TYBEE ISLAND NATURAL INFRASTRUCTURE MASTER PLAN

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FINAL REPORT FOR THE

NFWF TYBEE ISLAND COASTAL MARSH AND COMMUNITY RESILIENCE ADAPTATION PROJECT

JANUARY 30, 2023

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PROJECT TEAM

Alan Robertson
Principal, *AWR Strategic Consulting* (Project Manager)

Jill Gambill
Coastal Resilience Specialist and Public Service Associate, *Marine Extension and Georgia Sea Grant, University of Georgia (UGA PI)*

Clark Alexander
Director and Professor, *Skidaway Institute of Oceanography, University of Georgia*

Brian Bledsoe
UGA Athletic Association Professor and Director of the Institute Resilient Infrastructure Systems, *College of Engineering, University of Georgia*

John Calabria
Associate Professor, *College of Environment & Design, University of Georgia*

Craig Landry
Professor, Agricultural and Applied Economics, *College of Agricultural and Environmental Sciences, University of Georgia*

Felix Santiago Collazo
Assistant Professor, *Institute for Resilient Infrastructure Systems, College of Engineering, University of Georgia*

Alison Smith
Associate Professor, *College of Environment and Design, University of Georgia*

Alfie Vick
Professor, Director of Environmental Ethics Certificate, *College of Environment and Design, University of Georgia*

STUDENT CONTRIBUTORS

Nicholas Bradley, Daniel Buhr, Matt Chambers, Haley Selsor

ACKNOWLEDGEMENTS

Sincere thanks to Mayor Shirley Sessions, Shawn Gillen, Pete Gulbronson, George Shaw and Brent Levy from the City of Tybee Island, as well as to the entire CIty Council. Without your support and assistance this endeavor would not have been possible. Additional gratitude to Emily Dolatowski, Emily Kenworthy, Trey Cooper, Sophia Milazzo, Yasmine Callan, Grace Dusenbury, Charlotte James, Mary Lee McQuigg, Emilie Dolatowski, William Spivey, Lauren Sullivan, Bailey Williams, the Tybee Island Engineering Capstone Team and students in Alison Smith's Spring and Fall 2021 Landscape Architecture Design Studio classes. This project was funded by the National Fish and Wildlife Foundation and Georgia Department of Community Affairs.

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EXECUTIVE SUMMARY

The Tybee Island Natural Infrastructure Master Plan provides recommendations on integrated nature-based features to help the island better absorb and recover from more frequent storms and flooding caused by rising, warming seas. Developed in collaboration with the University of Georgia and numerous local, state and federal partners, the plan assesses flood risks and adaptation solutions, with particular focus on areas near the tidal marsh that borders Tybee Island's marsh shoreline. This project was made possible with funding from the National Fish and Wildlife Foundation (NFWF) and Georgia Department of Community Affairs.

The Tybee Island Natural Infrastructure Master Plan includes an array of prioritized design options, available for implementation independently and in combination, for consideration by Tybee Island City Council. The preliminary designs meet the 50-60 percent design criteria required by the conditions of the NFWF grant. The plan also considers the risks of doing nothing and the subsequent impact on natural habitats, properties and vital infrastructure.

What is Natural Infrastructure?

As community growth and a changing climate strain transportation, stormwater and other infrastructure systems, local governments look to more sustainable management and engineering practices to ensure health and wellbeing. Natural infrastructure uses landscapes, waterways and natural processes to reduce flooding, improve water quality, stabilize shorelines, restore wetlands, protect property and meet other needs. They are actively managed to provide multiple environmental, economic, and social benefits. Gray infrastructure refers to traditional urban systems that are often constructed with concrete or steel (e.g. pipes, storm drains, seawalls, etc.). However, unlike these features, natural infrastructure can grow and adapt to changing conditions. Hybrid infrastructure is when nature-based solutions are integrated with gray infrastructure to strengthen the resilience of communities and ecosystems.

Flood Hazards on Tybee Island

Since 1935, a National Oceanic and Atmospheric Administration *(NOAA)* tide gauge has been in place just over two miles from Tybee Island at the Fort Pulaski National Monument. Measuring water levels every six minutes, the long-term data from the gauge shows a steady increase in water heights and flooding around Tybee Island. From 2016 to 2021, the rate of flooding events increased by 30 percent, largely due to sea-level rise. In 2022, a federal interagency task force released a technical report that statistically extrapolated these observations, estimating that sea levels around Tybee Island may rise an additional 1.39 feet by 2050. This could very likely result in at least 50 days of flooding per year by 2040.

Planning Process

The Tybee Island Natural Infrastructure Master Plan was developed through a community-centered design process that blended natural and traditional infrastructure and adaptation measures to:

- **Provide increased resilience to flooding on Tybee Island**
- **Preserve and restore fish and wildlife habitat**
- **Improve connectivity throughout the island**
- **Align with community values**
- **Consider cost and time to implement**
- **Recognize regulatory requirements and constraints**

Strategies were rigorously assessed to determine if they were well suited to the unique culture and interests of those who live, work, and recreate on Tybee Island. The project's education and outreach efforts reached over **525 people through virtual and in-person events** during 2021-2022. **More than 120 volunteers** were actively engaged in the project, including residents, professionals representing interested governmental entities, non-profit agencies, and private industry.

The Tybee Island Natural Infrastructure Master Plan was created in conjunction with the community's Stormwater Master Plan, which was completed by the engineering firm Thomas & Hutton in late 2022. Using coordinating models, scenarios, and software, the two teams determined that the frequency of flood events on Tybee Island has increased steadily during this century. This is mainly due to climate change-induced sea-level rise and aging stormwater infrastructure.

The teams worked closely with a **technical advisory group** composed of local, state and federal partners and a **resident advisory group** made up of home and business owners and local leaders. Through meetings, site visits, workshops, and design charrette exercises, these groups worked with the engineers and scientists to explore how nature-based features like rain gardens, bioswales, pocket parks and permeable pavement in the interior of the island could increase stormwater storage and drainage capacity, while also treating rainfall-runoff, expanding the biodiversity of green spaces and offering leisure opportunities for residents and visitors.

The boards additionally examined how coastal elements, such as berms and living shorelines, could help prevent rising tides from eroding or overtopping Tybee Island's marsh front, while also enhancing marsh connectivity and migration. The project team met frequently with CIty staff and hosted three workshops for Tybee Island City Council to keep them abreast of progress and gain feedback on emerging ideas.

Approximately, **83 undergraduate and graduate students** worked on this project through UGA's College of Engineering, College of Environment and Design, and Marine Extension and Georgia Sea Grant. The students and researchers utilized insights gained through extensive stakeholder engagement to (1.) prepare conceptual project designs, (2.) assess potential project sites, (3.) evaluate risk reduction benefits, and (4.) begin preliminary engagement with permitting agencies.

Figure 1. Project members Alan Robertson and Alfie Vick inspect drainage near critical infrastructure.

The team then modeled a subset of these preliminary design alternatives under different weather and climate scenarios to determine their performance. Baseline data collected from water level sensors, marsh cores, rain gauges, and eight groundwater wells installed specifically for this project helped to inform the preliminary designs by providing information on hydrodynamic, infiltration and marsh accretion processes.

Public Perceptions and Observations

To further understand public perceptions and preferences, the University of Georgia project team launched the **Tybee Island Geosurvey**, which allowed residents to identify locations on the island that have issues with flooding, erosion, marsh die off and marine debris. In addition to crowdsourcing these hotspots, residents submitted photos and videos of flooding to use in education, outreach and planning.

The team also administered the **Coastal Empire Adaptation Survey**, which sampled residents in ZIP codes along the Savannah River and Atlantic Ocean in Chatham County (zip codes 31328, 31410, 31404, 31411, 31419). Of the 176 completed survey responses, 41 percent were located in the Tybee Island zip code (31328).

The majority of respondents expect rising sea levels in the future (76 percent) and a worsening of flooding (79 percent), erosion (79 percent), and coastal storms (68 percent). The majority also agreed that coastal infrastructure will need to be fortified against climate change (84 percent) and that some parts of the coast will need to embrace a retreat adaptation strategy (68 percent).

However, there was considerable uncertainty about individual flood risk. Almost 12 percent of respondents were not sure if they live in a flood zone. For those that recognized they are in a flood zone, the majority were not sure which zone they are in.

The survey instrument included a stated preference "choice experiment" that was designed to assess preferences for gray, natural, and hybrid infrastructure designs for shoreline protection (relative to a do-nothing status quo option). Based on existing scientific literature, each of the designs were ascribed different values as to how well they would limit storm and high tide flooding and provide wildlife habitat. The natural and hybrid infrastructure options were chosen as the desired options 45 percent and 33 percent of the time, respectively. Traditional gray infrastructure was chosen only 18 percent of the time.

The survey also evaluated how much households would be willing to pay to reduce the risk of severe flooding in low lying areas. **Table 1** shows the high preference respondents showed for supporting projects that benefit wildlife habitat.

Table 1. Annual household marginal willingness to pay for infrastructure services

SERVICE	WILLINGNESS TO PAY (PER YEAR FOR 10 YEARS)	95% CONFIDENCE INTERVAL
Reduce risk of severe flooding over 30 years by 1%	$10.21	$3.85 – $16.57
Reduce annual nuisance flooding by 1 day	$3.17	-$0.33 – $6.68
Improve wildlife habitat from poor to good	$658	$271 – $1050
Improve wildlife habitat from poor to best	$814	$375 – $1250

Recommendations

The Coastal Empire Adaptation Survey informed the development of a **multi-criteria decision approach (MCDA)**, where different combinations of natural infrastructure were assessed using a weighted system that aligned with public values. These scenarios included doing nothing, relying solely on the proposed gray infrastructure from the Stormwater Master Plan, and enhancing the proposed gray infrastructure with different arrangements of natural infrastructure. The performance of each alternative was then tested across various rainfall depths, tides, and a future projection for sea-level rise.

Based on the advisory board input, public survey results, observations, data collection, modeling, and multi-criterion decision analysis, the most impactful and desirable portfolio of natural infrastructure interventions is listed in **Table 2**.

Table 2. Project recommendations from the Tybee Island Natural Infrastructure Master Plan

SITE ID	PROJECT NAME / LOCATION	ACTION ITEM (PROJECT DURATION)	HABITAT IMPROVEMENTS
NI-1	Venetian Drive *(Venetian Dr. from Aj's to 12th St.)*	• Create a horizontal levee or berm with a naturalized shoreline along Venetian Dr. • Raise road elevation by 1 ft. • Construct living shoreline around the levee toe. • Reroute 13th St. stormwater outfall along 6th St. to connect to 14th St. outfall • Implement one-way traffic. • Create a bike / pedestrian path. • Provide dock access from the updated shoreline.	• Provide pathway for marsh migration • Enhance marsh habitat • Improve water quality • Control erosion
NI-2	6th Street *(6th St. from Lewis Ave. to Miller Ave.)*	• Replace and enlarge culvert under the bridge that lies between Lewis and Miller Ave. • Construct a living shoreline.	• Enhance marsh connectivity • Improve water quality • Control erosion • Improve wildlife crossing
NI-3	Lewis Avenue	• Add a submerged culvert to connect marshes on both sides of the road. • Extend Sally Pearce Trail.	Enhance marsh connectivity
NI-4	US HWY 80 / Butler Avenue *(US HWY 80 from Lazaretto Creek to Tybrisa St.)*	• As GDOT makes roadway improvements, implement curb cut rain gardens to reduce runoff along sidewalks and right-of-ways. • Integrate natural infrastructure into a Green Space Network.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution

SITE ID	PROJECT NAME / LOCATION	ACTION ITEM (PROJECT DURATION)	HABITAT IMPROVEMENTS
NI-5	14th Street *(14th St. from Butler to Chatham Avenues)*	• Demarcate right-of-way with stakes/flags. • Utilize permeable pavers on the road. • Use the right-of-way to create a swale on the shoulder or place a median in the middle of the road. • Consider implementing a one-way traffic pattern. • Integrate natural infrastructure into a Green Space Network.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution
NI-6	Stormwater Inlet Rain Gardens *(13th, 14th and 15th Streets from Butler Avenue to Chatham and Venetian Avenues)*	• Relocate storm grates out of the roadway. • Create rain gardens at 19 stormwater inlets. • Integrate natural infrastructure into a Green Space Network.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution
NI-7	Rainwater Storage *(Parcels located along 13th, 14th and 15th Streets between Butler Avenue and Chatham or Venetian Avenues)*	• Encourage residents and businesses to start rainwater harvesting from building roofs. • Implement rain storage on all public buildings, such as Town Hall, Fire House, etc. • Implement UGA's Coastal Georgia Rain Garden program. • Reuse harvested rain to maintain green infrastructure.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution • Provide habitat for pollinators and increase biodiversity
NI-8	South Beach Pocket Park *(Unused lot at the intersection of 15th Street and Butler Avenue)*	• Engage Hotel Tybee in planning the use of the unused go-kart track. • Replace current use with green space—replacing soil, creating a grassy berm, and installing permeable pavers. • Integrate natural infrastructure into a Green Space Network. • Put the parcel under a conservation easement.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution • Increase green space near the tourism hub of South Beach

SITE ID	PROJECT NAME / LOCATION	ACTION ITEM (PROJECT DURATION)	HABITAT IMPROVEMENTS
NI-9	Permeable Pavers *(Island-wide)*	• Install permeable pavers on public domains (parking lots and on-street parking), with a special emphasis on the South Beach area. • Conduct outreach to commercial properties to encourage use of permeable pavers.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution
NI-10	Urban Tree Canopy *(Island-wide)*	• Identify vacant lots. • Integrate urban tree canopy into natural infrastructure model. • Conduct community outreach on the benefits of native urban trees.	• Improves shade, air and soil filtration, and wildlife habitat • Serves as a shelter and resting place for birds within the Atlantic Flyway
NI-11	Elevating Homes *(Island-wide)*	• As homeowners continue to elevate homes, educate homeowners on green infrastructure best practices, like permeable pavers, rain gardens, and native plants. • Apply for additional FEMA Hazard Mitigation Funding to continue to offset out-of-pocket expenses for homeowners wanting to elevate their home. • Consider adopting a plant ordinance where a certain percent of the lot has to be kept green.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution • Provide habitat for pollinators and increase biodiversity
NI-12	Right-of-Ways *(Island-wide)*	• Map right-of-ways and identify green infrastructure opportunities. • Demarcate right-of-ways in high priority areas. • Utilize right-of-ways to create a Green Space Network.	• Provide habitat for pollinators and increase biodiversity • Increase connectivity of green spaces

NI-1: VENETIAN DRIVE

Marshes provide critical services to both humans and wildlife by improving water quality, protecting against storm surges, reducing erosion, and supplying critical habitat. NOAA estimates that 15 feet of marsh can reduce incoming wave energy by as much as 50 percent (NOAA Office of Coastal Management, 2023). Marshes are facing threats to their long-term sustainability, most importantly from rapid sea-level rise, but also from contaminant-laden runoff from land. As sea levels rise, the marsh will naturally retreat onto the upland to remain in the intertidal zone. However, if it reaches a vertical structure, like a revetment or bulkhead, it cannot retreat landward any further, and a process called coastal squeeze occurs, wherein the marsh eventually drowns and is converted to open water. Nature-based solutions at the upland-marsh interface can stabilize the shoreline while still providing a pathway for marsh migration. Berms and levees are raised embankments that protect against flooding and slow or divert stormwater runoff from entering the marsh. Living shorelines are a method of stabilizing embankments with natural materials such as sand, rock, and plants. They reduce erosion, improve water quality and provide valuable habitat for birds, aquatic life, and other wildlife.

NI-2: 6TH STREET

The culvert under 6th St. between Lewis and Miller Avenues is currently too small for the volume of water attempting to travel through it, resulting in the pooling of saltwater on either side of the road. Additionally, the existing culvert does not allow safe passage for animals attempting to traverse the creek. Enlarging the culvert would equilibrate the water flux to the marsh pond north of 6th St. while reducing inundation in the surrounding areas. Shoreline analysis conducted on Tybee Island indicates that 78 percent of the land that borders open water is currently armored. This means that a manmade structure, such as a seawall, revetment, or bulkhead, has been erected where the land meets the open water to prevent erosion. However, only 8 percent of the land that borders the marsh on Tybee Island is armored. This presents a key opportunity to implement natural infrastructure and strengthen the resilience of the marsh and corresponding habitat.

NI-3: LEWIS AVENUE

Lewis Avenue is a residential street built upon manmade land between two marshes. Because of its location, residents on this street experience some of the worst flooding on the island. The plan proposes installing a cross-culvert that will run under Lewis Avenue to connect the two sections of the marsh the street is situated between. The placement of the culvert is based on historical images that show where the marsh was originally connected, and the implementation of this culvert will restore part of the marsh back to its original condition. To integrate Lewis Avenue into the Green Space Network designs, the plan also includes designs to extend the Sally Pearce Trail. This would improve connectivity and public access to the marsh to support ecotourism and recreational opportunities.

NI-4: US HWY 80 / BUTLER AVENUE

Several roads present critical opportunities for natural infrastructure, either due to being central conduits for stormwater runoff or having low elevation. US HWY 80/Butler is one of the high-impact areas where nature-based solutions would provide the most benefit. The Georgia Department of Transportation (GDOT) is currently replacing the Bull River and Lazaretto Creek Bridges on the stretch of US80 that connects Tybee Island to the mainland. In the coming years, GDOT will begin working on the portion of US HWY 80 on the island, starting at the base of Lazaretto Bridge, curving to become

Butler Ave., and stretching along the beachfront shoreline. As improvements are made to this main thoroughfare, there are opportunities to augment traditional stormwater features with curb-cut rain gardens.

NI-5: 14TH STREET

The lowest elevation on the island occurs along 14th St., which makes it a natural recipient and conveyor of water. However, the street is already at peak capacity for stormwater infrastructure with large pipes running along both sides of the road. As such, the Stormwater Master Plan calls for adding another large pipe along 15th St. to transport drainage from the 14th St. beachfront parking areas to the 14th St. outfall. Natural infrastructure can increase the capacity of 14th St. to absorb rainfall and runoff that naturally flows into that depression. Adding a bioswale along the length of the road in the right-of-way would provide a channel for the water to flow through and be stored. It should be planted with native vegetation that provides habitat and infiltrates rainfall. The design calls for converting the two-way, asphalt road into a one-way road, replacing the asphalt with permeable pavers, and adding a bike lane.

NI-6: STORMWATER INLET RAIN GARDENS

The area of 13th, 14th, and 15th Streets between Butler, Chatham, and Venetian Avenues has been termed 'The Bowl' by Tybee Island residents because it is a localized low spot where frequent ponding occurs on the streets and around homes. Drainage in the 'The Bowl' needs to be improved, and so this location is a critical focus of the Natural Infrastructure Master Plan. Currently, 19 storm grades are located within the intersection of these streets. Most of these grates are located out of the roadway and placed at the corners of intersections so rain gardens can be planted in the right-of-way around these inlets. Inlets within the roadway should be considered to be moved toward the grass right-of-way within the intersections. Rain gardens function similarly to bioswales, as they are shallow, excavated areas of land replaced with mixed engineered soil and native vegetation. This aesthetically pleasing and sustainable system uses the natural processes of infiltration and evapotranspiration to control stormwater. These natural infrastructure features will improve connectivity and provide a network of habitats for wildlife, such as pollinators.

NI-7: RAINWATER STORAGE

Another aspect of the design for 'The Bowl' is a voluntary, residential rainfall capture program. In this initiative, residents will be supported by professionals in implementing either rain harvesting or a rain garden on their property. Planting native vegetation, such as sea oxeye daisy, saltmeadow cordgrass, and saw palmetto, can help capture initial rainfall and filter out suspended solids in the runoff. Both the rain harvesting and rain gardens will reduce the volume of stormwater and pollutant loading to the surrounding marsh systems while also delaying flood peaks via retaining and re-routing processes.The plan targets houses in "The Bowl" due to its high impact on this region, but these features can be implemented island-wide if desired. Based on the MCDA, the most impactful combination of rainwater storage entails 50 percent implementation on residential properties in the Bowl area (201 parcels) and 100 percent implementation on public buildings.

NI-8: SOUTH BEACH POCKET PARK

There is a lot currently owned by Hotel Tybee located at the intersection of 15th Street and Butler Avenue that is partially grassed with an unused go-kart track. In recent years, it has been used for parking and for hosting community events. This lot provides an opportunity for intentionally enhancing green space through the creation of a pocket park. The proposed park includes removing the go-kart track and planting natural vegetation and trees to provide habitat and improve the urban canopy cover. With agreement from the parcel owners, the city could also get an easement to maintain the lot as green space and prevent future development. The lot is adjacent to the new stormwater pipe that will transect the island along 15th Street. By replacing soil, creating a grassy berm, and installing permeable pavers, the lot will improve the performance of the gray infrastructure by reducing the volume of water. Having permeable pavers on a portion of the lot will allow the owners to use it for parking still when desired.

NI-9: PERMEABLE PAVERS

Leveraging the Stormwater Master Plan, natural infrastructure should be incorporated into Phase 1 of the 14th Street Parking Area/15th Street Outfall capital improvement project. This portion of the project involves constructing an underground stormwater detention system and repaving the beach parking area between 14th and 15th Streets. Stormwater runoff from the parking areas will be pumped to the new storm main that will be installed on 15th Street and discharged at the 14th Street outfall into the marsh. Rather than repaving these parking lots with impermeable asphalt, permeable pavers should be utilized to reduce flooding near the beach and relieve pressure on the stormwater system. This intervention is also suitable for on-street parking lanes and commercial parking lots in the area, as well as homeowner driveways, which have been implemented before on the island.

NI-10: URBAN CANOPY COVER

Urban canopy cover is a natural infrastructure feature that involves planting trees in order to intercept rainfall, reduce rainfall runoff, and combat flooding during rain events. Urban canopy cover improves infiltration and hosts other benefits such as shade, air and soil filtration, wildlife habitat, and aesthetic appeal. For example, these trees can serve as a shelter and resting place for birds within the Atlantic Flyway, which is one of four major flyways for migratory birds in the Americas. Data from the National Audubon Society has tracked over 255 unique bird species that have visited Tybee Island, of which some are classified as Near Threatened based on the International Union for Conservation of Nature (IUCN) Red List Category. These trees can be implemented on vacant lots and publicly owned property across the island, such as right-of-ways and public parks.

NI-11: ELEVATING HOMES

Tybee Island has been awarded two Hazard Mitigation Grants through the Federal Emergency Management Agency (FEMA) to support home elevations. Both grants were related to the damage from Hurricane Irma in 2017. The grant pays for 85 percent of the cost, meaning that the homeowners are responsible for 15 percent plus any overruns. To be lifted out of the flood hazard area, homes on Tybee Island must be elevated at least one foot above base flood elevation (BFE). For those elevating their homes and those considering this investment, there is an opportunity to provide education on natural infrastructure best practices, like permeable pavers, native plants, and living shorelines. When homes are raised, landscaping often needs to be redone, offering the chance to change designs, materials, and plant species. Best practices could be encouraged through an incentive program or a plant ordinance where a certain percentage of the lot has to be kept green.

NI-12: RIGHT-OF-WAYS

Much of Tybee Island is developed, and most of the area bordering the marsh is privately owned. This limits the City's ability to implement natural infrastructures. One innovative approach that emerged from the planning process was to use public right-of-way for natural infrastructure. Street right-of-ways are land adjacent to the road that is typically used for water/sewer lines, drainage, and transportation infrastructure. Many communities are reclaiming that valuable space to implement natural infrastructure. On Tybee Island, it is first necessary to determine where the right-of-way is located. Demarcating it with flags or other markers in high priority areas for natural infrastructure could help educate residents on ownership and potential uses for this land.

