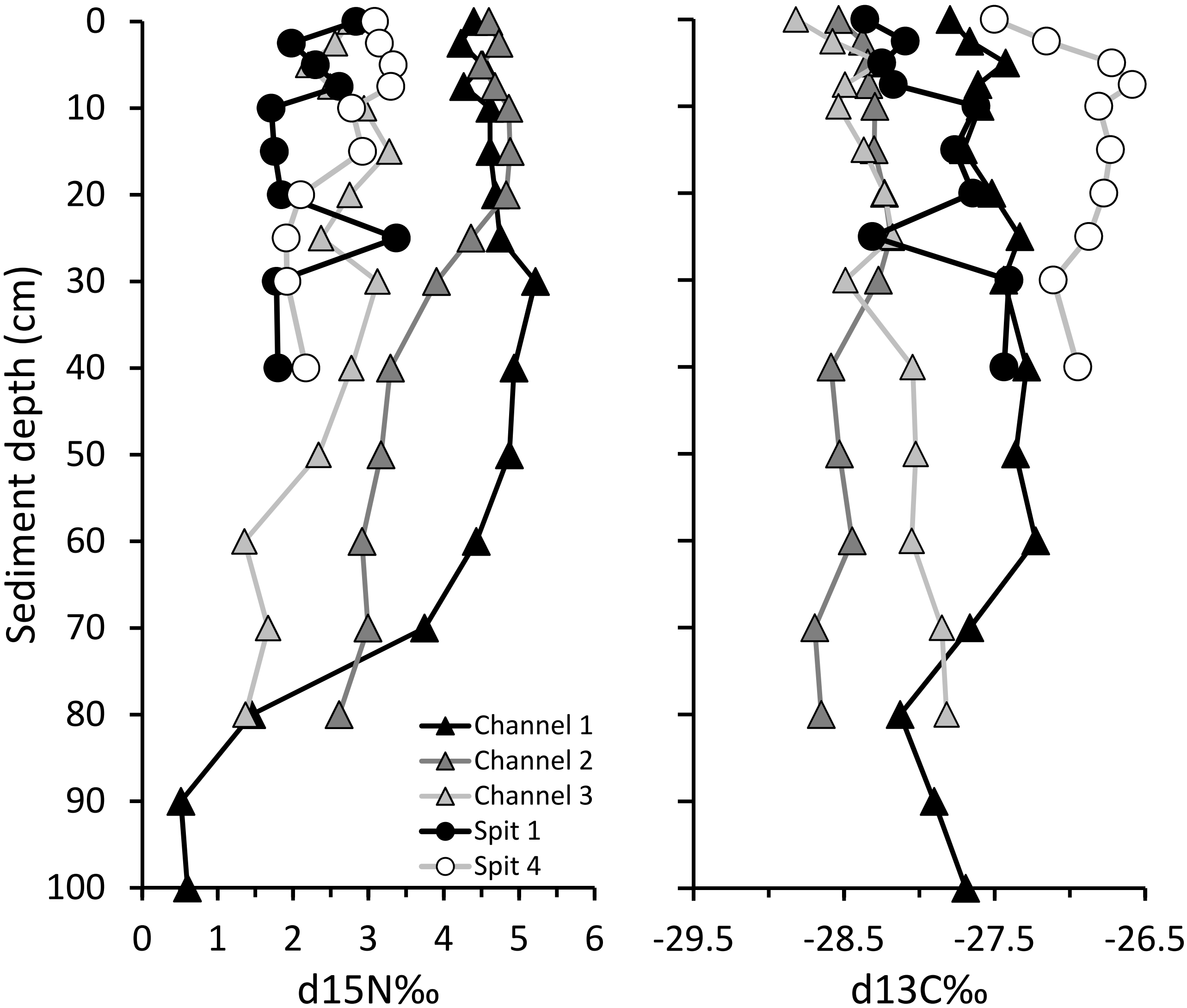

Figure 4. C and N stable isotope ratios in sediment core samples from channels 1-4 and spits 1 and 4 (shown in Fig. 1).

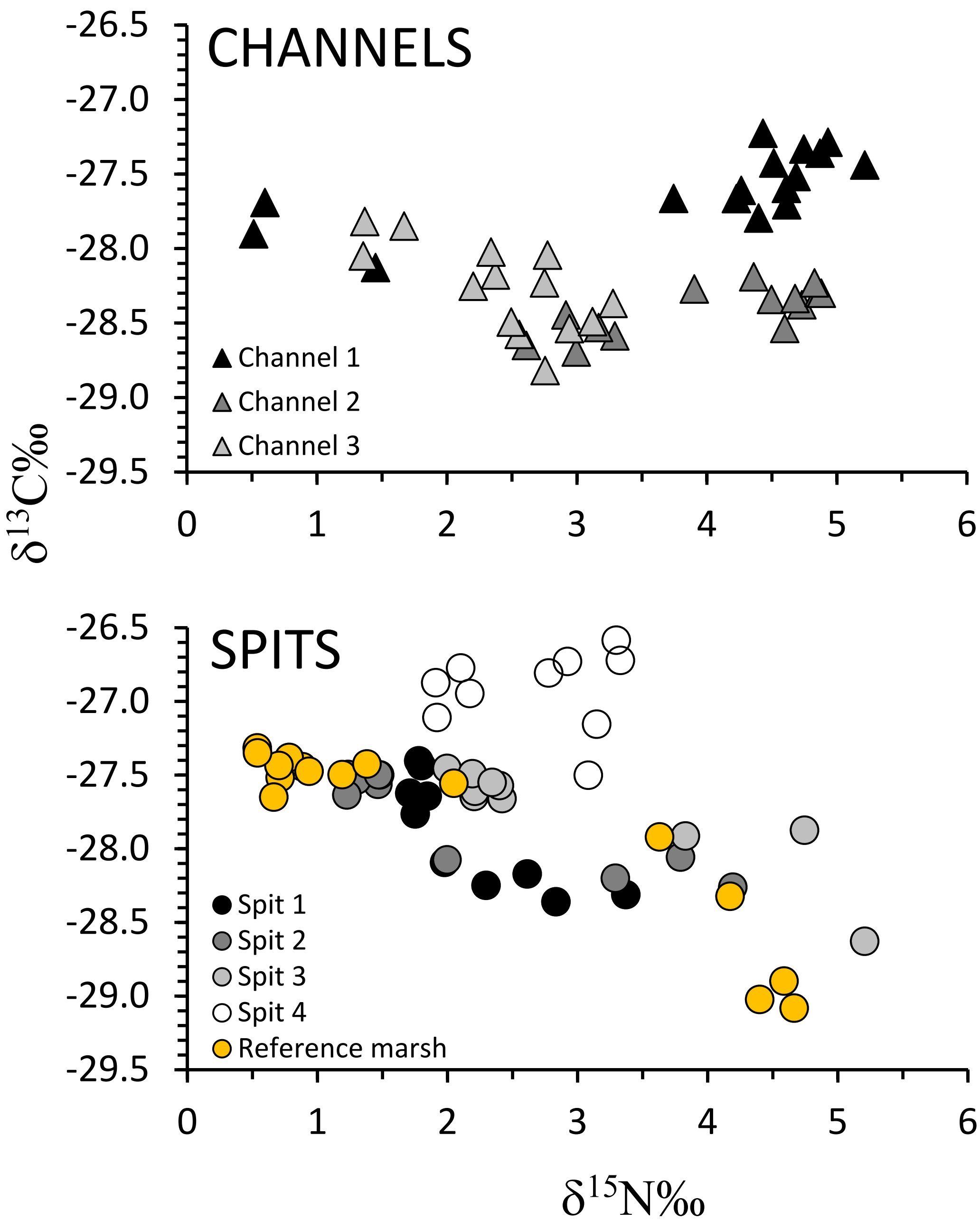

Figure 5. C and N stable isotope ratios in sediment core samples from all sites, separated by channels and spits (Spits: Pearson Correlation: $r = -0.52$, $p < 0.001$)

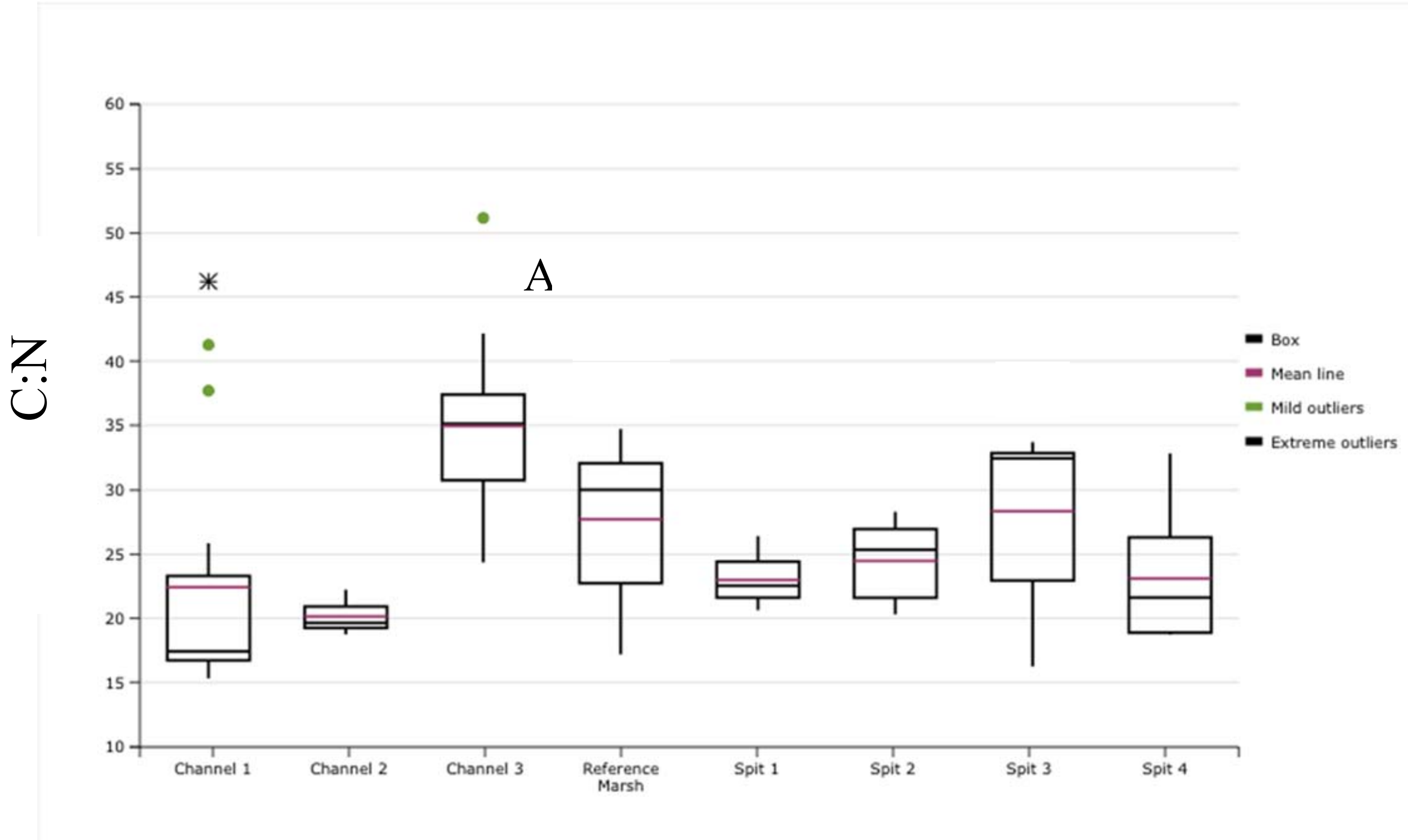

Figure 6. C:N values in sediment from channel, reference marsh, and spit sites in Fowl River.

C:N values in sediments showed no clear pattern between channel and spit sites (Figure 6; ANOVA: F8,91 = 6.94, $p < 0.001$; Tukey's post-hoc test: $p < 0.04$ for all comparisons). Two sites of highest C:N (reference marsh, spit 3) were among the sites that also showed down-core changes in C and N stable isotope ratios consistent with changes in urbanization through time (Figure 3).

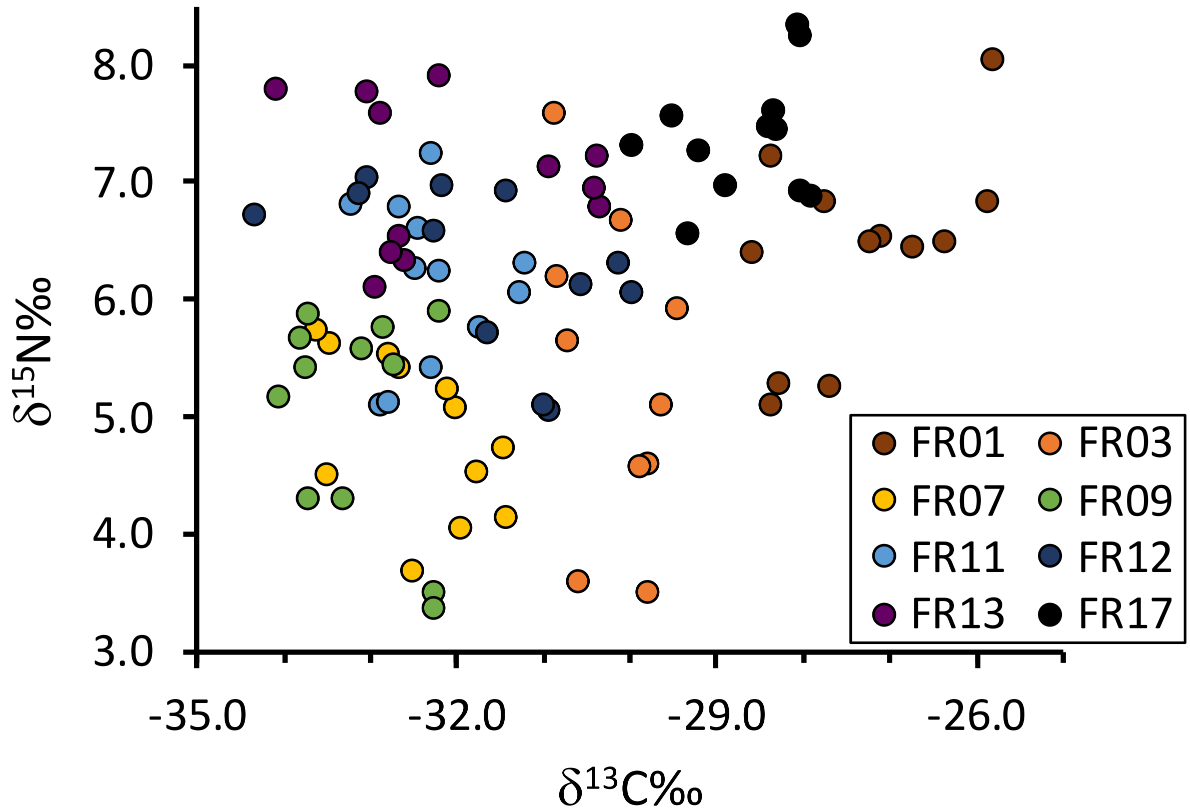

Figure 7. N and C stable isotope ratios in suspended particles from water at sites shown in Fig. 2.

Stable isotope ratios in particles suspended in the water column along Fowl River showed high variation in both C and N. C values reflected marsh and terrestrial vegetation sources (Cifuentes et al. 1988, Cloern et al. 2002). Sites 1 and 17 had the heaviest $\delta^{13}C$ values and were different from other sites (ANOVA: $F_7 = 59.03$, $p < 0.001$; Tukey's: $p < 0.02$ for all significant comparisons). Site 17 also had higher N values, while sites 3, 7, and 9 had lower N values than other sites (ANOVA: $F_7 = 11.91$, $p < 0.001$; Tukey's: $p < 0.03$ for all significant comparisons). The combination of C and N stable isotope ratios at these latter sites (3, 7, 9) suggest greater terrestrial and potential unprocessed human wastewater inputs to these areas (Cifuentes et al. 1988, Vaalgamaa et al. 2013). Of note, sites 7 and 9 are adjacent to spit site 3 at which core samples also indicated changes in stable isotope ratios through time, coincidental with timing of urbanization. Samples did not show significant or ecologically meaningful differences by month or between top and bottom sampling locations within the water column.

Conclusions

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Hydrologic and Hydrographic Component

A Hydrologic and Hydrographic Subgroup examined the processes controlling water surface elevation, salinity, and nutrients in the estuary and how these processes are related to marsh spits. In the first of three reports, Dr. Bret Web and Dr. Stephanie Smallegan investigated the impacts of waves and boat wakes on the degraded marsh spits. In the second report, Dr. John Lehrter and Alexis Hagemeyer characterized estuarine surface water and marsh porewater variables that may be related to observed changes in marsh spit shorelines and vegetation. In the third report, Dr. Brian Dzwonkowski and Jeff Coogan focused on salinity dynamics due to the potential ecosystem implications associated with changing salinity exposure on marsh platform vegetation.

Characterization of Impacts of Waves and Boat Wakes on Marsh Spits in the Transitional Zone of Fowl River

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April 2019

Boat Wake Characteristics

The boat wake magnitudes in Fowl River are typically small and well below the often-cited Roland and Douglass (2005) threshold for wave tolerance of saltmarsh vegetation (i.e., H_s < 0.3 m). However, this is only strictly true for the more extreme conditions and our measurements show that the frequency of boat wakes may play an important role in the ongoing degradation of marshes and land spits in Fowl River.

Overview

Fowl River experiences substantial pressure from recreational boating (i.e., fishing, tow watersports, personal watercraft, pleasure boaters). The wakes generated by these recreational boats have been cited as a factor contributing to the degradation of marshes and spits within the study area. To that end, boat wake characteristics were sampled at a number of locations, nearly continuously, from May through October 2018. These measurements allow us to characterize the magnitude and frequency of boat wakes impinging on shorelines. The results of these analyses provide some of the information needed to develop appropriate strategies for shoreline stabilization. A brief summary of the gauge deployments, results, and conclusions follow.

Deployment Information

Boat wakes in Fowl River were measured using pressure gauges manufactured by RBR Global. Six RBR Solo and four RBR Virtuoso gauges were utilized in the study. The six RBR Solo gauges sampled pressure at a frequency of 8 Hz. The four RBR Virtuoso sampled pressure at a frequency of 6 Hz (maximum possible). The six RBR Solo gauges were deployed at long-term locations for the duration of the study period: one at each target location, one at a reference marsh in the "coastal" zone, and one at a reference marsh in the "freshwater" zone. The four RBR Virtuoso gauges were deployed for shorter durations at each of the target spits. This deployment strategy resulted in both long-term, longitudinal measurements throughout the study area and shorter-term but higher resolution measurements at the spits targeted for restoration. The deployment locations are shown in *Figure 2*. In that figure, each yellow "bullseye" symbol denotes a deployment location during the study period. The bullseye symbols encircled by the larger hollow circle represent the long-term deployment locations of the six RBR Solo gauges.

