GEORGIA DOT RESEARCH PROJECT 19-05

Final Report

BIRD-LONG ISLAND MANAGEMENT STUDY PHASE 2A: ENHANCEMENT AND RESTORATION INTERVENTIONS FOR BIRD-LONG ISLAND SHORELINE ALTERNATIVES: DESIGN AND MODELING FOR STEWARDSHIP

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This study evaluated a variety of design interventions using nature-based solutions to preserve a culture resource on Bird-Long Island and promote indigenous vegetative communities by maintaining or increasing vegetative biodiversity. Several alternatives were proposed that utilized a combination of green and gray infrastructure, such as living shorelines, thin layer placement, and beneficial dredge. Strengths and weaknesses accompany each design alternative with relative construction costs. Environmental site data was collected during study and demonstrated that naturally occurring, reef forming organisms were naturally present and could likely populate proposed nature-based solutions.

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Metric Conversion Chart

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mLL
gal ft^3	gallons	3.785	liters	m^3
yd^3	cubic feet	0.028	cubic meters	m^3
	cubic yards	0.765	cubic metersNOTE:	
	volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 32)/1.8	Celsiusor (F-	^oC
		ILLUMINATION		
fcfl	foot-candles	10.76	lux	lx cd/m^2
	foot-Lamberts	3.426	candela/m^2	
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fcfl
cd/m^2	candela/m^2	0.2919	foot-Lamberts	
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

The GA Department of Transportation (GDOT) owns Bird-Long Island and a portion of Cockspur Island at the mouth of the Savannah River along the border of Georgia and South Carolina. Bird-Long Island has an extant civil-war historic resource, Battery Hamilton, a civil-war era gun emplacement, and is mostly an anthropogenic island created by dredge fill that merged three extant islands. Bird-Long Island is composed of low and high marsh and is rimmed by forested uplands on its northeastern shore along the North Channel of the Savannah River.

This study proposes unranked design alternatives to evaluate management options to preserve the island and cultural resource in the near term given the excessive erosion, subsidence, and rising sea level in this area. The design alternatives are based on suitability analyses for nature-based systems (NbS) for thin layer placement (TLP), beneficial dredge placement, living shorelines, and solutions that may use gray infrastructure. Professors and their graduate students explored environmental data, analyzed control sites, and suggested alternatives to better understand stewardship opportunities. Designs and interventions were based on a suitability map of the possible solutions. Alternatives that utilized different components were costed relative to each other. Strengths and weaknesses associated with each design alternative were presented, and no preferred alternative was recommended. The conceptual designs should elicit much conversation internal to GDOT, as well as external discussions with regulators and other agencies

CHAPTER 1 INTRODUCTION

The shoreline of Bird-Long Island, an anthropogenically altered island, is changing in ways that threaten cultural and natural resources on this property that GDOT owns and intends to use for saltwater marsh mitigation. The first phase of the Bird-Long Island project investigated shoreline movement over time, deployed spat sticks, documented vegetative alliances, and quantified channel velocities (Phase 1A: Alexander, C. and Calabria, J. and Phase 1B: Haas, K.). Results from the first phase informed the second phase of design interventions, which balance cultural and natural resources in light of environmental changes. Design interventions are proposed with unranked strengths and weaknesses that explain their efficacy. Several conceptual plans that include passive and active strategies to enhance natural and cultural resources on this property are proposed.

PHASE 1 REPORT SUMMARY

Phase 1 of this study evaluated the current character of shorelines on Bird-Long Island, determined rates of shoreline change on the island, determined the threat to historic resources (Battery Hamilton, a civil-war era gun emplacement, important in the bombardment of Ft. Pulaski), evaluated the potential for living shoreline stabilization, and delineated the plant alliances currently present (Alexander and Calabria, 2019; Haas, 2019).

Shoreline change rates, measured in meters per year (m/yr), along Bird-Long Island shorelines were determined to be rapid (1.4-3.3 m/y) on the north shore but relatively slow on the south channel shoreline (0.20-0.51 m/y), reflecting prevailing environmental energy. Episodic events dramatically alter the steady-state system and increase change rates on both the north and south shores. Change rates have remained elevated for at least two years (the duration of our dataset, which ended prior to Hurricane Irma). Within that time frame, shoreline change rates have not shown a tendency to return to long-term averages. From the AMBUR analysis results, it was predicted that Battery Hamilton, where shoreline change rates are low (0.1-0.4 meters per year), in line with its location on the south shore of Bird-Long Island, will begin undergoing erosion in approximately 23 years, and will be completely eroded away in approximately 186 years. An initial spat-stick study documented that oysters and other reef-forming organisms would likely colonize a living shoreline or other intervention that would promote habitat and minimize excessive erosion. A variety of plant alliances exist on the island, most of which are indigenous vegetation with a few exotic species that will require control if the area is to be used as a mitigation site. Salinity dieback of several woody species suggests an opportunity to proceed with vegetative management planning for this area.

Phase 1 provided critical information to develop enhancement and restoration interventions that will stabilize the island's shorelines, increase resilience of biological communities, and protect the historical resources on the island (Alexander and Calabria, 2019).

LITERATURE REVIEW

In emergency management literature, disasters are classified as slow- or fast-moving. A fast-moving disaster is easy to pinpoint—a sudden event that quickly strikes a population, like a hurricane or tornado. Slow-moving disasters develop over long periods of time as a result of changing long-term patterns, both environmental and/or anthropogenic. In these cases, it can be hard to tell when the event has crossed the imaginary threshold that warrants calling it a disaster (Phillips, Neal, and Webb 2016). Sea Level Rise (SLR), though accelerating in pace, is a gradual process and goes relatively unnoticed on a daily basis. However, the accumulating gradual changes it produces cannot be ignored. There are also fast-moving disasters, namely coastal storms, whose increased impacts are also associated with SLR and storm surge.

One of the most important ecosystems along the East Coast is the common salt marsh dominated by *Spartina alterniflora*, or saltmarsh cordgrass. The marsh forms a buffer between inland areas and tidal waters, typically occurring behind barrier islands or at the mouths of tidal rivers (Tiner 1993). It provides vital habitat, filters out pollutants from runoff, and buffers wave energy to provide erosion control and protection during storms (Borchert et al. 2018). It also lends a unique and iconic natural beauty to the coast.

Within the salt marsh ecosystem, there are two primary vegetation zones: low marsh and high marsh. The low marsh is flooded daily due to the tides, as it sits at a lower elevation. Very few plant species other than *S. alterniflora* can survive in these high salinity levels, so there is low floristic diversity, but high biomass relative to other vegetative communities. The high marsh is flooded only irregularly, so it can support a wider range of species like salt grass, salt meadow cordgrass, black needlerush, and glassworts. As the high marsh transitions to upland, the edge supports a wide variety of woody plants and shrubs such as wax myrtle, palmetto, red cedar, and groundsel tree. (Tiner 1993)

Marshes maintain their elevation relative to sea level through accumulation of mineral and organic matter (Schile et al. 2014). If lacking adequate sediment supply, the lowest areas of marsh are drowned as sea level rises, so the marsh gradually migrates upland, outcompeting the coastal forests that border it inland. Due to the advent of Geospatial Information Systems (GIS), it is now possible to predict—with varying degrees of accuracy—the position, rate, and species composition that marshes exhibit as they move upland, called Sea Level Affecting Marshes Model (SLAMM). However, there are certain barriers to the seemingly inevitable process of marsh migration, caused by the consequences of anthropogenic climate change as well as direct human actions.

Public and private landholders, with marsh-front property are loath to lose upland acreage to encroaching wetlands. Hardening tactics like bulkheads and revetments maintain the current shoreline and protect property (J.D. Rosati et al.,2015). Salt marsh seaward of these hardened shores faces an insurmountable obstacle in keeping pace with the rising sea. This phenomenon is known as “coastal squeeze” (Borchert et al. 2018) that does not allow for marsh migration.

Due to the advent of Geospatial Information Systems (GIS), it is now possible to predict—with varying degrees of accuracy—the position, rate, and species composition that marshes exhibit as they move upland, called Sea Level Affecting Marshes Model (SLAMM).

More generalized climate change-related processes also pose threats to the marsh. Rising temperatures and more frequent droughts can negatively affect salt marshes. For instance, a drought during the summer of 2002 suddenly killed almost 1,000 acres of Georgia salt marsh due to lack of freshwater supply and resulting over-salinization, heat stress, and altered soil pH. The altered pH caused uptake of toxic metals in the soil and reduced the ability of vegetation to take in freshwater from upstream (Seabrook 2013).

Nutrient enrichment has presented itself as a driver of salt marsh loss in recent years as well. When soils are oversaturated with agricultural nutrients, particularly nitrogen, these compounds are washed into rivers and down to the ocean. While nutrient enrichment at today's high rates increases above-ground leaf biomass in marshes, it decreases below-ground biomass of roots and increases microbial decomposition of organic matter. These alterations lead to reduced soil stability, causing creek bank collapse and conversion to unvegetated mud (Deegan et al. 2012). This has negative implications for marshes' resilience to hurricane damage (Mo, Kearney, and Turner 2020).

Coastal erosion is defined in terms of "the movement of shore contours," caused by chronic SLR and/or consequent removal of geologic materials that compose the shoreline. Erosion rates are increasing in response to SLR because new portions of the shoreline are exposed to wave and current action (Council 2007, 37).

Loss of land due to shoreline erosion becomes a problem when there is no space upland to accommodate the occurring changes (Rangel-Buitrago, de Jonge, and Neal 2018). As with marsh migration, landholders typically resist conceding their limited parcels of land as sea level rises, so they implement protective measures to prevent the shoreline from creeping upland. Bulkheads are among the most common purported solutions. However, in the long term, bulkheads can end up exacerbating the problem (Polk and Eulie 2018). Heightened tides inevitably overtop walls, allowing waves to scour around them, pulling sediment back out to leave water and collapsing soil behind (Hesselgrave 2019). Also, bulkheads reflect almost all of the wave energy that strikes them, leading to sediment scour from the bottom of the structure, which deepens the area and degrades benthic habitat (Council 2007; Palinkas, Sanford, and Koch 2018). On a larger scale, bulkhead armoring permanently withholds sediment from the littoral transport system that should be nourishing downstream shorelines (Council 2007).

Climate change is undeniably altering the “intensity, spatial extent, duration, and timing” of extreme weather events (Field et al. 2012). On the Southeastern coast, the most common disruptive events are hurricanes and tropical storms (Marcy et al. 2012). Storms have always been the primary drivers of coastal sediment shift/erosion, even before human activity accelerated the pace of SLR. Strong currents and wave energy from storm tides scour the shoreline, removing sediment and depositing it elsewhere along the coast. (Council 2007).

Coastal storms can be devastating to infrastructure on their own, and they also accelerate the effects of the previously mentioned “slow-moving” emergencies. While wind damage can be a problem, depending on location, the most damaging aspect of any storm is storm surge (NOAA 2020).

Storm surge is a “non-tidal addition to the predicted tide level,” caused by the winds and low pressure associated with an atmospheric front that is caused by a storm (Marcy et al. 2012). Because of the weight of water, infrastructure that is not specifically designed to withstand such forces may be damaged or destroyed upon impact. Storm surge is also responsible for flooding/saltwater inundation and acute erosion (NOAA 2020). It produces all the same effects of nuisance flooding mentioned in the previous section, but more strongly. The damaging consequences are exacerbated when a storm surge coincides with a high tide. The combination of storm surge and tide is referred to as a “storm tide,” (NOAA 2017). The storm tide gives the best estimate of how much water is experienced on land.