Conclusion

The Tybee Island Natural Infrastructure Master Plan was designed to be integrated with the community's new Comprehensive Stormwater Master Plan. While upgrading gray stormwater infrastructure will be critical for reducing flood impacts on the island, the models used by the University of Georgia and Thomas & Hutton show that enlarging and densifying conduits alone will not be sufficient to manage the volume of water poised to inundate the island in the decades to come. As heavy rain events are increasingly compounded and exacerbated by higher tides, integrated hybrid infrastructure will be needed. The hybrid natural infrastructure features recommended in this plan can capture and retain up to 21 percent (115,556 gallons) of the total freshwater rainfall-runoff volume that drains into the marsh. This can prolong the service life of these new gray infrastructure investments by reducing flooding stress while conserving wildlife habitats and wetlands.

Next Steps: Final Design and Permitting

This project produced preliminary design and feasibility assessments so that Tybee Island City Council can decide which activities to pursue in the short, medium and long term. Should Tybee Island City Council approve these initial concepts and authorize pursuit of more detailed site designs, the next steps for the project team will be to conduct education and outreach activities as described above and apply for the next phase of NFWF National Coastal Resilience Funding, which are for 3 year projects with a maximum budget of $1 million. Non-federal match is encouraged but not required to demonstrate broad support for the project. Larger match ratios and matching fund contributions from a diversity of partners will make the application more competitive according to past instructions.

Next Steps: ***Public Engagement and Outreach***

There is strong public support for natural infrastructure on Tybee Island and in surrounding areas, particularly when it promotes healthy wildlife habitat. However, it will be critical to educate residents, particularly those adjacent to natural infrastructure features, about their benefits to increase understanding and collective will. Specific outreach recommendations are to:

- Demarcate the right-of-way on 14th and 15th St. to educate residents about the right-of-way and provide visual guidance for discussing natural infrastructure along these corridors.
- Collaborate with partners to host workshops for residents on rain storage, such as a rain barrel workshop in partnership with the Georgia Department of Natural Resources Coastal Resources Division or a rain garden workshop in partnership with UGA Marine Extension and Georgia Sea Grant.
- Provide training on the design and function of swales so they are properly maintained. Currently, there are several swales on the island where sediment has built up preventing water from accessing the swale (e.g. 7th St. and Miller Ave.).
- Seek funding to incentivize the adoption of rain storage practices on residential properties, such as implementing the Coastal Rain Garden Program. These efforts should prioritize 13th, 14th, and 15th Streets between Butler Avenue and Venetian Drive/Chatham Avenue.
- Engage residents who live on Venetian Drive to share options for protecting their properties and preserving the marsh.
- Conduct community outreach on the benefits of native urban trees.

Next Steps: ***Research***

Next steps needed for research and data collection are to:

- Adapt the proposed gray infrastructure in the Comprehensive Stormwater Master Plan to align better with recommended natural infrastructure.
- Integrate urban tree canopy into the natural infrastructure model.
- Assess the functionality of adding control features on proposed 6th St. and Lewis Ave. culverts, in order to ascertain potential impacts on the marsh and net ecological lift.
- Analyze optimal locations for buyouts of repetitive loss properties (FEMA Hazard Mitigation Grant) to enhance natural infrastructure.

Next Steps: ***Funding***

In order to advance the preliminary designs in this plan and implement recommendations, additional funding will be needed. Listed are suggestions for securing this support:

- Apply for NFWF Phase 3 grant to further work on design and permitting.
- Investigate creative options for securing matching funds for project proposals, such as the Department of Defense's REPI Program.
- Leverage this plan to access state, federal, and private sector funding. Having concepts packaged in a plan and approved by City Council will strengthen proposals, helping to attract funders and financial opportunities.
- Continue dialogue with permitting/regulatory agencies on proposed activities.
- Integrate natural infrastructure into current and future planning, transportation, and public works projects. This includes both Phase 1 and 2 of the stormwater capital improvement project involving 14th Street Parking Area/15th Street Outfall and improvements by the Georgia Department of Transportation to US Hwy 80 / Butler Avenue.

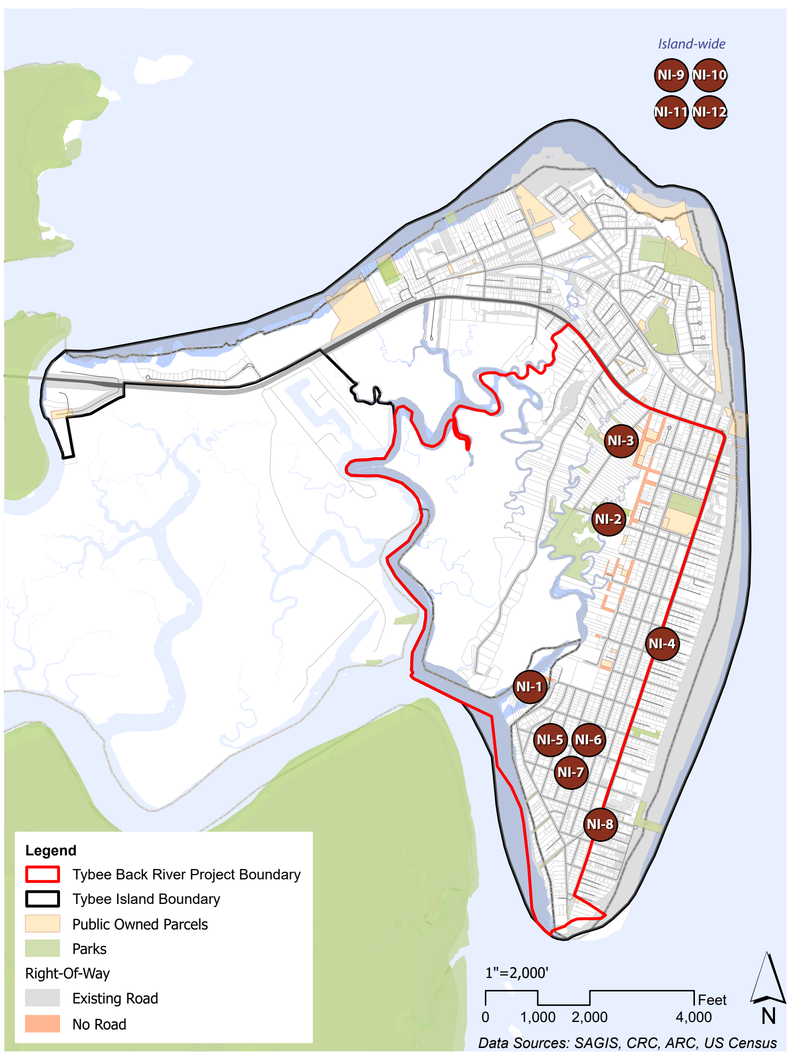


Figure 2. Locations of project recommendations in the Tybee Island Natural Infrastructure Master Plan.

Figure 1.1. Signage on Tybee Island after Hurricane Irma.

SECTION I: INTRODUCTION

Tybee Island is a barrier island located off the coast of Savannah, Georgia. Spanning less than three square miles, the island has a year-round population of roughly 3,000. During the summer, the island welcomes upwards of one million visitors.

The salt marshes that stretch between Tybee Island and the mainland are one of the most biologically productive natural systems on Earth. They also help reduce wave erosion along the coast by acting as buffers to decrease the effects of storms. The waters and wetlands surrounding Tybee Island serve as habitats and nurseries for many fish and shellfish, as well as diverse bird, reptile, and mammal species.

Sea Level Rise Adaptation Plan

In 2016, Tybee Island became the first community in Georgia to adopt a municipal sea-level rise adaptation plan, assessing exposure to sea-level rise and flooding over the next 50 years The plan examined the vulnerability of existing infrastructure and developed recommendations for immediate and long-term adaptation actions.

> The **Tybee Island Sea Level Rise Adaptation Plan** created a nationally recognized framework for sea level rise planning and public engagement on coastal hazards.

As a result of this planning, and in the wake of Hurricanes Matthew (2016) and Irma (2017), Tybee Island stood ready to access the subsequent funding made available by these back-to-back 100-year storm events. Having established a shared understanding of flood vulnerabilities and desired adaptation actions, the City utilized this state and federal funding to execute almost every recommendation in its sea-level rise plan. This included renourishing the island's beach, restoring its dune systems, raising beach access pathways, retrofitting its stormwater system, elevating homes, and lifting critical infrastructure.

The City also quickly sought out partnerships to address emerging challenges, such as the inundation of residential neighborhoods near the marsh. While Tybee Island's sea-level rise plan broke new ground for coastal Georgia, it focused primarily on reducing risks to public assets and infrastructure. It intentionally stopped short of assessing how flooding from sea-level rise might affect private properties, local businesses, and ecosystems on the island. Recent hurricanes, including Hurricanes Mathew in 2016, Irma in 2017, and Michael and Florence in 2018, and high tide events have shown that these vulnerabilities greatly impact the community's overall resilience.

Securing support from the National Fish and Wildlife Foundation (NFWF) and the Georgia Department of Community Affairs, the City of Tybee Island collaborated with an multidisciplinary research team at the University of Georgia to further fill these critical gaps in current planning. The project utilized an innovative approach that reconsidered the totality of the Tybee Island's built, natural,, and social systems.

The project team drew on methodologies and tools from engineering, ecology, landscape architecture, planning, geology, economics, and geography. Continuing to leverage the assistance and engagement of the numerous partners already in place, a participatory framework was used to co-produce, assess, and prioritize strategies that increase the island's resilience to storm and flood events.

The resulting **Tybee Island Natural Infrastructure Master Plan** outlines this proposed integrated and community-centered system, which utilizes natural elements to provide increased resilience to flooding while protecting natural habitat and enhancing the quality of life.

What is Natural Infrastructure?

In coastal regions throughout the country, community growth and climate change are straining transportation, stormwater, and other infrastructure systems. In response, local governments are looking to more sustainable management and engineering practices to ensure health and wellbeing. **Natural infrastructure** uses landscapes, waterways, and natural processes to reduce flooding, improve water quality, stabilize shorelines, restore wetlands, protect property, and meet other needs. They are actively managed to provide multiple environmental, economic, and social benefits. **Gray infrastructure** refers to traditional urban systems that are often constructed with concrete or steel (e.g. pipes, storm drains, seawalls, etc.). However, unlike these features, natural infrastructure can grow and adapt to changing conditions. Natural infrastructure offers numerous co-benefits, such as improving air and water quality, beautifying streets, and providing habitat for birds, fish, and other wildlife. While traditional stormwater pipes or concrete seawalls provide functional value under certain conditions, natural infrastructure supplies services continuously. **Hybrid infrastructure** is when nature-based solutions are integrated with gray infrastructure to strengthen the resilience of communities and ecosystems.

Figure 1.2. An example of natural infrastructure is the living shoreline located at the UGA Burton 4-H Center on Tybee Island.

SECTION II: FLOOD HAZARDS ON TYBEE ISLAND

Coastal communities around the world have seen an increase in flood events over recent decades. Data from the long-term National Oceanic and Atmospheric Administration (NOAA) at the Fort Pulaski National Monument shows a steady increase in these annual flood events around Tybee Island **(Figure 2.1)** for both minor flood thresholds. The year with the most flood events under the previous flood threshold (9.2 ft above mean lower-low water) was 2019, with 42 events, while for the current flood threshold (9.5 ft above mean lower-low water) is 2020, with 15 events. Similar findings have been reported by Evan et al. (2016). However, from 2016 to 2021, the rate that these events occurred increased by approximately 30 percent for both flood thresholds.

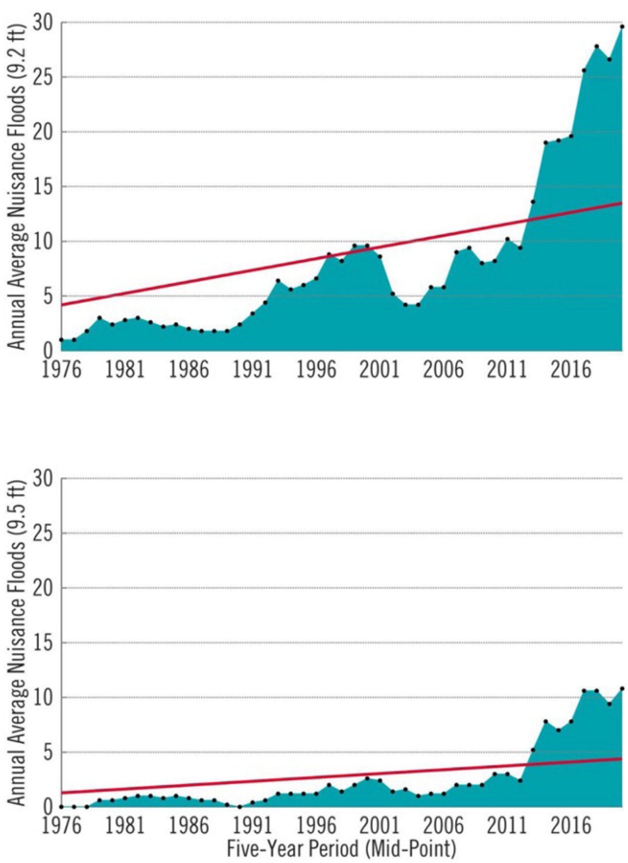


Figure 2.1. Nuisance flooding on Tybee Island from 1935-2022. The values represent the annualized average of tide events that exceeded 9.2 feet (before 5/1/2020; top panel) or 9.5 feet (after 5/1/2020; bottom panel) above mean lower-low water over a rolling five-year period at NOAA's Fort Pulaski tide gauge. Listed years represent the mid-point of a given five-year period.

Sea Level Rise

Rising sea levels around Tybee Island are not only increasing the frequency of flooding, but also the potential for damaging storm surge and compound flooding from rain. In the near term, the main contributing factors for this relative sea-level rise are processes like subsidence (vertical land motion) and changes in the ocean's circulation, temperature, and salinity. However, over time, processes like melting land ice, particularly in Antarctica and Greenland, will increasingly affect the rate and magnitude of sea-level rise near Tybee Island.

The Fort Pulaski tide gauge has measured over 12 inches of sea-level rise since 1935. This rate is expected to accelerate dramatically along the South Atlantic coast in the future. In 2022, the federal government released an interagency technical report on sea-level rise scenarios for the United States written by scientists from NOAA, the National Aeronautics and Space Administration

(NASA), Environmental Protection Agency (EPA), U.S. Geological Survey (USDS), U.S. Army Corps of Engineers, and academic partners. The report estimated an additional 1.39 feet of sea-level rise for Tybee Island by 2050, based on statistically extrapolating observations from the Fort Pulaski tide gauge *(Sweet et al, 2022)*. There is a 98 percent chance that this would result in at least 50 flooding days per year by 2040 *(Thompson, 2023)*. The model-based intermediate scenario indicates 3.91 feet of sea-level rise for the Georgia coast by the end of the century.

Higher water levels can compromise the safety and functioning of instructure like stormwater and wastewater systems, roads, and bridges. For example, Tybee Island's current stormwater system becomes overwhelmed during small storm events (e.g., 4.5 to 6 inches of rain in 24 hours). When this coincides with high tides events, performance can be even more compromised with saltwater filling stormwater pipes and limiting their storage capacity. During a November 2021 perigean spring tide, street flooding primarily occurred by saltwater traveling backwards through the stormwater system to the island's interior and overflowing onto streets. This event consisted of a 10.44 ft. tide above mean lower-low water (MLLW) at the Fort Pulaski tide gauge and two inches of rainfall.
Imagine now if a storm generating 7.5 inches of rain occurs simultaneously with a high tide event like a spring tides (occuring once every 14 days) and perigean spring tides (occurring 6 to 8 times per year). The water infrastructure would fail even more dramatically. Severe flooding could be expected along multiple streets (e.g., 14th St., Chatham Ave., 5th St., Miller Ave., Alley St.) with maximum depths greater than 1 feet **(Figure 2.2 A)**.

Projected sea-level rise will exacerbate flooding conditions even further. For instance, an intermediate sea-level rise scenario for 2050 could increase the flood depths during a spring tide event compared to current climate conditions **(Figure 2.2).** Flooding differences of more than 1 ft .of depth can be in many locations, meaning that more frequent events will have a bigger impact under climate change projections.

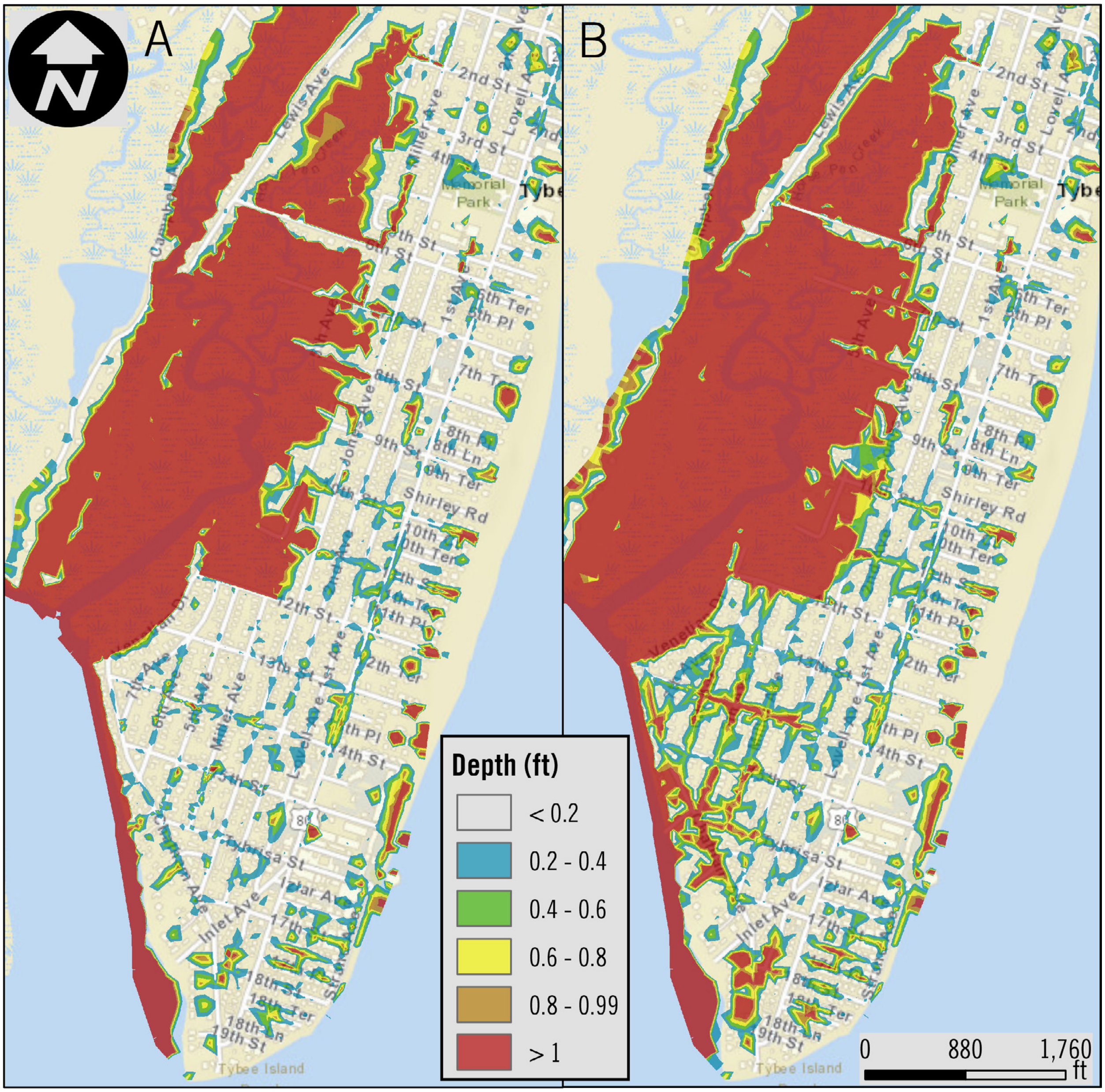


Figure 2.2. *Flood hazard conditions at Tybee Island under current conditions (A) and future projections (B). The maximum flood depth was obtained from a spring tide plus a 7.5 in rainfall event to assess the current flood conditions, while the future conditions are based on the same environmental drivers with the additions of the intermediate sea-level rise scenario for 2050.*

SECTION III: PLANNING PROCESS

The Tybee Island Natural Infrastructure Master Plan was co-produced by researchers, community members, and a diverse group of coastal partners by integrating local and technical knowledge through a collaborative approach to protect the people, environments, and livelihoods of Tybee Island. The experiences and perspectives of the Tybee Island community were critical in identifying a vision for Tybee Island's future.

Building upon Tybee Island's nationally recognized planning framework, this project continued to advance a inclusive model for community engagement by (1) soliciting input from local stakeholders, (2) educating policymakers and residents on the risks of coastal hazards and benefits of building community resilience, and (3) building support for climate adaptation alternatives. This included sustained iterative discussions about trade-offs and uncertainties of options being considered, balancing cost and time and environmental and social impacts. The project's education and outreach efforts reached over 525 people through virtual and in-person events during 2021-2022. More than 120 volunteers were actively engaged in the project, including residents, professionals representing interested governmental entities, non-profit agencies, and private industry.

PROJECT GOAL

To design an integrated, community-centered system that:

- Increases resilience to flooding on Tybee Island
- Protects and improves fish and wildlife habitat
- Acknowledges community values
- Considers cost and time to implement
- Recognizes regulatory requirements and constraints

PROJECT VISION

To utilize green, gray, and blue infrastructure and adaptation measures to provide increased resilience to flooding, preserve natural habitat and improve connectivity throughout the island.

Advisory Groups

The project was advised by professionals and residents who provided both technical expertise and local knowledge, informing the project's methods, analyses, and findings.

Figure 3.1.. Technical Advisory group members Michael Blakely (Chatham County) and Kevin Smith (Thomas & Hutton) discuss student renderings based on the design charrette.

Technical Advisory Group

Federal: U.S. Army Corps of Engineers, NFWF, NOAA, Rep. Buddy Carter's Savannah Office

State: Georgia Department of Natural Resources Coastal Resources Division, Georgia Emergency Management Agency

Local: Chatham County-Savannah Metropolitan Planning Commission, Chatham Emergency Management Agency, Chatham County, City of Savannah, City of Tybee Island

NGOs: Georgia Conservancy, One Hundred Miles

Private sector: Goodwyn, Mills and Cawood, Thomas & Hutton

Academia: University of Georgia, Georgia Institute of Technology

Resident Advisory Group

Tybee Island residents

Tybee Island business leaders (real estate, vacation rentals)

Tybee Island Planning Commission

Tybee Island Beach Task Force

City of Tybee Island staff

Design Charette

In March 2021, a 2-part (5 hours total) virtual design charette was hosted to identify strategies for creating an integrated, community-centered system that increases resilience to flooding on Tybee Island, protects ecosystem health, and addresses the priorities of community members. A design charette is an intensive participatory planning process where participants collaborate through hands-on activities to achieve a shared vision for a project.

The design charette was attended by members of the technical and resident advisory groups. Beforehand, the project team held a one-hour introductory webinar to show participants how to use the mapping resources and collaborative design tool (Mural) that were to be utilized in the workshop. In the charette itself, participants prioritized project objectives, engaged in role playing activities and created integrated site designs that brought together perspectives of environmental health, quality of life, economic interests, and regional planning. The designs developed in the charette focused on different areas of the island and included policy recommendations, green, gray, and hybrid infrastructure strategies and land use modifications to better capture, hold, and absorb flood water (See **Appendix C**).