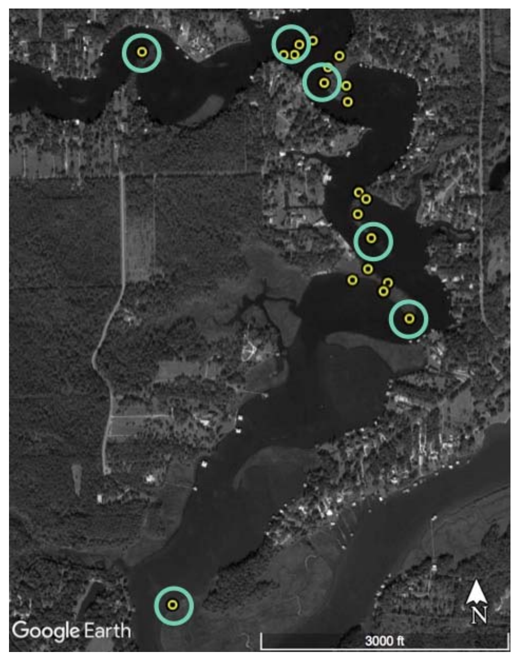

Figure 2. Wave Gauge Deployment Location Map

The deployment dates, corresponding data durations, and target (short-term deployment) spit locations are summarized in *Table 1*. All ten gauges were used in Deployments 1 and 2. Only nine gauges were used in Deployments 3 and 4 due to mount failure in the field. For the duration of the study, the six RBR Solo gauges remained at their respective locations. Only the four RBR Virtuoso gauges were relocated during the study period. The "target spit" location identified in *Table 1* denotes the location of those four (or three) RBR Virtuoso gauges during each deployment.

Table 1. Wave Gauge Deployment Dates and Durations

Deployment	Dates	No. Days	No. Gauges	Target Spit
1	5/24/18-6/13/18	20	10	Closing Hole
2	6/14/18-7/11/18	27	10	Tapia
3	7/17/18-8/24/18	31	9	Lightcap
4	8/30/18-10/19/18	34	9	Strout

Each gauge was deployed vertically on its own mount fabricated using PVC pipe. The pressure sensor was oriented downward, facing toward the bed, for every deployment. With few exceptions, the gauges were deployed such that their pressure sensors were within 20 cm of the bed. Gauges were typically deployed in water depths of approximately 1 meter. A number of ancillary measurements were taken during each gauge deployment and recovery, including:

- Sensor geographic location;
- Sensor elevation (relative to NAVD88);
- Water depth;
- Water temperature;
- Water salinity; and
- Water density.

Methods

The RBR gauges measure absolute pressure, which is the sum of atmospheric and gauge pressure. Gauge pressure is the sum of the hydrostatic (tide) pressure and the hydrodynamic (wave) pressure. Atmospheric pressure was removed from the absolute pressure measurements to yield a more accurate measurement of gauge pressure, and subsequently more accurate estimates of boat wake characteristics. For the purposes of this study, atmospheric pressure in Fowl River was assumed to be equal to that measured by the NOAA/CO-OPS station on the east end of Dauphin Island (Station 8735180). The NOAA/CO-OPS meteorological data were resampled from their native frequency of once every six minutes to 8 Hz or 6 Hz as appropriate.

Boat wake characteristics were estimated from the pressure measurements using linear wave theory and standard time-domain analysis techniques. These analyses resulted in estimates of individual wave height and period for each boat wake event. The records of wave height and period were further processed to yield statistical representations that are often used in coastal engineering design (e.g., significant wave height, average wave period, etc.). Statistical quantities representing the entire study period were coalesced from each deployment using a weighting equation based on the number of waves measured.

Results & Discussion

Selected statistical quantities for wave height and wave period are listed for each of the six long-term deployment locations in *Table 2*. The wave height and wave period quantities derived from the short-term deployments at Tapia, Lightcap, Closing Hole, and Strout were not substantially different from those listed in *Table 2*. However, there was a fairly clear pattern at most spit locations where wave heights were larger on the upstream sides of spits than on their downstream sides. The exception to this statement was Closing Hole, which exhibited larger wave heights on the downstream side of the spit.

Table 2. Summary of Boat Wake Height and Period Results

Location	No. Waves > 5 cm	H_s (cm)	H_{max} (cm)	T_{avg} (s)
Bellingrath	162168	11.8	65.0	1.68
Tapia	76881	11.3	39.8	1.49
Lightcap	57478	10.5	33.9	1.67
Closing Hole	84671	12.8	43.3	1.61
Strout	122087	12.2	62.0	1.50
Harrison Pt.	157098	14.6	88.0	1.45

The significant wave height (H_s)—the average of the largest one-third of the waves measured—at each location is well below the often-cited vegetation tolerance threshold of 33 cm (Roland and Douglass 2005). However, that tolerance threshold is a function of both wave height and frequency of occurrence as shown in *Figure 3*. Our measurements indicate that the tolerance threshold is exceeded at least 20% of the time at almost every deployment location, and up to 80% of the time at some of the deployment locations. So, while no location exhibits large significant wave heights, every site exhibits measurable wave action for long periods of time. A summary of the tolerance exceedance percentage values in the study area is provided in **Error! Reference source not found.**.

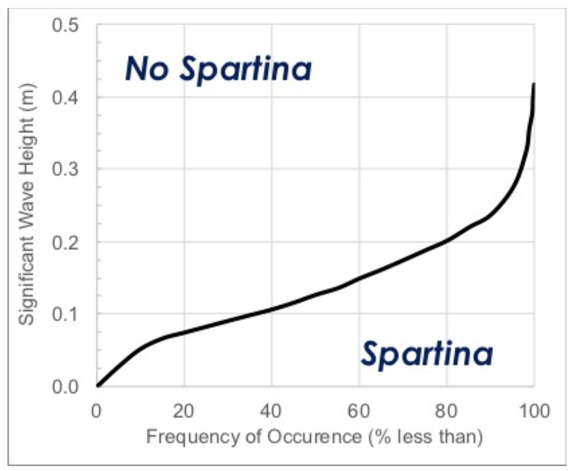

Figure 3. Simplified Wave Tolerance Curve

Conclusions

The deployment of pressure gauges in Fowl River during the period May – October 2018 provides the measurements necessary to characterize boat wakes in the study area during high-traffic periods. Recreational boating in the winter months tends to be less frequent. It is reasonable to assume that the potential for boats to generate wave heights and periods in the study area remains constant regardless of the season, but the frequency of boat wake events will generally be higher in the more temperate months of the year.

The analysis of boat wake characteristics has yielded a number of substantial conclusions:

- Almost 100% of the wave energy in the study area is attributed to boat wakes;
- Almost 100% of the boat wake events occur during the period 7:00 am to 7:00 pm;
- Significant wave heights are small and range from 8 cm to 18 cm;
- Average wave periods range from 1.4 to 2.5 s;
- Wave heights are generally larger on the upstream sides of spits; and

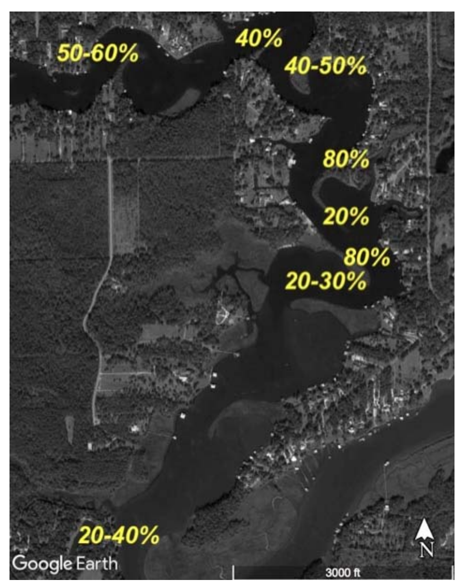

Figure 4. Summary of Tolerance Exceedance Values

- Significant wave heights routinely exceed the threshold for vegetation tolerance.

The boat wake measurements, particularly when combined with other data collected during the study period, provide important context that may inform restoration design in the future. For example, the relatively small but frequent wave heights suggest that the spits may require persistent wave attenuation in the form of edge protection. This edge protection could be achieved using appropriately designed sills or wave screens. Since the wave heights are typically small, the required stone size for a rock sill may be of a moderate size. Confined oyster shell could likely be incorporated into edge protection strategies. While many sills are low in elevation, an effective sill design in Fowl River may require a crest elevation above or close to mean high water. In the summer months, high tide occurs during the daylight hours when boat traffic is heaviest. Therefore, much of the frequent wave action occurs at high tide and the edge protection should continue to provide an appropriate amount of wave attenuation during those times.

Literature cited

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Fowl River Marsh Study – Hydrology and Hydrography

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Introduction

The objective of this component of the study was to characterize estuarine surface water and marsh porewater variables that may be related to observed changes in marsh spit shorelines and vegetation. For example, estuarine water surface elevation, salinity, and temperature play major roles in structuring the species composition and zonation of marsh plant communities (Eleuterius and Eleuterius 1979; Bertness 1991). Suspended sediment, organic matter, and nutrient inputs to a marsh are necessary to maintain sediment accrual rates at a pace equal to or greater than sea level rise (Stevenson 1986; Craft 2007). Thus, we conducted a study to observe the temporal and spatial patterns and variation in these variables in Fowl River. Quantifying these patterns is key to understanding how changes in hydrology and hydrography may be impacting the marshes in Fowl River. In the following sections we describe our methods, results, and conclusions. An overall conclusion is that the marsh spits are being impacted by several stressors, including sea level rise, salinity intrusion, and nutrient enrichment. We also measured widespread hypoxia ($[O_2] < 2$ mg L^{-1}) in the Fowl River estuary that may warrant separate management and restoration actions.

Methods

The Fowl River estuary has three distinct regions we used to facilitate comparisons along the river. Region 1 is the upstream region characterized by freshwater inputs from the watershed. Region 2 is a transition area between freshwater and more marine influence where the priority marsh spits are located. Region 3 is the most marine area connected to Mobile Bay and Mississippi Sound. The connection to Mississippi Sound is through an artificial canal that enters Fowl River where stations 13 and 14 are located (Figure 1). The borders of the regions are shown in Figure 1.

Sampling of the estuary was conducted from February 2018 to December 2018 with ten monthly surveys of the estuary. On these surveys, estuarine ranges and dynamics of salinity, temperature, oxygen, suspended sediments, organic matter, and nutrients were measured. Per survey, there were 18 hydrographic stations (Figure 1) for quantifying horizontal and vertical gradients of salinity, temperature, and oxygen across the three regions. At eight of 18 stations (Figure 2), we collected discrete surface and bottom water samples that were analyzed for salinity, temperature, and concentrations of suspended sediments, organic matter, and nutrients. At three of the marsh spits (Figure 2), porewater salinity, temperature, and oxygen were collected continuously from April to December 2018 at 15-minute intervals using in situ field sensors in porewater wells. Further details for each of the sampling programs is provided below.

Hydrographic Profiles

During 10 surveys, a vertical profile of salinity, temperature, and O_2 was collected at the 18 stations with a conductivity, temperature, and depth (CTD) sensor. Variables measured on the CTD instruments (Seabird Instruments Inc.) included water salinity, temperature, and oxygen concentration. For each cast, the CTD was first submerged at 1 m depth for one minute to purge the system of bubbles. After purging, the instrument was brought back to the surface and then slowly lowered with a hand winch through the water column to the bottom to obtain a vertical

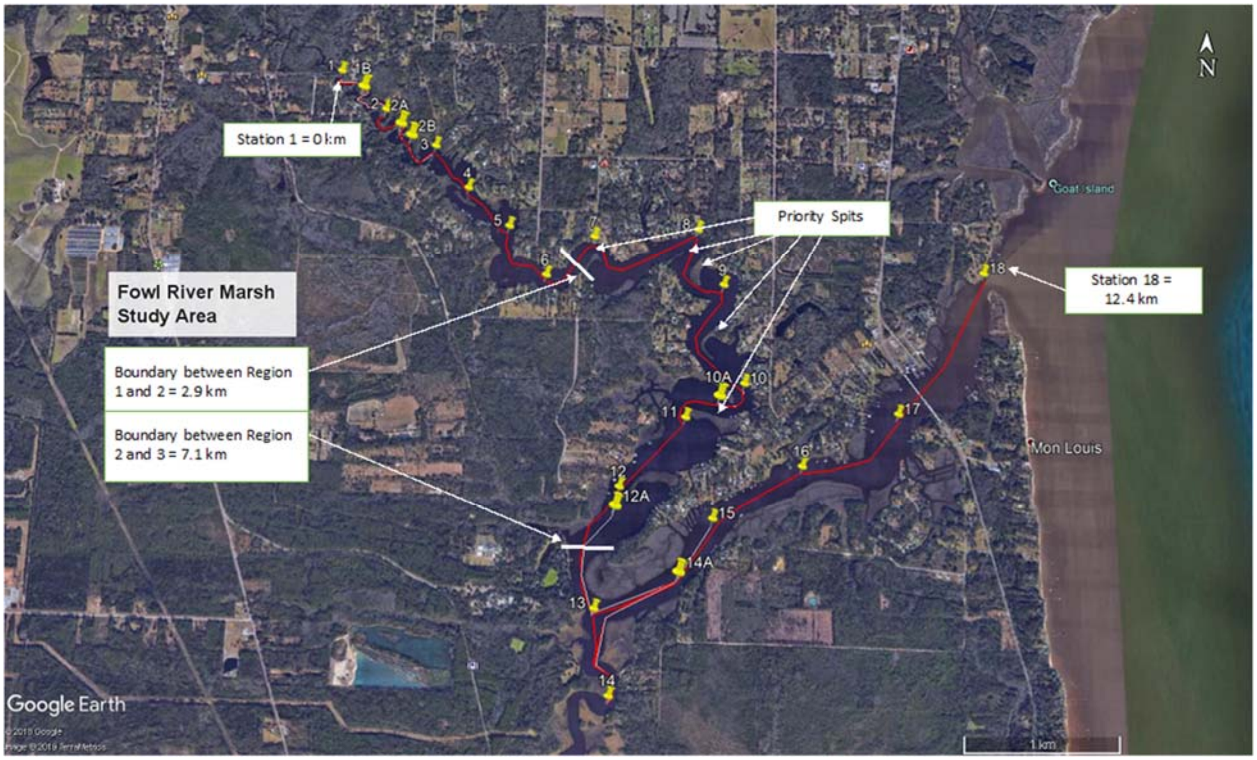

Figure 4. Map of Fowl River study area. The hydrographic stations (yellow pins) are overlaid on a Google Earth image. The red line was used to measure the along channel distances between stations and across the transect (total distance = 12.4 km) using station 1 as the reference location for the beginning of the estuary (0 km) and station 18 as the end of the estuary. White boundary lines for the study regions are shown between stations 6 and 7 and between 12 and 13. Region 1 stations included stations 1-6, Region 2 stations were stations 7-12, and Region 3 stations were 13-18.

profile. While best efforts were made to sample the exact same locations over the course of the study, bottom depths were not consistent at some of the stations due to the heterogeneity of the bathymetry in the river and to currents.

Discrete Water Column Measurements

Surface and bottom water samples were collected at eight stations during each monthly hydrographic survey (Figure 2). Surface water samples were collected via grab sample and bottom water samples were collected with a 2L Niskin bottle lowered to within one meter of the bottom. Salinity, temperature, and oxygen were measured in surface and bottom water samples using a YSI 2030Pro meter. Sample bottles for collection of water that was later analyzed at the lab were triple-rinsed with site water before collecting samples. Samples were stored in the dark on ice until processed at the lab within four to six hours of collection. Samples were processed and prepared for analysis of chlorophyll-*a* (chl*a*), total suspended solids (TSS), volatile suspended solids (VSS), dissolved nutrients, particulate carbon and nitrogen (PCN), and dissolved organic nitrogen (DON) and organic carbon (DOC). Sample analyses were conducted using established procedures, briefly described below.

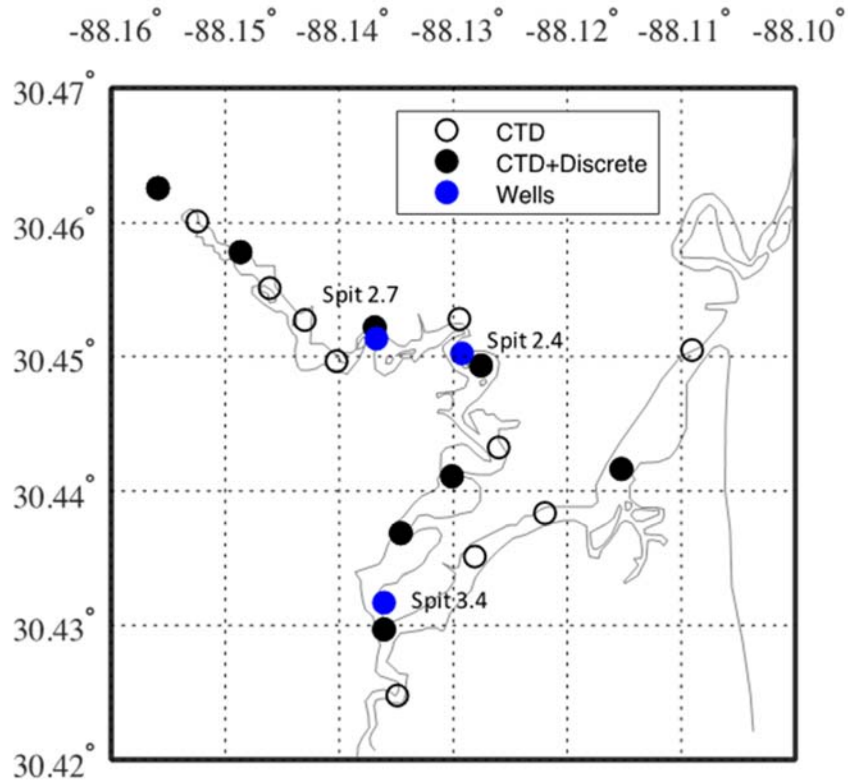

Figure 2. Sampling locations for synoptic surveys (open and closed black circles) and for marsh water surface elevation and porewater hydrography (blue circles). X-axis represents latitude, and Y axis represents longitude.