Both storm surge and storm tide are difficult to predict because they are so sensitive to minor changes in wind, pressure, speed, and size of the storm—and the shape and position of the land area can affect it as well (NOAA 2020). The damaging consequences are exacerbated when a storm surge coincides with a high tide. The combination of storm surge and tide is referred to as a “storm tide,” (NOAA 2017). The storm tide gives the best estimate of how much water is experienced on land.

Resilience, as presented by the Army Corps of Engineers in 2015, is “the ability of a system to prepare, resist, recover, and adapt to disturbances in order to achieve successful functioning through time” (Rosati, Touzinsky, and Lillycrop 2015). This definition requires characterizing functions and performances on all systemic levels. Thus, successful coastal planning usually addresses natural and nature-based features (e.g. naturally occurring or created marshes, dunes), structural interventions (e.g. seawalls, breakwaters), and nonstructural interventions (e.g. floodplain building policies, education programs, evacuation plans) (Bridges et al. 2013). Natural and structural features, as well as hybrids between the two, function to stabilize shorelines to protect infrastructure and human well-being in populated areas.

A large part of coastal resilience or adaptation consists of protecting infrastructure and population. Though people have been modifying the coast for these purposes for hundreds of years, SLR has increased concern recently. Because land loss from erosion and inundation are the most urgent issues, most of the defense measures work to stabilize the shoreline. shoreline stabilization techniques range from natural (naturally protective coastal ecosystems) to “hard armoring” (engineered man-made structures made of hard materials like rock, concrete, or steel). “Nature-based” solutions may refer to natural, soft, or hybrid stabilization measures (Bridges et al. 2015). Regional variation in SLR rates, topography, municipality size, building density, shoreline change rate, etc., preclude a one-size-fits-all approach to planning these structural defenses, so planners must develop objectives and consider context (Bridges et al. 2013; EPA 2009; Gedan et al. 2011; Palinkas, Sanford, and Koch 2018).

Increasing evidence shows that natural shoreline habitats like dunes, submerged aquatic vegetation, mangroves, coral reefs, salt marshes, and oyster reefs reduce the risk of coastal flooding by forming physical structures that can attenuate wave energy, block winds, and reduce erosion, depending on the ecosystem’s context and health (Van Wesenbeecket al. 2013; Gedan et al. 2011; Sutton-Grier, Wowk, and Bamford 2015; Sutton-Grier et al. 2018; Shepard, Crain, and Beck 2011). Coastal ecosystems provide co-benefits like greenhouse gas mitigation, water quality enhancement, habitat provisioning for economically important species (e.g. shrimp, fish), and natural beauty (Needelman et al. 2012). Restoration of natural shorelines may include removal of structural modifications and enhancement of natural features but does not include any added components (Gianou 2014).

Soft shoreline stabilization uses natural materials to enhance or restore natural processes and topography, increasing connectivity between aquatic and terrestrial environments. The approach can involve removal of structural modifications like seawalls and riprap, with the intent of restoring a lower gradient. Examples include beach nourishment with dredged material, strategic placement of large woody debris, vegetation enhancement, marsh toe reinforcement with coir logs, structures made of natural materials, and some forms of "living shoreline." While soft stabilization provides more ecological benefits than hybrid or hard stabilization, short-term environmental damage still occurs (Gianou 2014).

Living shorelines have gained attention for shoreline stabilization in recent years. On the east coast, living shorelines typically consist of salt marsh and/or oyster reef creation or restoration, sometimes with benches, sills, or breakwaters (Bridges et al. 2015). Depending on how much engineering and man-made material goes into a project, it can range from "soft" to "hybrid." Successful projects can provide services similar to those of natural shorelines: wave energy dissipation, erosion reduction, sediment accretion, and habitat (Mitchell, Bilkovic, and Pinto 2019; Polk and Eulie 2018; Smee 2019; Bridges et al. 2018). Unlike hard or some hybrid stabilization techniques, the biotic components of oyster reef and marsh living shorelines have the potential to keep pace with SLR (Rodriguez et al. 2014, Mitchell, Bilkovic, and Pinto 2019). However, some living shoreline installations fail because of poor siting and insufficient maintenance (Mitchell, Bilkovic, and Pinto 2019).

Sometimes it is most useful to enhance or rebuild coastal ecosystems systems to address human objectives via engineering, in which case the approach becomes "hybrid" or "nature-based" (Bridges et al. 2015, Sutton-Grier et al. 2018). A "hybrid approach" may also refer to a solution that combines specifically selected hard armoring with natural systems (Sutton-Grier, Wowk, and Bamford 2015). These solutions are gaining traction in recent literature because they combine the best of both approaches—gray infrastructure performs well in reducing flood risk, while green infrastructure complements it with co-benefits from ecosystem services (Alves et al. 2019). Hybrid coastal infrastructure has the potential to function like hard armoring while retaining and/or conferring social, economic, and ecological co-benefits, potentially making it more cost-effective in the long term (Sutton-Grier, Wowk, and Bamford 2015). Examples of hybrid solutions include stream-design culverts to restore natural tidal flow and reduce flood damage, and breakwaters made from artificial oyster reef habitat to attenuate waves and mitigate the effects of storm surge (Sutton-Grier et al. 2018, Bridges et al. 2018).

The traditional solution to stabilizing the shoreline is armoring with engineered structures—often referred to as “gray” or “hard” infrastructure. These structures use materials such as large rock, concrete, or steel to alter shoreline configuration (Gianou 2014). They include seawalls, bulkheads, levees and storm surge barrier gates, culverts, dikes, jetties, breakwaters, groins, and revetments (Sutton-Grier et al. 2018; Sutton-Grier, Wowk, and Bamford 2015; Bridges et al. 2013). Seawalls, bulkheads, levees, and storm surge barrier gates are intended to reduce flooding, while the other structures are created to reduce erosion and/or promote sediment accretion; all are capable of reducing storm wave damage (Bridges et al. 2013).

Each of these structures comes with its own set of drawbacks. Moreover, gray infrastructure ages and degrades in condition over time, necessitating expensive repair or replacement. Failure to perform when needed can be catastrophic (Sutton-Grier et al.

2018). For instance, flooding in New Orleans during Hurricane Katrina was exacerbated when levees failed. While the structures may be temporarily effective in flood protection, they are expensive to construct and maintain, and inflexible—as climate conditions continue to change, static structures become less practical (Hamin et al. 2018, Alves et al. 2018). Generally, coastal armoring confers few ecological benefits and severely limits natural processes (Sutton-Grier et al. 2018, Gianou 2014). In many places gray infrastructure has contributed to significant declines in aquatic organism abundance due to habitat loss (Morris et al. 2018, Sutton-Grier et al. 2018).

NATURE BASED SOLUTIONS AND GRAY INFRASTRUCTURE

Nature Based Solutions vary in scale and context. A variety of measures and methods with the potential to benefit Bird-Long Island are described in more detail below. These green infrastructure measures include thin layer placement (TLP), living shorelines (LS), beneficial dredge, submerged reefs, sills, groins, and vegetation enhancement or management. Potential gray infrastructure solutions for Bird-Long Island include revetments and sea walls.

Thin layer placement (TLP) is a technique used to restore intertidal habitats by ways of placement of sediment or dredged material to simulate natural accretion. The sediment is placed at various depths to accommodate project goals. TLP is often used for marsh stabilization or nourishment and to elevate areas in shallow open water. TLP offers a more environmentally sensitive way to elevate areas, with the goal of overall maintenance of established natural processes like supporting existing and new vegetation.

Living shorelines (LS) “is a sloped, erosion control technique built to protect an embankment which: mimics natural habitat; provides increased opportunities for species diversity and productivity; and can serve to improve water quality and the ecological integrity of the area" (GDNR 2013), Living shorelines can provide a more natural alternative to 'hard' shoreline stabilization methods while enhancing long-term coastal resilience.

Beneficial dredge is composed of suitable fill material that is pumped from navigation channels, such as the North Channel of the Savannah River. It can be placed in different forms to support natural functions, including increasing the sediment budget in sediment starved areas, filling in thin layers, or placement in bulk to meet earthwork needs. The dredged material is tested for content and texture to determine its suitability.

Submerged reefs are placed parallel to the coast on the seaward side of the low marsh areas to reduce wave energy and coastal erosion. Other benefits include sediment deposition that helps strengthen coastlines through vegetation establishment.

Sills are placed at the toe of bank or on the toe of living shorelines. Depending on the energy in the system, sills can be constructed of rock or coir rolls.

Groins are structures placed perpendicularly to the shoreline to intercept longshore flows to impede excessive coastal erosion. Often, they are constructed of large rock and can be manipulated to provide habitat.

Vegetation enhancement or management has many facets, but generally it involves arresting invasive exotic vegetation and replanting with indigenous vegetation that corresponds with the appropriate successional trajectory. Using local ecotypes and suppressing exotics are best practices.

Gray infrastructure includes revetments and sea walls, which do not offer habitat that enhances biodiversity like green or hybrid infrastructure. Revetments are often constructed on large stone laid on a sloping bank, sometimes referred to as Johnson rocks. Sea walls are usually gravity retaining walls or stem walls that have a vertical or battered face, but not as steeply sloped as revetments. Sea walls are often constructed from concrete, not rock, and protect against over wash.

SITE CONTENT

Bird-Long Island is the second seaward island in the mouth of the Savannah River. The island was formed by adding dredge to multiple, extant islands (Figure 1).

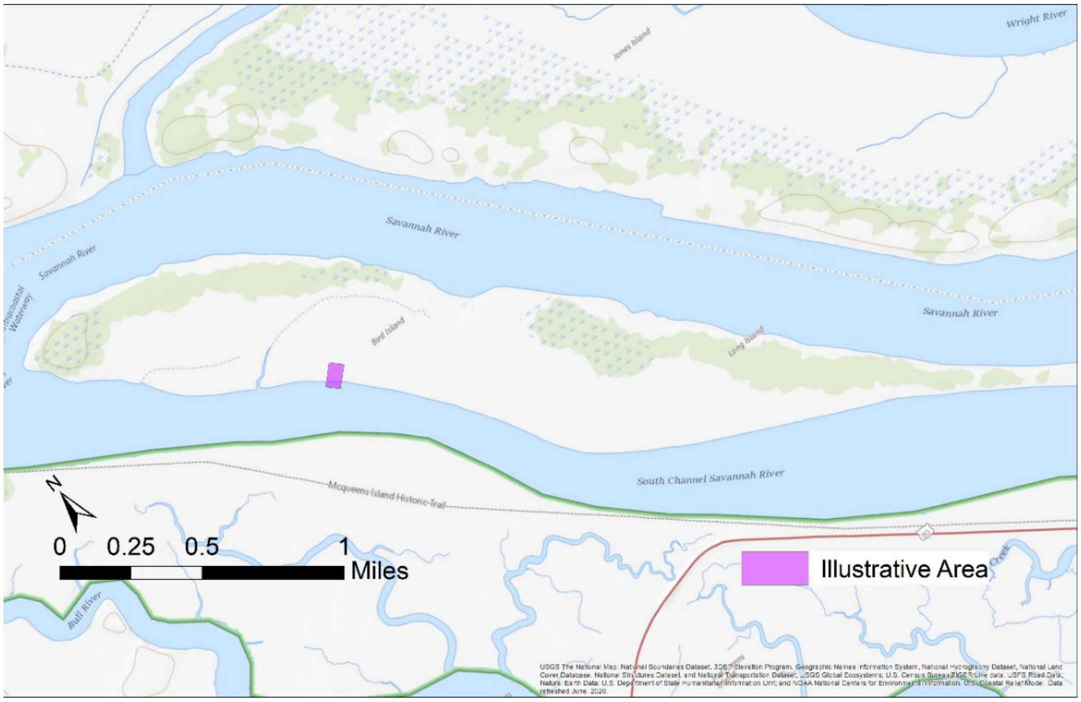


Figure 1: Illustration. Context map of Bird-Long Island depicting Battery Hamilton (shown in magenta).