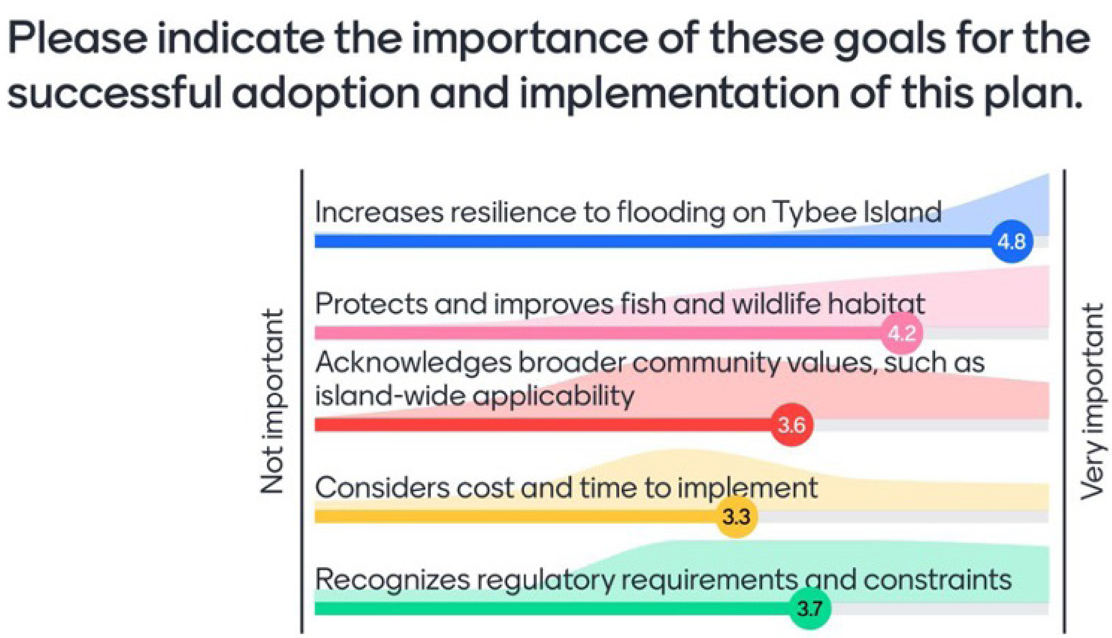


Figure 3.2. Live poll administered during the design charette ranking project goals

DESIGN CHARETTE ROLES

- **Environmental / Climate Advocate**
  Prioritized nature (maximize nature and biodiversity)
- **People of the Place**
  Prioritized wellbeing of residents who are affected in this area
- **Developer / Investor**
  Maximized value of individual private and commercial properties
- **Regional Planning / Regulator**
  Prioritized regional interests

DESIGN CHARETTE PROCESS

- **REFINE**
  Focus groups refined combined concepts
- **EVALUATE**
  Assessment of refined concepts based on goals
- **NEGOTIATE**
  Discussion to determine priorities moving forward
- **INTEGRATED SITE DESIGN**
  Development of site designs by combining and integrating concepts.

Figure 3.3. Role-playing characters and process of the design charrette

Student Engagement

Undergraduate and graduate students were instrumental in developing the ideas and recommendations put forth in this report. Approximately, **83 undergraduate and graduate students** worked on this project through UGA's College of Engineering, College of Environment and Design, and Marine Extension and Georgia Sea Grant.

Over the course of the Spring and Fall 2021 semesters, 30 students enrolled in a UGA landscape design studio helped to organize and host a virtual design charrette and developed renderings for targeted spots within the study area. The integrative, cross-disciplinary effort also involved four undergraduate engineering students who spent the academic year developing hybrid green and gray infrastructure designs to help mitigate flooding, utilizing strategies such as a horizontal levee, elevated bike path, living shoreline, and thin layer placement in the marsh. This student work was integrated and built upon as the project team developed a suite of adaptation options for the City of Tybee Island to consider.

Interns with UGA Marine Extension and Georgia Sea Grant also assisted with the project, developing an ArcGIS StoryMap Collection and Resilient Tybee website. Students in a graduate course at Emory University on the health impacts of climate change assisted with the health summaries within these resources.

Figure 3.4. and 3.5 Project team members assess student renderings.

Surveying Public Perceptions and Observations

Tybee Island Geosurvey

The Tybee Island GeoSurvey was an online instrument developed specifically for this project using Geoforage.io geographic data collection software. Promoted through news media and City emails, Tybee Island stakeholders were invited to help identify locations that experience flooding, erosion, marsh die off, and marine debris. Residents also submitted photos and videos of flooding to use in education, outreach, and planning.

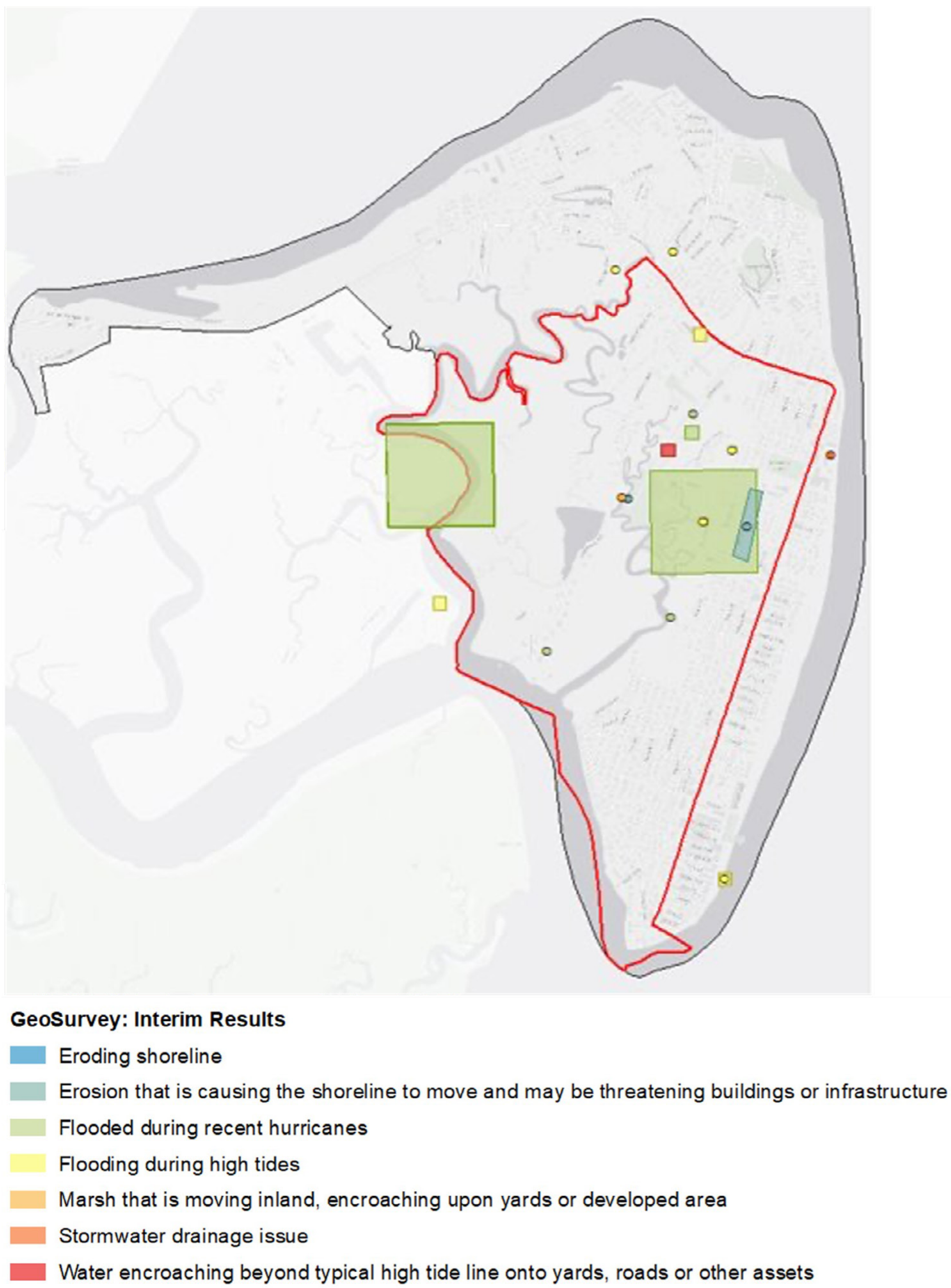


Figure 3.6. Map of results from the Tybee Island Geoforager.

Coastal Empire Adaptation Survey

The Coastal Empire Adaptation Survey was administered in early 2022 to assess the experiences, knowledge, risk perceptions, and adaptation preferences of residents who live near the Savannah River or Atlantic Ocean in Chatham County. Of the 176 completed survey responses, 41 percent were located in the Tybee Island zip code (31328 zip code). More information on the methodology and results can be found in Section IV.

Education and Outreach

This project launched in March 2020 at the start of the COVID-19 pandemic, which resulted in several initial outreach events being canceled and numerous delays in field work and site visits. The project team quickly shifted to virtual platforms to share information and collaborate, and postponed work that required in-person observations and site assessments. The virtual Design Charette, Tybee Island GeoSurvey and Coastal Empire Adaptation Survey were developed as alternatives to in-person engagement. As COVID rates declined, in-person events resumed.

Figure 3.7. Project member Clark Alexander conducts outreach to Tybee Island City Council

From 2021-2022, the following education and outreach efforts reached over 525 people:

- The project team hosted **3 Tybee Island City Council Workshops**, presenting on project progress and seeking feedback on emerging ideas.
- The project team conducted **4 in-person site visits**, meeting with residents and walking properties to gain on-the-ground knowledge applicable to the place-based designs. On one of these visits, a UGA Landscape Architecture Studio class visited Tybee Island along with a group of UGA engineering graduate students and an Emory University public health graduate student. They met with City leaders and gained valuable first-hand knowledge of the island's vulnerability to flooding.

- The project team met **8 times with the technical and residents advisory groups.**
- Tybee Island Mayor Shirley Sessions, City Manager Shawn Gillen, and Project Manager Alan Robertson visited Athens twice, presenting in a **UGA Environmental Ethics Seminar, Marine Policy class, and Public Administration Seminar.**
- Project members hosted and presented in a **2-hour webinar on "Building a Resilient Georgia: Funding Opportunities"** in December 2021 and a **full-day workshop on "Building a Resilient Georgia: Partnerships and Funding"** in August 2022.
- Project members participated in a **NASA Sea Level Summit** and hosted a field trip to Tybee Island for 32 members of the NASA Sea Level Change Science Team.
- Project members hosted a field trip to Tybee Island for 25 practitioners from throughout the U.S. as part of the **National Extension Tourism Conference.**

Figure 3.8. Project member Alan Robertson presents to Tybee Island City Council.

To further expand the reach of the project, the following onlinere sources were developed to spread awareness of Tybee Island's vulnerabilities to flooding and adaptation efforts in response:

- Building Flood Resilience on Tybee Island is an Esri ArcGIS StoryMap Collection that provides an overview of the threats, impacts, and solutions to flooding, storm surge, and sea-level rise on Tybee Island. Detailing past, current, and future flood risks, the StoryMap collection describes how the island is building flood resilience within its beaches, marshes, infrastructure systems, private properties, and wildlife.
- The Resilient Tybee website shares information on how the island is increasing its resilience to climate change, extreme weather events, and other threats. It serves as a clearinghouse for resilience-related projects and news stories and provides a central location to recognize Tybee Island's partners and successes.

- The video on “Restoring Dunes to Protect Coastal Communities” is part of the Faces of Resiliency video series, highlighting how communities are increasing their resilience to sea-level rise, storm surge, and flooding.

A list of these publications and a sample of the extensive media coverage this project received is included in Appendix B.

As Tybee Island strives to adapt to and mitigate climate change, the project team felt that connecting with peer communities could help build capacity and knowledge of best practices. During this project, Tybee Island joined the **Southeastern Sustainability Directors Network**, a collaborative of local government sustainability professionals from cities and counties in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia. It also joined the **Coastal Empire Resilience Network**, which brings together regional community partners, municipal staff, and policymakers to coordinate strategies for addressing the physical, economic, and social challenges that coastal Georgia faces due to a changing climate. Local Tybee Island leaders additionally met with representatives of the **Athens-Clarke County Unified Government** to discuss shared challenges and experiences related to climate impacts.

Data Collection

As part of this project eight groundwater wells were established around the community (See **Figure 3.9**) with the purpose of monitoring and understanding the subsurface hydrodynamics. By knowing in more detail the subsurface hydrodynamics, the natural infrastructure features that use the infiltration process as their main technique can be properly designed. These wells include pressure transducer gauges to continuously monitor groundwater levels and help determine the amount of underground storage for the rainfall-runoff through the infiltration-based natural infrastructure. Four rain gauges with a capacity to hold six inches of rainfall were distributed to augment the groundwater wells with hyper localized weather data.

To understand the current marsh conditions at Horsepen Creek, cores were collected through the west region of the island (See **Figure 3.9**). These cores facilitate the computation of current accumulation rates and determine the likelihood of the marsh to survive in future conditions. The project team also utilized water level monitoring data provided by the Georgia Institute of Technology from two ultrasonic sensors and one pressure transducer. These instruments measure the depth of the water along the tidal creeks and located on bridges or piers to facilitate the access to continuous wetted regions (See **Figure 3.9**).

Synthesizing Designs

The Tybee Island Natural Infrastructure Master Plan was created in conjunction with the community’s Comprehensive Stormwater Master Plan, which was completed by the engineering firm Thomas & Hutton in late 2022. Using coordinating models, scenarios, and software, the two teams collaborated closely through frequent meetings and shared stakeholder outreach.

The project team utilized insights gained through extensive stakeholder engagement (Design Charette, advisory board meetings, City Council Workshops, Geosurvey, and Coastal Empire Adaptation Survey) to:

1. Prepare preliminary project designs
2. Assess potential project sites
3. Evaluate risk reduction benefits
4. Begin preliminary engagement with permitting agencies.

Stakeholder engagement also informed the development of a multi-criteria decision approach (MCDA), where different combinations of natural infrastructure were assessed using a weighted system that aligned with public values. The performance of each alternative was tested across various combinations of rainfall depths, tides, and a future projection for sea-level rise. These weather and climate scenarios were consistent with the stressors used by Thomas & Hutton in the Stormwater Master Plan. Baseline data collected from water level sensors, rain gauges, marsh cores, and groundwater wells helped to inform the preliminary designs by providing information on hydrodynamic, infiltration, and marsh accretion processes.

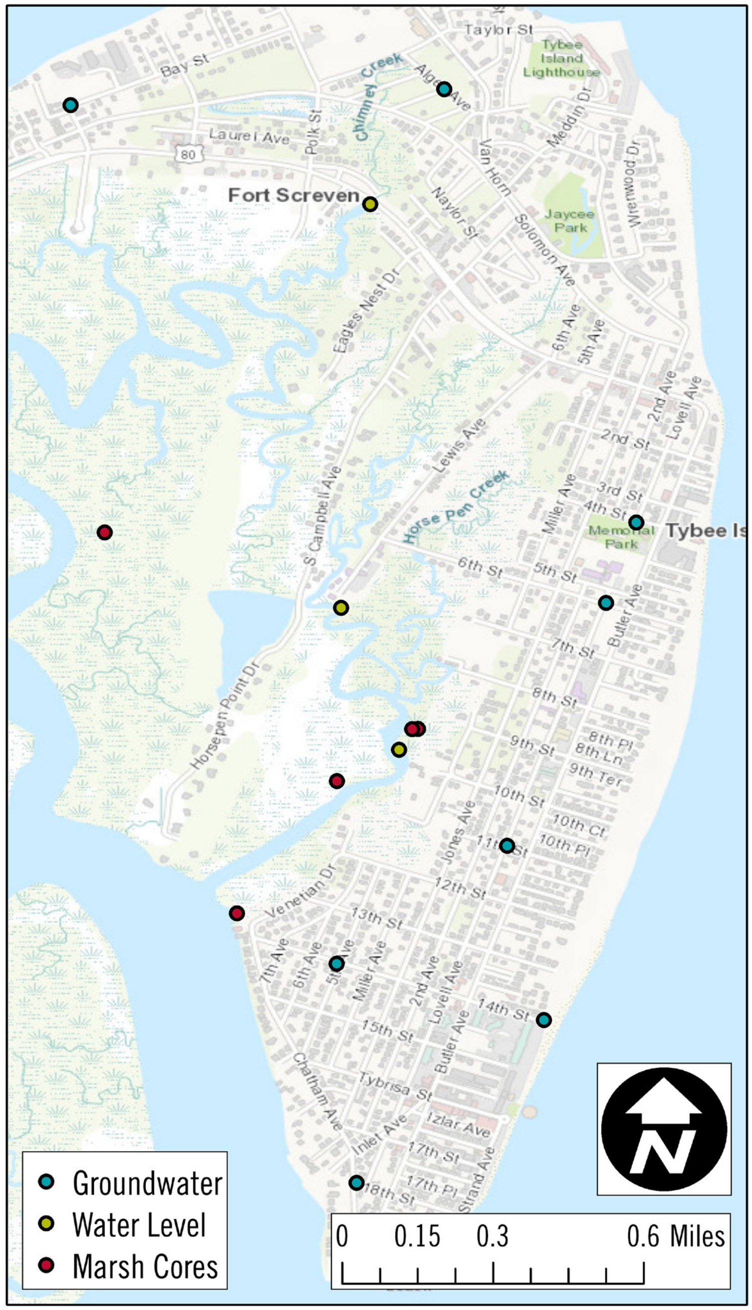


Figure 3.9. Location of data collection sites based on the different types of monitoring.

SECTION IV: COASTAL EMPIRE ADAPTATION SURVEY

The University of Georgia contracted with M/A/R/C/Online Sampling Solutions to sample residents in ZIP codes located along the Savannah River and adjacent to the Atlantic Ocean in Chatham County (zip codes 31328, 31410, 31404, 31411, 31419); in addition, the team engaged in "snowball sampling" initiated by the Mayor and City Council on Tybee Island, as well as other people in leadership positions in Chatham County. This multi-mode approach resulted in 176 survey completes for the relevant zip codes (though the total dataset is larger). Of these, 41 percent were located in the Tybee Island zip code (31328).

The survey questionnaire was designed to **assess expectations of future economic and environmental changes on the coast, perceptions of coastal risk, insurance, and risk mitigation behaviors, flood experience, and preferences for green infrastructure investments to reduce flood risk and provide for environmental benefits.** Expectations of change are measured using Likert-scale responses (i.e., "strongly agree" to "strongly disagree") to statements about future economic and environmental conditions. Risk is assessed using the likelihood (i.e., probability) and consequence (e.g., financial/social/psychological impact) framework; recognizing that people often have a difficult time assessing probability, the researchers used a range of instruments to assess likelihood of various negative events (e.g., hurricanes, floods, etc.). Taking account of likelihood and consequence, one can model *Risk = ProbabilityConsequence*; in this framework, a risk will be considered severe if probability and/or consequence are relatively large. On the other hand, if probability and consequence are perceived as low, the risk would be considered mild. This formulation also plays a role in economic theories of decision-making under risk *(e.g., Expected Utility and Prospect Theory)*.

Two sections of the survey instrument are expressly focused on adaptation to coastal risks. To reduce the risk of repeated flood damages and facilitate coastal retreat, some levels of government have explored buyouts to remove private property in high-risk areas. There is very little research on homeowners' **willingness to accept (WTA) buyouts**, how much they need to be compensated, and determinants of the potential magnitude of buyout payments. Researchers used a stated preference approach to assess WTA buyouts in Chatham County; this entails creating a buyout scenario, assessing buyout magnitude, and priming the respondent to answer truthfully (permitting rejection of the buyout offer and uncertain responses). In addition, they explored the potential for a rentback program, which would pay homeowners' full market value for their property and allow them to rent the property back from the government until the property is sufficiently damaged due to storms/climate change, or some other provision is triggered (Keeler, et al. 2022).

The stated preference approach is also used to assess preferences for risk management infrastructure investments along riverbanks in Chatham County. A "choice experiment" is designed to evaluate preferences for traditional gray, green, or hybrid infrastructure investments that would lower flood risk, reduce nuisance flooding, and provide for improved wildlife habitat. Potential projects are to be funded by a Special Purpose Local Option Sales Tax (SPLOST) referendum, lending credibility to the valuation scenarios. The results are used to estimate household **willingness to pay (WTP) for risk reduction and environmental quality.**

Data

Descriptive statistics for demographic factors are indicated in Appendix Table D.1. The average respondent is 58 years old (median age 63), with an average (median) household income of just over $115,000 ($88,000). The most common level of educational attainment is graduate school (29 percent), followed by college graduate (28 percent), "some college" (16 percent), high-school graduate (11 percent), professional degree (10 percent), associated degree (4 percent), and vocational school (2 percent). The simple majority of the sample is retired (44 percent). Thirty-five percent of the sample is employed full-time, while 13 percent is employed part-time. The majority of the sample is white (76 percent), but there is a significant proportion of African-American respondents (12 percent), as well as Hispanic (3 percent), Native American, Indian-American, Japanese, Korean, Vietnamese, and "Other Asian" (1 percent each). Eighty-nine percent of respondents are registered to vote. The most common political affiliation is moderate (28 percent), followed by conservative (20 percent), and liberal (17 percent). The least common political affiliations were in the tails (very conservative at 15 percent and very liberal at 11 percent).

Property Ownership and Expectations

Appendix Table D.2 presents descriptive statistics for residency and property ownership. Ninety-four percent of respondents claim their Chatham County property as their primary residence and have been living on the coast (generally defined) for about 19 years (median = 15 years) (Note: coastal residency top-coded at 35 years). The data are 20 percent renters, 76 percent owners with clear title (46 percent), and 3 percent heirs' property distinction (without clear title, which complicates adaptation decisions involving private property). Seventy-eight percent of respondents own their residence (either mortgaged or out-right), while 3 percent respond affirmative to "own business", 5 percent "own property leased to others", and 3 percent "own other property". The average respondent spends about 47 weeks per year in Chatham County (median = 50 weeks). Ninety-four percent consider themselves full-time residents; five percent consider themselves part-time residents, and (despite best efforts) 1 percent percent do not consider themselves residents. Average time living in Chatham (as opposed to the coast, in general) is 17.5 years (median = 15 years). Regarding attachment to place, the project team assesses prospective moving plans; ten percent (7 percent) indicate they have plans to move out of Coastal Empire in the next 5 years (10 years), with an additional 2 percent indicating plans to move over a longer time horizon. Eighty percent indicate no plans to move away in the future.

Figures 4.1-4.3 present Likert scale responses for expectations of environmental change, economic change, and future risk management interventions. The majority of respondents "Agree" or "Strongly Agree" that the sea level will rise (Statement 1 in blue in **4.1**), flooding problems will get worse (Statement 2 in Magenta), erosion problems will get worse (Statement 3 in Green), and coastal storms will get worse (Statement 4 in Purple), but a significant proportion were "Neutral" in response to these statements. Very few (less than 6 percent) "Disagreed" or "Strongly Disagreed" with these statements. Using regression analysis, the project team find that being a self-identified “conservative” reduces the likelihood of agreeing with statements about sea-level rise and worsening of flooding problems and coastal storms (controlling for education, wealth, income, and understanding of statistical independence in storm occurrence), but conservative political ideology is not correlated with expectations of erosion. Nonetheless, most of the households sampled perceive future environmental change that will make coastal resilience and sustainable development more difficult to achieve.

There was greater consensus on economic change, with the overwhelming majority “Agreeing” or “Strongly Agreeing” that housing prices (Statement 5 in blue in **4.2**), insurance prices (Statement 5 in magenta), and property taxes (Statement 7 in green) will increase. This is evidence of expectations of future economic hardship for coastal residents. Such expectations may serve to push people away from the coast, particularly when combined with expectations of environmental change. Given the lack of variation in expectations of economic change, they find no evidence of correlation with household level factors (like education, income, wealth, or political ideology).