Chlorophyll *a*

Samples for chlorophyll were filtered onto 25 mm Whatman GF/F filters (nominal pore size of 0.7 μm) and stored frozen at -20°C or colder in a 50 ml polypropylene centrifuge tube or an aluminum foil packet. Prior to analysis, the chlorophyll was extracted in 10 mL of methanol buffered with ammonia acetate and centrifuged at 4000 rpm for 10 minutes. The supernatant was assayed for raw fluorescence measurement on a Turner Trilogy fluorometer calibrated with a known chl*a* standard.

Dissolved Nutrients

Samples were collected by filtration through a combusted GF/F filter and stored frozen at -20ºC in a high-density polyethylene (HDPE) bottle. Dissolved nutrients (nitrate, nitrite, ammonium, phosphate, and silicate) were assayed colorimetrically on an automated nutrient auto-analyzer. Dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) were analyzed following high temperature combustion on a Shimadzu TOC/TDN analyzer.

Particulate C, N (PCN)

Samples for PCN were collected onto combusted (90 min at 500°C) 25 mm Whatman GF/F filters. Filters were stored dry in a desiccator or frozen at -20°C, typically in 47 mm polystyrene petri dishes. PCN samples were combusted and analyzed on an elemental analyzer.

Total and Volatile Suspended Solids (TSS/VSS)

Samples for TSS/VSS were filtered onto combusted 47mm GF/F filters of known weight, and stored in a desiccator or frozen at -20°C. Upon analysis, samples were dried in a drying oven at 70-80°C and weighed to obtain TSS. Samples were then combusted at 490°C for 90 minutes and final combusted weight of the filter was used to calculate VSS.

High Frequency Marsh Porewater Time-Series Measurements

HOBO logger instruments were deployed from April 2018 to present to collect time-series data on three spits (2.4, 2.7, and 3.4). Within each spit, five-inch PVC wells were installed at three locations across the spit (upstream, middle, and downstream). Within each well, loggers were deployed to observe water surface elevation, salinity, dissolved oxygen concentration and temperature. Well locations were surveyed with an RTK GPS to obtain horizontal and vertical positions within each marsh spit.

Data Management and Analysis

Data were recorded and stored in Microsoft Excel files. Data processing, analysis, and visualization were conducted in Matlab (Mathworks, Inc). Excel files and Matlab scripts used to generate the figures in this report are available upon request to the authors.

Results

Water Column Hydrographic Profiles

Water-column salinity in Fowl River ranged from 0-13 ppt (Figure 3). Temperature ranged from 14-31°C (Figure 4). Dissolved oxygen concentrations ranged from 0.1 to 12.8 mg L^{-1}, and oxygen concentrations were commonly below the hypoxic threshold of 2 mg L^{-1} during summer and fall of 2018 (Figure 5).

Monthly, synoptic sampling revealed the expected salinity gradient with freshwater at the upper river and increasing salinity down river towards the mouth of the estuary (Figure 6). From March to April, the water-column was well-mixed with surface and bottom salinity being nearly equal. From May through November, salinity begins to intrude up the estuary mainly in the bottom waters with maximum salinity (> 12) occurring in the bottom water during fall. The salinity characteristics of Region 2 tend to mirror those of Region 1.

Temperatures were at their minimum of (~14 °C) in March and increased to their maximum (>31 °C) in September (Figure 7). On average, temperatures were 4-6 °C cooler at the upstream sites than at the mouth of the estuary.

Oxygen concentrations were highest in March and April, when [O_2] exceeded 10 mg L^{-1}, and lowest at stations in Region 2 where bottom waters were hypoxic ([O_2] < 2 mg L^{-1}) on six of the 10 surveys (Figure 5). Hypoxia also occurred at the border of Region 1 and 2 and in the upstream area of Region 3 (Figure 8).

Discrete Water Column Measurements

There was a clear positive correlation between TSS and salinity, with TSS peaking at approximately 50 mg m^{-3} at the mouth of Fowl River (Figure 9). This relation with salinity resulted in lowest TSS in Region 1 and Region 2 and highest in Region 3. Also bottom waters generally

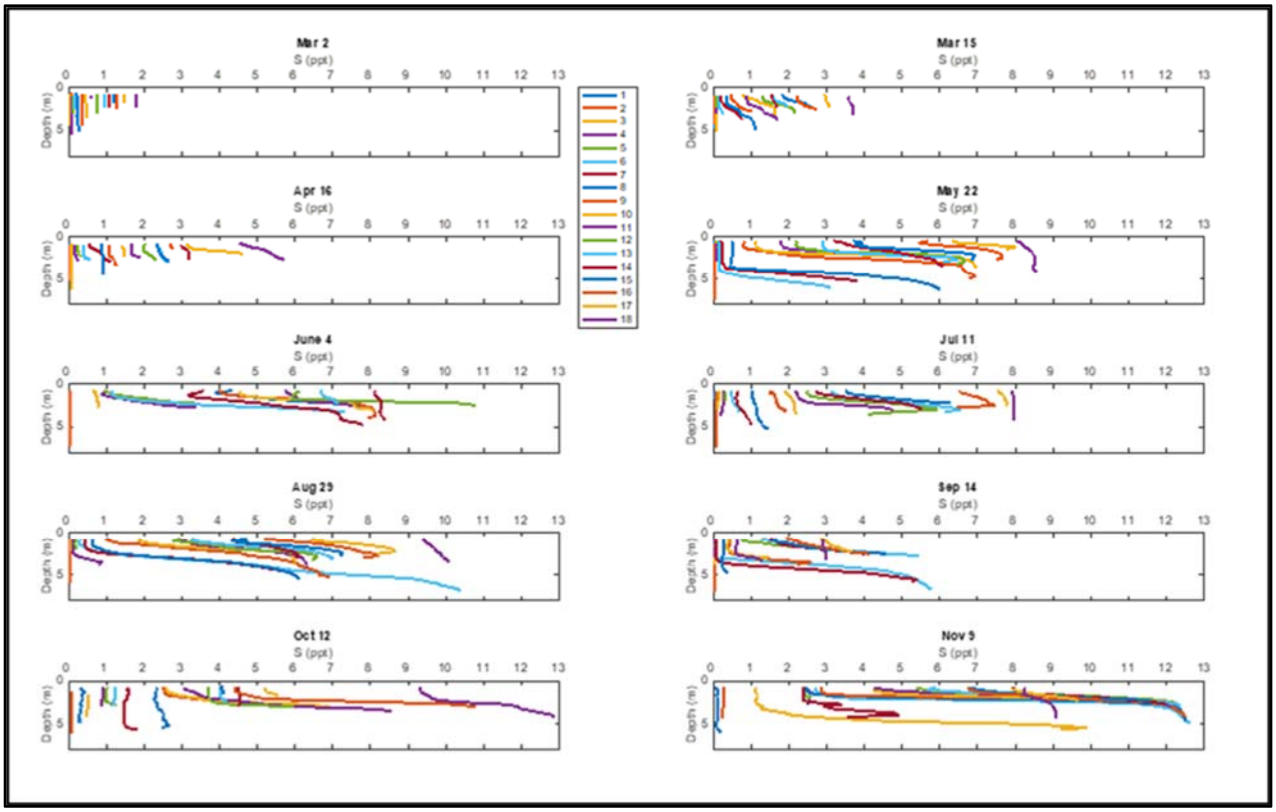

Figure 3. Salinity (S) profiles at 18 stations per monthly survey.

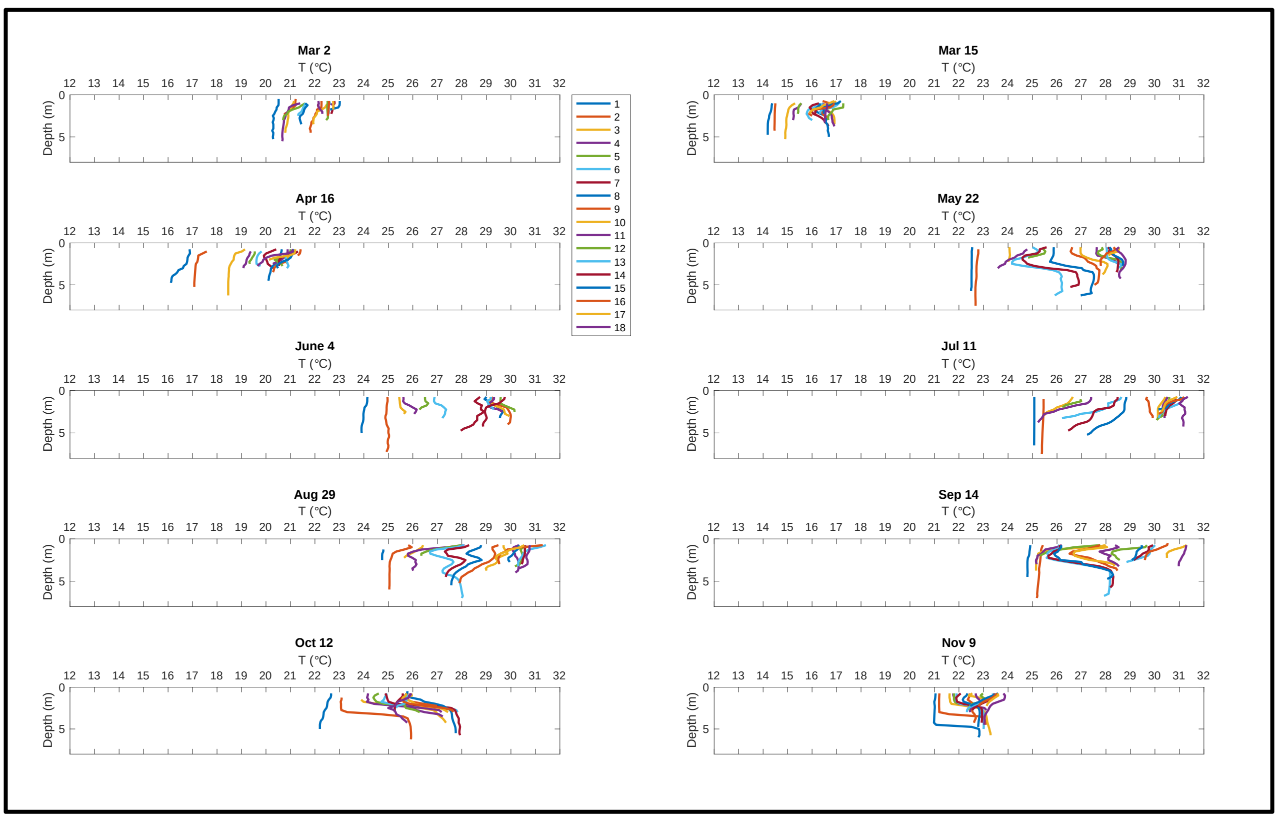

Figure 4. Temperature (T) profiles at 18 stations per monthly survey.

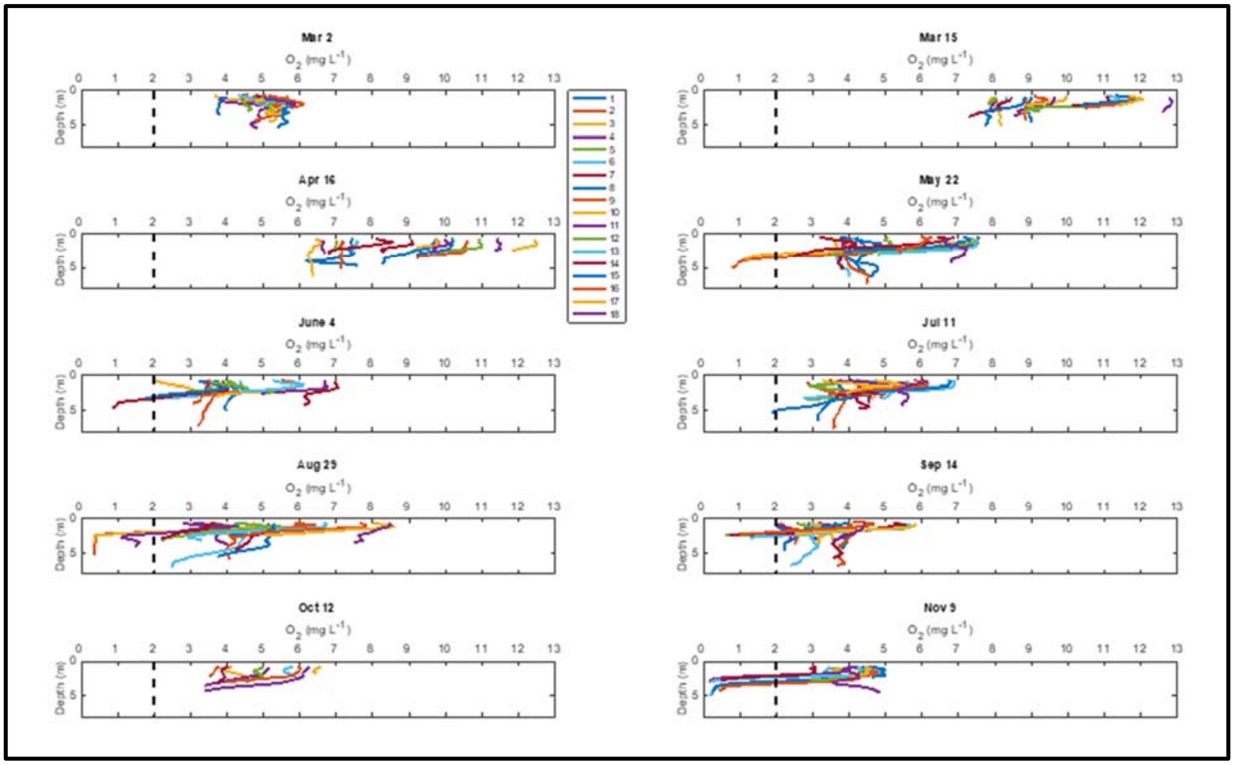

Figure 5. Oxygen (O2) profiles at 18 stations per monthly survey. The dashed vertical line indicates the commonly defined hypoxic threshold concentration of 2 mg L-1.

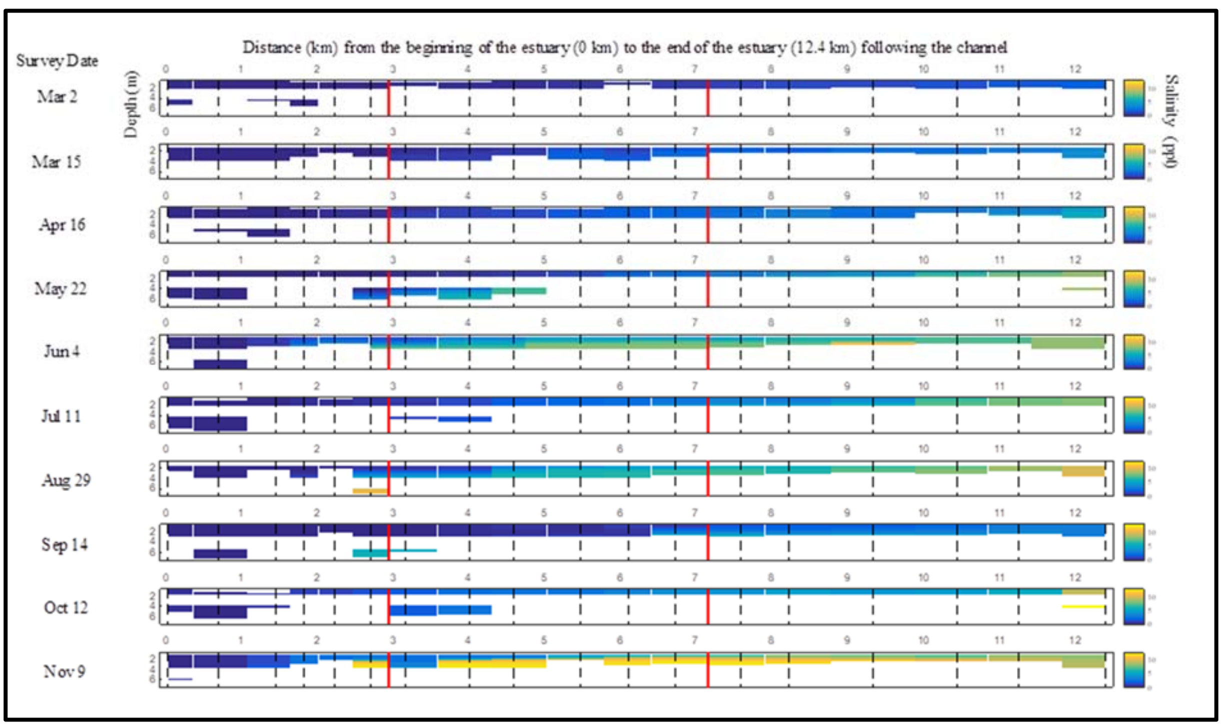

Figure 6. Survey side views of salinity plotted along the transect in Figure 1. Salinity variation is shown by color (see the color bar) and varies by depth (0.25 to 7.75 m) on the y-axis and distance (km) along the estuary on the x-axis. Vertical dashed lines show the location of CTD profile stations. Solid red

lines mark the boundaries for the study regions: from the left, the first red line separates Regions 1 and 2 and the second red line separates Regions 2 and 3.