It contains Battery Hamilton, a cultural resource that is threatened by erosion and has already lost some of its features, such as the primary berm adjacent to the South Channel of the Savannah River (Figure 2).

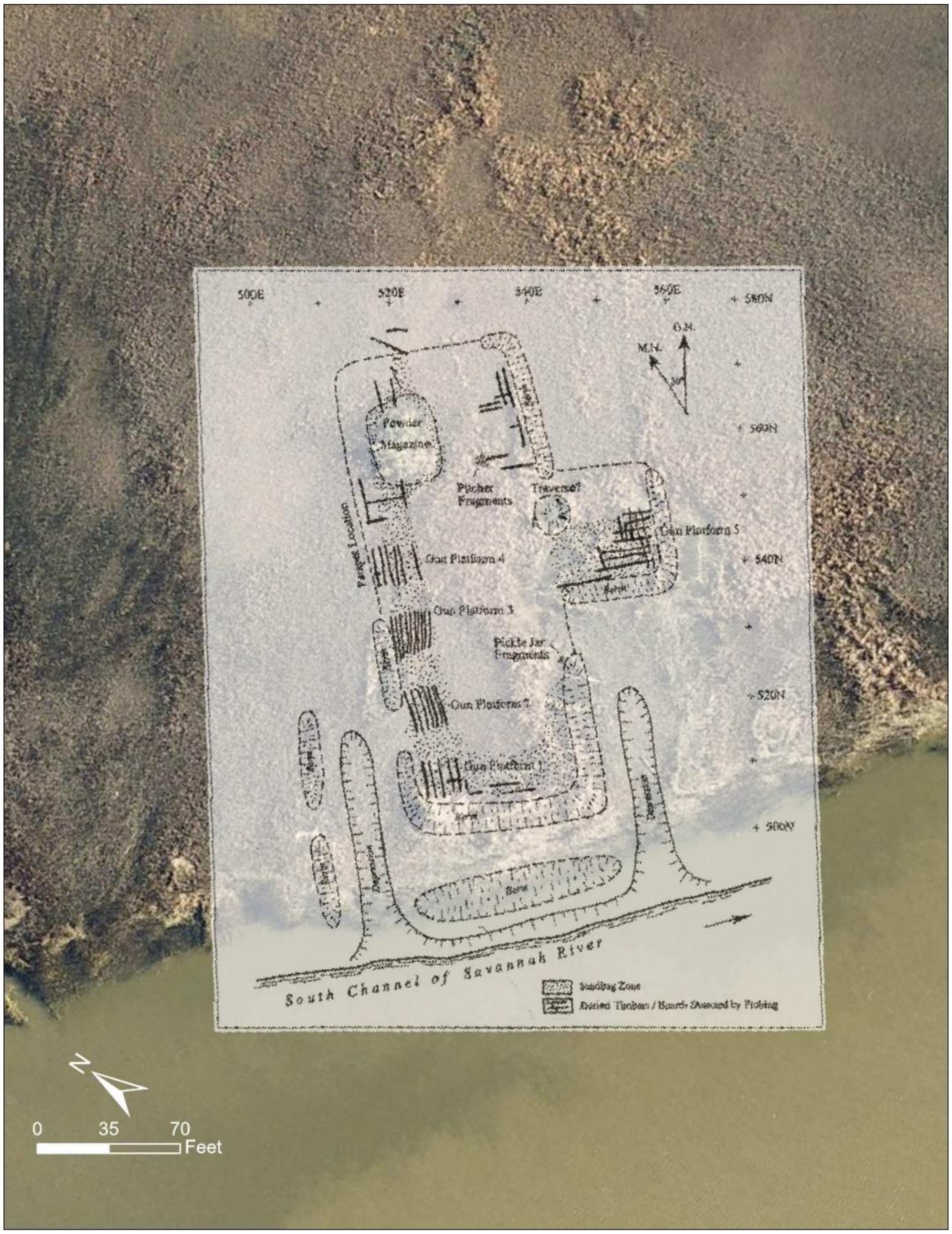


Figure 2: Illustration. Depiction of erosion of primary berm of extant Battery Hamilton overlaid on 2021 aerial image.

CHAPTER 2 METHODOLOGY AND RESULTS FOR FIELD TESTS AND GIS

Several methods were used for data collection, analysis, and design for this project. Field-based methodologies included evaluating a living shoreline to better understand factors that contribute to a successful design, spat stick placement during the growing season to confirm that reef-forming organisms would likely occupy any interventions, and collection of environmental condition data to inform vegetative management and planting strategies. Desktop analysis using various geospatial assessments to generate suitability analysis informed design interventions.

EXISTING LIVING SHORELINE ANALYSIS

The Burton 4-H Center is located near the study area. A living shoreline was constructed there several years ago and is the closest living shoreline to the site. A permit was issued to investigate velocity and water level measurements for this study. The measurements were used to determine the feasibility of installing a living shoreline at Battery Hamilton or other areas along the coast of Bird-Long Island.

The turbulence characteristics and drag coefficients on the living shoreline were determined through four days of velocity measurements obtained with acoustic doppler velocimeters (ADVs) at two sites on the Burton 4-H property: a reef site (R) and a control site (C). As indicated on Figure 3, the reef site (R) is located on the living shoreline located along the small tidal creek at the western edge of the 4-H property. The control site (C) is located on a muddy bank 150 m south of the reef site in the ebb direction.

Figure 3: Illustration. The reef (R) and control (C) field sites where the ADVs were deployed are indicated with yellow dots on the map of the Burton 4-H Center and surrounding properties. The living shoreline, located on the western edge of the 4-H property, is boxed in red. Ebb tides flow southwest along the living shoreline, while flood tides flow northeast.

The frames were designed to minimize damage to the living shoreline, motion of the instrument, and risks to boaters. The reef site was also designed to allow adjustment of the instrument location in the cross-shore direction so it could measure velocities over the different features of the living shoreline, labeled in Figure 4. The instrument was moved progressively deeper down the living shoreline over the course of the measurements such that tides 1-2 were measured over the bagged shells located at the top of the reef, tides 3-4 were measured over a mix of loose shells and mud at the base of the bags, tides 5-6 were measured over the upper portion of the oyster reef, and tides 7-8 were measured at the lower portion of the oyster reef.

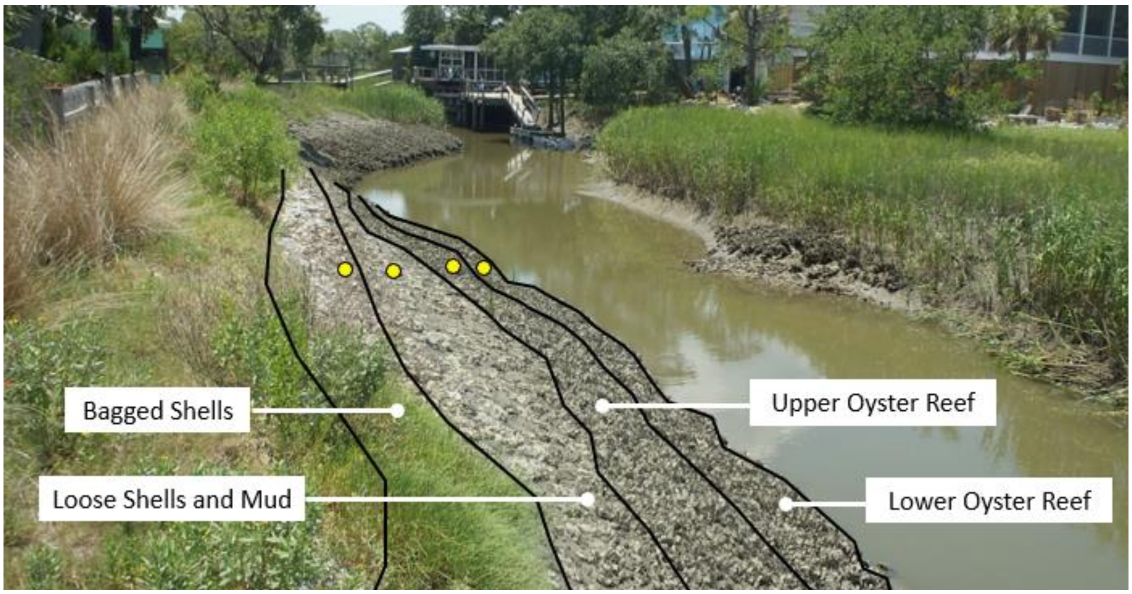


Figure 4: Illustration. The ADV was repositioned daily to measure velocities over four regions of the living shoreline. Its approximate locations are indicated by the round yellow markers.

The turbulent environment was assessed separately for each intertidal location on the living shoreline to capture variation in the hydrodynamics over the bagged shells, loose shells, and upper and lower reef. Since the reef site ADV was deployed over each feature for one day, data from two tidal cycles were included in the analysis for each position. The control site instrument was not substantially moved, so two representative tidal cycles were selected from its measurements for comparison to the reef site.

The velocity time series of a representative tidal cycle measured at the muddy control site is shown in Figure 5. This is the fourth tide of the total of eight that were recorded during the four days of field measurements. The time series demonstrates that the majority of the tidal flow at the control site is in the alongshore direction v, with only very small velocities in the cross-shore and vertical. Mean velocities were much stronger during ebb tide and peaked at 43 cm/s; instantaneous values reached over 60 cm/s. By comparison, flood tide velocities were much smaller, not exceeding 40 cm/s.

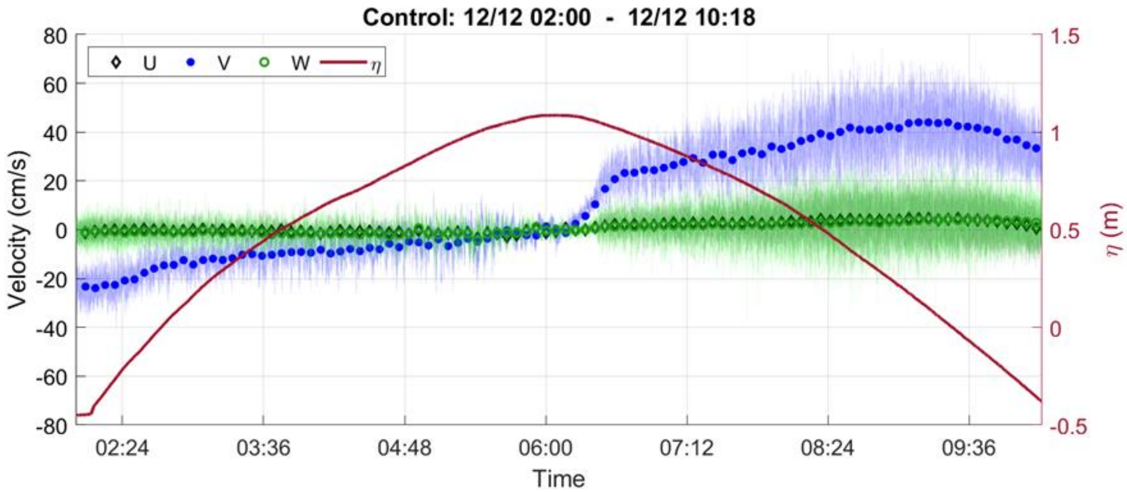


Figure 5: Graph. The time series of the mean (symbols) and raw (lines) velocities in the alongshore (ebb positive), cross-shore, and vertical are shown for a portion of one flood-to-ebb tidal cycle as measured at the control site. The tidal stage (η) is provided on the right vertical axis.