Turning to risk management strategies, most subjects “Agree” or “Strongly Agreed” that expanded investment in flood control measures will be necessary (Statement 8 in blue in **4.3**) and that infrastructure needed to be fortified against sea-level rise and storms (Statement 10 in green). There was less consensus on moving or demolishing building to avoid flood and erosion risk (Statement 9 in magenta). Using regression analysis, the project team finds that individuals that understand independence of storm occurrence as well as those that think the occurrence of storms makes future storms more likely (which this project classifies as falling prey to the “availability heuristic” – more on this below) are more likely to agree that retreat will be necessary in some areas (controlling for education, income, wealth, and political ideology).

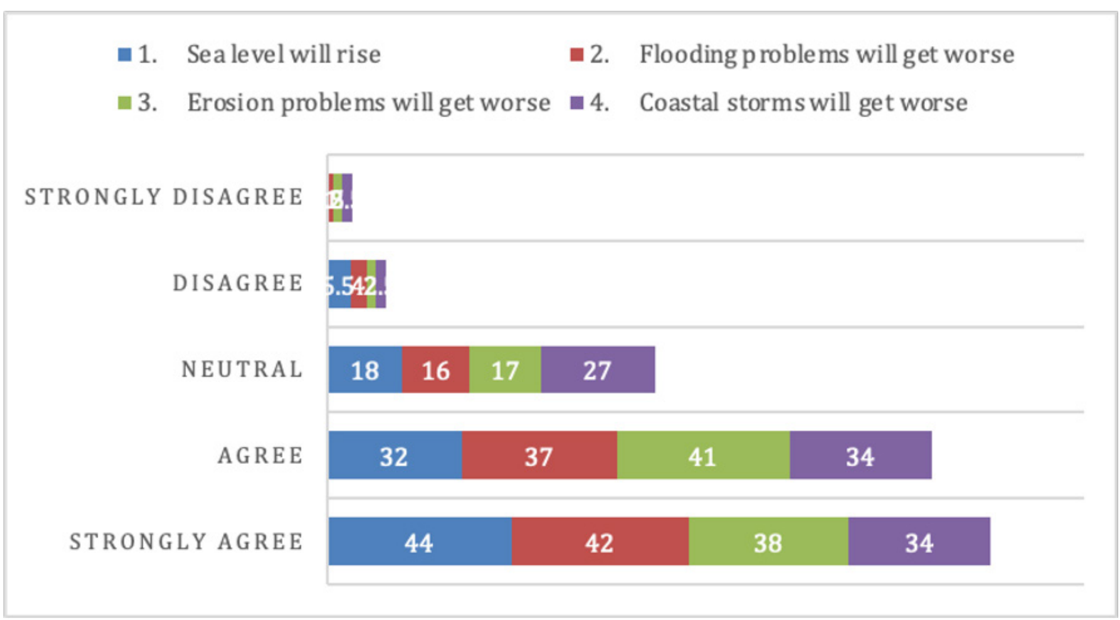


Figure 4.1. Likert Scale Responses for Expectations of Environmental Change

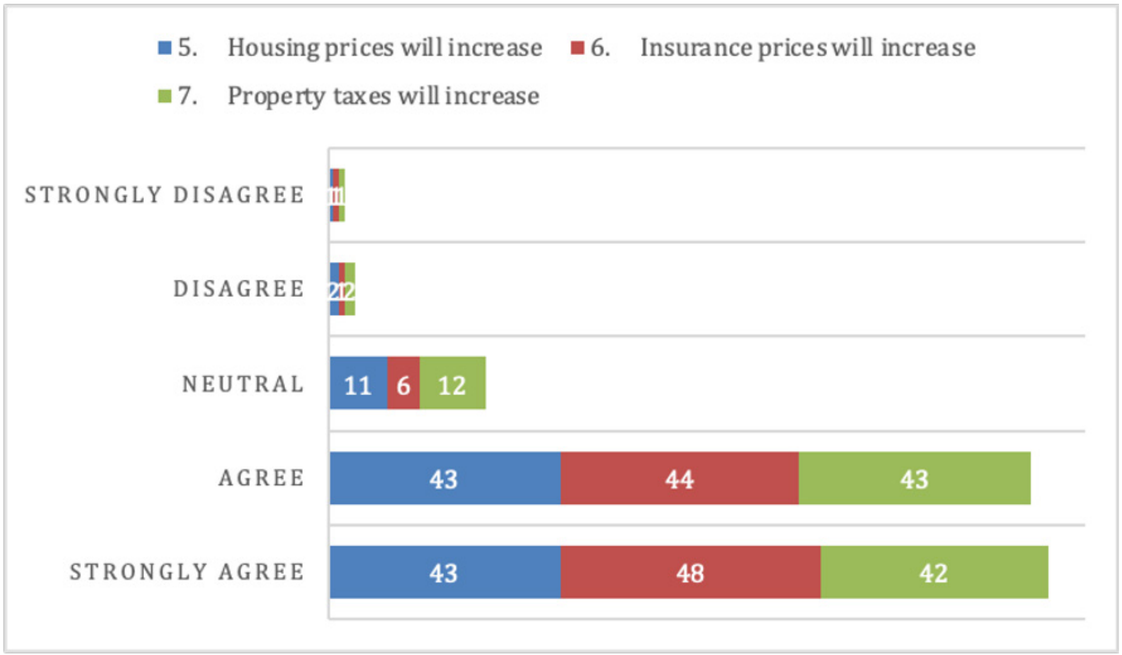


Figure 4.2. Likert Scale Responses for Expectations of Economic Change

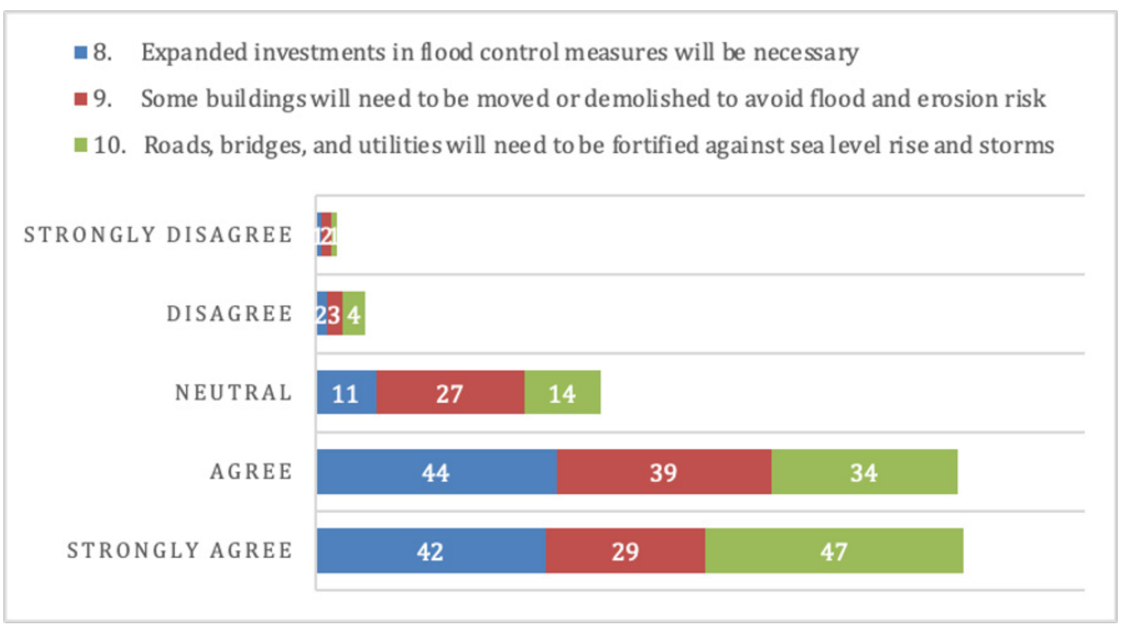


Figure 4.3. Likert Scale Responses for Environmental Risk Management

Insurance

Focusing on property owners (**Table 4.1**), the average (reported) property value is $572,000, with a minimum of $40,000 and a maximum of $2.25 million. Ninety-one percent of property owners have homeowner's insurance; forty-nine percent indicate that wind insurance is included in their homeowner's policy, while 9 percent have a separate windstorm policy (presumably because they are in a high storm-risk area). Seventy-six percent have flood insurance, and 11 percent indicate they have other insurance coverage (perhaps for their business). The average deductibles for each type of insurance are around $2500 but range from $500 to $10,000.

Preliminary regression analysis of flood and wind insurance holdings indicate that households with higher education tend to have wind insurance and self-identified "conservatives" are less likely to have flood insurance. (See **Appendix Table D.3.**) Likelihood of flood insurance is increasing in income but decreasing in a proxy variable for household wealth (suggesting that wealthy household may forego flood insurance, opting to "self-insure"). There is a positive correlation among holding flood and wind insurance. Since there is little variation in homeowner's insurance, the researchers do not analyze likelihood of holding this type of coverage. Future research will take a deeper dive into determinants of insurance holding, attempting to address issues of endogeneity and measurement error (briefly discussed in **Appendix D**).

	N	MEAN/PROP.	MEDIAN	SD
prop_value	140	572.57	475.00	405.73
h_ins	140	.91	1.00	.28
w_ins_inc	140	.49	.00	.50
w_ins_sep	140	.09	.00	.28
f_ins	140	.76	1.00	.43
o_ins	140	.11	.00	.31
h_ded	90	2288.89	2000.00	1556.03
w_ded	40	2703.50	2000.00	2089.43
f_ded	62	2387.10	2000.00	1630.70

Table 4.1. Descriptive Statistics – Property Owners

Table 4.2 presents descriptive statistics for renters. Fifty-eight percent of renters have renter's insurance, with an average coverage level of $49,000 and a deductible of $696. Only 19 percent of renters have flood insurance to cover the contents of their home, with an average coverage level of $52,000 and an average deductible of $917. Forty-seven percent also indicate that they have other insurance coverage (which could include life insurance or other types of products). Due to the small sample size, the project does not attempt further analysis of the renter data.

	N	MEAN/PROP.	MEDIAN	SD
r_ins	36	.58	1.00	.50
f_insr	36	.19	.00	.40
o_insr	36	.47	.00	.51
r_cov	17	48.97	37.50	41.86
f_covr	6	51.67	28.75	61.03
r_ded	14	696.43	500.00	440.48
f_dedr	6	916.67	500.00	1020.62

Table 4.2. Descriptive Statistics – Renters

Natural Hazard Risk Perceptions

Under theories of planned behavior, perceptions of risk are important determinants of location choice, insurance purchase, and mitigation decisions. Figure 4.4 depicts flood zone perceptions. Almost 12 percent of respondents are not sure if they are in a flood zone, whereas 14 percent believe they are outside of the flood zone. (Note, these proportions are significantly lower than the larger sample that covers Chatham, Liberty, and Bryan counties; this suggests that households that face greater flood risk are more cognizant of their formal risk classifications.) For those that recognize they are in a flood zone (74 percent), the majority are not sure which zone they are in (almost 26 percent). Seventeen percent are in the X Zone (500-year flood zone); twenty-three percent are in the A Zone (Special Flood Hazard Area (SFHA), 100-year flood zone), and 8.5 percent are in the V Zone (SFHA with additional risk due to storm surge).

The survey instrument included several risk-perception measures, designed to capture the likelihood and consequence of coastal hazards. Such perceptual measures are notoriously difficult to assess, so the project team employs a number of instruments to provide multiple measures. **Appendix Table D.4** presents the four questions that were used to assess likelihood of natural hazards. The questions vary in time frame (ranging from 12 months to 50 years) and format (e.g., open-ended response v. multiple choice). **Table 3** presents the descriptive statistics for the resulting hazard likelihood measures.

The first five rows of **table 4.3** present estimates of the likelihood of coastal hazards. The average probability of flooding over the next 12 months (open-ended, fractional response) is 15 percent (median 5 percent), with a large standard deviation of 20 percent, a minimum of 0 percent, and a maximum of 100 percent. Thus, taken at face value, some respondents think flooding is virtually impossible over the next 12 months, while others think flooding is inevitable. (See **Table D.4** for precise language of the question.) It is possible that the extremes represent a misunderstanding of the question, but it is also possible that some owners of elevated property do not foresee their house flooding and some property owners live in locations that flood frequently. The probability of a Category 3 (or greater) hurricane striking within 60 miles of Chatham County in the next year (multiple choice format) exhibits an average of 16 percent (median of 9 percent), with a standard deviation of 15 percent, a minimum of 0 percent, and a maximum of 50 percent (top-coded most likely occurrence choice). These measures of subjective probability assessment are relevant for analyzing individual/household insurance and mitigation choices over a short time horizon.

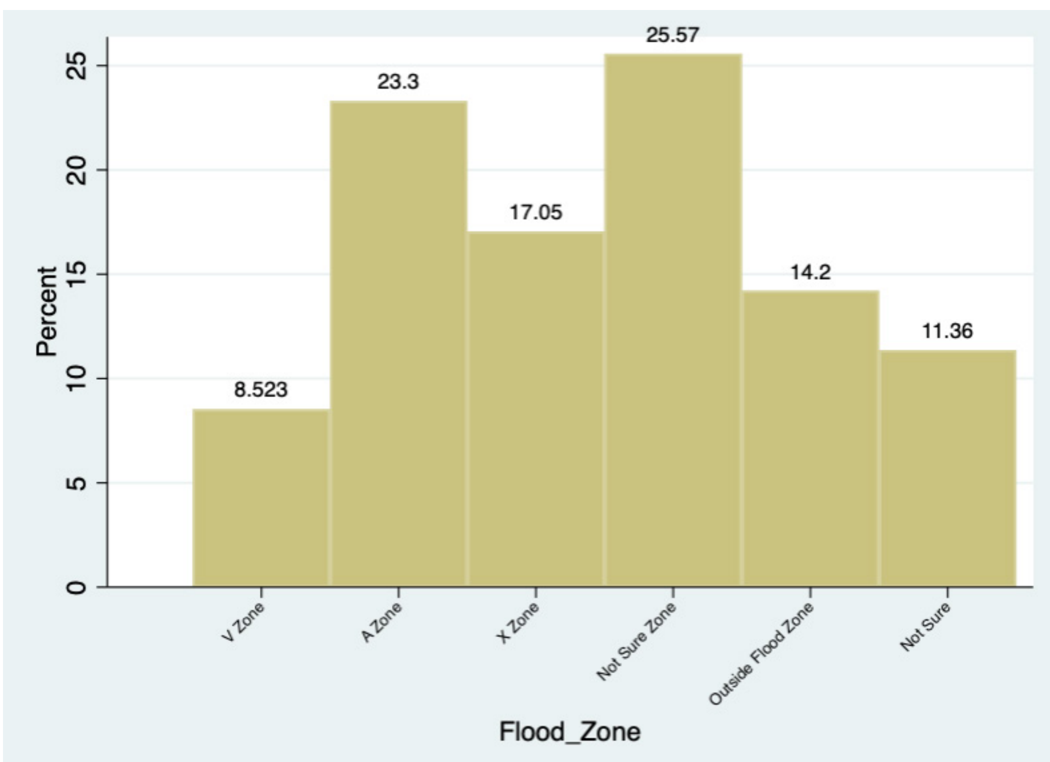


Figure 4.4. Flood Zone Perceptions

Turning attention to longer time horizons, the next two questions focused on i) the likelihood of flooding (from any source) over the next 25 years using a Likert scale, and ii) the number of expected major hurricanes (Cat 3 or greater) over a 50-year time horizon (open-ended count). (Again, see **Table D.4** for the scenario descriptions and response formats.) Sixty-four percent of respondents considered flooding over the next 25 years "somewhat likely", "likely", or "very likely", while 8.5 percent responded "Don't Know". The average hurricane count over 50 years is 5, and the median is 3. This metric is transformed into an annual average probability by dividing by 50. The annual probability of a Category 3 hurricane (or greater) over the next 50 years striking within 60 miles of the Chatham County was 10 percent (median = 6 percent), with a minimum of 0 percent and a maximum of 100 percent. These measures of subjective probability assessment are relevant for analyzing individual/household location and investment choices, as well as support for long-lived infrastructure investments.

Appendix Table D.5 presents results of a fractional regression model that can be used to decompose determinants of risk perceptions. For this example, the model examines the determinants of annual flood risk (floodp_12). It finds annual flood risk perceptions to be greater for those located in the v-zone and a-zone (as expected), but also greater perceptions of risk for those that do not know their flood zone. The number of past floods is correlated with greater risk perception, as one might expect. It also finds those that fall prey to the availability heuristic (in which recent occurrence of hazards increase perceived likelihood) to have greater flood risk perceptions, while self-described "liberals" have lower risk perceptions.

	N	MEAN/PROP.	MEDIAN	SD
LIKELIHOOD				
floodp_12	176	15.07	5.00	20.33
hurrp_12	176	15.66	9.00	14.58
likely_flood25	176	.64	1.00	.48
hurrp_50	176	.10	.06	.17
hurr_count50	176	5.01	3.00	8.40
CONSEQUENCE				
damage_cat3	169	$220,991.12	$150,000.00	$233,794.21
damage_cat3_po	140	$262,489.29	$201,625.00	$236,410.76
damage_cat3_r	29	$20,655.17	$12,500.00	$18,052.06
flood_repair_min	109	$45,913.55	$20,000.00	$69,647.64
flood_repair_avg	117	$93,407.33	$50,000.00	$119,435.75
flood_repair_max	114	$212,631.32	$100,000.00	$221,084.75

Table 4.3. Descriptive Statistics for Risk Perception

Flood Experience and Risk Tolerance

Table 4.4 presents descriptive statistics for flood experience. The average household has experienced flooding near their property 3.64 times (median=1; minimum = 0; maximum = 150), but only 44 percent of households have experienced flood-related damage to their property. The average amount of property damage from flooding is $17,718 (median = $2,720), with a minimum $30 of and a maximum of $150,000. Year of latest flooding occurrence (n=40) ranges from 1900 to 2021, with a mean of 2013 and median of 2017. Fifty percent of respondents indicate that they received a flood insurance claim for damage, but the average household was displaced for an average of 8.3 days (minimum = 0; maximum = 200).

	N	MEAN/PROP.	MEDIAN	SD
past_floods	176	3.64	1.00	11.70
past_floods_damage	176	.44	.00	1.01
past_flood_amt	36	$17,718	$2,750	$31,474
past_flood_year	40	2013	2017	19
past_flood_claim	36	.50	.50	.51
displace_days	40	8.30	.00	31.74

Table 4.4. Descriptive Statistics – Flood Experience

To complement models of decision-making under risk, a series of questions were focused on statistical numeracy, insurance understanding, and risk tolerance across various behavioral domains (e.g., career, health, driving, sports). To assess understanding of the statistical independence of flooding events, a question assesses whether respondents perceive flooding as more likely (akin with the psychological phenomenon known as "availability heuristic"), less likely (known as the "gambler's fallacy"), or about equally likely (which is statistically correct) to occur in year immediately following a flood. Fifty-six percent of respondents correctly assessed the likelihood as "about the same"; twenty percent expressed beliefs consistent with the availability heuristic, while 10 percent claimed flooding would be less likely (consistent with gambler's fallacy). The remaining respondents (5 percent) were not sure whether flooding would be more or less likely, or about as likely. (See **Table 4.5.**)

	N	MEAN/PROP.	MEDIAN	SD
ind_risk	176	.56	1.00	.50
avail_heur	176	.20	.00	.40
gamble_fal	176	.10	.00	.30
deduct_understand	176	.61	1.00	.49
rt_health	176	2.93	2.00	1.97
rt_fam_health	176	2.57	2.00	1.94
rt_finance	176	3.28	3.00	1.61
rt_driving	176	2.89	3.00	1.87
rt_sports	176	3.41	4.00	1.77
rt_career	176	3.45	4.00	1.83

Table 4.5. Descriptive Statistics – Statistical Numeracy and Risk

A survey question was designed to assess the respondent's understanding of insurance; the question asked whether a higher deductible would lower the insurance premiums (which is true). Sixty-one percent responded affirmative to this query. To assess risk tolerance (without invoking a monetary experiment – which is standard in the field), professed tolerance of risk is measured on Likert scales (1="Not Very Willing"; 7="Very Willing" to take risks) across the domains of individual health, family health, financial decisions, automobile driving, sport/leisure activities, and career decisions. While stated tolerance of risk is not the "gold standard" in empirical research, these measures have been shown to be valid in analysis of risky decision making (Dohman, et al. 2018). Sports and career exhibit the greatest degree of risk tolerance (median of 4), while personal and family health garner the least risk tolerance (median of 2). Finance and driving are in between, each with a median of 3.

Adaptation: Buyouts and Rentbacks

A series of questions that are relevant for assessment of adaptation decisions relate to willingness to accept (WTA) a buyout and willingness to pay (WTP) for a rentback after selling to a government agency that will retain ownership but allow habitation while the property is deemed "safe" under environmental/risk standards. Among property owners, the mean WTA for a buyout was 98 percent of property value (median = 100 percent), with a minimum of 10 percent and a maximum of 200 percent. Eleven percent of respondents indicated that they would not accept a buyout; eighteen percent indicated that they did not know how to respond to a buyout question. For those respondents that would accept a buyout, the average payment (calculated as buyout percentage multiplied by property value) was $576,000 (median = $535,500), with a minimum of $12,500 and a maximum of $2.2 million.

	N	MEAN/PROP.	MEDIAN	SD
buyout_perc	99	97.95	100.00	39.53
no_buyout	140	.11	.00	.32
dk_buyout	140	.18	.00	.38
buyout	99	$576,356	$535,500	$416,002
rentback	59	$1,980	$2,000	$994
no_rentback	140	.35	.00	.48
dk_rentback	140	.23	.00	.42

Table 4.6. Descriptive Statistics - Adaptation Measures

For rentbacks, the average monthly WTP was $1,980 (median = $2,000), with a minimum of $200 and a maximum of $6000 (which were the limits of the payment card). Thirty-five percent of respondents indicated that they were not willing to engage in a rentback contract, whereas 23 percent were not sure. Regression analysis can be used to assess the determinants and correlation across buyouts and rent-backs.

Adaptation: Willingness to Pay for Risk Management Infrastructure Investments

The survey instrument included a stated preference “choice experiment” that was designed to assess preferences for gray, green, and hybrid river protection infrastructure designs that would limit storm flooding, nuisance flooding, and provide riverine wildlife habitat. The choice experiment was a branded design, and it limited amenity provision in ways that are consistent with realities of infrastructure design. The choice experiment defined the options of gray/hybrid/green along a spectrum of adaptability to environmental change, ranging from low to high.

Table 4.7 summarizes the infrastructure services and levels by "brand" (i.e., gray/hybrid/green). To accord with actual performance of the different infrastructure types, the attribute levels were restricted such that "Green" infrastructure could not provide the highest levels of flood protection and "gray" could not provide the highest level of coastal habitat (as evidenced by the attribute levels listed in the first 3 rows). Hybrid was able to provide the entire array. The status quo situation was described as consistent with coastal trends for the next 30 percent: 90 percent chance of severe flooding in low-lying areas; 150-200 days of standing water in low-lying areas each year; poor riverbank wildlife habitat; $0 additional cost to households.

An efficient design algorithm was used to select among attribute levels (ecosystem services and TSPLOST costs) resulting in choice set designs that permitted respondents to choose among different types of infrastructure investments, at different costs, or "opt-out" for the status quo (last column in **Table 4.7**). To be clear, each choice task included only one of the attribute levels (e.g., gray storm flood risk was either 10 percent, 30 percent, or 50 percent chance of severe flooding in low-lying areas over the next 30 years) for each service and "brand". The payment vehicle for the choice experiment was a special purpose local option sales tax (SPLOST), which is routinely on the ballet in Georgia (providing some measure of construct validity). To personalize the SPLOST payment, the survey also inquired about household size (mean = 2.3) and income category (1=low; 2=mid; 3=high; mean =2.13). Each respondent saw three choice sets and was allowed to make three selections for infrastructure investments, opting for gray investment strategy, hybrid, green, or status quo.