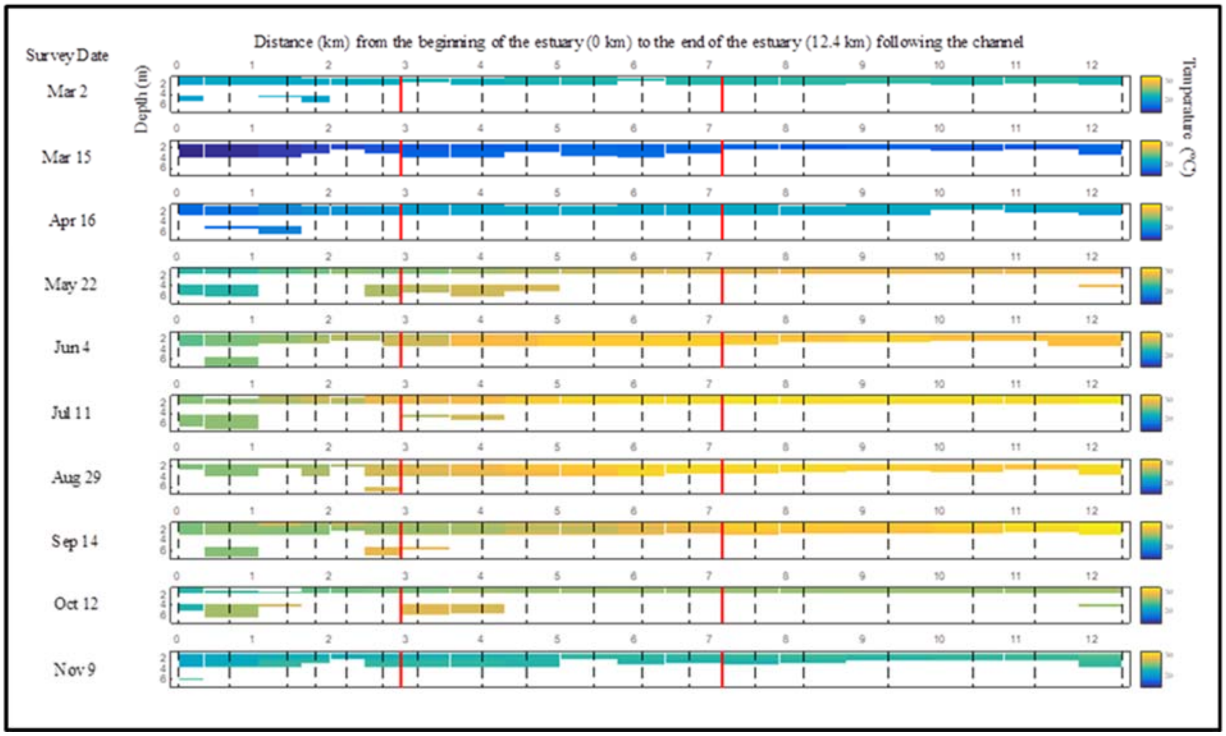

Figure 7. Survey side views of temperature plotted along the transect in Figure 1. Temperature variation is shown by color (see the color bar) and varies by depth (0.25 to 7.75 m) on the y-axis and distance (km) along the estuary on the x-axis. Vertical dashed lines show the location of CTD profile stations. Solid red lines mark the boundaries for the study regions: from the left, the first red line separates Regions 1 and 2 and the second red line separates Regions 2 and 3.

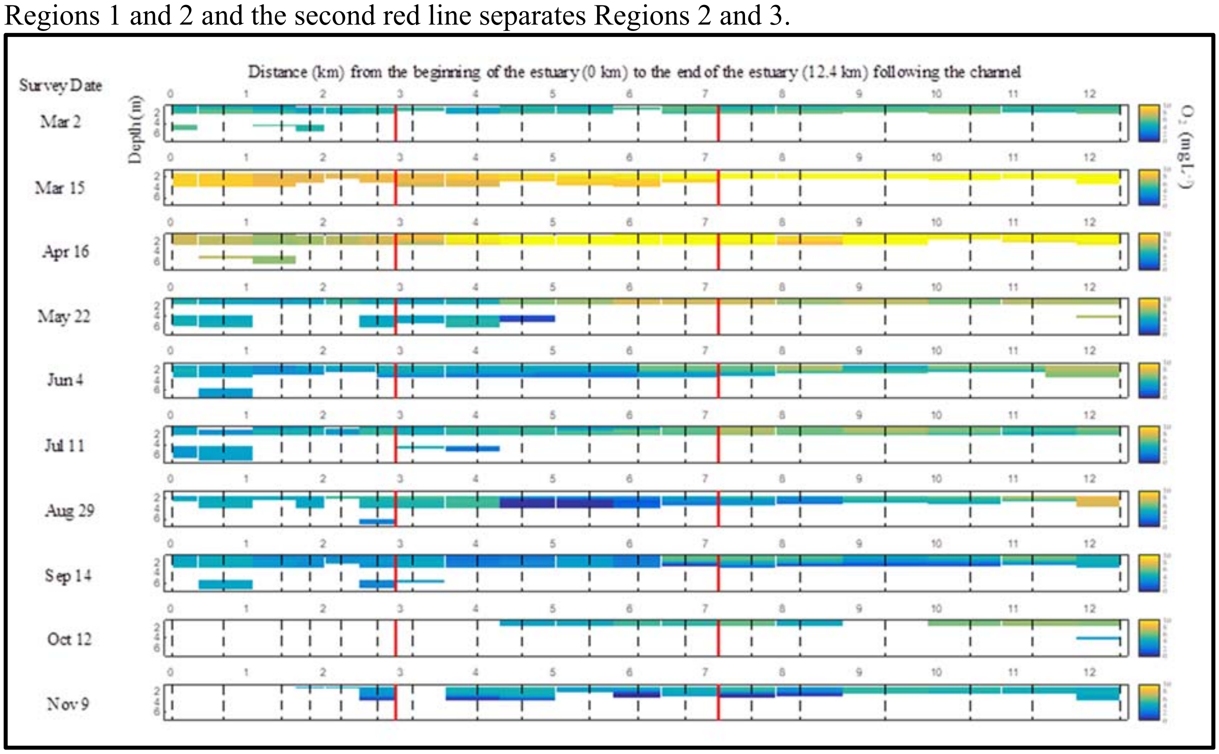

Figure 8. Survey side views of dissolved oxygen plotted along the transect in Figure 1. Oxygen variation is shown by color (see the color bar) and varies by depth (0.25 to 7.75 m) on the y-axis and distance (km) along the estuary on the x-axis. Vertical dashed lines show the location of CTD profile stations. Solid red lines mark the boundaries for the study regions: from the left, the first red line separates Regions 1 and 2 and the second red line separates Regions 2 and 3.

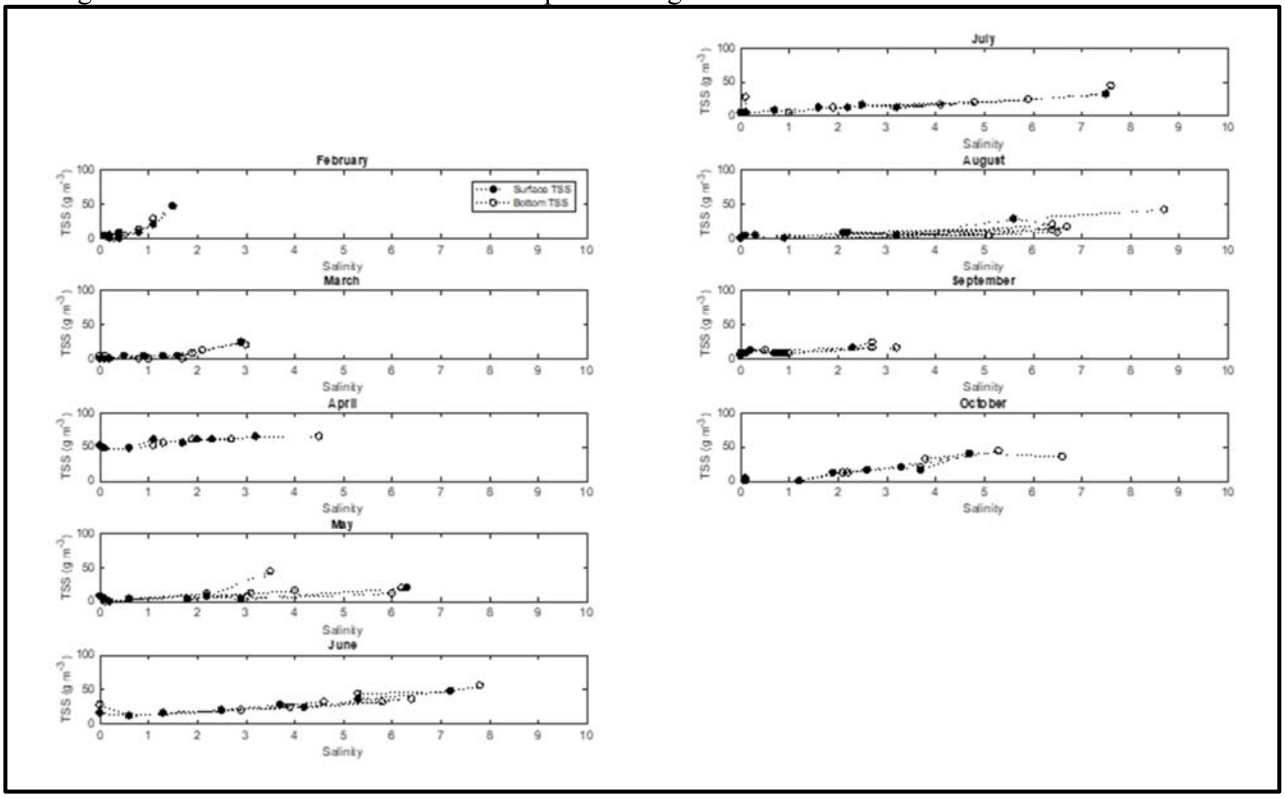

Figure 9. Monthly Water column suspended sediment concentrations as a function of salinity.

had higher TSS than surface water. Overall, this pattern indicated that the primary source of suspended sediments to this system was Mobile Bay rather than the Fowl River Watershed.

NO_3^- concentrations of approximately 40 mmol m^{-3} were common in the upper estuary and decreased down estuary (Figure 10). High NO_3^-, NH_4^+ (not shown) and PO_4^{3-} (not shown) concentrations translated to high chl*a* concentrations (Figure 11), which often exceed 40 mg m^{-3}. Eutrophication and associated poor water quality condition is generally indicated at chl*a* > 20 mg m^{-3} (Bricker et al. 2003; US EPA 2015)

High Frequency Marsh Porewater Time-Series Measurements

Surface water elevation data obtained from the wells indicated that the marshes were flooded from April-October 2018 (Figure 12). The instruments were still in the field collecting data at the time of this report. The instruments will be brought back to the lab in April 2019, which will terminate the time-series measurements in the marsh.

Porewater salinities (Figure 13) were lower at spits 2.4 and 2.7 and highest at spit 3.4, which was located across from Bellingrath Gardens and closest in proximity to Mobile Bay. Within a spit, there was a noticeable gradient in salinity with the upstream portion of the spit having lower salinity than the downstream portion, with salinity values generally highest in the middle of the spits.

Conclusions

Results suggest the observed marsh spit degradation is likely due to a combination of factors. First, the marsh surface was inundated for nearly the entire period from April-October (Figure 12). Sea-level rise is occurring in Mobile Bay at a rate of ~3.6 mm y^{-1} (calculated from surface elevation data at Dauphin Island and Mobile State Docks). During this study, the current sea level is greater than the mean elevation of the surface marsh. Further, suspended sediment concentrations were mainly driven by inputs from Mobile Bay (Figure 9). Thus, the spits in the middle and upper river are removed from the sediment sources and may not be receiving and accreting sediments fast enough to keep up with sea-level rise.

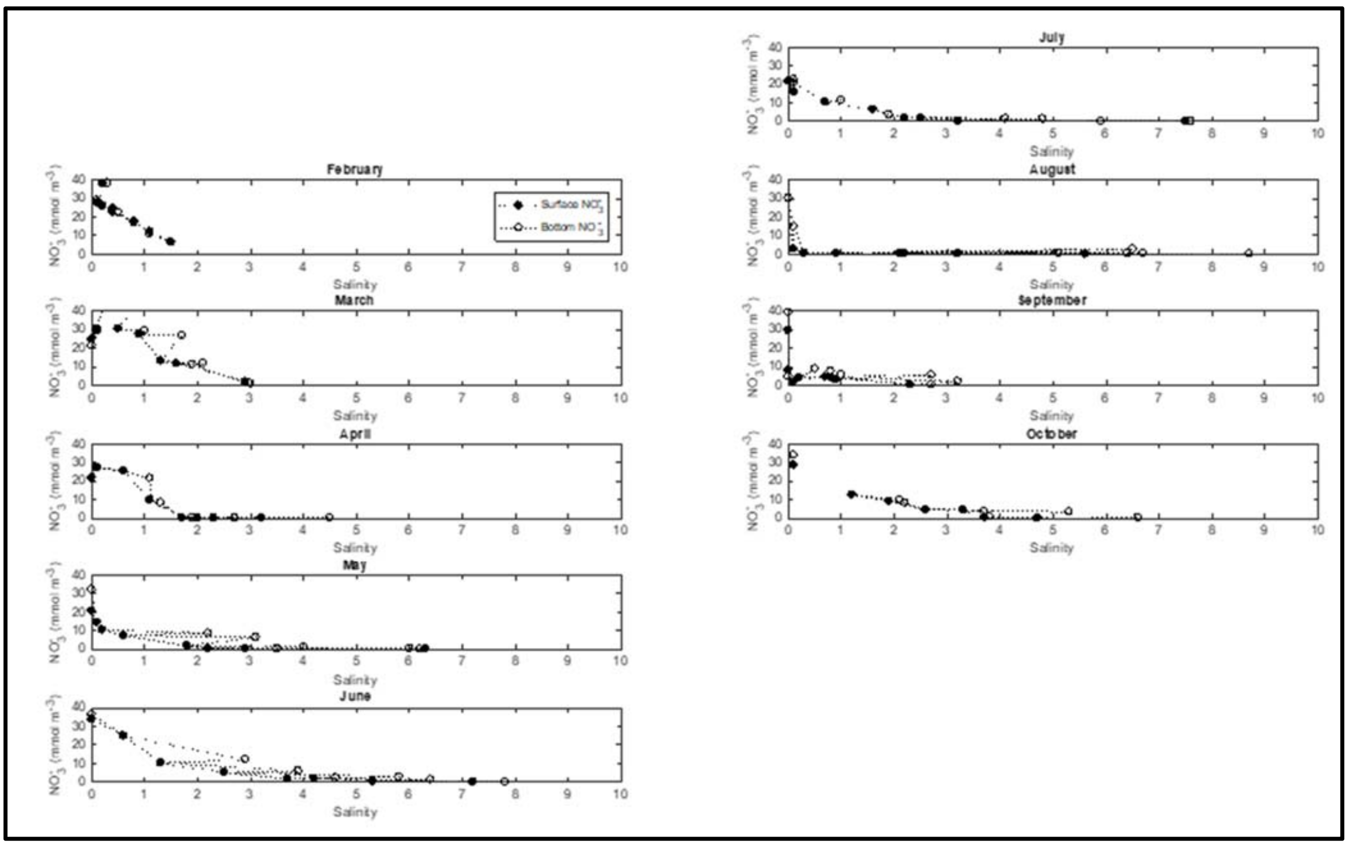

Figure 10. Monthly water column nitrate concentrations as a function of salinity

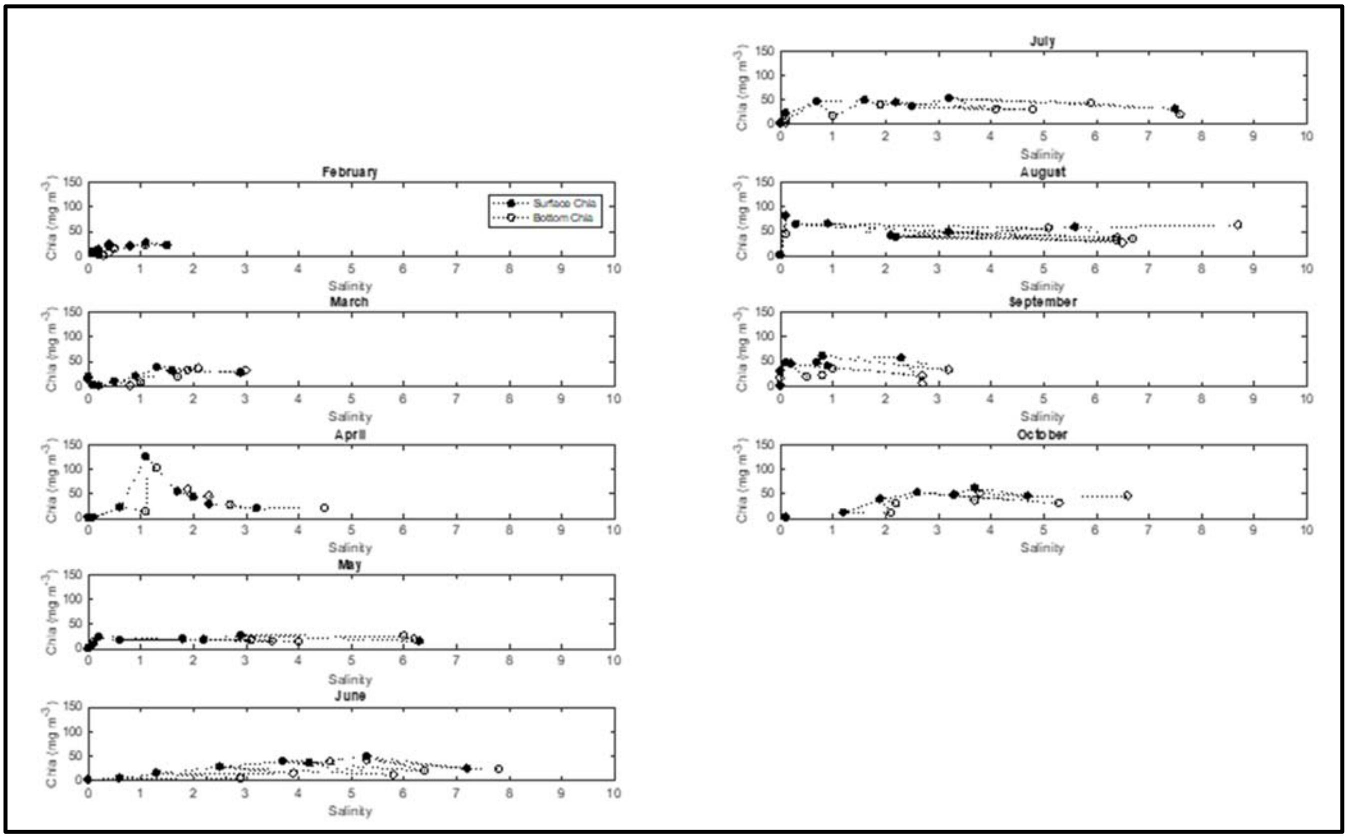

Figure 11. Monthly water column chlorophyll-a concentrations as a function of salinity.