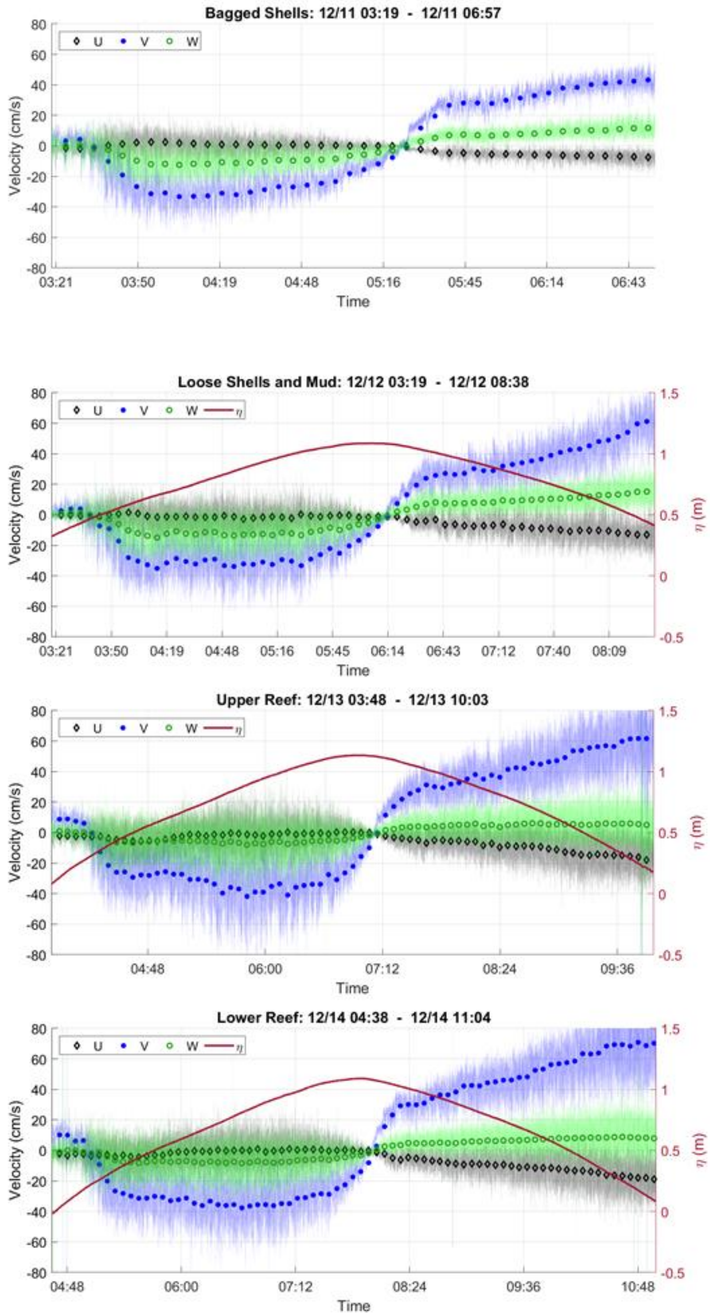


Figure 6: Graph. The time series of the mean (symbols) and raw (lines) velocities in the alongshore (ebb positive), cross-shore, and vertical are shown for a portion of one flood-to-ebb tidal cycle as measured at the control site. The tidal stage (η) is provided on the right vertical axis.

shoreline), loose oyster shells and mud, upper oyster reef, and lower oyster reef are shown in Figure 6. While the majority of the tidal flow is clearly in the alongshore direction v, there are sustained velocities in the cross-shore and vertical that are indicative of secondary circulation. The tidal stage is also provided using data from a nearby pressure gauge that was installed. between tides 2 and 3.

The magnitude of the alongshore Reynolds stress is plotted against the squared mean alongshore velocity in Figure 7. This data is used to estimate the drag coefficient, taken as the slope of the linear fit to this data. While the flood and ebb data produce similar coefficients at the control site, there are strong discrepancies between them at the living shoreline. This is a result of the reduced coherence at ebb tide. It is assumed that the upstream creek bend at ebb tide generates secondary circulation on the living shoreline, and the resulting drag coefficients are unrealistic. The drag coefficients calculated from flood tide, when the upstream creek is straight, are much more physically reasonable and representative of the South Channel, where these drag coefficients are to be incorporated into numerical modeling. For these reasons, the living shoreline drag coefficients are taken from the flood tide data alone. Additional measurements are needed to better understand the complex ebb tide flow on the living shoreline.

The drag coefficient on the control site is 0.005. At the reef site, the coefficient is 0.016 over the bagged shells, 0.029 over the loose shells and mud, 0.029 also over the upper reef, and 0.026 over the lower reef. The values are shown over the corresponding components of the living shoreline in Figure 8.

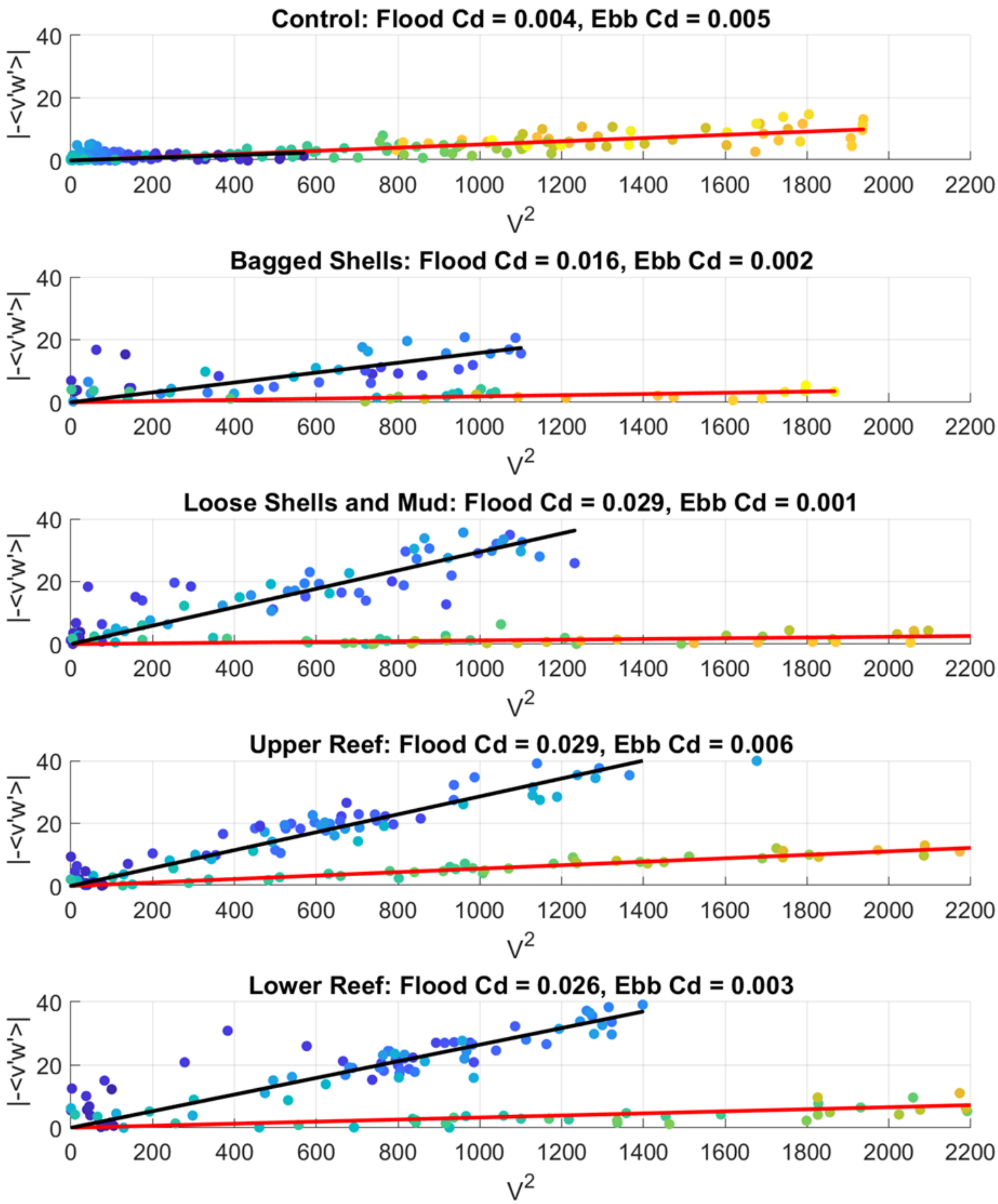


Figure 7: Graph. Drag coefficients are calculated as the slope of the line fitted to alongshore Reynolds stress against mean current magnitude squared. The data are fitted to flood (black) and ebb (red) separately. The color of the dots indicates progression through the tidal cycle, with blue at the beginning and yellow at the end.

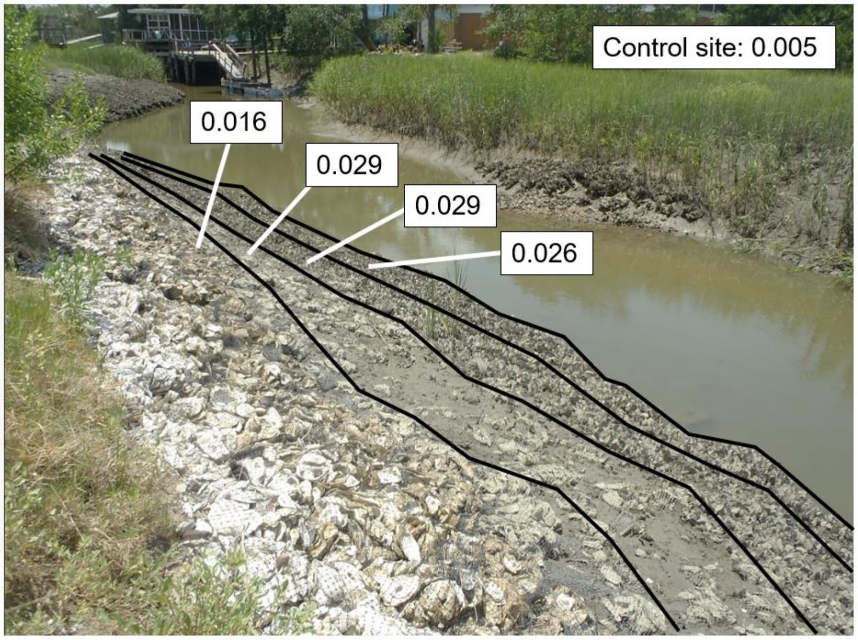


Figure 8: Illustration. The drag coefficient at the control site was 0.005, while those at the living shoreline varied from 0.016 over the bagged shells to 0.029 over the upper oyster reef.

Table 1 provides the peak velocities and corresponding peak shear stress estimated under forcing tidal currents and ship wake (where applicable) for the Main Channel and South Channel sites in the Savannah River and for the Living Shoreline and Control sites at the Burton 4-H Center. Shear stresses are computed by:

Formula Shear Stress= 1/2 ρc_d U_peak^2

where ρ is the density of seawater, c_d is a drag coefficient, and U_peak is the peak velocity. Shear stresses are calculated using multiple drag coefficients to estimate stresses for shorelines of varying characteristics; 0.005 represents a smooth muddy bank (control site), 0.016 represents bagged oyster shells, and 0.029 represents a mature oyster reef. The two processes considered are tidal currents (blue rows) -- applicable at both the

Burton 4-H Center and the Savannah River -- and low-frequency (LF) cargo ship wake (orange rows), applicable only in the Savannah River. For each process, the shear stress was calculated using both the maximum strength current/wake observed and the mean current/wake observed.