ATTRIBUTES	GRAY	HYBRID	GREEN	STATUS QUO
Storm Flood Risk *"chance of severe flooding over 30 years"*	10%, 30%, 50%	10%, 30%, 50%, 70%	30%, 50%, 70%	90%
High Tide / Nuisance Flooding *"days of standing water in low-lying areas/year"*	10-20, 40-60, 65-90	10-20, 40-60, 65-90, 100-130	40-60, 65-90, 100-130	150-200
Coastal Habitat *"improving fish and wildlife habitat along riverbanks – biodiversity and migration corridors for wildlife"*	Good, Poor	Best, Good, Poor	Best, Good	Poor
SPLOST Cost *"Annual household cost for each of 10 years"* LOW INCOME HOUSEHOLDS		$10, $50, $150, $300		$0

ATTRIBUTES	GRAY	HYBRID	GREEN	STATUS QUO
SPLOST Cost *"Annual household cost for each of 10 years"* MEDIUM INCOME HOUSEHOLDS		$20, $90, $200, $500		$0
SPLOST Cost *"Annual household cost for each of 10 years"* HIGH INCOME HOUSEHOLDS		$30, $150, $350, $900		$0

Table 4.7. Choice Experiment Design

Table 4.8 presents descriptive statistics associated with the choice experiment. Forty-nine percent of respondents claim to have heard of green infrastructure prior to the survey. The importance of the attributes of infrastructure projects was measured on a 5-point Likert scale; the highest (on average) was storm flood risk reduction and the lowest (on average) was nuisance flooding reduction. Lastly, the survey measured individual confidence in ability to provide information on infrastructure investments for public policy purposes (average of 1.10, where 1 = confident; 2 = not confident; 3 = not sure). **Figure 4** presents the choice frequencies for the four options in the choice experiment.

	MEAN/PROP.	MEDIAN	SD
heardof_GI	.49	.00	.50
imp_stormfloodrisk	4.51	5.00	.80
imp_nuisanceflood	4.30	5.00	.85
imp_hab	4.36	5.00	.87
imp_cost	4.11	4.00	.94
Hhsize	2.30	2.00	1.08
inc_category*	2.13	2.00	.76
conf_CE	1.10	1.00	.37

N=176, except for income_cateogory (n=175)

Table 4.8. Descriptive Statistics - Choice Experiment

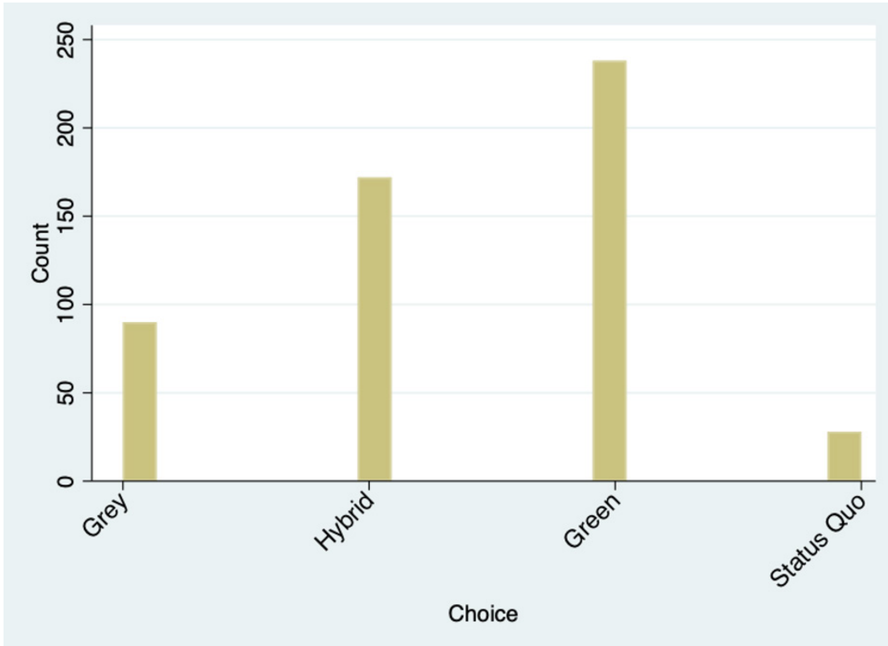


Table 4.8. *Descriptive Statistics – Choice Experiment*

The Random Utility Model (RUM) provides the empirical basis for discrete choice analysis (as is standard in the economics literature). Details are provided in **Appendix D**. In general, green infrastructure was preferred to the status quo and gray investment strategy, followed by hybrid. Household marginal Willingness to Pay (WTP) for infrastructure services from the preferred model are presented in **Table 4.9**.

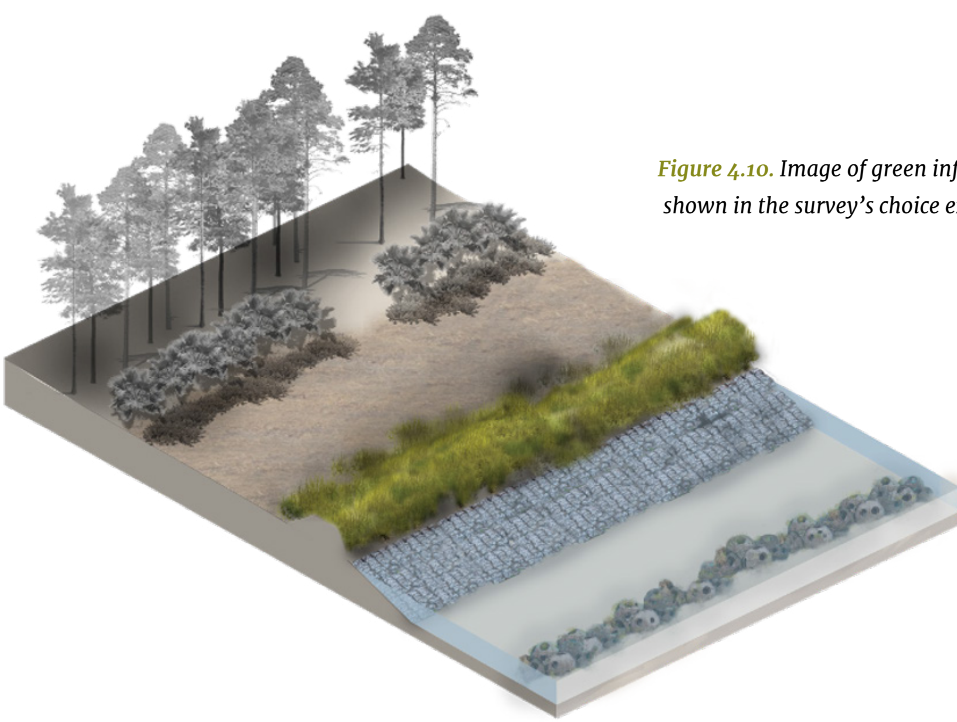


Figure 4.10. *Image of green infrastructure shown in the survey's choice experiment.*

SERVICE	WILLINGNESS TO PAY	95% CONFIDENCE INTERVAL
Reduce Risk of Severe Flooding over 30 years by 1%	$10.21	$3.85 – $16.57
Reduce Annual Nuisance Flooding by 1 day	$3.17	-$0.33 – $6.68
Improve Wildlife Habitat from Poor to Good	$658	$271 – $1050
Improve Wildlife Habitat from Poor to Best	$814	$375 – $1250

Table 4.9. Annual Household Marginal Willingness to Pay for Infrastructure Services

The TSPLOST costs were incurred annually over 10 years, so the estimates in **Table 4.9** represent annual household WTP over the course of 10 years. The average household is WTP $10.21 to reduce risk of severe flooding over 30 years by 1 percent. The 95 percent confidence interval (produced via the "Delta Method") is $3.85 - $16.57. To utilize these numbers in project assessment, the analyst would need to scale up by the number of households in the relevant zip codes and apply the estimate to the project change in flood risk. For example, if flood risk were to change by 10 percentage points (i.e. from 90 percent to 80 percent), the WTP estimate would be $102.10, which would need to be scaled by the number of households.

WTP for reducing nuisance flooding by one day annually is $3.17 (95 percent confidence interval -$0.33 - $6.68); the negative lower bound of the confidence interval is due to the relatively large standard error on the coefficient estimates (p-value =0.07). Wildlife habitat is measured in 3 qualitative intervals: Poor (weak support of ecosystem - low biodiversity; limited migration corridors for wildlife), Good (limited support of ecosystem - medium biodiversity; some migration corridors for wildlife), Best (strong support of healthy ecosystem - high biodiversity; extensive migration corridors for wildlife). Estimated household WTP to move from Poor to Good is $658 per year (95 percent confidence interval $271 - $1050), and WTP to move from Poor to Best is $814 per year (95 percent confidence interval $375 - $1250). The choice experiment data can also be used to estimate Total WTP for a particular infrastructure investment (e.g., hybrid investment that provides particular levels of services).

To utilize these numbers in project assessment, the analyst would need to estimate willingness to pay for the desired impact and scale up by the number of households in the community. For example, if severe flood risk were decreased by 10 percent, the WTP estimate would be $102.10, which would then need to be scaled by the 1,463 households on the Tybee Island—leading to total WTP of almost $150,000 per year. Tybee Island households would be willing to pay a total of $962,654 per year (good) to $1.19 million per year (best) to improve degraded wildlife habitat.

SECTION V: NATURAL INFRASTRUCTURE DESIGNS

The Tybee Island Natural Infrastructure Master Plan seeks strategies that provide co-benefits of enhancing natural features and protections to support fish and wildlife populations while mitigating impacts of flooding to community property and critical infrastructure. The suite of preliminary designs developed through this project meet the 50-60 percent design criteria and aim to reduce risks to both the local population and the ecosystem, thereby increasing the resilience of the overall socio-environmental system.

Marsh Conditions

The large contiguous tract of Tybee Island's marsh front provides protection and buffering from coastal storms, sea-level rise, inundation, and coastal erosion. As water levels rise, however, this valuable habitat and open space is at risk of being squeezed out. The island's marsh shoreline is where the first and worst impacts of inundation from sea-level rise are being experienced. As noted in Figure 2.2, flooding will disproportionately affect this side of the island.

The marsh is home to diverse wildlife, including fish, crabs, birds, and shrimp. The NFWF Regional Coastal Assessment for the Savannah River Watershed identified Tybee Island's estuarine shoreline as having the **highest possible risk rating** in the:

- Aquatic Index (5 on a 1-5 scale) - prevalence of priority aquatic species and their habitats
- Threat Index (10 on 1-10 scale) - risk of storm surge and flooding potential
- Community Exposure Index (10 on 1-10 scale) - exposure community assets to flooding threats

NFWF's Resilience Hub index measures areas of open lands and protected space that are most suitable for resilience-building efforts. The marsh side of Tybee Island is rated as a 7 on a 1-10 scale.

The interface between the marsh and upland terrain provides a critical opportunity for reducing tidal and storm surge flooding. However, creative solutions are required to provide future resilience, maintain or enhance habitat, and work within the constraints of city prerogatives and private ownership. These solutions must be implemented for a variety of environments and types of interfaces. Within the study area, there are almost 2,000 hectares of upland, 128 hectares of marsh and 22 hectares of open water and intertidal channels (**Table 5.1**).

AREA CLASSIFICATION	AREA (M^2)	AREA (HECTARES)
Upland	19,387,373	1,939
Marsh	1,274,746	128
Water/channels	223,609	22
Impoundment	43,700	0.4

Table 5.1. Types of ecosystems within the project study area

The boundary between upland and wetlands is long and sinuous (just over 30,000 m; **Table 5.2**), reflecting the island's beach-ridge origins and subsequent tidal channel erosion between ridges. This boundary consists of upland-beach, upland-water, and upland-marsh interfaces, with upland-marsh interfaces predominant (88 percent of total, Table 5.2).

UPLAND INTERFACE TYPE	LENGTH (M)	% OF TOTAL	% ARMORED
All types	31,310	100.0	11.3
Beach	1,206	3.9	35.2
Marsh	27,658	88.3	8.0
Water	1,275	4.1	78.3
Impoundment	1,171	3.7	0.0

Table 5.2. Length of upland interface and percent that is armored

The dominance of upland-marsh interfaces provides an important opportunity for natural infrastructure, as many of the solutions proposed in this plan are those that maintain and enhance salt marsh habitat, and little of that shoreline is currently armored (8 percent, **Table 5.2**). Conversely, 35 percent and 78 percent of beach and water interfaces, respectively, have already been armored, providing less opportunity to implement solutions.

Looking to the future, modeling for this project found that potentially 100 acres of upland area could be impacted by sea-level rise by 2050 under NOAA's intermediate-high scenario (19,387,373 m2 of upland in 2020 and 18,987,373 m2 in 2050). Much of the area under threat is not currently armored. As the marsh migrates and flooding impacts increase, homeowners will face pressure to implement mitigation.

STRUCTURE	TOTAL LENGTH 2018 (M)	CHANGE 2006-2018 (%)	ADDED LENGTH (M)	PROJECTED TOTAL LENGTH 2050 (m)
Bulkhead	1,908	29	553	2,461
Revetment	1,411	22	310	1,721
Bulkhead + Revetment	153	47	72	225
Total	3,472	33	935	4,407

Table 5.3. Type of armoring on Tybee Island with past and future changes

Figure 5.1. Current armoring along the upland boundary on Tybee Island.

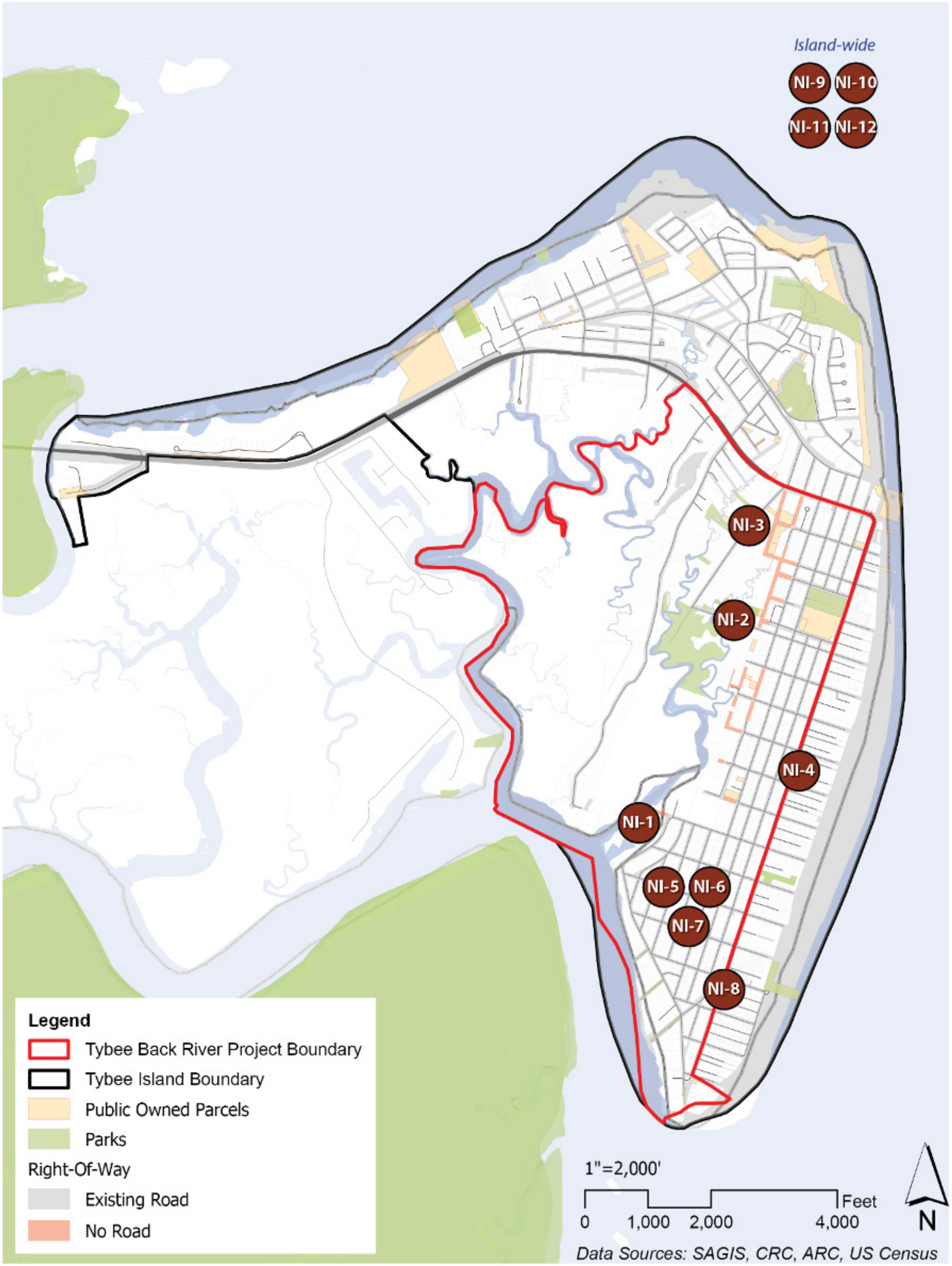


Figure 5.2. Locations of preliminary designs developed in the planning phase.

Coastal Natural Infrastructure Strategies

Focus on the low-lying western side of the island, which is impacted more frequently by tidal and storm surge flooding, is also appropriate given their importance in naturally protecting upland environments from the worst effects of tidal and storm surge flooding. Marshes absorb floodwaters and decrease wave energy, thereby protecting the coast from erosion. NOAA estimates that 15 feet of marsh can reduce incoming wave energy by as much as 50 percent (NOAA Office of Coastal Management, 2023). However, marshes are facing threats to their long-term sustainability, most importantly from rapid sea-level rise, but also from contaminant-laden runoff from land, and coastal squeeze, a process wherein a marsh, which naturally retreats onto the upland to remain in the intertidal zone as sea levels rise, reaches a vertical structure and cannot retreat landward any further, eventually drowning. Many of the proposed solutions in this project serve to minimize coastal squeeze and maximize the marsh's ability to remain viable into the future.

SITE ID	PROJECT NAME / LOCATION	ACTION ITEM (PROJECT DURATION)	HABITAT IMPROVEMENTS
NI-1	Venetian Drive *(Venetian Dr. from Aj's to 12th St.)*	• Create a horizontal levee or berm with a naturalized shoreline along Venetian Dr. • Raise road elevation by 1 ft. • Construct living shoreline around the levee toe. • Reroute 13th St. stormwater outfall along 6th St. to connect to 14th St. outfall • Implement one-way traffic. • Create a bike / pedestrian path. • Provide dock access from the updated shoreline.	• Provide pathway for marsh migration • Enhance marsh habitat • Improve water quality • Control erosion
NI-2	6th Street *(6th St. from Lewis Ave. to Miller Ave.)*	• Replace and enlarge culvert under the bridge that lies between Lewis and Miller Ave. • Construct a living shoreline.	• Enhance marsh connectivity • Improve water quality • Control erosion • Improve wildlife crossing
NI-3	Lewis Avenue	• Add a submerged culvert to connect marshes on both sides of the road. • Extend Sally Pearce Trail.	Enhance marsh connectivity

Table 5.4. Coastal natural infrastructure strategies.

NI-1: VENETIAN DRIVE

Venetian Drive is a critical location for both habitat and flooding on the island. Near the outlet of Horsepen Creek, sediment in the marsh is rapidly accumulating due to accelerated infilling after developers dredged that area in the early 1900, using the deposits to fortify adjacent land. Initial, limited radiochemical data suggest that salt marshes along Horsepen Creek are accreting at rates approaching 0.39 inches per year (1 cm/y), which are not realistically sustainable over the long term. These high rates suggest that these sites were disturbed by natural and anthropogenic processes. Further up the creek, channel migration has produced an extensive reworking of the upper few meters of marsh, which then rapidly infills. Based on an examination of aerial photography from 1938 to 2018, little intact marsh remains in the Horsepen Creek drainage area on 100-year timescales. Most of the marsh bordering Tybee Island has been reworked by channel meandering or human activities like dredging and dumping.

Cores collected in July 2022 from the one small patch of intact marsh that could be identified in Horsepen Creek and from three other marshes directly adjacent and west of Tybee Island exhibit accumulation rates of approximately .08 inches per year (0.2 cm/y), similar to those observed in other salt marshes in Georgia. This rate of accretion is not keeping up with the current sea-level rise, which is 0.135 inches per year (0.34 cm/y) at Fort Pulaski over the past 87 years. This suggests that marshes in this area could benefit from natural infrastructure and green engineering solutions that provide elevation enhancement in the future.

There is a section of marsh sandwiched between the high spot of Venetian Drive and the low spot of the Horsepen Creek channel that is at risk of "coastal squeeze" due to sea-level rise. Coastal squeeze occurs when the marsh does not have room to migrate because of a constricting high spot, so it drowns under sea-level rise. In order to provide space for marsh migration and flood protection, a horizontal levee is included in the plan. A horizontal levee differs from a standard levee by using a shallow slope, allowing the marsh to migrate up over time. The chosen design uses a slope that balances both the marsh and flood protection while minimizing the impact on the current landscape. Residents report that there is frequent overtopping on Venetian Drive, as well as ponding rainfall. To provide additional flood protection, the plan includes raising Venetian Drive by 1 ft.

The Tybee Island Stormwater Master Plan currently calls for dramatically increasing the size of the 13th St. outfall at Horsepen Creek to reduce inundation in the vicinity. This would be incompatible with the horizontal levee, creating erosion issues at the site. Modeling from the UGA team indicates that a similar level of service can be achieved by rerouting the 13th St. stormwater line along 6th St. to connect with the 14th St. outfall. Initial estimates show that this would save the City approximately $500,000.

To prevent erosion, a living shoreline should be implemented at the toe of the levee. Living shorelines are a method of stabilizing embankments with natural materials such as sand, rock, and plants. They reduce erosion, improve water quality, and provide valuable habitat for birds, aquatic life, and other wildlife. A 2016 study by Northeast University found that hard armoring structures support 23 percent lower biodiversity and 45 percent fewer organisms than natural shorelines (Gittman, 2016). Unlike bulkheads and other hard infrastructure, living coastlines grow over time. Evidence also shows that living shorelines perform better against large storms and are more cost-effective than armored shorelines (Jacobsen, 2019).

Tybee Island would be a very receptive location for the implementation of living shorelines. Important qualities that lead to the greatest levels of success are low slopes, low fetch, strong marsh presence, and distance from an erosion hot spot. There are several locations that fit these criteria across the island, while there are other different areas with successful oyster populations. Further design specifications are included in **Appendix E**.