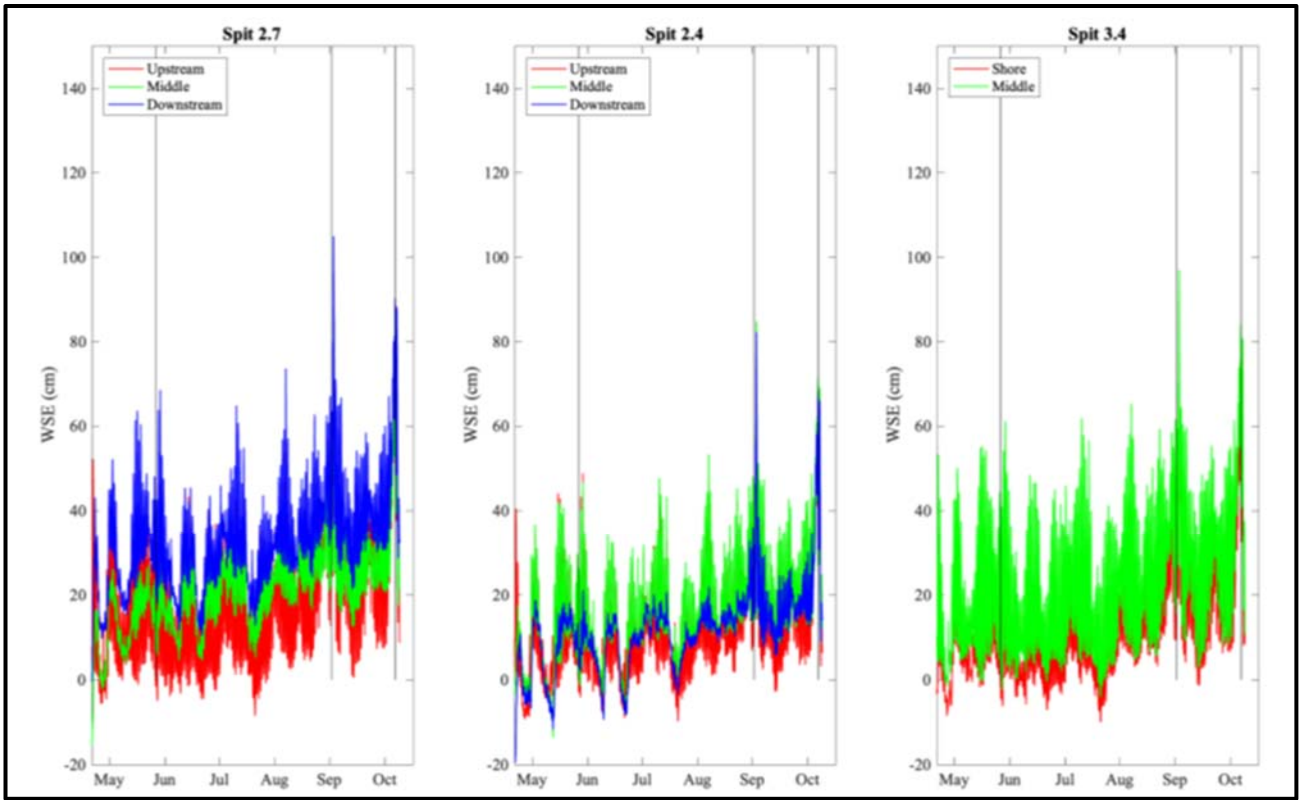

Figure 12. Time-series of water surface elevation from spits 2.7, 2.4, and 3.4.

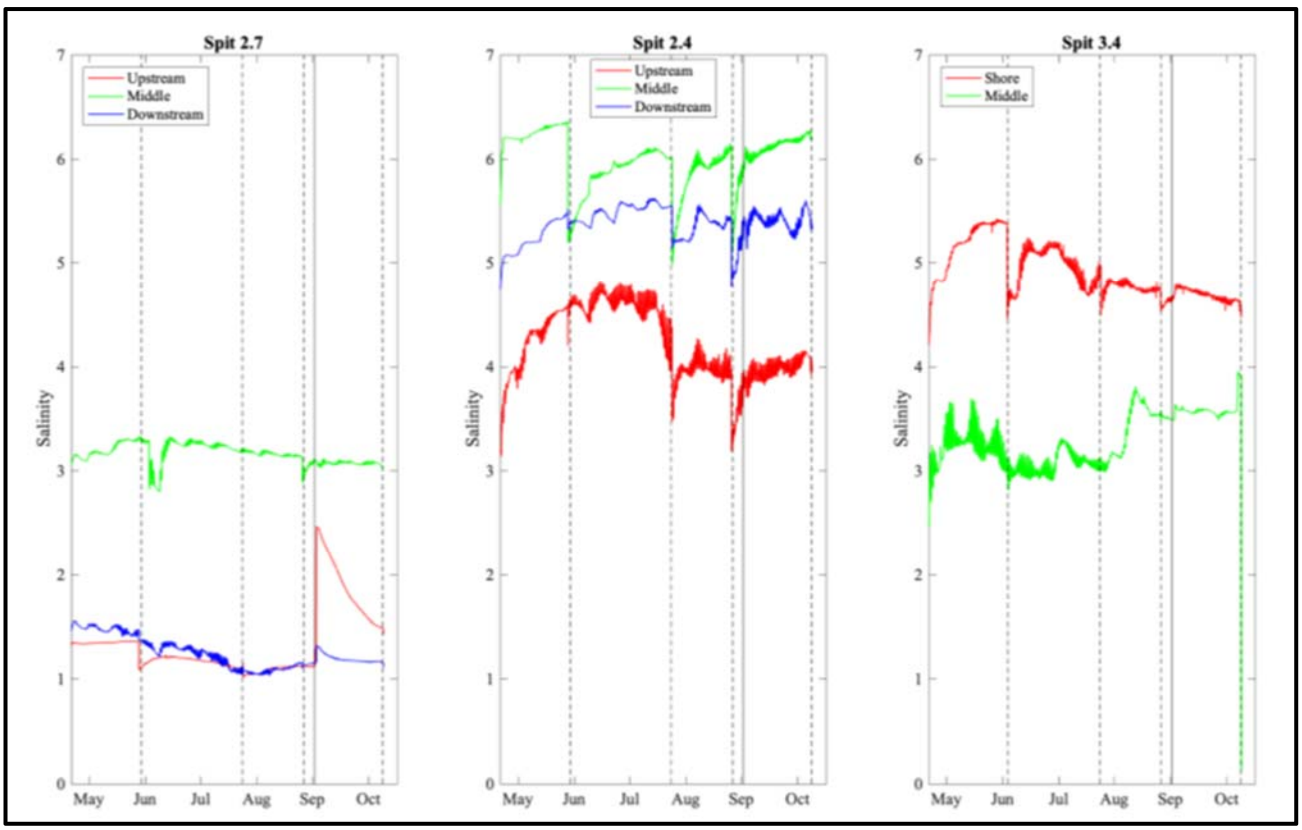

Figure 13. Time-series of porewater salinity from spits 2.7, 2.4, and 3.4.

Second, it is likely that salinity is increasing in this system due to observed sea-level rise and decreasing freshwater inflows from the greater Mobile Bay Watershed (USGS data). In this study, salinity in Region 2 was like salinity in Region 3 (Figure 6), indicating salinity changes experienced at the mouth of the Fowl River estuary will affect Region 2. Salinity in Region 1 appears to be mainly controlled by the freshwater inputs from the watershed maintaining nearly fresh conditions. Higher bottom-water salinity was observed to be encroaching into Region 1 in the summer and fall. Our salinity data from the marsh porewaters also confirm these patterns, with salinity from spit 2.4 and spit 3.4 (lower part of Region 2 and upper part of Region 3, respectively) being more similar than with spit 2.7, which was located at the border of Region 1 and 2.

Third, the nutrient, chl*a*, and oxygen observations indicate Fowl River is a eutrophic system. The impacts of eutrophication on marsh health are not well understood in the Gulf of Mexico. However, in other systems, such as New England marshes (Deegan et al. 2012), eutrophication is linked to collapse and loss of the marsh edge. Also, a recent study indicates nutrient enrichment affected a Louisiana marsh plant (*Spartina patens*) by weakening its roots and making it more vulnerable to collapse (Hollis and Turner 2019). In sum, nutrient impacts result in 1) changes in plant root:shoot ratios with plants investing more energy in shoot production under high nutrient conditions, 2) reduction in the strength of the roots, and 3) enhanced remineralization of marsh soil organic matter due to elevated nutrients and labile organic matter from phytoplankton. In combination, these effects may cause slumping and erosion of marsh edges. Though not directly related to marsh health and thus not a focus of this study, hypoxia is prevalent in Fowl River. Hypoxia was observed frequently in Regions 2 and 3 and suggests that large areas of the estuary were impacted. It is likely the hypoxia is related to the surface water eutrophication, but further work is required to confirm this linkage.

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1. Subproject title: **High frequency Salinity Intrusion in Fowl River, Mobile Bay, AL**

2. Subproject Lead (PIs and Co-PIs):

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4. Amount of Total Grant **:** $30,000

5. Project Abstract:

This component focused on salinity dynamics due to the potential ecosystem implications associated with changing salinity exposure on marsh platform vegetation. To understand how Fowl River and the associated land spits are changing temporally and spatially, time series data were collected during the selected study period (May 1- July 11, 2018) from five monitoring stations within the system to support the ecological and biogeochemical sampling. System salinity generally increased over the course of the study period, consistent with reduced discharge expected during the transition from spring to summer, and there was significant temporal variability in the salinity signal with low frequency changes on the order of 4-8 practical salinity units (psu, equivalent to parts per thousand) day-to-week time scales. The salinity dynamics in Fowl River are clearly influenced by the conditions from both Mississippi Sound and Mobile Bay, as an interior site was, at times, saltier than the mouth of Fowl River. During periods of low discharge, wind conditions, through changes in water level, represent an important forcing mechanism controlling salinity variability. Finally, the close relationship between wind conditions and water level have indirect implications for the impacts of salinity under rising sea level. These results suggest that as sea level rises, the impacts of salinity will more strongly affect the system.

Motivation

The success of estuarine restoration efforts often depends on a range of interdisciplinary marine and fluvial processes that interact in complex ways. Physical forcing is a critical factor in controlling the environmental conditions in which biogeochemical and ecosystem processes must operate. Thus, a major consideration in estuarine restoration are the physical conditions at site locations due to their importance in determining whether biological organisms can survive and flourish. As highlighted by Bates et al. (2018), it is essential for biologists to understand how systems are changing both locally (as compared to globally) and temporally (at 'ocean weather' time scales). To that effect, high frequency measurements (~ hourly) are critical to better understanding relationships between environmental forcing, hydrographic changes, and subsequent biological response over a broad range of spatial and temporal scales.

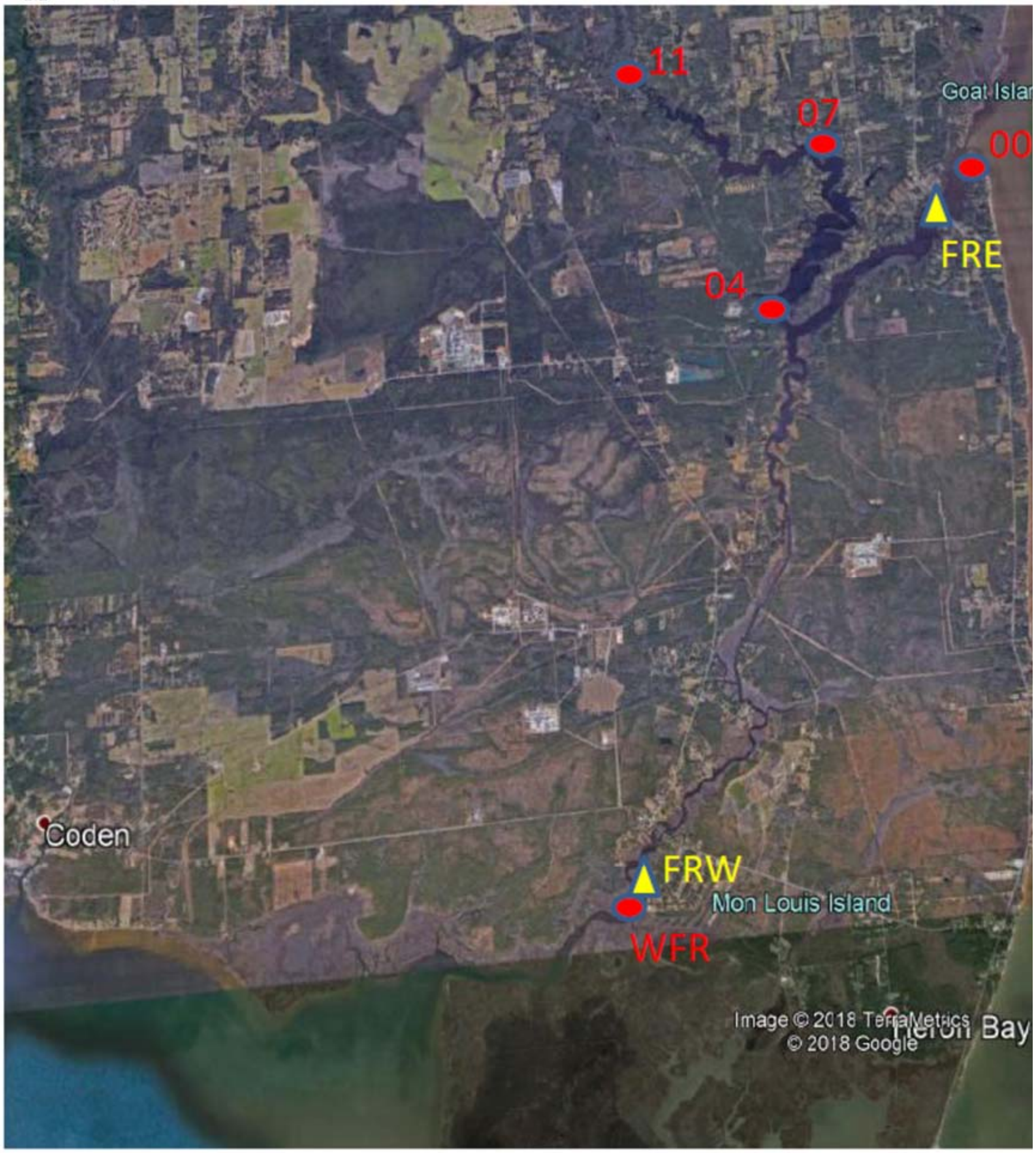
While many environmental conditions in an estuarine system can change quickly, this study focused on salinity dynamics due to the potential ecosystem implications associated with changing salinity exposure on marsh platform vegetation. The extent to which salt enters an estuarine system depends on several parameters, with classic estuarine studies focused on the impacts of freshwater discharge (Abood 1974; Garvine et al. 1995; Monosmith et al. 2002). However, a number of studies highlight the importance of wind forcing in modifying the salinity dynamics, where wind direction and magnitude can both change the extent to which salinity impacts a system (Scully et al. 2005; Ralston et al 2008; Coogan and Dzwonkowski 2018). This study focused on characterizing the high-frequency temporal and spatial variability in the horizontal salinity structure of the system during the spring/summer season, when marsh growth rates are typically high. In addition, the main drivers controlling the extent and duration of salt intrusions into the system are investigated to provide key information on the factors that would be expected to lead to periods of enhanced salt inundation and potential salinity stress on the marsh platforms. By providing a characterization of the system salinity field as well as the associated drivers, a better understanding of their impacts on ecosystem processes and the likelihood of restoration success can be achieved. This new information on salinity dynamics will be critical to informing management of the existing habitats as well as identifying ideal restoration sites.

Data and Methods

Time series data were collected during the selected study period (May 1- July 11, 2018) from various monitoring stations in order to support the ecological and biogeochemical sampling. Within the estuary, the data were primarily derived from YSI 6600 V2 and V4 water quality sondes located at four sites in Fowl River (Figure 1), including a site at the Mouth (0 km), at Bellingrath Gardens (4.3km), at an upriver spit (7.3 km) and at the Fowl River bridge (11.3 km). In addition, an Arduino-based sonde developed by Dauphin Island Sea Lab (Lockridge et al. 2016) was deployed at the mouth of West Fowl River. The YSI 6600 instruments measured temperature, salinity, dissolved oxygen, and pressure at depths of ~0.25 m off the bottom (with site water depths ~3-5 m) and the Arduino-based sonde measured only temperature and salinity. The sampling frequency was Δt = 5 minutes for the YSI 6600s and the Arduino. The YSI 6600 sondes were cleaned and calibrated every 3-4 weeks during the 10-week study period. The Arduino-based sonde was changed out approximately half way through the study period. These data were compared to available CTD casts at the deployment and recovery times as well as despiked to ensure high quality measurements. The four Fowl River sites were distributed along an expected salinity gradient to characterize changes over the extent of the system (Fig. 1). The West Fowl River site was intended to assess any influences from the Mississippi Sound. Velocity data from two acoustic Doppler current profilers (ADCPs), an acoustic Doppler velocimeter (ADV), and four tilt meters were collected at the four Fowl River sites but are beyond the scope of this work. Details regarding water velocity data collection can be found in the Coogan and Dzwonkowski (Submitted 2019).

Additional environmental data, including meteorological data, freshwater discharge, and water levels, were obtained from various sources (Figure 1). Hourly wind data were collected

Figure 1. Locations of time series stations in Fowl River and West Fowl River during the May-July study period. The ● were short-term deployment stations measuring near-bottom water properties (temperature, salinity, and dissolved oxygen and velocity (at station 00, 04, 07 and 11). The △ are long-term water level stations support by NOAA NOS.



from the NOAA National Data Buoy Center (NDBC) station DPIA1 at Dauphin Island. Daily discharge data for Fowl River were obtained from a U.S. Geological Survey gaging station

(30°30'02" N, 88°10'53" W: USGS 02471078). The study period data (May-July 2018) are listed as “provisional” on account of USGS waiting to review the data until the end of each water year (i.e., October). Hourly water level data were obtained from a regional NOAA tide station at Dauphin Island, Alabama (station ID: 8735180) as well as two sites including one at the mouth of Fowl River (station ID: 8735523; near our mouth site) and one at the mouth of West Fowl River (station ID: 8738043; near our West Fowl River site). These water level data were de-meaned so that differences in the site responses could been readily compared. Data from DI were considered to be representative of water level along the coast (hereinafter referred to as coastal water level).

Several basic procedures were applied to the time series data. With a few exceptions, the data were generally continuous, and any gaps associated with the despiking process were filled using linear interpolation. All data collected at frequencies higher than hourly were averaged to hourly to match the additional environmental data. Wind data at Dauphin Island, measured at 13.5 m above sea level, were standardized to10 m above sea level using a log wind profile. Given the coastline orientation, the east-west component of the wind vector was used as the along-shelf component consistent with previous work in the region (e.g. Dzwonkowski and Park 2012). In addition, Fowl River is connected to both Mobile Bay and Mississippi Sound with perpendicular primary orientations of north/south and east/west, respectively. With the exception of daily freshwater discharge, a low pass 40-hr Lanczos filter was used to isolate low frequency processes in the time series data.