At the Burton 4-H Center, the maximum shear stress was estimated at 7.9 N/m^2, and resulted from the maximum tidal current conditions and the established oyster reef drag coefficient. Using this same drag coefficient but the mean rather than maximum tidal current magnitude, the shear stress was only 1.4 N/m^2, emphasizing the importance of current strength. Mean currents over the bagged shells and muddy control site produced weaker shear stresses of 0.1 – 0.8 N/m^2 due to the smaller c_d values.

While all c_d values were determined from measurements at the Burton 4H Center, they may also be applied to velocities in the South Channel to achieve a very rough estimate for the order of magnitude of the shear stresses that could be produced by its tidal currents over various shoreline features. For example, the shear stress estimates for peak South Channel currents were 0.7 N/m^2 on a muddy bank and 3.8 N/m^2 on an oyster reef. The latter is about half the peak shear stress generated on the Burton 4-H Living Shoreline, suggesting that oyster viability in the South Channel would not be hindered by excessive tidal current shear stress. However, additional factors including sedimentation, predator-prey relationships, and wake exposure could be important contributors to reef success or failure.

Low-frequency (LF) cargo ship wake is the dominant source of energy in the South Channel, and its impacts on oyster reef health remain unknown. However, estimates of shear stress produced by wake were computed using known wake-induced velocities in the South Channel and found to be smaller than the stress estimates for tidal currents. This implies that oysters can likely withstand the shear stresses induced by LF wake in the South Channel. Still, additional research is required to determine if oyster success if limited by other aspects of cargo ship wake, such as dramatic spikes in hydrodynamic energy that may prevent spat recruitment and/or intermittent flushing of the chemical signals that direct predator-prey relationships.

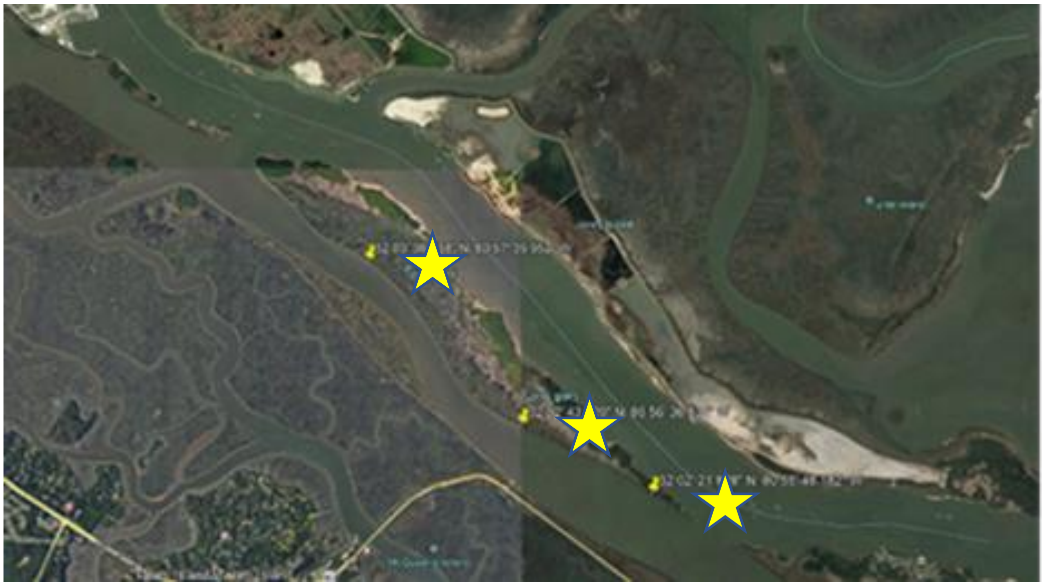
Table 1: Velocities and shear stresses for the Living Shoreline, control site, south channel and main channel.

Site	Hydrodynamic Condition	Velocity (m/s)	Shear Stress (N/m^2) for Various C_d Control C_d	Bagged Shells C_d	Reef C_d
			0.005	0.016	0.029
Living Shoreline, Burton 4H Center	Maximum Tidal Current	0.73	1.4	4.3	7.9
	Mean Tidal Current	0.31	0.2	0.8	1.4
Control Site, Burton 4H Center	Maximum Tidal Current	0.45	0.5	1.7	3.0
	Mean Tidal Current	0.20	0.1	0.3	0.6
South Channel, Savannah River	Maximum Tidal Current	0.51	0.7	2.1	3.8
	Mean Tidal Current	0.21	0.1	0.4	0.7
	Maximum LF Wake	0.31	0.2	0.8	1.4
	Mean LF Wake	0.19	0.1	0.3	0.5
Main Channel, Savannah River	Maximum Tidal Current	0.62	1.0	3.1	5.7
	Mean Tidal Current	0.25	0.2	0.5	0.9
	Maximum LF Wake	2.25	12.9	41.3	74.9
	Mean LF Wake	0.72	1.3	4.2	7.7

In the Main Channel of the Savannah River, LF wake induces much larger velocities than do tidal currents, so the estimated shear stress induced by wake far exceeds that induced by tidal currents. If an oyster reef drag coefficient is applied to peak LF wake velocities in the Main Channel, the resulting shear stress estimate is 74.9 N/m^2, which is an order of magnitude greater than the maximum stress observed at the Burton 4-H Center Living Shoreline. Therefore, the presence of oysters at the 4-H Center cannot inform whether oysters would be able to withstand the comparatively extreme shear stresses generated by ship wake in the Main Channel.

SPAT STICK PLACEMENT AND RESULTS

Spat sticks are small diameter, sanded PVC pipe placed in various locations to determine if reef-forming organisms attach. If the organisms settle onto the stick, then there is a greater likelihood of colonization of a living shoreline. Spat sticks were placed at near Battery Hamilton and two other locations along the South Channel of the Savannah River in groups of three at each site. The locations are: 32 03' 36.558" N, 80 57' 35.952" W (West), 32 02' 43.320" N, 80 56' 36.834" W (Center), 32 02' 21.828" N, 80 55' 48.182" W (East) and illustrated below (Figure 9).



Original Photo: © 2023 Google®

Figure 9: Illustration. Spat Stick Locations (indicated with Yellow Stars) in the South Channel of the Savannah River. NTS and North is up.

Each spat stick was divided into three seven-inch increments (Lowest, Middle, Highest) and collected on 4/7/2021, 5/20/2021, 6/8/2021 and 7/21/2021. Spat colonized all three increments at each site (West, Center, East) the majority of the time during the 2021 growing season. (Unfortunately, no spat sticks could be deployed during the 2020 growing season due to the University System of Georgia travel ban during the Covid-19 pandemic.) Table 2 below illustrates weekly average counts during the majority of the growing season. The West site, located at Battery Hamilton, had the highest average weekly count of 14.9 spat per week, which suggests colonization is viable. Summary counts are available in Appendix A.

Table 2: Average Weekly Spat Counts per Site by Spat Stick Segment

Site	Average of Lowest 7" Weekly Average Count	Average of Middle 7" Weekly Average Count	Average of Highest 7" Weekly Average Count
West	17.4	17.7	9.8
Center	7.1	3.6	1.0
East	18.7	16.2	8.0

PREDICTED IMPACT OF ARMORING ON VEGETATION

Estimates for vegetation shift predict very different possible futures for Bird-Long Island. Baseline and armoring scenarios suggest different outcomes based on various increases in sea level rise. The baseline alternative illustrates a do-nothing approach for the year 2100 (Figure 10) and predicts an almost total loss of “dry land” and transformation of “beach” and “marsh” mostly to “tidal flat” in a 6.3 foot rise scenario.

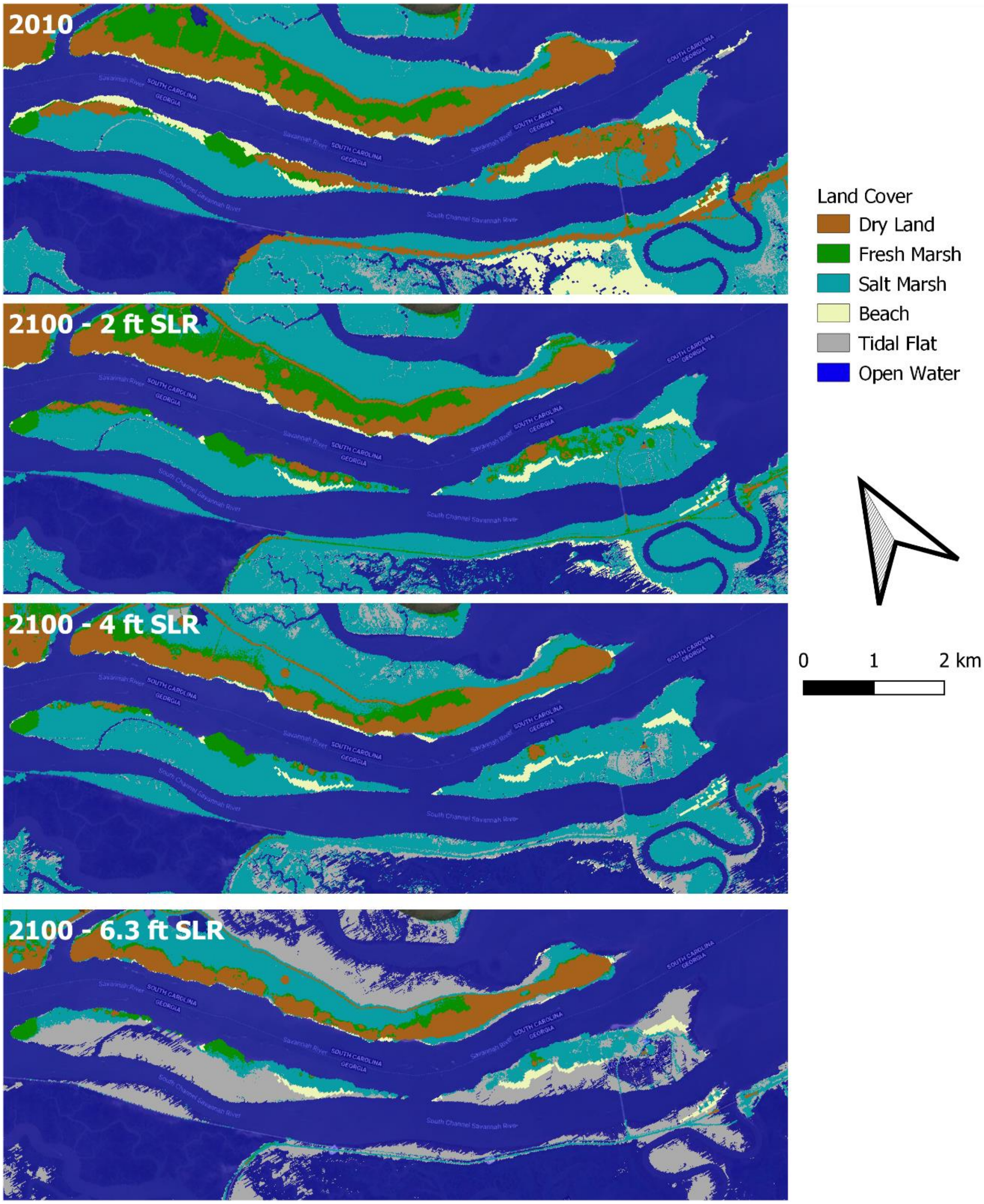


Figure 10: Illustration. Baseline "Do Nothing" for Various Sea Level Rise Estimates

If a different intervention is applied that includes shoreline armoring, then “Dry Land” is preserved and slightly increases in the same 6.3 feet SLR by year 2100 scenario. These predictions illustrate future states depending on whether armoring is implemented or not (Figure 11).