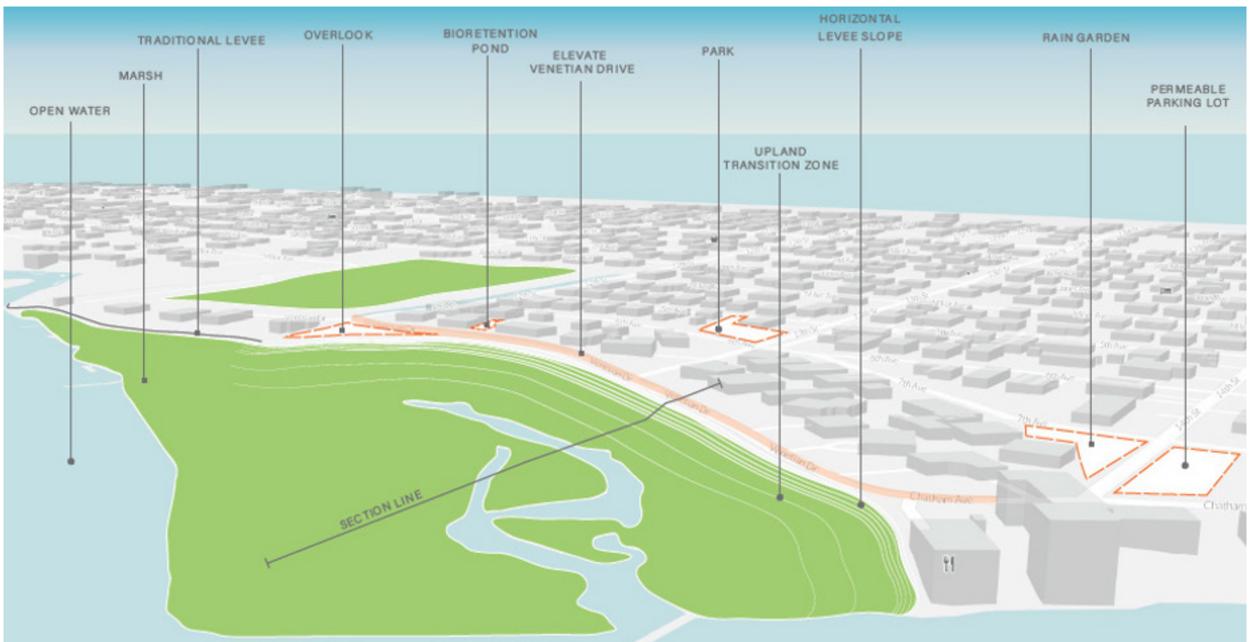


Figure 5.3. Conceptual renderings of the horizontal level

Figure 5.4. The UGA Burton 4-H Center on Tybee Island is stabilizing the shoreline and providing habitat.

NI-2: 6TH STREET

Currently, there is an undersized culvert that runs under 6th street to connect two sections of marsh located on the north and south side of the road. Aerial images have shown the fragmented conditions of the marsh upstream of the culvert, and residents have reported that creatures, such as manatees, have been stuck in the pipe culvert while navigating through the tidal waterway. The existing culvert acts as a bottleneck, inhibiting the flow of water in and out of the marsh and constraining flora and fauna in that area. The plan proposes expanding the culvert to enhance hydrologic connectivity, improve marsh health, and improve habitat and migration. Enlarging the culvert would equilibrate the water flux to the marsh pond north of 6th Street, flushing the marsh more effectively. It would also increase the speed of drainage, reducing inundation in the surrounding areas. A living shoreline should be implemented in eroding areas along 6th Street to stabilize the shoreline and restore the degraded marsh. Further design specifications are included in **Appendix E.**

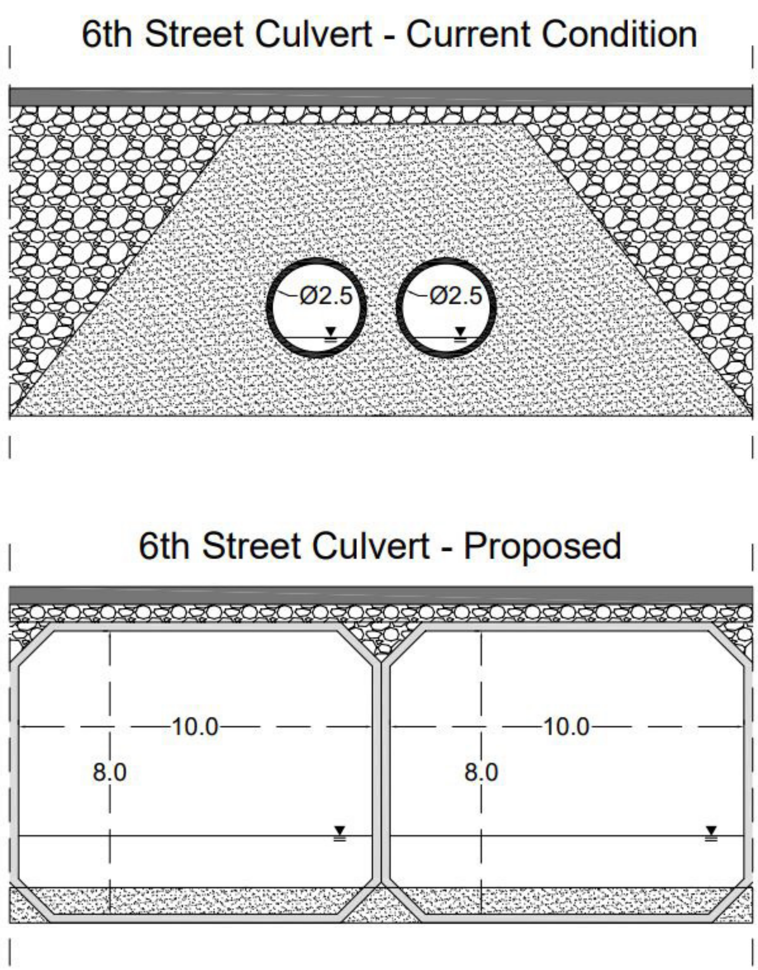
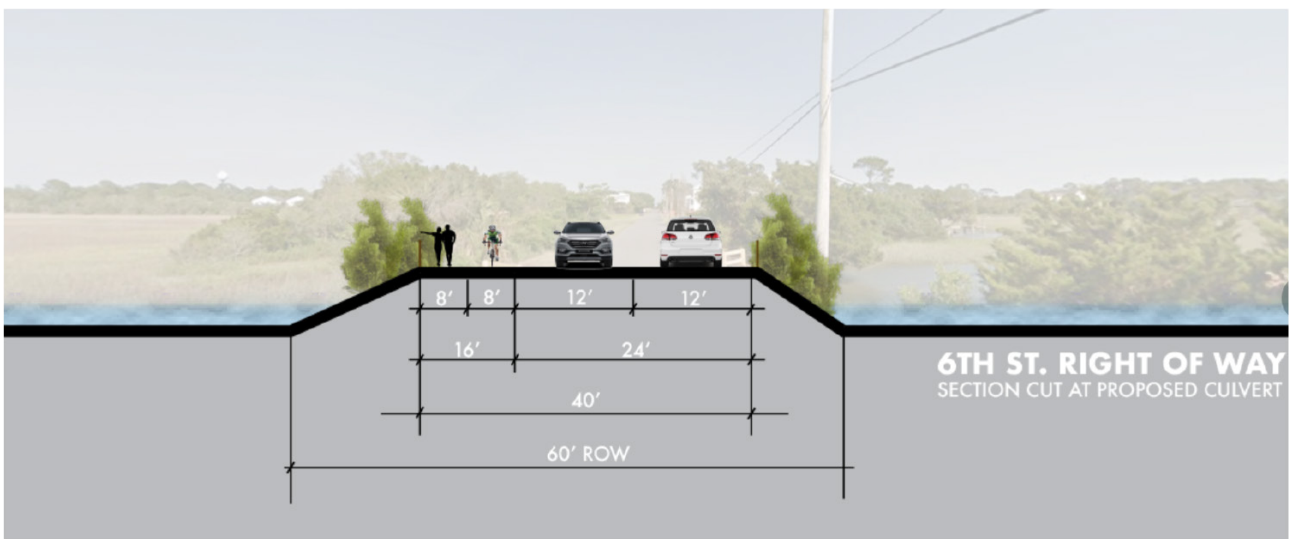


Figure 5.5. Cross-section of the existing and the proposed culvert at 6th Street. Dimensions shown are in feet.



Figures 5.6 and 5.7. Conceptual renderings of the 6th Street culvert improvements

NI-3: LEWIS AVENUE

Lewis Avenue is a residential street built upon manmade land between two marshes. Because of its location, residents on this street experience some of the worst flooding on the island. In response, many residents on Lewis Avenue have applied for and received grants from FEMA/GEMA to elevate their homes. To supplement the efforts of the residents, the plan proposes installing a cross-culvert that will run under Lewis Avenue to connect the two sections of the marsh the street is situated between. The addition of a culvert under Lewis Ave. could balance the flow between the two marshes, which translates into healthier and improved conditions for habitat and wildlife. The placement of the culvert is based on historical images that show where the marsh was originally connected, and the implementation of this culvert will restore part of the marsh back to its original condition.

To integrate Lewis Avenue into the Green Space Network, the plan proposes extending the Sally Pearce Trail. This would improve connectivity and public access to the marsh to support ecotourism and recreational opportunities. Possible components of the trail could include a marsh boardwalk, educational signage about the marsh to increase conservation and stewardship, a bird and wildlife viewing station and privacy screenings where the trail draws near to private property.

Figure 5.8. Conceptual rendering of the Sally Pearce Trail extension

Figure 5.9. Potential location of the underground culvert to reconnect both marshes around Lewis St.

Inland Place-Based Natural Infrastructure Strategies

The Tybee Island Natural Infrastructure Master Plan describes a network of connected features and green space distributed throughout the island. In addition to specific place-based features, the plan also provides recommendations for island-wide strategies. Together, the proposed features and strategies will improve the resilience of Tybee Island through increasing the presence of habitat on the inland areas of the island, expanding the capacity of the stormwater system, cooling and cleaning runoff before it reaches the marsh, and protecting residents from flood damages. In addition to the direct benefits to the ecosystem and residents of Tybee, the proposed plan will also provide indirect benefits through the improvement of the island's aesthetics and highlighting the natural marsh resources on the island, which draw tourists. Overall, the goal of these proposed inland natural infrastructure features is to make Tybee Island a more climate resilient and beautiful place to live.

The following place-based features were developed based on strategic locations across the island identified by a high frequency of nuisance flooding and proximity to habitat. These areas were designed to include natural infrastructure features that best fit the specific location context.

SITE ID	PROJECT NAME / LOCATION	ACTION ITEM (PROJECT DURATION)	HABITAT IMPROVEMENTS
NI-4	US HWY 80 / Butler Avenue *(US HWY 80 from Lazaretto Creek to Tybrisa St.)*	• As GDOT makes roadway improvements, implement curb cut rain gardens to reduce runoff along sidewalks and right-of-ways. • Integrate natural infrastructure into a Green Space Network.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution
NI-5	14th Street *(14th St. from Butler to Chatham Avenues)*	• Demarcate right-of-way with stakes/flags. • Utilize permeable pavers on the road. • Use the right-of-way to create a swale on the shoulder or place a median in the middle of the road. • Consider implementing a one-way traffic pattern. • Integrate natural infrastructure into a Green Space Network.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution
NI-6	Stormwater Inlet Rain Gardens *(13th, 14th and 15th Streets from Butler Avenue to Chatham and Venetian Avenues)*	• Relocate storm grates out of the roadway. • Create rain gardens at 19 stormwater inlets. • Integrate natural infrastructure into a Green Space Network.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution

SITE ID	PROJECT NAME / LOCATION	ACTION ITEM (PROJECT DURATION)	HABITAT IMPROVEMENTS
NI-7	Rainwater Storage *(Parcels located along 13th, 14th and 15th Streets between Butler Avenue and Chatham or Venetian Avenues)*	• Encourage residents and businesses to start rainwater harvesting from building roofs. • Implement rain storage on all public buildings, such as Town Hall, Fire House, etc. • Implement UGA's Coastal Georgia Rain Garden program. • Reuse harvested rain to maintain green infrastructure.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution • Provide habitat for pollinators and increase biodiversity
NI-8	South Beach Pocket Park *(Unused lot at the intersection of 15th Street and Butler Avenue)*	• Engage Hotel Tybee in planning the use of the unused go-kart track. • Replace current use with green space—replacing soil, creating a grassy berm, and installing permeable pavers. • Integrate natural infrastructure into a Green Space Network. • Put the parcel under a conservation easement.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution • Increase green space near the tourism hub of South Beach

Table 5.5. Summary of place-based strategies

NI-4: US HWY 80 / BUTLER AVENUE

U.S. Highway 80/Butler Avenue is the sole entrance road onto Tybee Island and runs the length of the island. It is also the only road on Tybee Island with curb inlets to the stormwater system. The Georgia Department of Transportation (GDOT) is currently replacing the Bull River and Lazaretto Creek Bridges on the stretch of US80 that connects Tybee Island to the mainland. will be adding a bike lane, middle turn lane, safety island, and roundabout at Tybrisa Street. In the coming years, GDOT will begin working on the portion of US HWY 80 on the island, starting at the base of Lazaretto Bridge, curving to become Butler Ave., and stretching along the beachfront shoreline. As improvements are made to this main thoroughfare, the City should utilize the construction process to convert the space between the sidewalk and the road into curb-cut rain gardens. The 'first flush' (initial highest pollution concentration) of pollutants from road runoff will be captured in the rain garden instead of entering the stormwater system and ending up in the marsh. The curb-cut rain gardens should be planted with native vegetation, providing connected habitat from the north end to the south end of the island. Further design specifications are included in **Appendix E.**

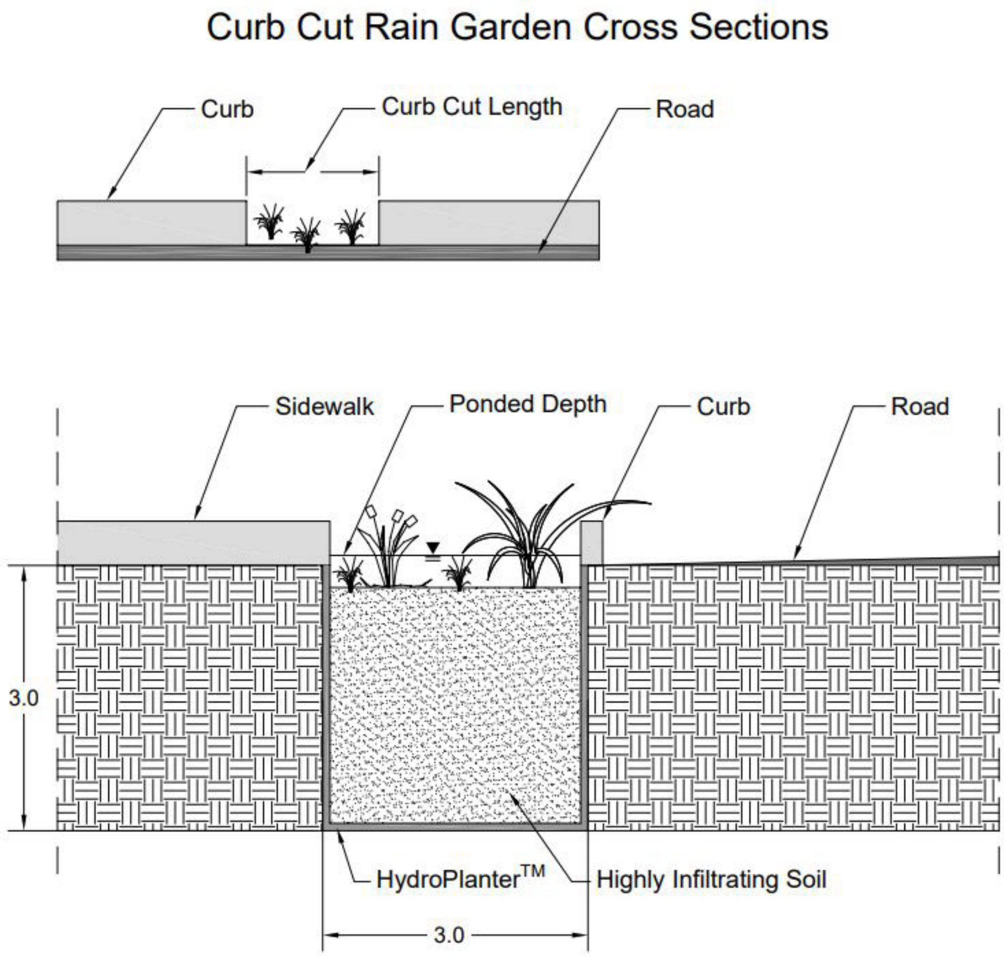


Figure 5.10. Cross section details for the curb cut rain gardens. Dimensions shown are in feet.

NI-5: 14TH STREET

The first capital improvement project presented in the Tybee Island Stormwater Master Plan is the 14th Street Parking Area/15th Street Outfall. Phase 2 of the project calls for a new storm main to be installed on 15th Street to convey stormwater runoff from Butler Avenue to the existing 14th Street outfall, which is located by A.J.s Dockside restaurant on the back river. The installation of the stormwater piping will take place along 15th Street in the southern edge of the right-of-way. During the construction process, natural infrastructure should be added to the corridor, allowing for additional stormwater filtration and storage.

The Natural Infrastructure Master Plan offers an innovative redesign of 14th Street, which is the lowest elevation on the island. The street is already at peak capacity for stormwater infrastructure with large pipes running along both sides of the road. As such, the Stormwater Master Plan calls for installing a new storm main on 15th Street to convey stormwater runoff from the 14th St. beachfront parking lots to the existing 14th Street outfall, which is located by A.J.s Dockside restaurant on the back river.

Natural infrastructure can increase the capacity of 14th St. to absorb the rainfall and runoff that naturally flows into that depression. Adding a bioswale along the length of the road in the right-of-way would provide a channel for the water to flow through and be stored. It should be planted with native vegetation that provides habitat and infiltrates rainfall. The design also calls for converting the two-way, asphalt road into a one-way road (a traffic calming technique), replacing the asphalt with permeable pavers and adding a bike lane. The bike lane improves connectivity across the island for pedestrians and tourists.

Figure 5.11. Conceptual rendering of a swale in the right-of-way

NI-6: STORMWATER INLET RAIN GARDENS

The area of 13th, 14th, and 15th Streets between Butler, Chatham, and Venetian Avenues has been termed 'The Bowl' by Tybee Island residents because it is a localized low spot where frequent ponding on the streets and around homes occurs. Drainage in the 'The Bowl' needs to be improved, and so this location is a critical focus of the Natural Infrastructure Master Plan. Currently, 19 storm grades are located in the roadway of these streets. These grates should be relocated out of the roadway and, when possible placed at the corners of intersections so that rain gardens can be planted in the right-of-way around these inlets. Rain gardens function similarly to bioswales, as they are shallow, excavated areas of land replaced with mixed soil and native vegetation. This aesthetically pleasing and sustainable system uses the natural processes of infiltration and evapotranspiration to control stormwater. These natural infrastructure features will improve connectivity and provide a network of habitat for wildlife. Further design specifications are included in **Appendix E.**

NI-7: RAINWATER STORAGE

Another aspect of the design for 'The Bowl' is a voluntary, residential rainfall capture program. In this initiative, residents will be supported by professionals in implementing either rain harvesting or a rain garden on their property. Planting native vegetation, such as sea oxeye daisy, saltmeadow cordgrass, and saw palmetto, can help capture initial rainfall and filter out suspended solids in the runoff. Both rain harvesting and rain gardens will reduce the volume of stormwater and pollutant loading to the surrounding marsh systems while also delaying flood peaks via retaining and re-routing processes. The plan targets houses in the bowl due to its high impact on these regions, but these features can be implemented island-wide if desired.

Figure 5.12. Example of native plants that can be used in a rain garden.

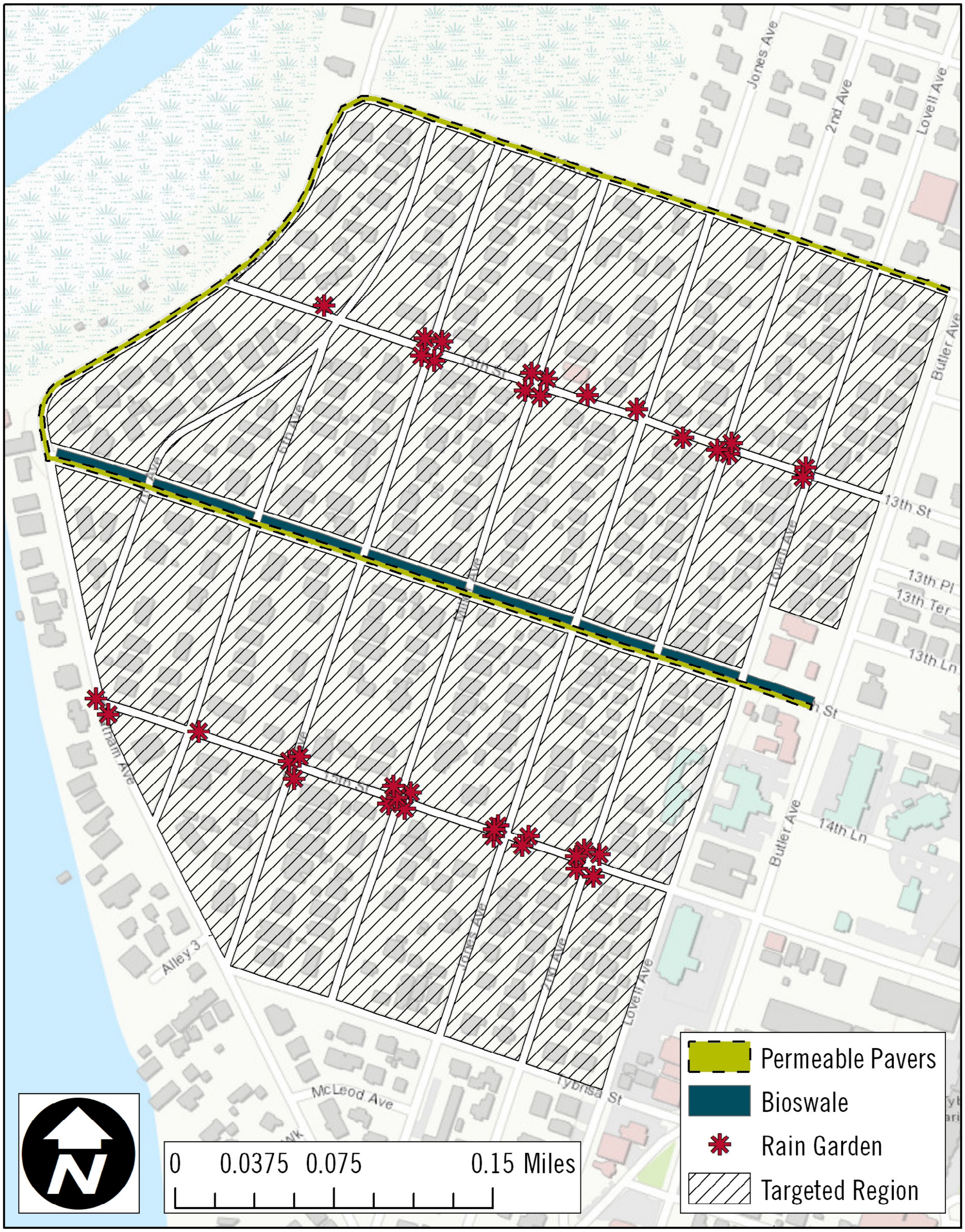


Figure 5.13. Location of proposed permeable pavers, rain storage (rain harvesting and rain gardens), and bioswale along "The Bowl."

NI-8: SOUTH BEACH POCKET PARK

There is a lot currently owned by Hotel Tybee located at the intersection of 15th Street and Butler Avenue that is partially grassed with an unused go-kart track. In recent years, it has been used for parking and for hosting community events. This lot provides an opportunity for intentionally enhancing green space through the creation of a pocket park. The proposed park includes removing the go-kart track and planting natural vegetation and trees to provide habitat and improve the urban canopy cover. With agreement from the parcel owners, the city could also get an easement to maintain the lot as green space and prevent future development. The lot is adjacent to the new stormwater pipe that will transect the island along 15th Street. By replacing soil, creating a grassy berm, and installing permeable pavers, the lot will improve the performance of the gray infrastructure by reducing the volume of water. Having permeable pavers on a portion of the lot will allow the owners to still use it for parking when desired.

Island-Wide Natural Infrastructure Strategies

The proposed island-wide strategies include both structural and nonstructural recommendations. The structural recommendations include natural infrastructure features that perform best when distributed across the island, creating an integrated Green Space Network.