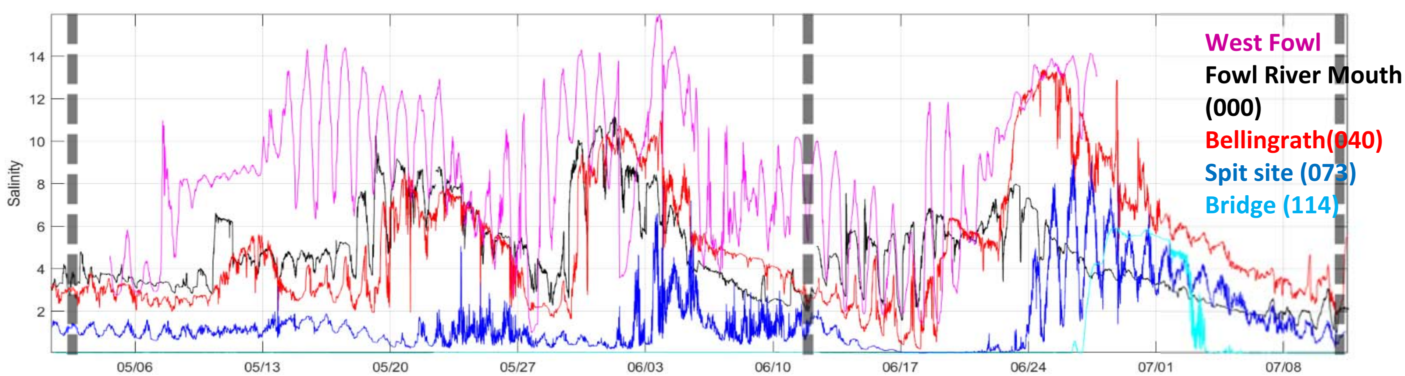


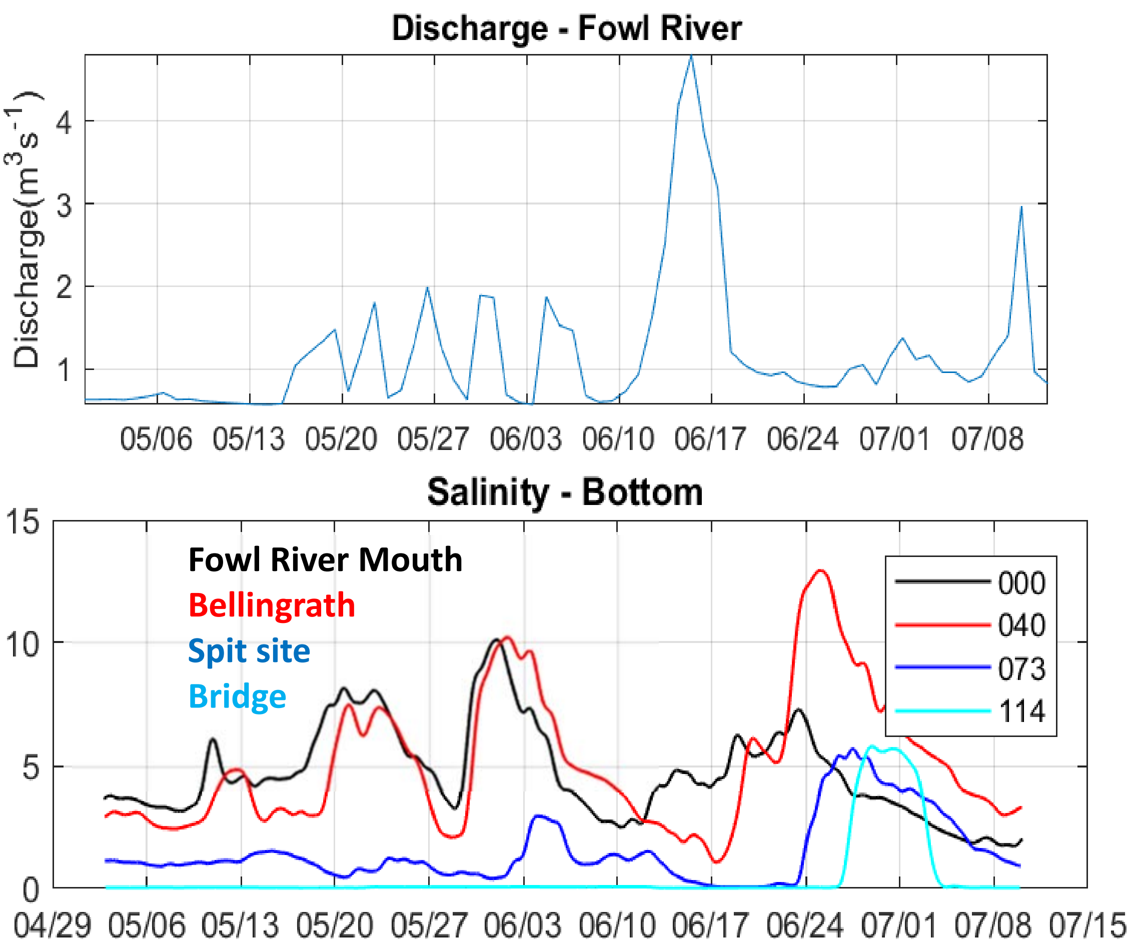
Figure 2. Times series of instantaneous salinity data from the short-term deployment stations during 2018.

Results and Discussion

Salinity Patterns

Time series of the salinity data from the five stations showed both spatial and temporal variability (Figure 2). Spatially, the sites ranged from brackish to completely fresh. The West Fowl River site was consistently the saltiest site and had the largest tidal signal. In contrast, the Bridge site had no tidal signal and was completely fresh through most of the study period. Over the 10-week study period, there were three prominent intrusions of salt that propagated into Fowl River to varying extents (~May 20, Jun 01, and Jun 26). From the stations in Fowl River, the progression of salt into the estuary during the events exhibited a general pattern of an increase in salinity being initiated at the Fowl River Mouth site with subsequent increases at stations further into the river. Over the course of the study period the extent of these salinity intrusions increased over time with the first event (May 20) being observed at only the Fowl River Mouth and Bellingrath sites (approximately ~4.3 km into the estuary), while the third intrusion event extended beyond all the sites with salinity values of nearly 6 psu at the bridge site, ~11.4 kms into the estuary.

Figure 3. Times series of the river discharge at the USGS Fowl River gauge (Top) and the low-pass salinity signal along the Fowl River stations (Bottom).

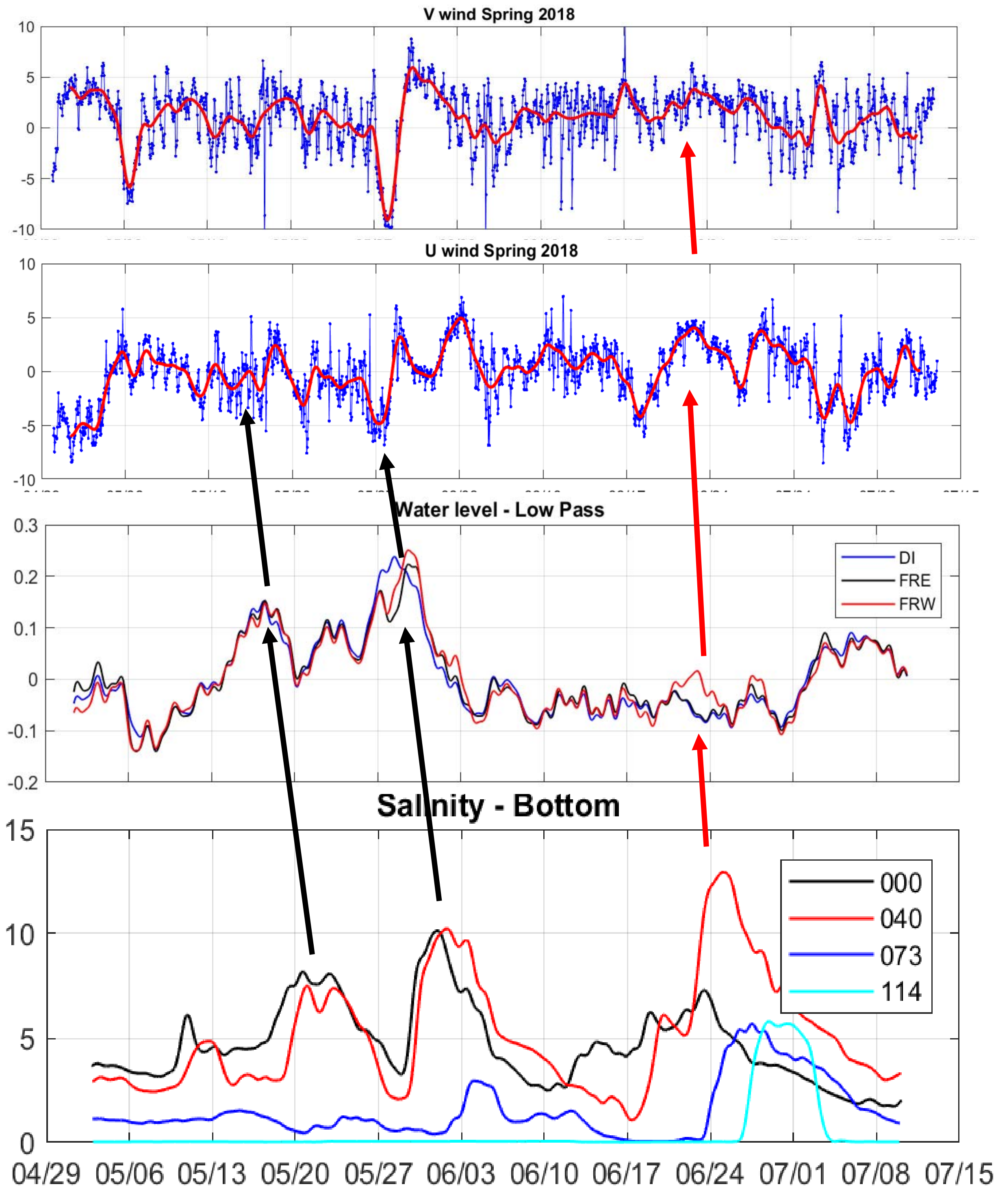


Each event had some subtle differences, and the influence from the Mississippi Sound was consistently observed at the Bellingrath site, as it was saltier than the Fowl River Mouth site to varying extents during each event. This salinity signal at the Bellingrath site was particularly notable in the second and third intrusion events. The second event began with a pulse of high salinity at the mouth of Fowl River that subsequently increased at the Bellingrath site. Following the salinity peak at both of these sites, there was an extended period (~9 days, June 2 to June 11) when the salinity remained 2 psu higher at the Bellingrath site. The third event had a somewhat different salinity pattern with a larger delay in the salinity increase between the two sites as well as a much larger peak in salinity, ~6-8 psu higher at the Bellingrath site compared to the Fowl River Mouth site. Tellingly, the salinity increase followed a large salinity increase at the West Fowl River site with the salinity values and patterns nearly overlapping at these sites (Figure 2).

Given the predominance of these three multi-day to week events, the low frequency signal in the salinity are compared to environmental conditions to better understand the forcing response of the system (Figures 3 and 4). River discharge feeding the system was relatively low during the study period with flow at ~1 $m^3 s^{-1}$ for most of the study period (Figure 3a). There was one multi-day event (6/11-6/18) with elevated discharge peaking around 4 $m^3 s^{-1}$. The salinity response to this signal was not clear. The Fowl River Mouth site actually increased in salinity during this event. While the interior sites did decrease to some extent in conjunction with the discharge event, the largest changes in salinity were not coupled with the river discharge. While the mean salinity conditions of the system were likely set by the interaction of river discharge with the two outlets (Fowl River and West Fowl River), the low frequency salinity variability was primarily driven by other mechanisms.

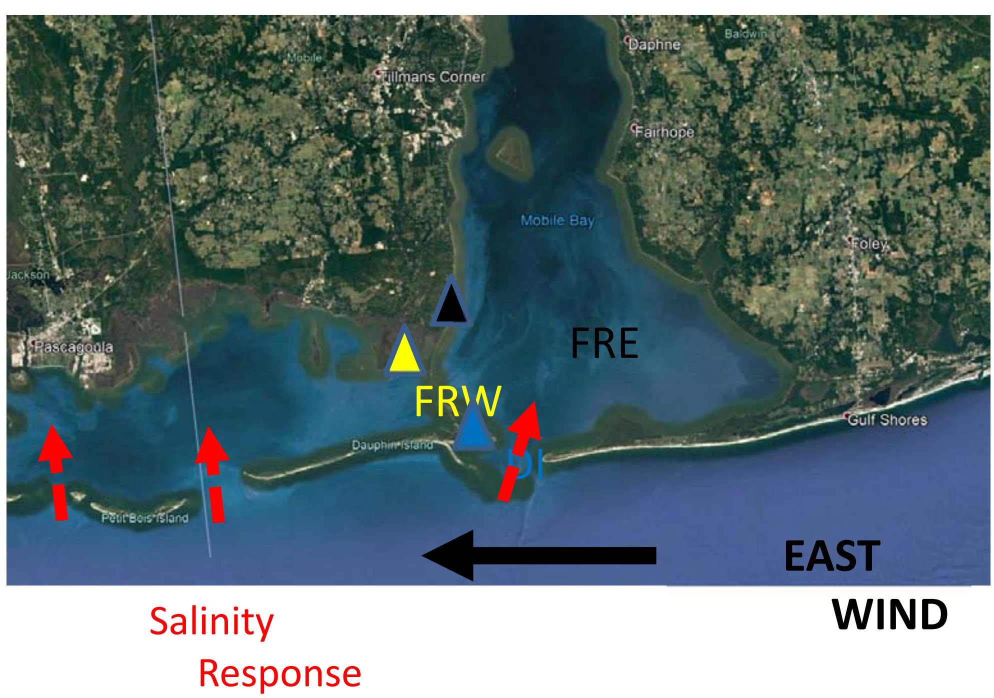
Time series of other environmental conditions provided additional insight on the system salinity dynamics. Water level from three regional sites had a generally consistent response across the region. There was some notable variation between sites around May 28 and again on June 23. Comparing the water level data against the salinity time series indicated that early in the time series the increases in water level were associated with increases in salinity (e.g., May 18), while later in the study period, the time series captured increases in salinity associated with differences between West Fowl River and Fowl River water levels (e.g., Jun 23). As a result, the characteristics of the salinity response were notably different. The May 18 water level event, where the water uniformly increased at all three sites (in the main stem of Fowl River), resulted in a sequential increase in salinity propagating upriver and reaching three of the Fowl River sites. In contrast, the water level difference during the Jun 23 event, with West Fowl River being higher, led to an intrusion event centered at the Bellingrath site. This is the location where Fowl River bifurcates, forming the direct connection to West Fowl River. The second event (Jun 28) appeared to be a blending of the two types of events, where the water level initially rose uniformly and then deviated, resulting in a sequential increase in salinity which then transitioned to an event with the highest salinity at the interior Bellingrath site. It is worth noting that this event was associated with the passage of Tropical Storm Alberto, so the salinity response to water level condition likely had complicating factors.

Figure 4. Time series of north/south (V, +/-) wind (first panel) and east/west wind (U, +/-) from Dauphin Island (second panel), demeaned low pass water level from regional stations (third panel), and low pass salinity signal from the Fowl River stations (fourth panel). The red and black arrows highlight two different types of salinity intrusion impacting the Fowl River and the associated spits. The black arrows are remotely forced events (Figure 5), and the red arrow is a locally forced event (Figure 6).



The relationship between salinity and water level naturally leads to mechanistic questions about water level variability. Wind forcing is a well-established mechanism for modifying coastal water level, and representative wind conditions for the region are shown in Figure 4a and c. During the first event, the wind conditions are predominately out of the east. The along-shore direction, relative to the Alabama/Mississippi coastline, is consistent with coastal Ekman dynamics generating a downwelling event driving sea level set-up at the coast. While the winds were relatively light, the persistent conditions over an approximately six-day period likely generated a cumulative effect on the water level. This is considered a 'remote' forcing, as interior water level changes in response to a change at the system boundaries (Figure 4). There was some hint of the remote effect during the third event, around June 17, where there was a slight sequential increase at both the Fowl River Mouth and Bellingrath sites. However, this event was dominated by the surge in salinity at the Bellingrath site (and the upstream salinity propagation), which occurred under a period of southwesterly winds. These wind conditions were ideal for generating a local forcing in Mississippi Sound/Portersville Bay, where direct wind forcing sets up water level slope at the downwind end of the system. This effect would be expected to result in higher water level at West Fowl River relative to Fowl River Mouth, and thus generating a barotropic pressure gradient that would be expected to force water from Mississippi Sound into Fowl River (Figure 6). This was consistent with the salinity response to such events in the study period. It is worth noting that the local wind forcing within Fowl River was small as the system is narrow and sinuous, so that no predominate wind direction is likely to have enough fetch to generate an appreciable circulation throughout the interior of the system. Thus, the local effect of the wind forcing in Mississippi Sound/Porterville Bay is still a remote effect, in that it is derived from an external forcing on the boundary of the system.

Figure 5. Conceptual diagram of the coastal wind forcing (large black arrow) in reference to the water level station at Dauphin Island (DI) and along Fowl River (FRE)/West Fowl River (FRW) and the associate salinity intrusion (red dashed arrows). The along-shelf wind sets up coastal water level (via Ekman transport) which subsequently forces Gulf of Mexico water into adjacent estuaries and bayous as implied from the time series data



Finally, the strongest wind conditions during the study period were associated with the second event when Tropical Storm Alberto influenced the region. The wind conditions were initially out of the east-northeast followed by a rotation to south-southwest. Thus, the initial easterly winds led to a ‘remote’ effect associated with coastal setup, followed by a ‘local’ water level gradient generated by the southwesterly winds. As a result, the salinity response was mixed, with an initial sequential salinity increase in the system followed by a persistent elevation in salinity at the Bellingrath site (relative to the Fowl River Mouth site).

The salinity response to wind forcing (via changes to water level) is somewhat limiting in that only three large intrusion events were observed in the time series. This small sample size represents statistical challenges as the salinity response to forcing conditions can be difficult to quantify due to the potential non-linear behavior of salinity time series arising from several competing controlling factors (e.g. river discharge, oceanic changes, tidal straining, wind mixing, etc.). For example, the tail end of the time series had a remote wind event (July 1-8) that increased the water level but did not have a clear salinity response. The reason for the lack of salinity response is unclear. However, this data indicates that monthly or seasonal sampling that is common in ecological studies could lead to significant aliasing of the salinity conditions, at least during the transition from spring to summer seasons when discharge is low.

Figure 6. Conceptual diagram of the implied salinity intrusion (red dashed arrow) into Fowl river during Southwest wind events (black arrow) captured during the times series measurements. The thick black arrow represents the wind stress and the red dashed arrow indicates how higher salinity water from the Mississippi Sound is forced through West Fowl River into Fowl River during these wind events.