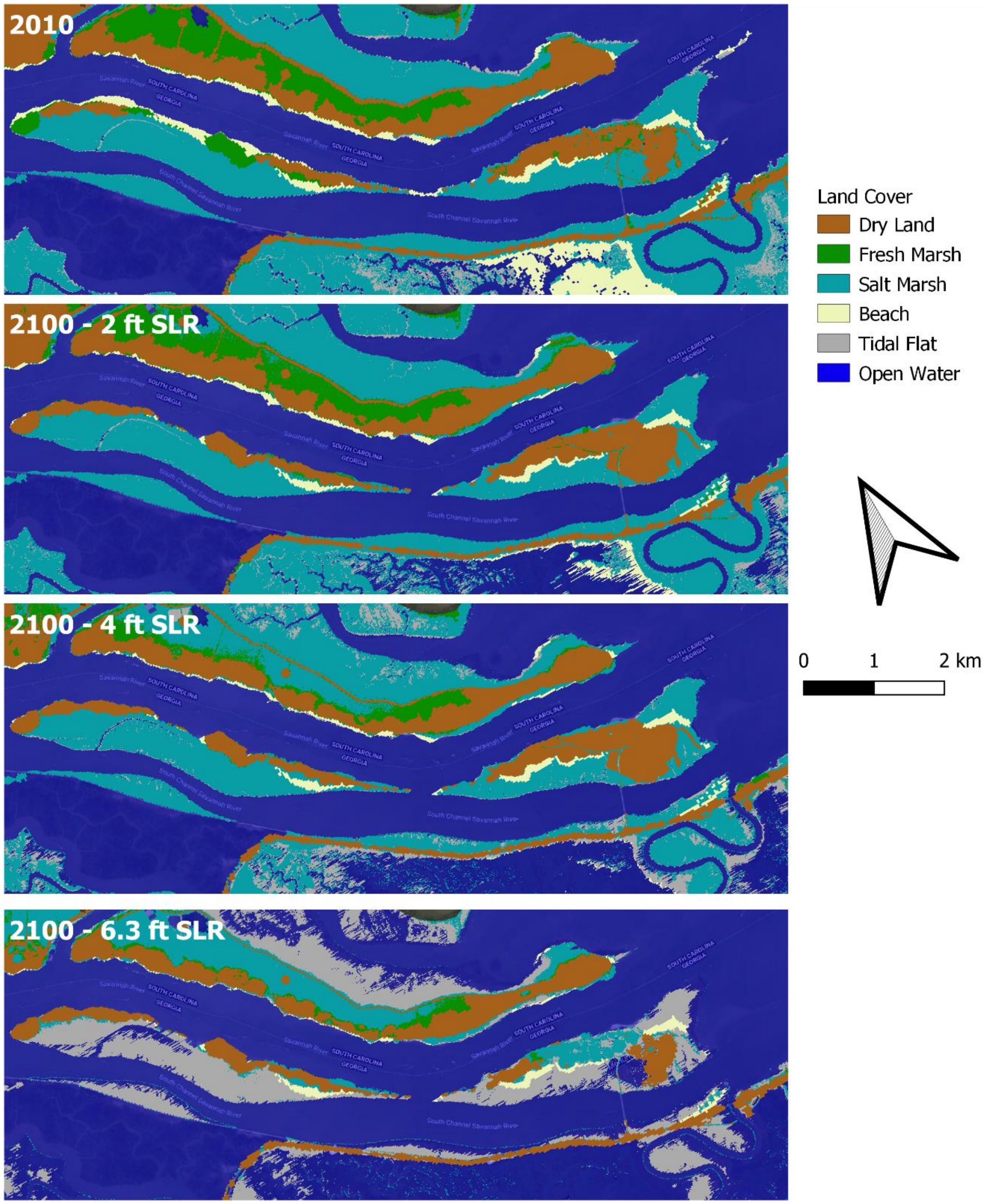


Figure 11: Illustration. Armoring Scenarios for Various Sea Level Rise Estimates.

Two types of armoring are available for armoring the shoreline against excessive energy from waves and additional ship wake when larger ships begin sailing the North Channel of the Savannah River after the channel deepening. A sea wall could be constructed where the existing breach between Cockspur Island and Bird-Long Island has formed. The sea wall would need to be about 6,900 linear feet to protect against further breaches between the two islands. If that is not feasible, then a revetment could be added for the entire length of the Bird-Long's coastline along the North Channel of the Savannah River and extend towards the Coast Guard station's existing revetment on Cockspur Island. About 24,375 linear feet of revetment would be required, unless part of that was a sea wall, in which case only 17,475 linear feet would be necessary.

VEGETATION RESTORATION TRAJECTORY

Much of the upland area of Bird-Long Island is forested with indigenous vegetation, particularly in the canopy where live oaks and pines are predominant. However, pressure from aggressive exotic vegetation, such as tallow tree, is outcompeting indigenous vegetation. Prescribed burning of this fire-dependent plant community could assist in alleviating pressure from unwanted species and create a restoration trajectory that is easier to maintain. Elba Island, the adjacent liquified natural gas storage area, was recently burned to encourage indigenous species, and could serve as a case study. If the coastal area on Bird-Long Island is armored, then upland area could be converted to a fire-dependent, 140-acre maritime longleaf pine plant community.

The lower areas are mostly marsh vegetation with some beach or mud areas. In all the various scenarios of sea level rise, the marsh area will be lost and change to tidal flats. To forestall this change, the addition of thin layer placement could be periodically added to discrete areas to help the marsh pace sea level rise and thus avert loss of the beneficial function of the marsh.

THIN LAYER PLACEMENT SUITABLITIY ANALYSIS

Suitability mapping involves querying environmental conditions to identify locations for the best placement of design components. The suitability analysis consists of layering data sets and applying weights to each data set to determine the most feasible location given the specified criteria. The suitability exercise examined TLP to prioritize areas for simulated accretion to help stabilize the marsh areas. The Suitability modeler tool (ESRI, ArcPro 2.8.1, 2021) combines weighted datasets and their attributes by converting data sets to rasters if needed, then ranking attributes in the raster on a "1" to "3" scale. The datasets were elevation, buffer setback from waterbodies, and vegetation. Elevation suitable at 3.4 feet. Buffer excluded any areas within 100 feet of a waterbody by using the 2.5 foot contour and the vegetation dataset prioritized *Spartina sp.* over unvegetated, muddy, or other vegetation because of *Spartina's* ability to withstand being overtopped with sediment. The weighting of the datasets was 50%, 30%, and 20% for buffer exclusion, elevation preference, and vegetation, respectively. The resulting suitability for TLP was divided into two priority areas and the amount of beneficial dredge was calculated for each area assuming ten centimeters of fill depth. The first priority area consumes about 41,663 cubic yards (CY) and the second area consumes about 128,121 CY of fill.

DESIGN INTERVENTIONS

The design interventions described above were combined on an overall suitability map to determine the maximum spatial extent of these design elements (Figure 12). Quantities of each intervention were estimated, which subsequent design will use as a starting point. Several management zones approximately a mile long each were specified, stretching the width of the island.

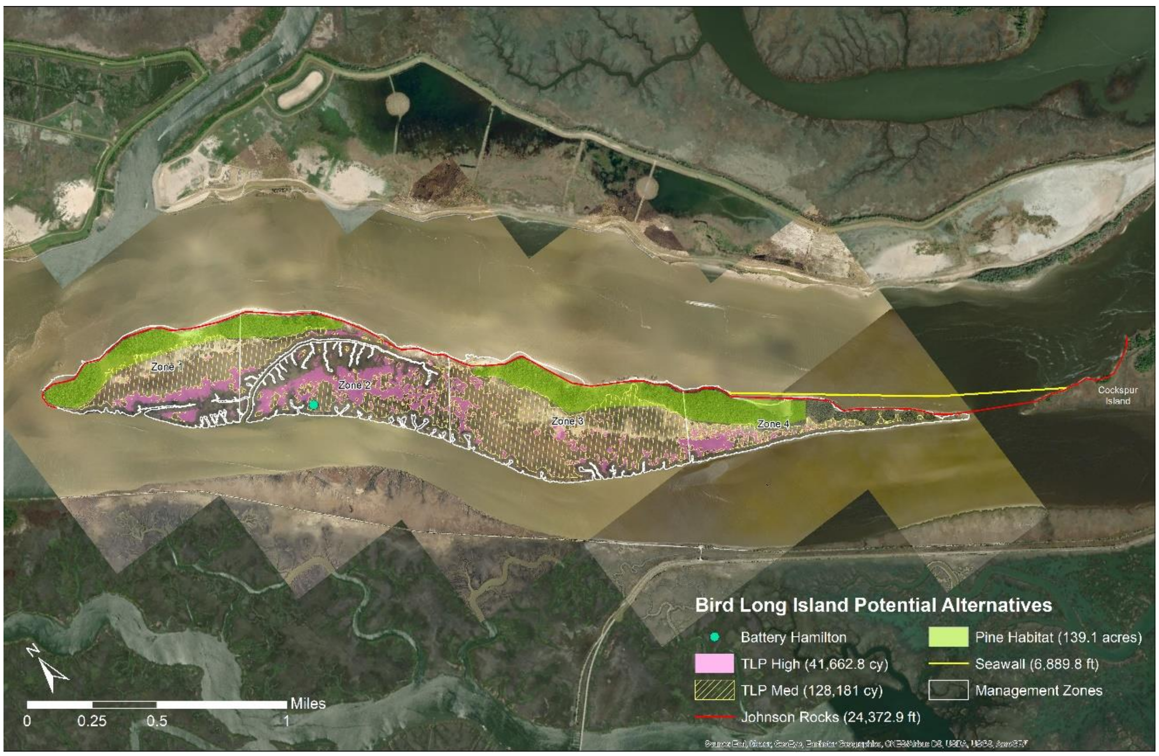


Figure 12: Illustration. Maximum Extent of Design Elements

CHAPTER 3 ALTERNATIVE DESIGN INTERVENTIONS

Various designs envisioned alternative futures, with their accompanying strengths and weaknesses. Designs were created based on the most suitable areas for particular NbS elements that include green, gray, and hybrid solutions. The first alternative evaluates a "Do Nothing" approach, while subsequent alternatives evaluate different shoreline stabilization techiniques for a portion or the entirety of the north coast of Bird-Long Island, revegetating upland areas with fire dependent, indigenious plant communities and utilizing thin layer placement to assist with marsh adaptation. The strengths and weaknesses of each design are posited below, with Battery Hamilton renderings conveying the shoreline treatment. The management zones for each alternative are shown in the Appendix, except for Alternative 1, which is the "Do Nothing" Alternative.

ALTERNATIVE 1

The strengths and weaknesses of doing nothing are enumerated below for Battery Hamilton (Figure 13) and Bird-Long Island (Appendix B: Do Nothing).