SITE ID	PROJECT NAME / LOCATION	ACTION ITEM (PROJECT DURATION)	HABITAT IMPROVEMENTS
NI-9	Permeable Pavers *(Island-wide)*	• Install permeable pavers on public domains (parking lots and on-street parking), with a special emphasis on the South Beach area. • Conduct outreach to commercial properties to encourage use of permeable pavers.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution
NI-10	Urban Tree Canopy *(Island-wide)*	• Identify vacant lots. • Integrate urban tree canopy into natural infrastructure model. • Conduct community outreach on the benefits of native urban trees.	• Improves shade, air and soil filtration, and wildlife habitat • Serves as a shelter and resting place for birds within the Atlantic Flyway

SITE ID	PROJECT NAME / LOCATION	ACTION ITEM (PROJECT DURATION)	HABITAT IMPROVEMENTS
NI-11	Elevating Homes *(Island-wide)*	• As homeowners continue to elevate homes, educate homeowners on green infrastructure best practices, like permeable pavers, rain gardens, and native plants. • Apply for additional FEMA Hazard Mitigation Funding to continue to offset out-of-pocket expenses for homeowners wanting to elevate their home. • Consider adopting a plant ordinance where a certain percent of the lot has to be kept green.	• Reduce stormwater inputs into the marsh to benefit habitat • Capture the initial rainfall runoff, which contains the highest pollution • Provide habitat for pollinators and increase biodiversity
NI-12	Right-of-Ways *(Island-wide)*	• Map right-of-ways and identify green infrastructure opportunities. • Demarcate right-of-ways in high priority areas. • Utilize right-of-ways to create a Green Space Network.	• Provide habitat for pollinators and increase biodiversity • Increase connectivity of green spaces

Table 5.6. Island-wide strategies

NI-9: PERMEABLE PAVERS

There are several large, public-owned parking lots on Tybee Island, including beach parking at the south end of the island and on-street parking. The plan proposes replacing the asphalt in these parking areas with permeable pavers. Permeable pavers have space between them that allows rainwater to infiltrate through to an underlying gravel layer to reach the ground. This infiltration improves the quality of water by capturing the 'first flush' (initial highest concentration of pollutant) of contaminants that have been transported by rainfall runoff. Due to this area's proximity to the beach, permeable pavers are recommended over permeable pavement, which has smaller pores that would get clogged with sand. Further design specifications are included in **Appendix E.**

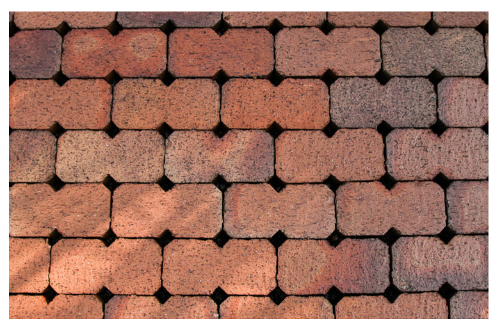


Figure 5.14. Examples of permeable pavers.

Figure 5.15. *Proposed permeable paver locations that include both commercial and public property.*

NI-10: URBAN CANOPY COVER

Urban Canopy Cover is a natural infrastructure feature that involves planting trees in order to intercept rainfall, reduce rainfall runoff, and combat flooding during rain events. Urban Canopy Cover improves infiltration and hosts other benefits such as shade, air and soil filtration, wildlife habitat, and aesthetic appeal. For example, these trees can serve as a shelter and resting place for birds within the Atlantic Flyway, which is one of four major flyways for migratory birds in the Americas. Data from the National Audubon Society has tracked over 255 unique bird species that have visited Tybee Island, of which some are classified as Near Threatened based on the International Union for Conservation of Nature (IUCN) Red List Category. Table E.4 in the appendix highlights the bird species with greater ecological concerns. These trees can be implemented on vacant lots and publicly owned property across the island, such as right-of-ways and public parks. A table (**Table E.3**) has been included in the appendix as an example of the native tree options that could be used for this purpose on Tybee Island.

NI-11: ELEVATING HOMES

Tybee Island has been awarded two Hazard Mitigation Grants through the Federal Emergency Management Agency (FEMA) to support home elevations. Both grants were related to the damage from Hurricane Irma in 2017. The grant pays for 85 percent of the cost, meaning that the homeowners are responsible for 15 percent plus any overruns. To be lifted out of the flood hazard area, homes on Tybee Island must be elevated at least one foot above base flood elevation (BFE). The process involves emptying the homes of all contents, running steel beams either through or beneath the home, and slowing lifting using multiple hydraulic jacks. Once the home is lifted, new foundation piers are built. In some cases, a new floor structure is built, and then the home is lowered back down and attached to the new foundation. For those elevating their homes and those considering this investment, there is an opportunity to provide education on natural infrastructure best practices, like permeable pavers, native plants, and living shorelines. When homes are raised, landscaping often needs to be redone, offering the chance to change designs, materials, and plant species. Best practices could be encouraged through an incentive program or a plant ordinance where a certain percentage of the lot has to be kept green.

NI-12: RIGHT-OF-WAY

Much of Tybee Island is developed, and most of the area bordering the marsh is privately owned. This limits the City's ability to implement the natural infrastructure. One innovative approach that emerged from the planning process was to use public right-of-ways for nature-based features. Street right-of-ways are land adjacent to the road that is typically used for water/sewer lines, drainage, and transportation infrastructure. Many communities are reclaiming that valuable space to implement the natural infrastructure. On Tybee Island, it is first necessary to determine where the right-of-way is located. Demarcating it with flags or other markers in high-priority areas for natural infrastructure could help educate residents on ownership rights and potential uses for this land. Some homeowners have erected structures or invested in the landscape in the right-of-way, so significant outreach will be needed before utilizing this asset.

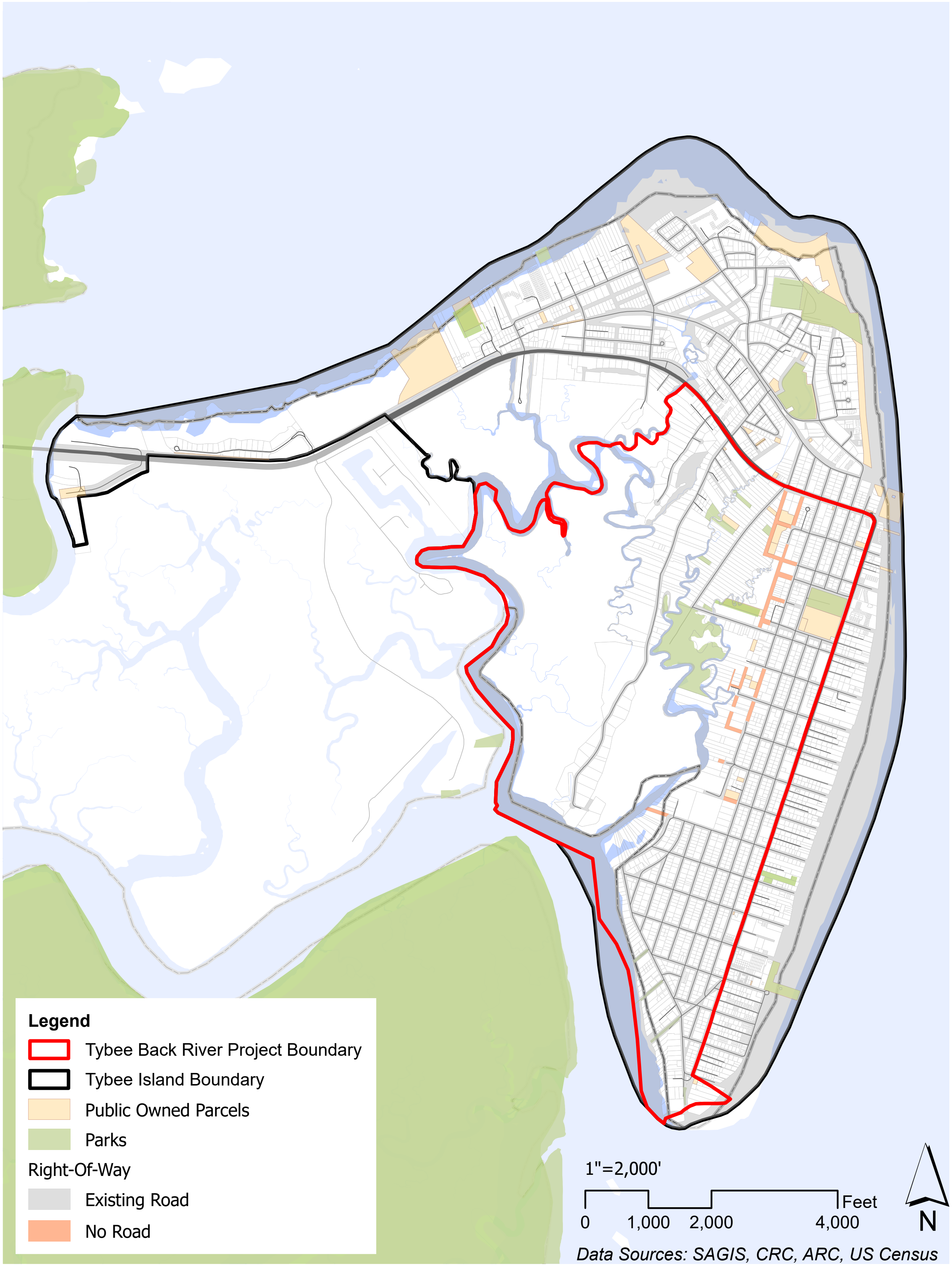


Figure 5.16. Identified right-of-ways on Tybee Island

SECTION VI: NATURAL INFRASTRUCTURE PERFORMANCE

Based on the Natural Infrastructure Master Plan, there is a variety of which features and the degree to which they could be implemented. In order to identify which combination of features is the most effective, the project team used a Multi-Criteria Decision Analysis (MCDA) to test different alternatives. The MCDA uses stakeholder input and results from the coastal empire adaptation survey to determine the weight or importance of the criteria. The alternatives were compared based on the criteria of flood performance, habitat improvement, cost, aesthetics, and feasibility. The researchers used numerical modeling to determine the flood performance of each alternative and tested them across various combinations of rainfall depths, tides, and a future projection for sea-level rise. The habitat improvement score considers the improvement in connectivity, diversification of habitat, and the total freshwater towards the marsh. The cost score was based on estimated costs to implement the features. The aesthetics score was based on the resulting appearance changes caused by implementing the proposed features. The feasibility scores are based on the cost and likelihood of implementation and the property type considered in each scenario. Additional details of the numerical model and the environmental forcings tested can be found in **Appendix F**.

The tested alternatives are hybrid infrastructure systems, as they encompass gray and natural infrastructure. The gray infrastructure is part of the Stormwater Master Plan of the City of Tybee Island, and thus it will not be discussed in detail in this report. However, the proposed hybrid infrastructure system adopted the most suitable gray infrastructure from that study. For the natural infrastructure, four different configurations were considered for this study. The alternatives are summarized in **Table 6.1** and are named by the owner of the feature location. For example, the alternative named Public has all of the natural infrastructure features located on land owned by the City of Tybee Island or the State of Georgia. Similarly, the label Residential and Commercial represents features located in private and commercial parcels, respectively. Note that these alternatives involve the same natural infrastructure between them and only vary on the amount and placement location of these features.

ID	ALTERNATIVE NAME	DESCRIPTION
X	Do Nothing	Current gray infrastructure
A	Public	Curb Cut Rain Garden (US 80/Butler), Swale (14th St.), Rain Storage on public parcels, Permeable Pavers on public domains (parking lots), 6th St. culvert, Venetian Dr. levee
B	Public + Residential	Same as A + 50% of residential parcels (201 parcels or ~10% total parcels) with rain storage at the “Bowl” region

ID	ALTERNATIVE NAME	DESCRIPTION
C	Public + Commercial	Same as A + 50% commercial parcels (47 parcels) with rain storage & permeable pavers at the "Bowl" region
D	Public + Residential + Commercial	Same as B + same as C
E	Only Gray	Proposed gray infrastructure improvements

Table 6.1. Proposed alternatives with their description.

The hybrid infrastructure alternatives (A to D) include the same coastal natural infrastructure features, which are the Venetian Drive horizontal levee and 6th street culvert expansion, as well as the proposed gray infrastructure from the Stormwater Master Plan. The Do Nothing alternative (Labled 'X') includes the current gray infrastructure, while the Only Gray alternative (Labeled 'E') only considers the proposed gray infrastructure, which includes larger pipes and backflow prevention on most outfalls. The following is a detailed description of the proposed hybrid infrastructure alternatives.

A: PUBLIC

This scenario includes four features: rain storage (rain harvesting and/or rain gardens), permeable pavers, curb cut rain gardens, and the 14th Street swale. Rain harvesting was applied to all buildings on public property. This includes the Tybee Island Branch Library, Tybee Island City Hall, Tybee Island YMCA, Tybee Island Fire Department, the Tybee Island Police Department, and the Tybee Shell Recycling Center. The permeable pavers are located at the large public beach parking lots between 14th and 18th street and in the parallel parking spots on the roads perpendicular to Butler on the east side. The permeable pavers placed at the 14th Street public parking lots can address the experienced nuisance of flooding. The pavers are an alternative to the proposed gray solution of incorporating a pump to drain water to the west side of the island. To accommodate the swale along 14th Street, 14th Street, Venetian Dr., and 12th Street on the west side of Butler are converted to one-way streets with permeable pavers. The curb-cut rain gardens run along Butler Avenue within the city of Tybee's right-of-way.

B: PUBLIC + RESIDENTIAL

In addition to the public features described in Alternative A, Alternative B includes residential rain storage. While the Natural Infrastructure Master Plan included either rain harvesting, a rain garden, or both on the residential parcels around the "Bowl" region, the researchers only accounted for rain harvesting in the numerical modeling. However, depending on the design, rain gardens can provide storage as the modeled rain harvesting. Rain harvesting was placed using a random sampling technique within the location prone to inundation, which is the low-lying residential area between 15th St and 12th St (See Figure 6.1). A total of 201 residential parcels were selected for this effort, which totals 50 percent of the parcels in this region and almost 10 percent of the total parcels in the city.

C: PUBLIC + COMMERCIAL

In addition to the public features described in Alternative A, Alternative C includes rain storage and permeable pavers on commercial properties. A random selection of 50 percent of the commercial parcels was assigned rain harvesting, while the rain gardens were not evaluated for this report. The large commercial parking lots that were asphalt were replaced with permeable pavers. This alternative also includes the pocket park at Butler and 15th street.

D: PUBLIC + RESIDENTIAL + COMMERCIAL

Alternative D includes all of the natural infrastructure features used in the previous alternatives.

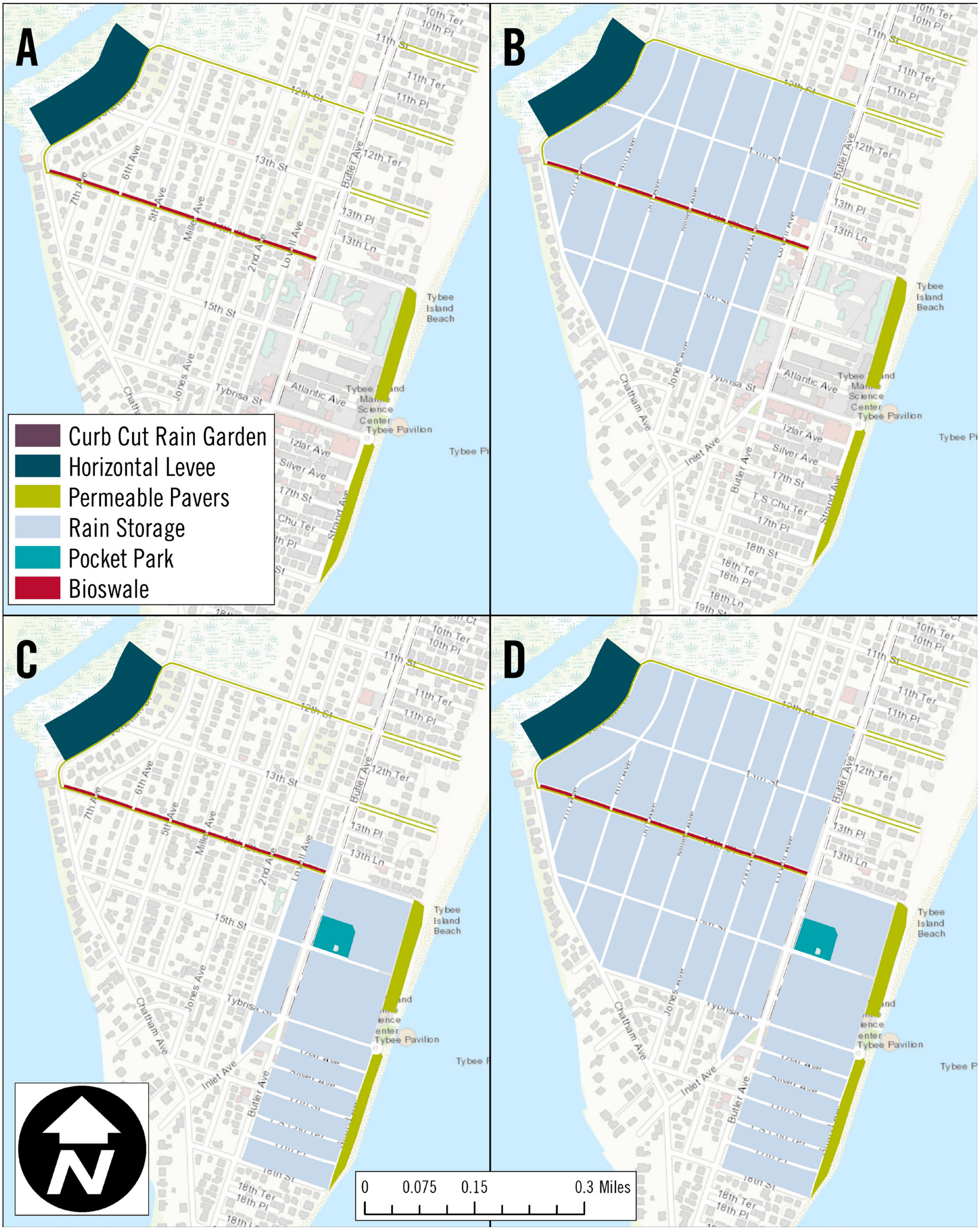


Figure 6.1. Location of the natural infrastructure features over the south end of Tybee Island for the proposed alternative A, B, C, and D.

Island-Wide Natural Infrastructure Strategies

The Multi-Criteria Decision Analysis (MCDA) was based on five main criteria: flood performance, habitat performance, cost, aesthetics, and feasibility. The most important parameter in the MCDA was the habitat performance criterion, with a relative importance of 0.35. It follows the flood performance and cost criteria with a relative importance of 0.25 and 0.2, respectively. Lastly, the feasibility and aesthetics criteria are the least important, with a relative importance of 0.1 for both. The selection of these criteria was based on surveys of the community and inputs from stakeholders, including the Coastal Empire Adaptation survey. However, additional surveys, town halls, and workshops would be conducted beyond the period of this project to ensure the correct weight of each criterion in the MCDA approach. The following subsection describes in more detail each criterion.

Results from the MCDA approach suggest that the tentatively selected alternative (TSA) is alternative B, the hybrid infrastructure system with green infrastructure on public and residential parcels. This alternative offered the optimal combination of flood reduction, habitat performance, cost, aesthetics, and feasibility (Table 6.2). Flood reduction and habitat performance were the most heavily-weighted criterion in the MCDA, and only alternative D had better flood reduction than B, but the cost and feasibility of D were prohibitive. Alternative B was the most cost-effective hybrid design besides A, which showed poor flood reduction. Habitat performance among the four hybrid systems was comparable. Alternative B received the lowest score for aesthetics due to adding rainwater harvesting to buildings, but this criterion was one of the least important in the MCDA. The feasibility of alternative B was moderate, considering both the city and homeowners would have to install green infrastructure.

		ALTERNATIVES					
CRITERION	**RELATIVE IMPORTANCE**	**X**	**A**	**B**	**C**	**D**	**E**
Habitat improvement	0.35	1.30	4.28	4.40	4.17	4.12	2.58
Flood Reduction	0.25	2.00	2.11	3.49	2.63	4.04	1.85
Cost	0.20	5.00	2.23	2.16	1.07	1.00	5.00
Aesthetics	0.1	2	4	3	5	4	1
Feasibility	0.1	1	5	3	3	2	4
	TOTAL SCORE	**2.26**	**3.37**	**3.44**	**3.13**	**3.25**	**2.87**

Table 6.2. : MCDA results for the various alternatives, including the "no action" alternative (X), four hybrid infrastructure alternatives (A through D), and a gray infrastructure alternative (E). Note that results for alternative E are not directly comparable to others because no future projections of floods were assessed.

Overall Performance

The natural infrastructure in hybrid alternative B provided substantial reductions in the total number of buildings inundated, but the relative importance of natural infrastructure depended on the storm size (**Figure 6.2**). Contrary to most findings, the project team found that natural infrastructure provided more benefits during larger storm events. For the 3-inch storm, the gray infrastructure drained much of the stormwater and thus provided a greater proportion of flood protection. The importance of natural infrastructure increased during the intermediate storms, peaking with the reduction of 73 buildings (3.5 percent improvement island-wide; 87 percent of the total reduction) during the 6-inch storm. For larger storms, the overall flood benefits were diminished, but natural infrastructure continued to substantially enhance the gray infrastructure, which offered little flood reduction for the 9-inch storm. This suggests that the proposed hybrid infrastructure system can improve flood conditions across a range of rainfall depths, with gray infrastructure being most important for small storms and natural infrastructure being most important for intermediate and larger storms.

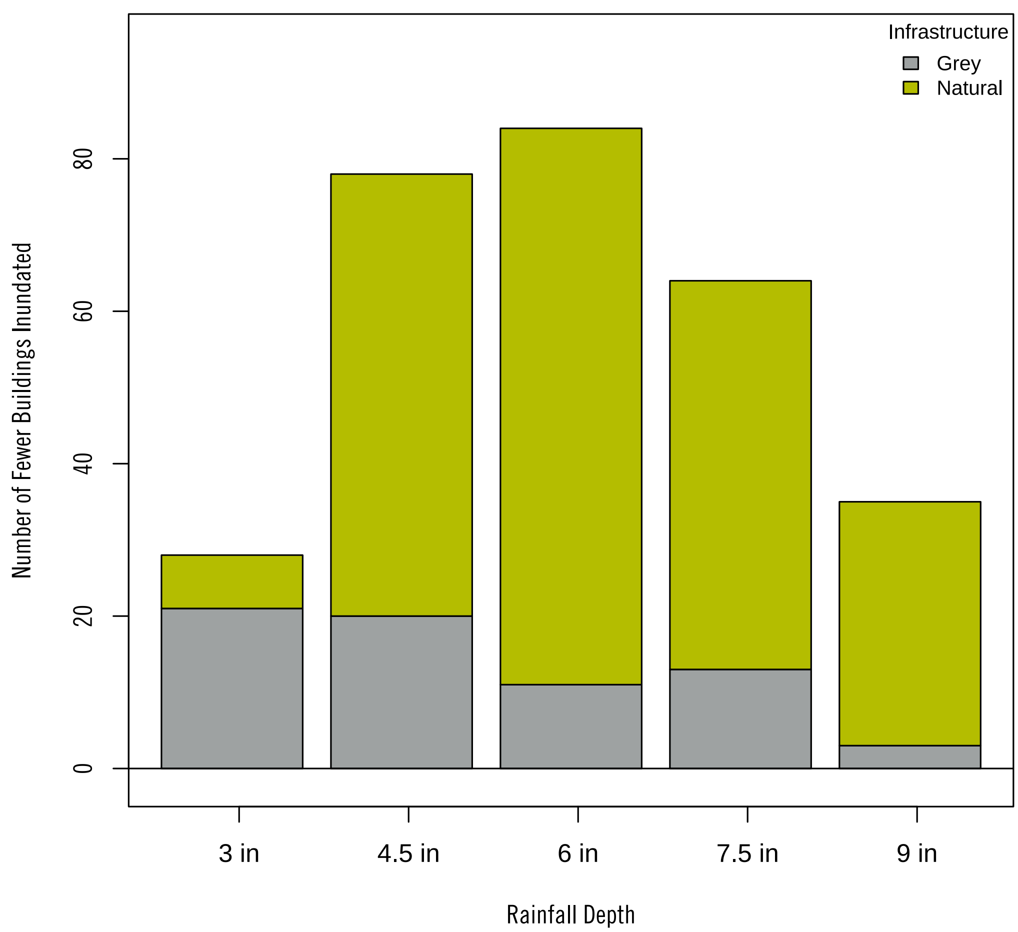


Figure 6.2. The number of fewer buildings inundated for the various storm depths, with mean tide conditions, for alternative B relative to existing conditions (alternative X). The total number of fewer buildings inundated is broken down into contributions from gray infrastructure (gray bars) and natural infrastructure (green bars).