In addition, the characteristics of the salinity signals were generally consistent with expected responses to wind-driven physical forcing where two types of remote wind events were influencing the system. Interestingly, the intrusions associated with the ‘local’ type of remote wind forcing appear to be more effective at bringing salinity into the spit region. Although this ‘local’ type of remote wind forcing occurred later in the summer season when the estuarine conditions would be expected to have an increased marine influence, due to low river inputs, the impact of this type of wind forcing may be amplified due to the timing of the event (i.e., it is able to push more salt into Fowl River due to the low river discharge at this time of the year). To get a better sense of the relative importance of remote verses local wind forcing on this system, long-term time series of wind and water level can be explored to assess the frequency and consistence of coastal setup and local setup. Future work could involve using long-term station data to show correlations between East wind and coastal water level and Southeast wind and the set-up between West Fowl River and East Fowl River following conventions of Wong et. al. (2009). Additional work could also look at DI station salinity with water level to potentially determine whether increases in water level are associated with increase is salinity over multiple years.

Summary

System salinity generally increased over the course of the study period, consistent with reduced discharge expected during the transition from spring to summer.

There was significant temporal variability in the salinity signal with low frequency changes on the order of 4-8 psu over day to week time scales.

The salinity dynamics in Fowl River are clearly influenced by the conditions from both Mississippi Sound and Mobile Bay, as an interior site was, at times, saltier than the mouth of Fowl River.

During periods of low discharge, wind conditions, through changes in water level, represent an important forcing mechanism controlling salinity variability

Two types of wind forced intrusions were observed: remote forcing events of coastal origin and remote forcing events of local origin. Remote forcing events of coastal origin altered water level at the coastal line and subsequently pump salt into estuary, whereas remote wind forcing of local origin resulted from local wind forcing changing the water slope in the main estuaries adjacent to the sub-estuary and ‘pushing’ salt into the system (via a barotropic pressure gradient).

Finally, the close relationship between wind conditions and water level have indirect implications for the impacts of salinity under rising sea level. These results suggest that as sea level rises, the impacts of salinity will more strongly affect the system.

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Project Summary and Conclusions

A case for the environmental and economic importance of these estuarine habitat features, as well as stakeholder priority, was expressed in the introduction. To improve understanding of marsh health in Fowl River and inform future management decisions and restoration activities, thorough characterizations of elevation, sediment, vegetation, salinity, and hydrology are needed to address the following questions: What is the marsh health status, and how does it vary along the salinity gradient studied? Is the diversity, distribution, and density of plant species changing? Is the elevation of the marshes stable or shifting, and what impacts can be expected from future sea level rise (SLR)? Are the marshes accreting, stable, or eroding? Is the sedimentation pattern and/or composition changing? Is the salinity regime shifting? How is the natural hydrology being affected by SLR, boat wakes, and/or storm surge? A summation of the comprehensive marsh characterizations above will be used to identify potential anthropogenic stressors to marsh health.

Vegetation Report – Tim Thibault, Dr. Just Cebrian, Ph.D., and Jared Goff

While the quality of marshes across the study area is similar, and hydrogeomorphic (HGM) assessment scores and floristic quality indices (FQIs) fall within a range expected for natural marshes in coastal Alabama, percent cover on target spits is generally lower than measured at high-quality marshes in the HGM reference domain. The four target spits have transitioned over the past four decades from forested wetlands to herbaceous marsh. Over the same time period, the marsh spits have lost a substantial amount of area. Changes in community composition and reduction of wetland area have coincided with recent sea level rise, and, potentially, increased salinity intrusion. In fact, comparison of historical aerial imagery of shoreline positions in 1940, 2002, and 2018 shows a progression in areal loss of wetlands, not only in the study area, but across all three regions of Fowl River.

Changes in community composition and decrease in size of the Fowl River spits is likely to continue due to a combination of sea level rise, subsidence, and lack of sediment deposition. Much of the marsh surface at the Fowl River sites is regularly flooded, and these wetlands are highly vulnerable to further increases in sea level and tidal inundation. With increases in relative water level, emergent marsh is likely to migrate to the higher elevation berms and landward where adequate space allows. However, in much of the Fowl River transition zone, existing armored shorelines could block inland migration of tidal wetlands.

In 1981, Stout and Lelong used aerial imagery and field surveys to map and characterize the four target spits as Tupelo-Cypress Swamp, but in recent decades these sites have, in whole or in part, transitioned from forested wetlands to herbaceous marsh. While this trend has coincided with rising sea levels and increased salinity intrusion, tree species in the family Lauraceae, particularly redbay (*Persea borbonia*) and swampbay (*P. palustris*), have experienced high mortality due to increased incidence across the Southeastern U. S. of laurel wilt, a vascular disease. Nearly all swampbay observed in this study were dead or dying from Laurel wilt disease.

The three most frequently recorded species surveyed were bull tongue arrowhead (*Sagittaria lancifolia* in 70% of sampled quadrats), black needlerush (*Juncus roemerianus* in 60% of sampled quadrats), and sawgrass (*Cladium jamaicense in* 50% of sampled quadrats). Bulltongue arrowhead was present at all sites, primarily along the lower elevation margins of emergent vegetation. Sawgrass was the most common species in the uppermost portions of the study. Black needlerush dominated the southernmost marshes, reflecting a gradient from upstream freshwater conditions and increasing salinity downstream through the transition zone and into Region 3, closest to Mobile Bay.

Higher transect elevations across surveyed spits (ranging from 0.65 m at Closing Hole to 0.20 m at the most downstream R3S1) generally align with berms on the upstream sides that support woody plants like wax myrtle (*Morella cerifera*) and eastern baccharis (*Baccharis halmifolia*). Lower elevations on downstream sides across the relatively broad and flat spit surfaces are dominated by herbaceous marsh vegetation.

Submerged aquatic vegetation (SAV) was mapped on the periphery of the four target spits. Any restoration activity undertaken to protect or maintain the existing marshes will be required to avoid direct and indirect impacts to SAV resources.

Vegetation Study Conclusions

- Comparison of historical aerial imagery of shoreline positions in 1940, 2002, and 2018 shows a progression in areal loss of wetlands, not only in the study area, but across all three regions of Fowl River.
- Changes in community composition and decrease in size of the Fowl River spits is likely to continue due to a combination of sea level rise, subsidence, and lack of sediment deposition.
- Fowl River Marsh spits have, in whole or in part, transitioned from forested wetlands to herbaceous marsh.
- The most frequently recorded plant species surveyed refleced a gradient from upstream freshwater conditions and increasing salinity downstream through the transition zone and into Region 3, closest to Mobile Bay.
- Spit topography across surveyed spits generally align with berms on the upstream sides that support woody plants and lower elevations on downstream sides with relatively broad, flat surfaces dominated by marsh vegetation.
- SAV mapped on the periphery of the four spits will restrain potential restoration measures to avoid impacting it.

Pre-Restoration Analysis of Discharge, Sediment Transport Rates, Water Quality, and Land-Use Impacts in the Fowl River Watershed – Marlon R. Cook

An assessment of dynamic sediment transport rates, water quality, and estimated sediment loads for the Fowl River Watershed was undertaken to determine if adequate sediment is available to sustain these estuarine marshes. Field parameters, including pH, temperature, turbidity, dissolved oxygen, conductivity, and salinity, were measured and water samples were collected at three sites – upstream, downstream, and in the area of the four target spits – for selected discharge events and tide levels from March to September 2018.

This investigation was combined with elements of a 2014-15 Geological Survey of Alabama assessment of water quality and sediment transport rates in the upstream, freshwater, fluvial parts of the Fowl River Watershed in 2014 and 2015 to comprehensively evaluate sediment transport conditions in the Fowl River Watershed.

Sediment loads in rivers or streams are composed of relatively small particles suspended in the water column (suspended sediment) and larger particles that move on or periodically near the streambed (bed sediment). A pre-monitoring assessment of sediment characteristics in the upstream, fluvial part of the watershed in 2014 indicated that relatively little bed sediment was present in the streams at selected Fowl River monitoring sites. Therefore, total sediment loads for the 2014-15 assessment were assumed to be primarily suspended. Water depth and tidal impacts prevented any attempt to quantify bed sediment transport in the estuarine part of the watershed during the 2018 assessment. Therefore, most sediment transported in the estuary was also assumed to be suspended.

Conclusions Derived from 2014-15 and 2018 Fowl River Sediment Transport Assessments.

- The Fowl River Watershed is relatively rural and dominated by forests, wetlands, and marshes that limit erosion and transport of sediment downstream to the estuary.
- Estimated sediment loads, significantly below the geologic erosion rate, confirm that the watershed is sediment starved.
- Evaluation of bottom sediment samples also confirms that coarse-grained sediment is limited, with deposition in isolated areas of the upper- and mid-estuary.

Therefore, adequate sediment to sustain marshes in the estuary is unavailable. Additionally, stratification caused by tidal movement of brackish water upstream along the bottom of the estuary has effectively trapped much of the suspended sediment on and near the bottom, preventing overbank deposition of sediment and limiting material for marsh accretion.

Fowl River Sediment Core Analysis – Dr. Alex Beebe, Ph.D.

Fowl River can be described geologically as a retrograding, flooded river estuary. As sea level has risen over the past several thousand years, the River’s sinuous channel meanders and freshwater wetlands have been inundated and replaced by a broad basin surrounded by salt marshes in its downstream reaches. As higher seas have invaded inland, so has the “ecotone,” or transitional zone between fresher and more salty water, and the river base level. As a result, freshwater and fluvial signatures within the ecotone, like point bars, freshwater vegetation, etc., are under constant threat of succeeding to more estuarine signatures, like mudflats, saltwater vegetation, etc.

Investigators performed sedimentological and geochronological analyses of replicate piston core samples to understand and isolate geological factors involved in spit transition and marsh loss. A total of 16 cores were collected for these analyses: two each on each of the four target spits; two on a downstream reference marsh spit; and two each at three river channel bottom locations upstream, downstream, and in the middle of the four target spits. Following core collection, loss on ignition, grain size characterization, and radiocarbon/fallout radionuclide dating were employed to detect changes in accretion over the past millennium. Lithological descriptions and dating enable reconstruction of recent marsh accretion and channel deposition rates and provide information regarding the timing of natural depositional facies transitions.

Core Lithology and Depositional Characteristics. Visual inspection of the **marsh cores** revealed unique and unexpected spatial differences, but few vertical (i.e., temporal) differences. The five pairs of marsh cores (e.g., four priority spits and one downstream reference marsh spit) were dominated by either a dark brown, muddy peat with coarse marsh plant macrofossils or by a brown to black, organic, rich sand with some coarse, deciduous plant litter. These visual descriptions were further supported by grain size analyses and loss on ignition, with muddy peat containing higher percentages of organic carbon and lower percentages of sand and organic sand containing lower percentages of organic carbon and higher percentages of sands. Subtle increases or “pulses” in percentages of sand were consistently observed from 5 and 10 cm and again between 14 and 20 cm below ground surface in the majority of marsh cores, perhaps corresponding to stochastic depositional events like tropical cyclones (e.g., Hurricane Frederic) and associated storm surges.

No apparent trends in marsh core lithology were noted, indicating stable depositional modes, but spatial differences suggested that depositional modes among or within the spits are different. Review of satellite imagery along with field observations revealed that muddy peat sediment was associated with grassy marsh vegetation, submerged hydrosoil, and downstream banks of the marsh spits. Organic, rich sand was associated with deciduous vegetation, emergent hydrosoil, and upstream banks of the marsh spits. These findings suggest a bi-modal depositional model for marsh spits, with downstream portions of spits accreting predominantly autochthonous plant litter and upstream portions accreting allochthonous coarse-grained sediment (i.e., sand) likely sourced as river bedload.

Visual inspection of **river channel cores** reveals both spatial and temporal lithological differences. Spatially, a fining downstream spatial pattern was observed, with upstream brown-to-white, organic rich-to-clean sand grading downstream to a dark brown-to-black, organic muck and estuarine mud. This trend of downstream fining is commonly observed in tidal rivers and estuaries, due to decreasing depositional energy as channel area increases, in addition to increasing fine organic and clastic sedimentation as increase in salinity promote flocculation and settling in the downstream direction.

Temporal changes in lithology were observed in the upstream and downstream channel cores, indicating changes in depositional mode through time. Lithology of the downstream core consisted of brown to black organic mud to a depth of 90 cm underlain by a 2.5-cm bed of clean coarse grained sand. Underneath the sand and to the bottom of the core (110 cm), the sediment transitions into brown to black organic rich sand, with some coarse, deciduous plant litter, not unlike that seen in cores from upstream banks of marsh spits. These lithological changes represent depositional environments evolving from a deciduous environment (organic rich sand) to an unvegetated shoreline (clean, coarse-grained sand) to an estuarine mud basin (brown to black organic mud). The burial of deciduous sediment beneath estuarine mud suggests marsh loss has occurred in the recent geologic history of Fowl River due to relative sea level rise and likely prior to human influence.

The most upstream river channel cores also demonstrated temporal lithological changes with an unexpected progressive increase in coarse, woody fragments from 35 to 75 cm depth. These fragments, angular in nature and nearly uniform in size, suggest anthropogenic sources, such as land clearing and development or lumber milling, corroborated by historical maps indicating mills in operation from 1837 through the early 1900s. A series of three anomalously clean, white sand beds lies immediately above the woody fragments likely correspond to stochastic, rapid, depositional events taking place since the introduction of the coarse woody fragments , presumably post-development. Possible sources of clean sand bed include land development or clearing in the early 1960s and/or tropical cyclones (e.g., Hurricanes Frederick and Ivan).

Radiocarbon Geologic Net Accretion/Deposition Rates. Subsamples from the bottom core interval of each coring location were analyzed for plant macrofossil extraction and radiocarbon dating (Table 1, page) to understand long-term. Results reveal marsh spit core-bottom ages of up to 950 years prior to time of collection and channel core-bottom ages of up to 4,690 years. Simple linear net accretion/deposition rates were calculated for each coring location by dividing the subsample depth by the radiocarbon date.

Linear accretion rates for the five marsh sampling locations ranged between 0.99 and 1.36 mm/yr and averaged 1.15 mm/yr with a low relative standard error. This demonstrates little difference between linear marsh accretion rates for these five marsh sampling locations, despite the differences in depositional mode evident in core lithology. This consistent rate indicates that marsh accretion is governed by a common factor, likely the relative rate of seas level rise (i.e., the sum of eustatic sea level rise and local geologic subsidence).

Given that the rate of sea level rise has increased over the last 150 years, a linear regression through the five marsh radiocarbon ages vs. subsample depth was developed to determine pre-development, background "geologic" accretion rates (Figure 11, page……). This regression offers a linear accretion rate between the measured subsample ages (i.e., 660 to 950 years before sample collection or between 1070 and 1360 A.D.), at which time seas level was relatively static. The accretion rate yielded by the slope of the regression (1.0 mm/yr,) approximates the current local subsidence as indicated by the historical elevation records from Dauphin Island (Figure 12 on page….). The intercept of the regression indicates of an additional 8.5 cm of accretion was likely prompted by the recent increase in sea level and suggests that the marshes are responding to sea level rise. However, eustatic sea level rise (2.74 mm/yr) has exceeded 13 cm in just the last 40 years (Figure 12 on page….), suggesting that marsh spits are not keeping pace with recent sea level rise and may be downing in place. Observations from the field revealed that the grassy marsh portions on downstream sides of the spits were consistently flooded with approximately 5 to10 cm of water, further lending support to this conclusion. Given the geologic record of marsh flooding and burial observed in CH-1, the threat of marsh flooding in the priority spits is almost a certainty. However, marsh loss along the shoreline can be offset by succession of hinterland terrestrial environments to marsh environments. In other words, the marshes should be considered dynamic ecosystems capable of migrating inland along with invading sea levels, provided inland accommodation area is available.

Fallout Radionuclide Accretion/Depositional Rates. The top 25 cm of one marsh spit (PS-1) and two river channel cores were further analyzed using high-purity germanium (HPG3) gamma-ray spectrometry to determine more recent rates of accretion and deposition from lead-210 (^{210}PB) inventories assuming constant rate of supply and cesium-137 (^{137}Cs) peaks related to man-induced atmospheric releases of nuclear fission products. ^{210}PB has a half-life of 22.3 years, making it a useful tracer for dating events up to 200 years before present. ^{137}Cs is only replenished in the environment as a result of human activities (i.e., above-ground nuclear weapons testing through 1963 and the Chernobyl nuclear disaster in 1986), making it a useful anthropogenic tracer.

All three cores analyzed for fallout radionuclides demonstrate a clear exponential decay of ^{210}PB with increasing depth. The ^{210}Pb constant rate of supply model (Appleby and Oldfield, 1978) was applied to determine ages and accretion and deposition rates over the period of record (Figures 13 and 14, pages …….). ^{137}Cs peaks were less useful in resolving timing, but rather serve to constrain ^{210}Pb data.

PS-1 had an average rate of accretion of 2.0 mm/yr over the past 131 years, which is nearly twice the average marsh linear accretion rate determined from the radiocarbon ages (i.e., 1.15 mm/yr; Table 1, page ……). This suggests that PS-1 is experiencing a recent increase in accretion, potentially explained by a response to the increased rate of sea level rise over the last century and a half and/or a decrease in compaction of the upper portion of the core due to more recent burial. In either case, the 2.0 mm/yr accretion rate still falls below the relative rate of sea level rise of 3.74 mm/yr (Figure 12, page), further suggesting that the marshes are succumbing to sea level rise (i.e., sinking). The rate of accretion over the past century at PS-1 has not been constant, with two notable increases taking place in the 1920's and yet again in the 1950's (Figure 15, page ……). A likely explanation for these increases are two periods of development booms in Mobile County that would have led to increased sedimentation from land-clearing and stormwater runoff.

The results from these core analyses provide evidence for a bi-modal depositional model of the Fowl River marsh spits. The model consists of a leading edge feature for marsh spits reliant upon sand for deposition, presumably sourced from river bed load. The leading edge protects the trailing marsh platform from erosive processes and is likely key for stabilizing marsh spits during transgressive geomorphic evolution and ecosystem succession. Therefore, plausible factors for marsh health decline include sediment starvation related to changes in land use, increasing erosion from boat wakes, and retrogradation associated with recent sea level rise. Furthermore, linear accretion rates derived from radiocarbon dating suggest that the marshes are not currently keeping pace with sea level rise and are essentially drowning in place (Figures 11 & 12, page …….). This is further supported by limited fallout radionuclide data which suggest that recent accretion has increased by nearly 75 %; however, the accretion rate over the last 131 years has remained well below the 50-year average relative rate of sea level rise (Figure 15).

Major Conclusions from Fowl River Sediment Core Analyses

Fowl River can be described geologically as a retrograding, flooded river estuary. As sea level has risen over the past several thousand years, the sinuous channel meanders and freshwater wetlands of Fowl River have been inundated by the sea and replaced by a broad basin surrounded by salt marshes in the downstream. The following were determined through sediment core analyses:

- Very little river sediment reaches the downstream Fowl River marsh spits.
- Core lithology indicates similar sediment types with changing composition over time.
- Sediment accretion is insufficient to keep up with sea level rise, so additional sediment will be necessary for restoration activities.