Strengths:

No Construction Cost

Weaknesses:

More of Battery Hamilton erodes within 23 years (without SLR)

Aggressive exotic vegetation continues to invade

Marsh is threatened due to subsidence and sea level rise

Breaches continue to develop and erode marsh and upland areas

Jeopardizes marsh mitigation credit

Excessive erosion releases sediment

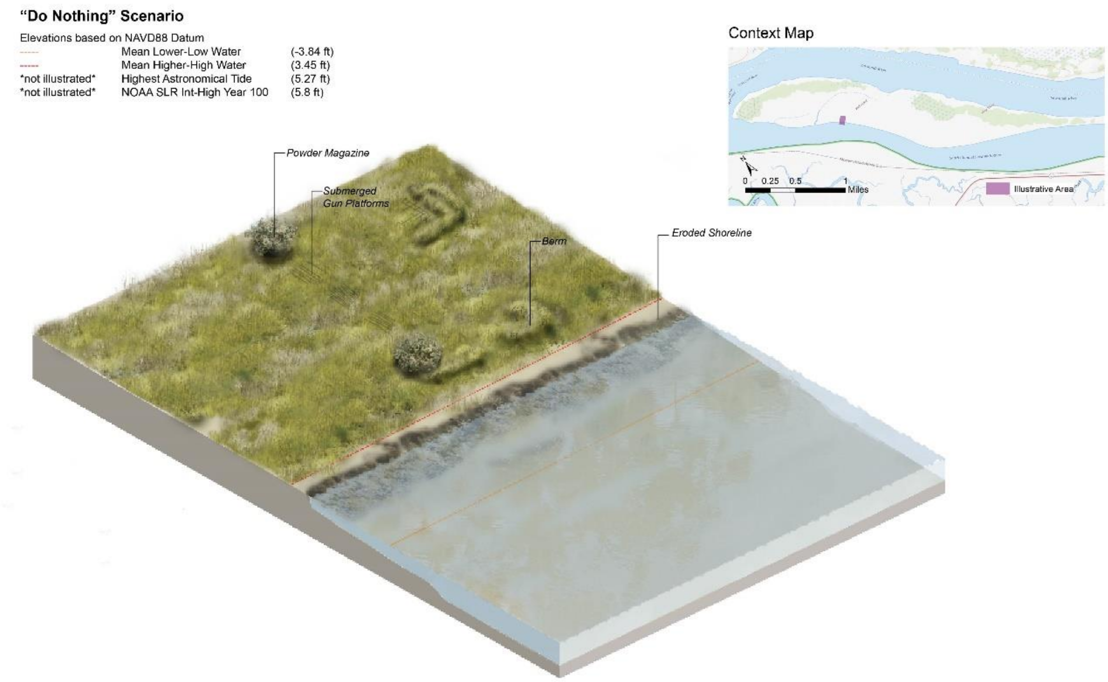


Figure 13: Illustration. Do Nothing Alternative

ALTERNATIVE 2

The strengths and weaknesses of Alternative 2 are enumerated below for Battery Hamilton (Figure 14) and Bird-Long Island (Appendix B: Alternative 2: Revetment). This plan seeks to protect the western side of the island.

Relative Construction Cost: $ (Lowest Cost)

Strengths:

Armor Battery Hamilton with living shoreline

Armor of upland area and marsh nearest Battery Hamilton with revetment

Transition to a fire-dependent maritime longleaf pine community

Weaknesses:

Aggressive exotic vegetation continues to invade eastern half of island

Marsh on eastern half is threatened due to subsidence and sea level rise

Breaches continue to develop and erode marsh on eastern half

Jeopardizes some marsh mitigation credit

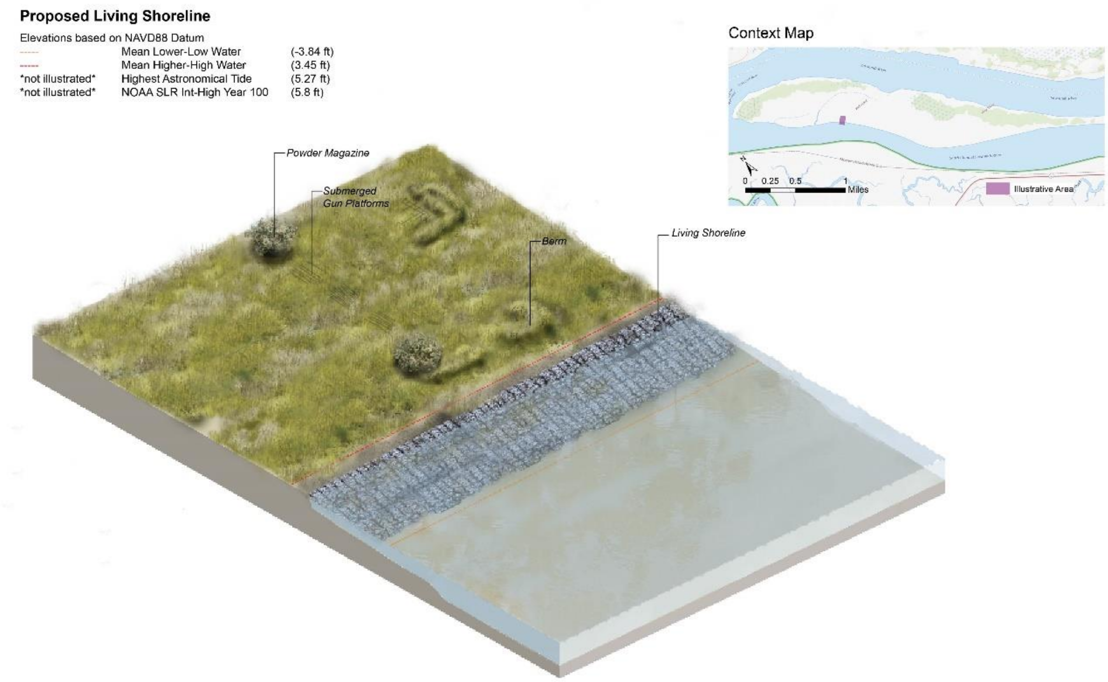


Figure 14: Illustration. Green Infrastructure Alternative Utilizing Living Shoreline

ALTERNATIVE 2b

The strengths and weaknesses of an upgrade to Alternative 2 include replacing the revetment with a partial sea wall. Battery Hamilton is still armored with living shoreline (Figure 14) and is same as Alternative 2, Bird-Long Island (Appendix B: Alternate 2b: Sea Wall), with the western side more protected than the eastern side.

Relative Construction Cost $$ (Lower Cost)

Strengths:

Same as Alternative 2 except that the revetment on the north shore is upgraded to sea wall with groins.

Transition to a fire-dependent maritime longleaf pine community

Weaknesses:

Same as Alternative 2

ALTERNATIVE 3

The strengths and weaknesses of protecting the entire north shore of Bird-Long Island are enumerated below for (Appendix B: Alternative 3). Battery Hamilton is still protected with a living shoreline (Figure 14).

Relative Construction Cost: $$$$ (Higher Cost)

Strengths:

Armors Battery Hamilton with living shoreline

Armors upland area and marsh

Reconnects Bird-Long and Cockspur Island

Transition to a fire-dependent maritime longleaf pine community

Marsh is protected and elevated with thin layer placement

Weaknesses:

Locks the north shore into place

Cuts off north shore beach areas from upland area

ALTERNATIVE 4

The strengths and weakness of Alternative 4 are enumerated below for Battery Hamilton as protected by a sea wall (Figure 15), with Bird-Long Island (Appendix B: Alternative 4) protected with a combination of revetment and sea wall on the north shore.

Relative Construction Cost: $$$$$$$ (Highest Cost)

Strengths:

Same as Alternative 3

Sea Wall with g3roins may capture more sediment

Weaknesses:

Same as Alternative 3

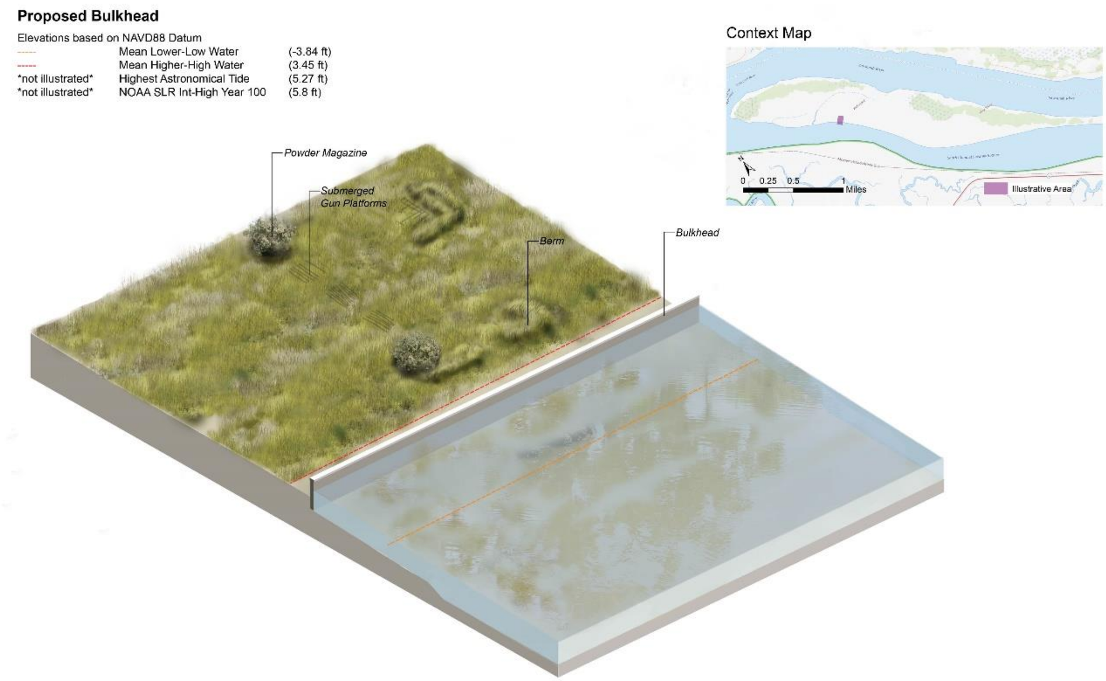


Figure 15: Illustration. Gray Infrastructure Alternative Utilizing Sea Wall

CHAPTER 4 CONCLUSIONS

Protecting the cultural resources and conserving marsh while creating an upland area with a fire-dependent plant community are some of the nature-based solutions that Georgia Department of Transportation should explore as they steward Bird-Long Island into an uncertain future. Rising sea level, marsh subsidence, exotic vegetation, deposition of marine debris, more severe storms, increased ship wakes, increased salinity, and drought conditions all threaten the status quo.

This study investigated responses to an uncertain future utilizing green and gray infrastructural responses. We found that a living shoreline or sea wall could protect Battery Hamilton from further erosion. Addling a thin layer of suitable beneficial dredge to the most appropriate area of the marsh could help protect Battery Hamilton and the marsh. Given the expectation of larger ship wakes and more severe storms, we explored armoring the north shore of Bird-Long Island using a revetment or a hybrid revetment with sections of sea wall with groins to minimize coastal erosion. Though an expensive option, this would protect the upland area that could be converted to a fire dependent ecosystem that would minimize known aggressive exotic vegetative threats to the island's biodiversity. Combinations of these elements, sited in the correct locations, are detailed in the unranked design alternatives. No preferred option is recommended, per the client, but we hope that these options will elicit much discussion as GDOT stewards Bird-Long Island into the future.