Fowl River Sediment Analysis of Organic Elements and Stable Isotope Ratios – Dr. Ruth H. Carmichael, Ph.D.

Changes in nutrient and hydrological regimes associated with anthropogenic land-use change can be traced by measuring organic nitrogen (N) and carbon (C) content and stable isotope ratios that reflect inputs from human wastewater sources and distinguish marine from freshwater influences. To determine if changes in Fowl River marsh structure of function may be related to changes in N and C sources associated with anthropogenic influences or variation in sea level through time, N and C content were measured in sediment core samples and suspended particulate matter (SPM) in the water. Sixteen core samples were collect on and around the four priority marsh spits and at one downstream reference site (Figure 1, page). Water samples were collected monthly from January through October 2018 at eight collection sites (figure 2, page) and filtered onto glass fiber filters to isolate SPM. Sediments and filters were analyzed by continuous flow isotope ratio mass spectrometry, yielding N and C stable isotope ratios and percent N and C content in the samples. These data were aligned with elemental dating outputs to determine changes through time relative to land use and marsh area to help define sources and mechanisms of change.

N and C stable isotope ratios in the reference marsh (site 3.4) and spits 2 and 3 (sites 2.3 and 2.4; Figures 1 and 3, page) showed distinctive changes with core depth between 20 cm depth and the surface, including an increase in N from ~1 to 5‰ and a decrease in C from -27.5 to -29‰. Assuming consistent sedimentation rates among sites, comparison to dates estimated for other sediment cores in this study suggests the sediment depth of greatest change (20 to 7.5 cm) corresponds to the period from 1900 to 1960.

These findings are consistent with known changes in C and N stable isotope ratios in sediments due to increasing human influence in the Watershed, particularly shifts from primarily vegetated to residential or urbanized areas that are occurring worldwide (Carmichael and Valiela 2005, Vaalgamaa et al. 2013). Higher N stable isotope ratios are typically associated with processed human wastewater and lower carbon values are typical to terrestrial and freshwater influences. The isotopic shifts in Fowl River, therefore, are common to areas that have experienced changes from vegetated to urbanized or residential areas (with more impervious surface and channelized flow), which allow more direct delivery of terrestrial C and human wastewater and stormwater to local estuaries. Our results suggest these changes began in the early 1900s and continued most intensively through 1960 in the Fowl River watershed. These findings are consistent with results of similar studies in the Grand Bay, MS area (Darrow et al. 2016).

Cores taken from river channels and spits 1 and 4 (Figures 1 and 4, page) did not show consistent or coincidental changes in C and N stable isotope ratios above 20 cm. This suggests that channels to not intercept and retain land-derived organic matter as effectively as marsh.

Stable isotope ratios in SPM in the water column along Fowl River showed high variation in both C and N. The combination of C and N stable isotope ratios at some sites suggested greater terrestrial and potential unprocessed human wastewater inputs to the area, especially those near spit site 3 at which core samples also indicated changes in isotope ratios coincidental with timing or urbanization.

Sediment Core Organic Element and Stable Isotope Analysis Conclusions
Locations along Fowl River had signatures of C and N in sediments and water that suggest human activities on the watershed have altered the hydrology of the river and changed the quality of organic matter entering the system. In particular, changes in marsh and spit sediments indicated shifts toward greater terrestrial C and wastewater or stormwater-associated N since the early 1900s. These changes are better recorded in marsh sediments than in river channels. Values in surface sediments and water suggest that these changes persist in the system and some locations may receive greater point sources of anthropogenic C and N than others.

Characterization of Impacts of Waves and Boat Wakes on Marsh Spits in the Transitional Zone of Fowl River – Dr. Brett Webb, Ph.D., PE and Dr. Stephanie Smallegan, Ph.D., PE

Fowl River experiences substantial pressure from recreational boating (i.e., fishing, tow watersports, personal watercraft, pleasure boaters). Wakes generated by these recreational boats have been cited as a factor contributing to the degradation of marshes and spits within the study area. To that end, boat wake characteristics were sampled at a number of locations, nearly continuously, from May through October 2018, allowing characterization of the magnitude and frequency of boat wakes impinging on shorelines.

Fowl River boat wakes were measured using ten pressure gauges manufactured by RBR Global: six RBR Solo (sampling pressure at a frequency of 8 Hz) and four RBR Virtuoso (sampling pressure at 6 Hz, the maximum possible) gauges. The six RBR Solo gauges were deployed at long-term locations for the duration of the study period: one at each target spit location and one at a reference marsh downstream in the “coastal” zone, and one at a reference marsh upstream in the “freshwater zone.” The four RBR Virtuoso gauges were deployed for shorter durations at each of the target spits. This strategy resulted in both long-term, longitudinal measurements through the study area and shorter term, but higher-resolution, measurements at the spits targeted for restoration. The deployment locations are shown in Figure 2 (page ….). In that figure, each yellow “bullseye” symbol denotes a deployment location during the study period. The bullseye symbols encircled by the larger hollow circle represent the long-term deployment locations of the six RBR Solo gauges. Over the duration of the study, the six RBR Solo gauges remained at their respective locations. The four (and ultimately three, due to a mount failure in the field) RBR Virtuoso gauges were relocated four times at roughly monthly intervals to the four target spit locations.

Each gauge was deployed vertically on its own PVC pipe mount with the pressure sensor oriented downward and generally within 20 cm of the bed in water with depths of approximately 1 m. The RBR gauges measure absolute pressure, which is the sum of atmospheric and gauge pressure. Gauge pressure is the sum of the hydrostatic (tide) pressure and the hydrodynamic (wave) pressure. Atmospheric pressure was removed from the absolute pressure to yield more accurate measurements of gauge pressure and more accurate estimates of boat wake characteristics.

Boat wake characteristics were estimated from pressure measurements using linear wave theory and standard time-domain analysis techniques, resulting in estimates of individual wave height and period for each boat wake event. Records of wave height and period were further processed to yield statistical representations that are often used in coastal engineering design (e.g., significant wave height, average wave period, etc.), and are included in Table 2 (page). There was a fairly clear pattern at most spit locations where wave heights were larger on the upstream sides of spits than on their downstream sides, with the exception of Closing Hole, which exhibited larger wave heights on the downstream side.

The significant wave height (H_S) the average of the largest one-third of waves measured – at each location is well below the often-cited vegetation tolerance threshold of 33 cm (Roland and Douglass 2005). However, that tolerance threshold is a function of both wave height *and* frequency of occurrence, as shown in Figure 3 (page ………). Measurements indicate that the tolerance threshold is exceeded at least 20% of the time at almost every deployment location and up to 80% of the time at some deployment locations. So, while no location exhibits large significant wave heights, every site exhibits measurable wave action of long periods of time.

Pressure gauge deployment in Fowl River during the period May – October 2018 provides measurements necessary to characterize boat waves during high traffic periods. Recreational boating in winter months tends to be less frequent.

Conclusions derived from analysis of boat wake characteristics:

- Almost 100% of the wave energy in the study area is attributed to boat wakes;
- Almost 100% of the boat wake events occur during the period 7:00 am to 7L00 pm;
- Significant wave heights are small and range from 8 cm to 18 cm;
- Average wave periods range from 1.4 s to 2.5s;
- Wave heights are generally larger on the upstream sides of spits; and
- Significant wave heights routinely exceed the threshold or vegetation tolerance.

The boat wake measurements, particularly when combined with other data collected in this inquiry, provide important context useful to inform restoration design. The relatively small, but frequent, wave height suggest that spits may require persistent wave attenuation in the form of edge protection. Since the wave heights are typically small, the requirements for wave attenuation may be more moderate and less robust. In the summer months, high tide occurs during daylight hours when boat traffic is heaviest. An effective sill design in Fowl River may require a crest elevation above or close to mean high water to provide an appropriate amount of wave attenuation during summer heavy-traffic times.

Fowl River Marsh Study – Hydrology and Hydrography – Dr. John Lehrter, Ph.D. and Alexis Hagemeyer

Investigators sampled water from February to December 2018 to facilitate comparison across the three regions Fowl River regions (See Figure 3 of the Marsh Plant Study): Region 1, the upstream area characterized by freshwater inputs from the watershed; Region 2, the transition area or ecotone between freshwater and more marine influence and where the priority marsh spits are located; and Region 3, the most marine of the three regions connected to Mobile Bay and Mississippi Sound. Ten monthly surveys were conducted to measure estuarine ranges and dynamics of salinity, temperature, oxygen, suspended sediments, organic matter, and nutrients. Eighteen hydrographic stations were established to quantify horizontal and vertical gradients of salinity, temperature and oxygen across the three regions. At three of the marsh spits (see Figure 2, page), porewater salinity, temperature, and oxygen were collected continuously from April to December 2018 at 15-minute intervals using in situ field sensors in porewater wells.

Hydrographic Profiles. During the 10 monthly surveys, vertical profiles of salinity, temperature, and dissolved oxygen concentrations were collected at the 18 stations with a conductivity, temperature, and depth (CTD) sensor. For each cast, the CTD was submerged at 1 m depth for one minute to purge the system of bubbles, before brining the instrument to the surface and then slowly lowering it with a hand winch through the water column to the bottom to obtain a vertical profile. Efforts were made to sample the exact same locations over the course of the study.

Water column salinity in Fowl River ranged from 0-13 ppt. Monthly synoptic sampling revealed the expected salinity gradient with freshwater at the upper river and increasing salinity down river towards the river mouth. From March to April, the water column was well-mixed with surface and bottom salinities nearly equal. From May through November, salinity intruded up into the river mainly in bottom waters, with a maximum salinity (> 12 ppt) occurring at the bottom during fall. Salinity characteristics of Region 2 tend to mirror those of Region 1.

Temperatures ranged from 14-31°C, with a minimum (~14) in March increasing to maximum (>31°C) In September. On average, temperatures were 4-6°C cooler at upstream sites than at the river mouth.

Dissolved oxygen concentrations ranged from 0.1 to 12.8 mg L^{-1} and were commonly below the hypoxic threshold of 2 mg L^{-1} during summer and fall of 2018. Oxygen concentrations were highest in March and April, when [O_2] exceeded 10 mg L^{-1}, and lowest at stations in Region 2, where bottom waters were hypoxic ([O_2] < 2 mg L^{-1}) on six of the 10 surveys. Hypoxia also occurred at the border of Region 1 and 2 and in the upstream area of Region 3.

Discrete Water Column Measurements. At eight of the 18 stations, discrete surface and bottom samples were analyzed for salinity, temperature, and oxygen using a YSI 2030Pro meter. Samples were then processed and prepared for analysis of chlorophyll-a (chla), total suspended solids (TSS), volatile suspended solids (VSS), dissolved nutrients, particulate organic carbon and nitrogen (PCN), and dissolved organic nitrogen (DON) and organic carbon (DOC).

TSS and salinity were clearly positively correlated, with TSS peaking at approximately 50 mg m^{-3} at the mouth of Fowl River. This relationship resulted in lowest TSS in Regions 1 and 2 and the highest in Region 3. Bottom waters generally had higher TSS than surface water. This pattern indicated that the primary source of suspended sediments to this system was Mobile Bay rather than the Fowl River Watershed.

Nitrate (NO_3^-) concentrations of approximately 40 mmol m^{-3} were common in the upper estuary and decreased downstream. High NO_3^-, NH_4^+, and PO_4^{3-} concentrations translated to high chl*a* concentrations, which often exceed 40 mg m^{-3}. Eutrophication and associated poor water quality condition is generally indicated at chl*a* >20 mg m^{-3}.

High Frequency Marsh Porewater Time-Series Measurements HOBO logger instruments were deployed from April to December 2018 to collect time series data on three spits. Within each of those spits, 5-inch PVC wells were installed at three locations across the spit (upstream side, middle, downstream side). Within each well, loggers measured water surface elevation, salinity, dissolved oxygen, and temperature. Well locations were surveyed with an RTK GPS to obtain horizonal and vertical positions within each marsh spit.

Surface water elevation data obtained from the wells indicated that the marshes were flooded from April-October 2018. Porewater salinities were lower at spits 2.4 and 2.7 and highest at spit 3.4, which was located across from Bellingrath Gardens and closest in proximity to Mobile Bay. Within a spit, there was a noticeable gradient in salinity with the upstream portion of the spit having lower salinity than the downstream portion, with salinity values generally highest in the middle of the spits.

Hydrologic/Hydrographic Conclusions

Results suggest that the observed marsh spit degradation is likely due to a combination of factors. First, marsh surfaces were inundated for nearly the entire period from April to October. With suspended sediments mainly driven by inputs from Mobile Bay, the spits in the middle and upper river are removed from sediment sources and may not be receiving or accreting sediments fast enough to keep up with sea level rise (~3.6 mm yr^{-1} calculated from surface elevation data at Dauphin Island and the State Docks).

Second, it is likely that salinity is increasing in this system due to observed sea-level rise and decreasing freshwater input from the greater Mobile Bay Watershed (Where is this indicated, John?). The similarity of salinities in Regions 2 and 3 suggest that salinity changes experienced at the mouth of Fowl River will also affect Region 2. While salinity in Region I appears to be mainly controlled by Watershed freshwater inputs maintaining nearly fresh conditions, higher bottom-water salinity was observed to be encroaching into Region 1 in the summer and fall.

Third, the nutrient, chl*a*, and oxygen data indicate Fowl River is a eutrophic system. While impacts of eutrophication on marsh health are not well understood along the Gulf of Mexico, in other systems, such as New England marshes, eutrophication is linked to collapse and loss of the marsh edge. Nutrient impacts result in changes in plant root:shoot ratios, with more energy devoted to shoot production under high nutrient conditions, general reductions in root strength, and enhanced remineralization of marsh soil organic matter due to elevated nutrients and labile organic matter from phytoplankton. In combination, these effects may cause slumping and erosion at marsh edges.

High-Frequency Salinity Intrusion in Fowl River, Mobile County, AL – Dr. Brian Dzwonkowski, Ph.D. and Jeff Coogan

These investigators focused on salinity dynamics to assess potential ecosystem implications associated with changing salinity exposure on marsh platform vegetation. To understand how Fowl River and its marsh spits are changing temporally and spatially, time series data were collected during the selected study period - May 1 – July 11, 2018 - from five monitoring stations within the system (shown in Figure 1 on page). The four Fowl River sites were distributed along an expected salinity gradient to characterize changes over the extent of the system, while the West Fowl River site was intended to assess any influences from Mississippi Sound.

Additional environmental data, including meteorological data, freshwater discharge, and water levels, were obtained from various sources. Hourly wind data where collected from the NOAA National Data Buoy Center station DPIA1 at Dauphin Island. Daily discharge data for Fowl River where obtained from a U. S. Geological Survey gaging station. Hourly water level data were obtained from regional NOAA tide stations at Dauphin Island (ID 8735180), the mouth of Fowl River near the sonde at the Fowl River Mouth (ID 8735523), and the mouth of West Fowl River near the installed sonde. Water level data were de-meaned so differences in site responses could be readily compared. Data from DI were considered as a reference to represent water level along the coast (referred herein as “coastal water level”).

Wind data at DI were measured at 13.5 m above sea level and standardized to 10 m above sea level using a log wind profile. The east-west component of the wind vector was used as the along shelf component, and since Fowl River is connected to both Mobile Bay and Mississippi Sound, with perpendicular primary orientations of north/south and east/west, respectively.
Time series of the salinity data from the five stations showed both spatial and temporal variability (see 1Figure 2, page --------). Spatially, sampling sites varied from brackish to completely fresh. The West Fowl River site was consistently saltiest with the largest tidal signal. In contrast, the most upstream Bridge site had no tidal signal and was completely fresh through most of the study period. Only three prominent salinity intrusions into Fowl Fiver occurred during the study period around May 20, June 1, and June 26. During these events, the progressions of salt into the estuary exhibited a general pattern of the increase being initiated at the Fowl River Mouth site, with subsequent increases progressing through upstream stations. The influence of Mississippi Sound was consistently observed at the Bellingrath site. River discharge, low over much of the study period, did not appear to be coupled with the three salinity pulses.

Water level data against the salinity time series indicated that early in the time series, increases in water level were associated with increases in salinity. Later in the study period, increases in salinity were associated with differences in water levels between West Fowl River and Fowl River. Wind forcing is a well-established mechanism for modifying coastal water level. Remote forcing of interior water level changes in response to a wind events at the system boundaries drive these differences. Locally forced increases in water levels (from wind events within a system) were noted in response to southwesterly winds at Mississippi Sound/Portersville Bay This effect would be expected to result in higher water level at West Fowl River relative to Fowl River Mouth, and thus generate a barotropic pressure gradient that would be expected to force water from Mississippi Sound into Fowl River. Thus, the local effect of the wind forcing in Mississippi Sound/Porterville Bay is still a remote effect, in that it is derived from an external forcing on the boundary of the system. Local wind forcing within Fowl River was small, as the system is narrow and sinuous, so that no predominate wind direction is likely to have enough fetch to generate an appreciable circulation throughout the interior of the system.

Salinity responses to wind forcing (via changes to water level) in this investigation were somewhat limiting, in that only three large intrusion events were observed during the time series. This small sample size presents statistical challenges as the salinity response to forcing conditions can be difficult to quantify due to the potential non-linear behavior of salinity time series arising from several competing controlling factors (e.g. river discharge, oceanic changes, tidal straining, wind mixing, etc.).

Salinity Intrusion Conclusions:

- System salinity generally increased over the course of the study period, consistent with reduced discharge expected during the transition from spring to summer.
- There was significant temporal variability in the salinity signal with low frequency changes on the order of 4-8 psu over day to week time scales.
- The salinity dynamics in Fowl River are clearly influenced by the conditions from both Mississippi Sound and Mobile Bay as an interior site was, at times, saltier than the mouth of Fowl River.
- During periods of low discharge, wind conditions, through changes in water level, represent an important forcing mechanism controlling salinity variability
- Two types of wind forced intrusions were observed: remote forcing events of coastal origin and remote forcing events of local origin. Remote forcing events of coastal origin altered water level at the coastal line and subsequently pump salt into estuary, whereas remote wind forcing of local origin resulted from local wind forcing changing the water slope in the main estuaries adjacent to the sub-estuary and ‘pushing’ salt into the system (via a barotropic pressure gradient).
- Finally, the close relationship between wind conditions and water level have indirect implications for the impacts of salinity under rising sea level. These results suggest that as sea level rises, the impacts of salinity will more strongly affect the system.