Appendix A. Spat Counts Table 3: Spat Stick Counts

ID	Rotation	Deployed	Retrieved	Days Deployed	Site	Description	Stick	Lowest 7"	Lowest 7" Weekly Average Count	Middle 7"	Middle 7" Weekly Average Count	Highest 7"	Highest 7" Weekly Average Count
1	First Set	4/7/2021	5/20/2021	43	A	Battery Hamilton	1	47	7.7	12	2.0	22	3.6
2	First Set	4/7/2021	5/20/2021	43	A	Battery Hamilton	2	44	7.2	37	6.0	30	4.9
3	First Set	4/7/2021	5/20/2021	43	A	Battery Hamilton	3	90	14.7	99	16.1	100	16.3
4	First Set	4/7/2021	5/20/2021	43	B	Sight Tower	1	91	14.8	21	3.4	13	2.1
5	First Set	4/7/2021	5/20/2021	43	B	Sight Tower	2	30	4.9	21	3.4	11	1.8
6	First Set	4/7/2021	5/20/2021	43	B	Sight Tower	3	24	3.9	19	3.1	3	0.5
7	First Set	4/7/2021	5/20/2021	43	C	Breach	1	161	26.2	98	16.0	22	3.6
8	First Set	4/7/2021	5/20/2021	43	C	Breach	2	31	5.0	30	4.9	19	3.1
9	First Set	4/7/2021	5/20/2021	43	C	Breach	3	12	2.0	40	6.5	10	1.6

10	Second Set	5/20/2021	6/8/2021	19	A	Battery Hamilton	1	34	5.5	21	3.4	2	0.3
11	Second Set	5/20/2021	6/8/2021	19	A	Battery Hamilton	2	30	4.9	14	2.3	1	0.2
12	Second Set	5/20/2021	6/8/2021	19	A	Battery Hamilton	3	26	4.2	21	3.4	5	0.8
13	Second Set	5/20/2021	6/8/2021	19	B	Sight Tower	1	4	0.7	2	0.3	1	0.2
14	Second Set	5/20/2021	6/8/2021	19	B	Sight Tower	2	4	0.7	1	0.2	1	0.2
15	Second Set	5/20/2021	6/8/2021	19	B	Sight Tower	3	1	0.2	1	0.2	1	0.2
16	Second Set	5/20/2021	6/8/2021	19	C	Breach	1	69	11.2	50	8.1	5	0.8
17	Second Set	5/20/2021	6/8/2021	19	C	Breach	2	91	14.8	105	17.1	23	3.7
18	Second Set	5/20/2021	6/8/2021	19	C	Breach	3	110	17.9	136	22.1	24	3.9
19	Third Set	6/8/2021	7/21/2021	43	A	Battery Hamilton	1	331	53.9	354	57.6	129	21.0

20	Third Set	6/8/2021	7/21/2021	43	A	Battery Hamilton	2	332	54.0	368	59.9	218	35.5
21	Third Set	6/8/2021	7/21/2021	43	A	Battery Hamilton	3	345	56.2	377	61.4	213	34.7
22	Third Set	6/8/2021	7/21/2021	43	B	Sight Tower	1	99	16.1	52	8.5	10	1.6
23	Third Set	6/8/2021	7/21/2021	43	B	Sight Tower	2	143	23.3	63	10.3	16	2.6
24	Third Set	6/8/2021	7/21/2021	43	B	Sight Tower	3	121	19.7	82	13.3	18	2.9
25	Third Set	6/8/2021	7/21/2021	43	C	Breach	1	275	44.8	256	41.7	205	33.4
26	Third Set	6/8/2021	7/21/2021	43	C	Breach	2	338	55.0	230	37.4	114	18.6
27	Third Set	6/8/2021	7/21/2021	43	C	Breach	3	281	45.7	249	40.5	166	27.0
28	Fourth Set	7/21/2021	8/4/2021	14	A	Battery Hamilton	1	0	0.0	1	0.2	0	0.0
29	Fourth Set	7/21/2021	8/4/2021	14	A	Battery Hamilton	2	0	0.0	0	0.0	0	0.0

30	Fourth Set	7/21/2021	8/4/2021	14	A	Battery Hamilton	3	0	0.0	0	0.0	0	0.0
31	Fourth Set	7/21/2021	8/4/2021	14	B	Sight Tower	1	2	0.3	0	0.0	0	0.0
32	Fourth Set	7/21/2021	8/4/2021	14	B	Sight Tower	2	0	0.0	0	0.0	0	0.0
33	Fourth Set	7/21/2021	8/4/2021	14	B	Sight Tower	3	1	0.2	0	0.0	1	0.2
34	Fourth Set	7/21/2021	8/4/2021	14	C	Breach	1	5	0.8	1	0.2	1	0.2
35	Fourth Set	7/21/2021	8/4/2021	14	C	Breach	2	3	0.5	1	0.2	0	0.0
36	Fourth Set	7/21/2021	8/4/2021	14	C	Breach	3	0	0.0	0	0.0	0	0.0

Appendix B. Alternatives 2, 2b, 3 and 4

Figure 16: Illustration. Alternate 2 (Revetment)

Figure 17: Illustration. Alternate 2b (Sea Wall)

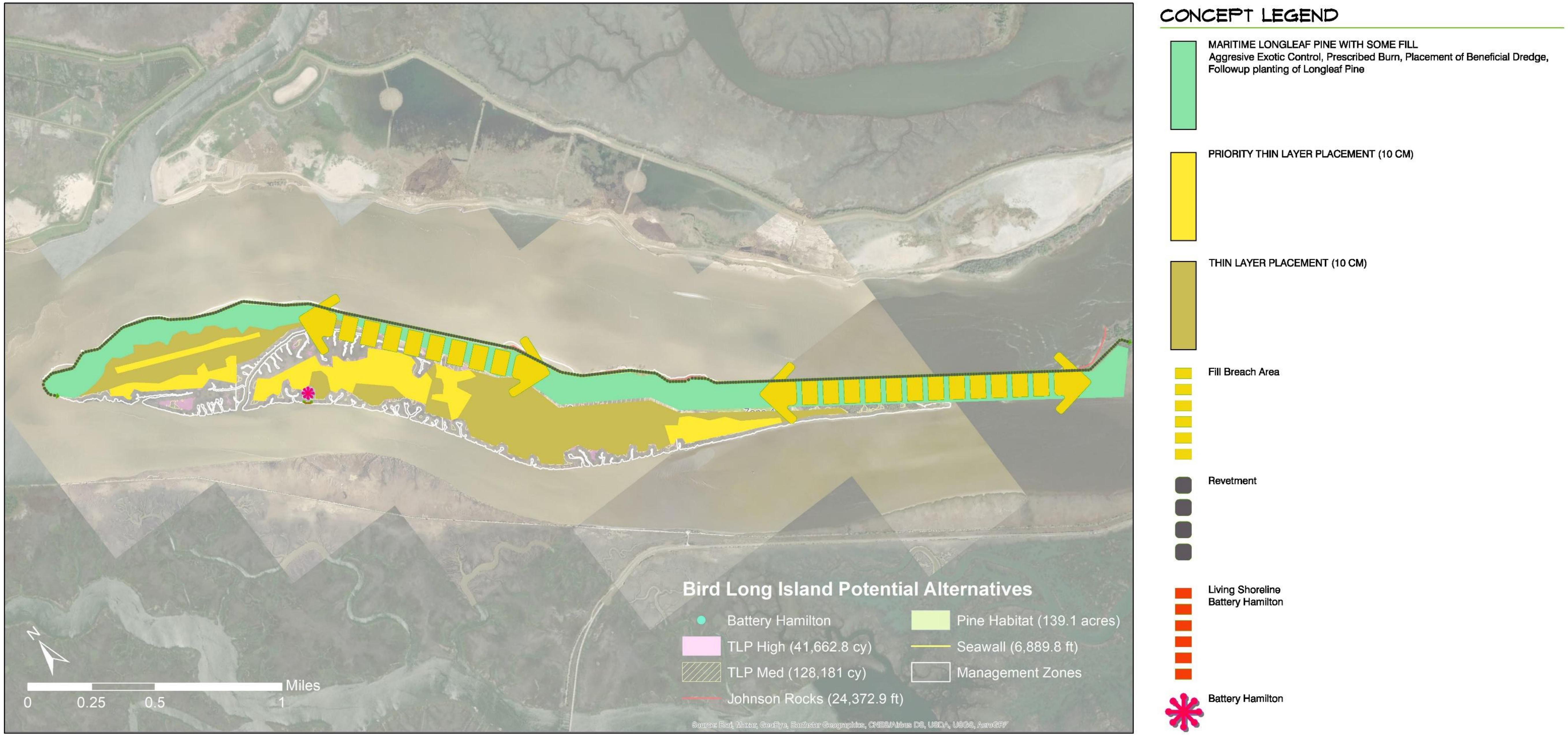


Figure 18:. Alternative 3 (Revetment)

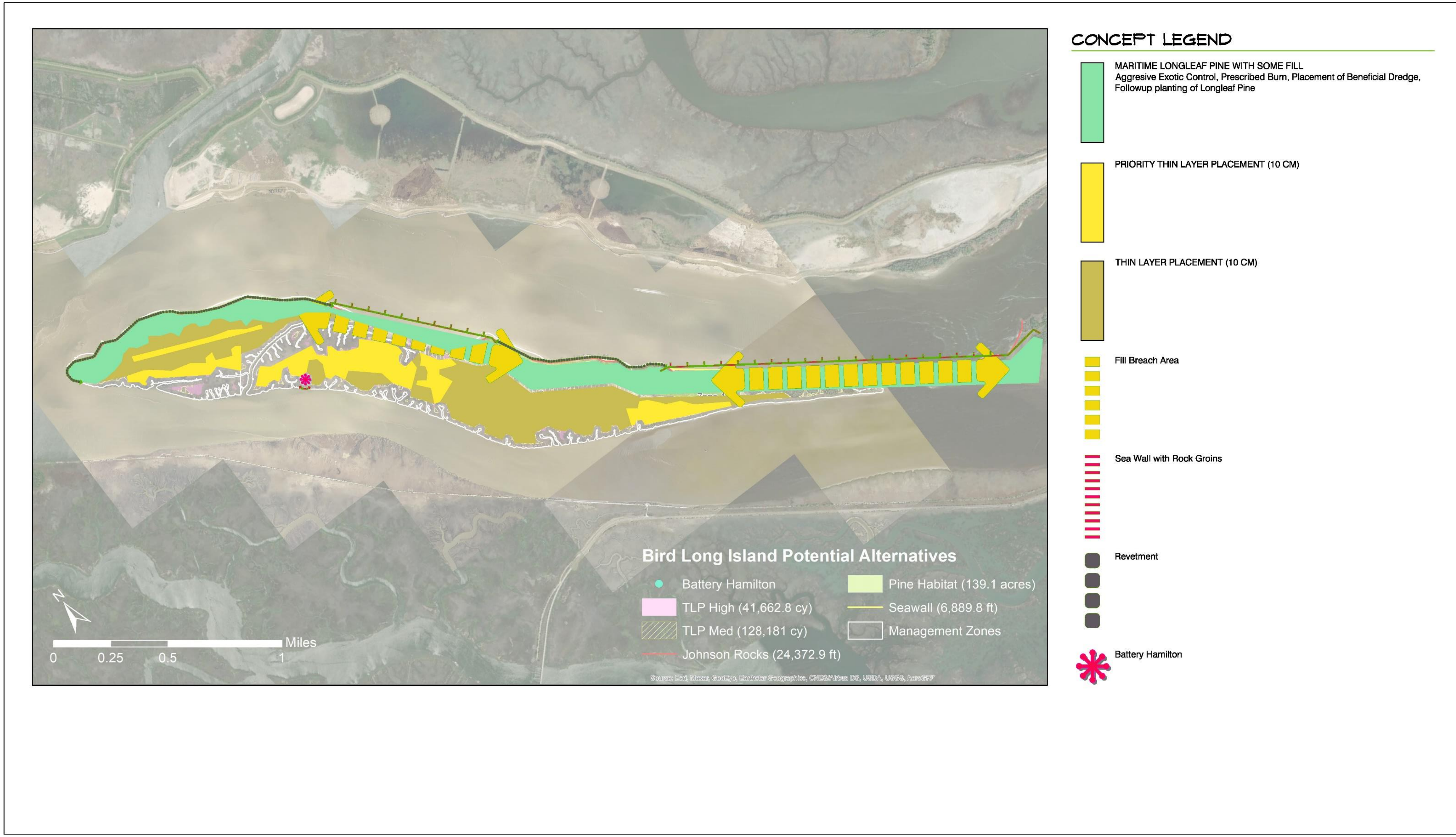


Figure 19: Illustration. Alternative 4 (Partial Sea Wall)

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