The TSA, alternative B, provided benefits for flood depth and duration when compared to the existing condition, alternative X (**Figure F.2**). The greatest reduction in the number of buildings flooded occurred for buildings with up to 0.5 inches of maximum inundation and up to one hour of inundation duration. For maximum inundation depth, flood benefits were greatest during the 6 inch storm, with 70 fewer buildings (4.1 percent improvement above the base condition) inundated less than 0.5 inches (**Figure F.2a**). Alternative B was most beneficial for flood duration during the 9 inch storm, reducing the number of buildings inundated 0.5 to 1.5 inches for up to an hour by 48 (7.2 percent improvement; **Figure F.2c**). Among all tidal conditions, hybrid infrastructure in alternative B was most beneficial in sea-level rise scenarios (**Figure A5.4b,d**). Most of the flood improvements occurred in buildings on the southern portion of the island (**Figure F.3**), west of Butler Ave. and between 12th St. and Inlet Ave. These results illustrate the potential efficacy of hybrid infrastructure because the southern end of the island is where flooding is most prevalent and where most hybrid infrastructure was implemented. More detailed results are discussed in the appendix.

Culvert Example

As previously mentioned, two metrics were explored to quantify the habitat performance due to the hybrid infrastructure system. First, the marsh connectivity across 6th St was evaluated using the amount of flow passing through the culvert. The flow rate for both the existing (alternative X) and proposed (alternative B) scenarios are summarized in **Figure 6.3** for a complete 4 tidal cycles. It is shown that during the flood tide (i.e., positive values of tidal amplitude), a larger amount of water enters (i.e., negative flow rate values) the marsh pond for the proposed conditions whereas for the current conditions remains than for the existing one, especially during the peak tidal amplitude. Similarly, the existing conditions have a greater amount of water leaving the marsh pond (i.e., positive flow rate values) during the ebb tide event (i.e., negative tidal amplitude values) than the current one, especially before the peak tidal amplitude. Therefore, the proposed culvert is enhancing the amount of water entering and leaving the marsh pond during tidal conditions. To further assess the marsh connectivity, the net volume of water passing through the culvert was computed for both the existing and proposed conditions at various tidal conditions (**Figure F.4**). Results highlighted that the current conditions promote a system that loses water even at high events, such as spring tides, meaning that more water is leaving than entering the system upstream of the 6th St. culvert. However, under the proposed conditions, this marsh system equilibrates the volume of water on each side. For example, during average tide events, the amount of water that enters the system is practically the same amount that leaving, thus providing favorable conditions for the flora. Despite this improvement, under future climatic conditions, both alternatives provide a system that will be greatly flooded, meaning that the sea-level rise will produce a failure of this infrastructure.

Second, the freshwater from the rainfall-runoff that was discharged into the marsh surrounding Horsepen Creek was quantified for each alternative. The implementation of the hybrid infrastructure can decrease the amount of freshwater reaching the marsh by up to 21 percent (115,556 gallons) compared to the current conditions (alternative X). However, the inland green infrastructure features are capable of retaining up to 5 percent of the freshwater that otherwise will go into the marsh system when compared to the proposed gray infrastructure plan only (Scenario E).

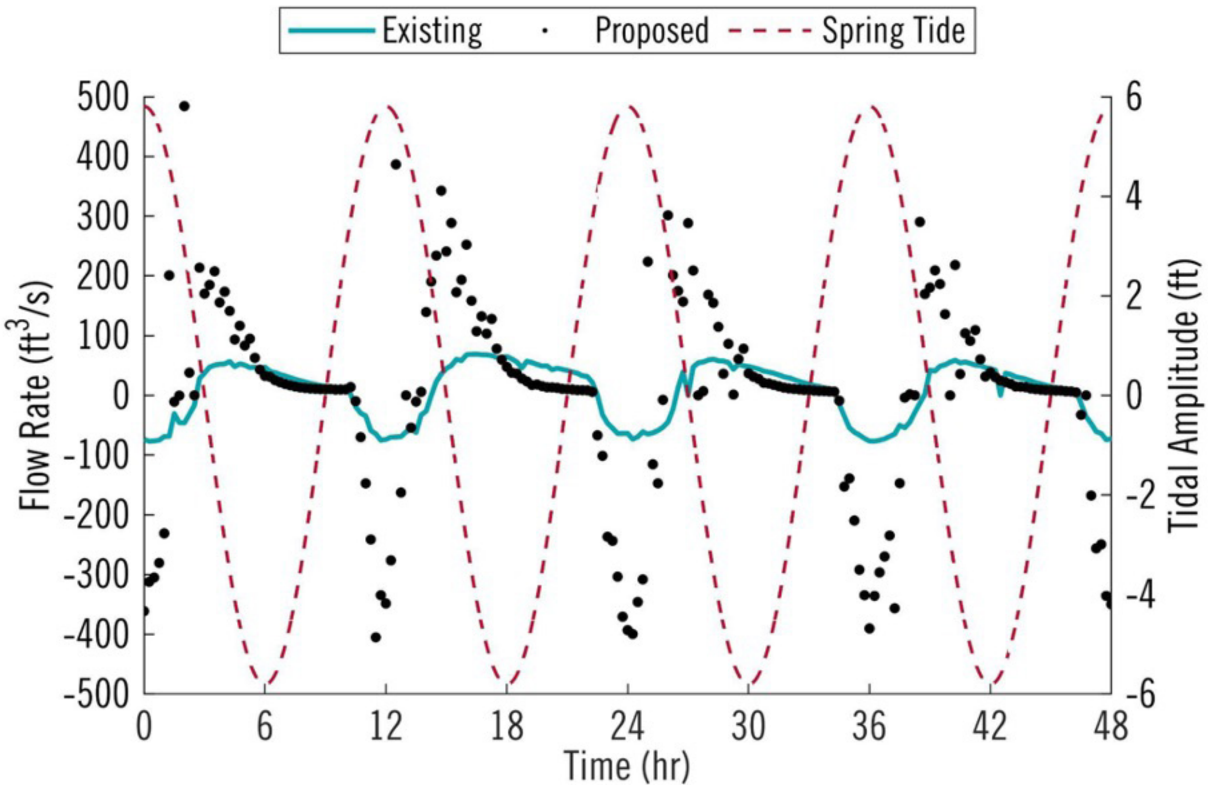


Figure 6.3. Amount of flow going through the 6th St culvert for the existing (blue solid line) and proposed (black dots) conditions. Negative flow rate values correspond to water entering the marsh pond (north of 6th St), while positive values are for water leaving the system. The spring tide amplitude value is shown as a red dashed line.

SECTION VII: CONCLUSION

The Tybee Island Natural Infrastructure Master Plan was designed to be integrated with the community's new Comprehensive Stormwater Master Plan. While upgrading gray stormwater infrastructure will be critical for reducing flood impacts on the island, the models used by the University of Georgia and Thomas & Hutton show that enlarging and densifying conduits alone will not be sufficient to manage the volume of water poised to inundate the island in the decades to come. As heavy rain events are increasingly compounded and exacerbated by higher tides, integrated hybrid infrastructure will be needed. The hybrid natural infrastructure features recommended in this plan can **capture and retain up to 21 percent (115,556 gallons)** of the total freshwater rainfall-runoff volume that drains into the marsh. This can prolong the service life of these new gray infrastructure investments by reducing flooding stress while conserving wildlife habitats and wetlands.

Final Design and Permitting

This project produced preliminary design and feasibility assessments so that Tybee Island City Council can decide which activities to pursue in the short, medium, and long term. Should Tybee Island City Council approve these initial concepts and authorize pursuit of more detailed site designs, the next steps for the project team will be to conduct education and outreach activities as described above and apply for the next phase of NFWF National Coastal Resilience Funding, which are for 3 year projects with a maximum budget of $1 million.

Projects in the next phase of NFWF funding advance preliminary designs into final designs and engineering plans with detailed cost estimates. They should result in 90-100 percent design completion. By the end of this phase, projects should demonstrate readiness to meeting regulatory and permitting requirements. NFWF states that proposals for larger, more comprehensive projects are likely to be more competitive. According to past guidance, larger match ratios and matching fund contributions from a diversity of partners will make the application more competitive. Proposals should also include sustained stakeholder engagement and efforts to transfer the planning and design approach to other communities in the state or region. Non-federal match is encouraged but not required to demonstrate broad support for the project.

Next Steps

Public Engagement and Outreach

There is strong public support for natural infrastructure on Tybee Island and in surrounding areas, particularly when it promotes healthy wildlife habitat. However, it will be critical to educate residents, particularly those adjacent to natural infrastructure features, about their benefits to increase understanding and collective will. Specific outreach recommendations are to:

- Demarcate the right-of-way on 14th and 15th St. to educate residents about the right-of-way and provide visual guidance for discussing natural infrastructure along these corridors.

- Collaborate with partners to host workshops for residents about rain storage, such as a rain barrel workshop in partnership with the Georgia Department of Natural Resources Coastal Resources Division or a rain garden workshop in partnership with UGA Marine Extension and Georgia Sea Grant.
- Provide training on the design and function of sales so they are properly maintained. Currently, there are several swales on the island where sediment has built up preventing water from accessing the swale (e.g. 7th St. and Miller Ave.).
- Seek funding to incentivize the adoption of rain storage practices on residential properties, such as implementing the Coastal Rain Garden Program. These efforts should prioritize 13th, 14th, and 15th Streets between Butler Avenue and Venetian Drive/Chatham Avenue.
- Engage residents who live on Venetian Drive to share options for protecting their properties and preserving the marsh.

Figure 7.1. The Coastal Rain Garden Program supports residents or small businesses interested in installing rain gardens in coastal communities

Research

Next steps needed for research and data collection are to:

- Update modeling with proposed improvements in the Comprehensive Stormwater Master Plan.
- Assess functionality of adding control features on proposed 6th St. and Lewis Ave. culverts, in order to ascertain potential impacts on the marsh and net ecological lift.
- Analyze optimal locations for buy outs of repetitive loss properties (FEMA Hazard Mitigation Grant) to enhance natural infrastructure.

Funding

In order to advance the preliminary designs in this plan and implement recommendations, additional funding will be needed. Listed are suggestions for securing this support:

- Apply for NFWF Phase 3 grant to further work on design and permitting.
- Investigate creative options for securing matching funds for project proposals, such as the Department of Defense's REPI Program.
- Leverage this plan to access state, federal, and private sector funding. Having concepts approved by CIty Council will strengthen proposals and help the designs appear more shovel-ready.
- Continue dialogue with permitting/regulatory agencies on proposed activities.
- Integrate natural infrastructure into current and future planning, transportation and public works projects. This includes both Phase 1 and 2 of the stormwater capital improvement project involving 14th Street Parking Area/15th Street Outfall and improvements by the Georgia Department of Transportation to US Hwy 80 / Butler Avenue.

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APPENDIX A: PROJECT METRICS

NFWF METRICS	TARGETED	ACHIEVED
Critical facilities and infrastructure benefiting from the project (those necessary or ensuring public health and safety such as, hospitals, shelters, emergency and evacuation routes, fire and police stations, etc. as well as critical infrastructure – wastewater treatment facilities, power plants, etc.) *(Island wide)*	50%	**50% *(8 critical facilities)***
Properties with enhanced protection (Commercial or residential properties within the radius of enhanced protection) *(study area- bowl region)*	50%	**52% *(231 properties)***
Outreach/ Education/ Technical Assistance (Number of municipalities, local, state, and federal government entities participating in the project)	5	**27**
Volunteer participation (number of volunteers participating in projects)	15	**121**

Outreach, Education and Technical Assistance partners:

Chatham County-Savannah Metropolitan Planning Commission

Chatham Emergency Management Agency

Chatham County

City of Savannah

Georgia Conservancy

One Hundred Miles

Goodwyn, Mills and Cawood

Thomas & Hutton

Georgia Department of Natural Resources Coastal Resources Division

Georgia Emergency Management Agency

University of Georgia Carl Vinson Institute of Government

University of Georgia Department of Public Administration

University of Georgia Department of Marine Sciences
Georgia Institute of Technology
Georgia Southern University
Emory University
NASA Jet Propulsion Laboratory
California Institute of Technology
U.S. Army Corps of Engineers
NFWF
NOAA
Rep. Buddy Carter's Savannah Office, District 1
National Sea Grant Network
Southeast Sustainability Directors Network
Climate Mayors
Center for Sea Rise Solutions
Athens-Clarke County Unified Government

Volunteers Participating

Abby Sterling
Adrienne Hines
Ajay Walther
Alessandria Schumacher
Alex Muir
Alexander Keaton
Alondra Ramirez
Amy Gaster
Annaliese Poliner
Anthony DAguillo
Arielle Mion
Audrey Long
Bailey Kainalu
Bailey Peak
Bailey Williams
Beth Williams
Bill Garbett
Binyu Yang
Brent Levy
Caitlin Duffy
Caroline Petithomme
Cathy Lewis
Cathy Sakas
Charles McMillan
Charlotte James
Christa Ishimwe
Clare McCarthy
Cole Allison
Corey Kemp
Courtney Reich
Dania Hussain
David McNaughton
Deb Barreiro
Demery Bishop
Drew Lonker
Elaine McGruder
Emanuele Di Lorenzo
Emilie Saksvig
Emily Wortman
Emma Hite
Erica Kahn
Ethan Li
George Shaw
Gina Zheng
Grace Dusenbury
Grace Morris
Harvey Ferrell
Helen Downing
Ian Rossiter
Isabella Martin
Jack Alperstein
Jackie Jackson
Jan Mackinnon
Jared Lopes
Jaylan Holman
Jennifer Kline
Joe Richardson
Kait Morano
Kate Burns
Kathryn Williams
Keith Gay
Ken Burns
Kevin Nastasi
Kevin Smith
Kim Cobb
Kim Garvey
Kiran Topiwala
Laura Williams
Lauren Farrington
Lauren Sullivan
Lindy Betzhold
Lisa Vandiver
Madeline Holodnik
Margarett Mcintosh
Marie Gooding
Marisa Wong
Mark Padgett
Mary Lee McQuigg
Matthew Bilskie
Matthew Wirth
Maya Bliss
Mayuri Makan
Meg McAloon
Melissa Turner
Michael Blakely
Michael Foran
Michael Hans
Michael Horneribler
Michaela DiGiovanni
Michelle Owens
Monzur Patwary
Morgan Hodgkinson
Nick Deffley
Norah McKinley
Patricia Stupp
Paul Coote
Paul Vila
Perry Taylor
Peter Gulbronson
Randall Mathews
Robertus Rioputra
Rory Granros
Russ Clark
Sam Adams
Sam Goldsmith
Sana Nag
Scott Pippin
Shahreen Hussain
Shana Jones
Shawn Gillen
Shihui Deng
Sipeng Zhang
Sophia Milazzo
Stephan A Durham
Surovi Nimmi
Susan Bentley
Susan Hill
Tammie Riddles
Tsedenya Bizani
Will Spivey
Yazmine Callan

APPENDIX B: PUBLICATIONS AND MEDIA

Online Resources

Resilient Tybee Website

Gambill, J., Milazzo,S. & Robertson, A. (2022). Resilient Tybee website. CIty of Tybee Island and My Agency Savannah.

Building Flood Resilience on Tybee Island StoryMap Collection

Gambill, J., Callan, Y., DiGiovanni, M., Dusenbury, G., James, C., McQuigg, M.L., Saksvig, E., Spivey, W., Sullivan, L., & Williams, B. (2022). Building Flood Resilience on Tybee Island. Esri ArcGIS StoryMap Collection. University of Georgia Marine Extension and Georgia Sea Grant.

Faces of Resilience Video Series

Gambill, J., Lindsay, A., & Kenworthy, E. "Restoring Dunes to Protect Coastal Communities." Faces of Resiliency video series. University of Georgia Marine Extension and Georgia Sea Grant.

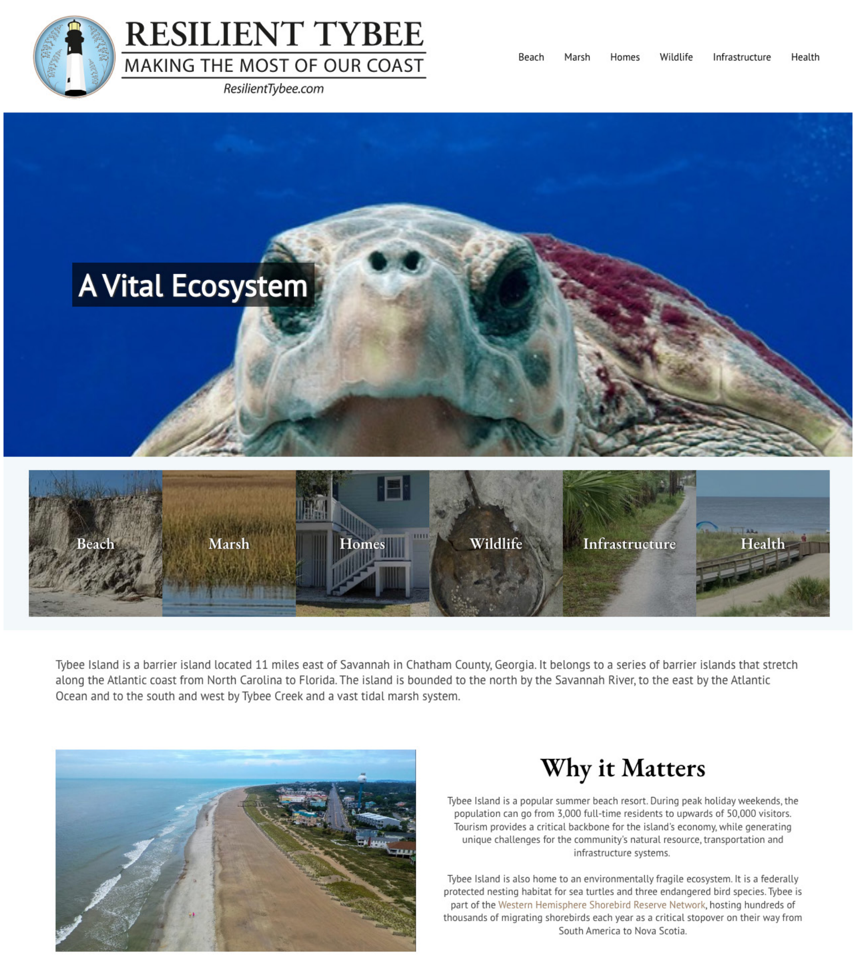


Figure B.1. The Resilient Tybee website was created through this project

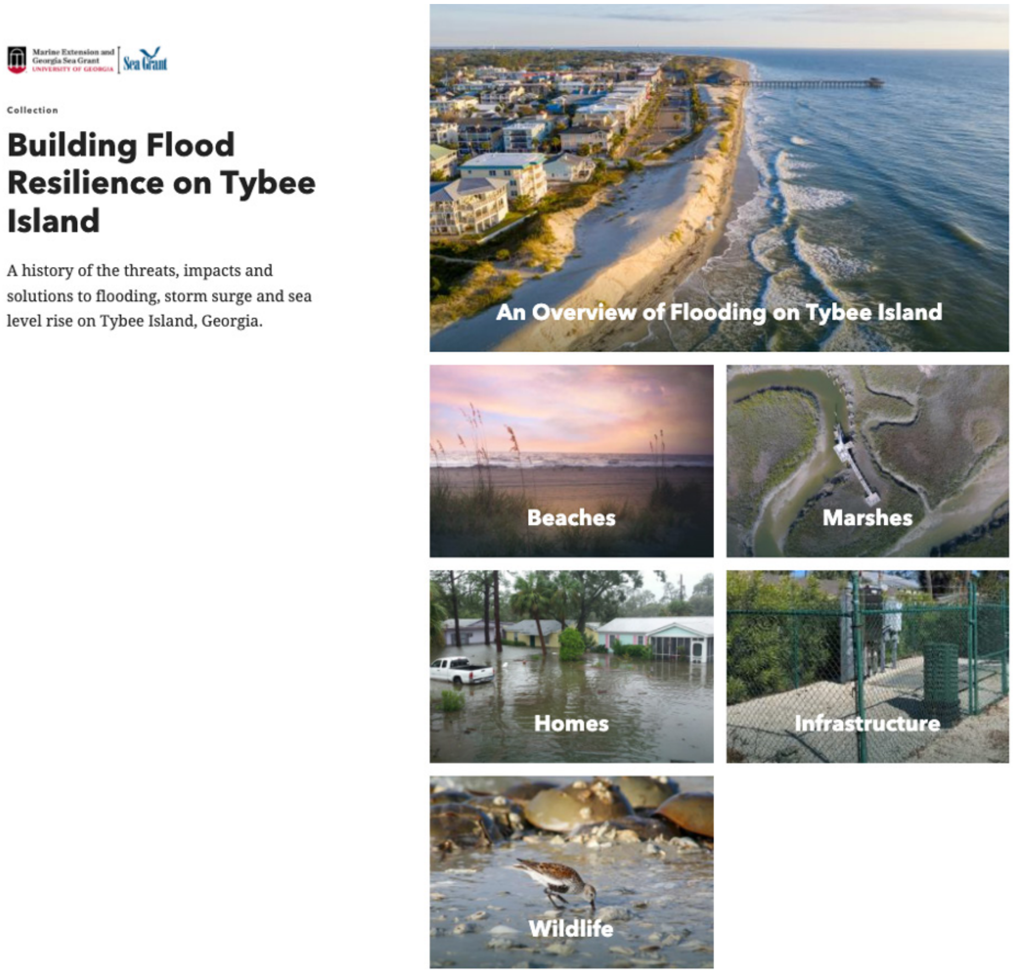


Figure B.2. The "Building Flood Resilience on Tybee Island" StoryMap Collection was developed through this project.

Recorded Presentations

Local and Regional Policy Efforts for Equitable Sea Level Rise Adaptation. Environmental Ethics Seminar. University of Georgia Environmental Ethics Certificate Program.

Building a Resilient Georgia: Funding Opportunities Webinar. UGA Marine Extension and Georgia Sea Grant Youtube Channel.

Figure B.3. Tybee Island Mayor Shirley Sessions, City Manager Shawn Gillen and project member Alan Robertson presented in the University of Georgia Environmental Ethics Seminar.

Sample Media Coverage

Brennan, P. In Savannah, a Sea Level Summit. NASA Sea Level Portal. Dec. 21, 2022.

Buckleitner, S. Tybee Island Natural Infrastructure Plan. University of Georgia Institute for Resilient Infrastructure Systems. Nov. 15, 2022.

Mecke, M. Tybee prepares for long-term solutions to climate change, erosion, storms. Savannah Morning News. June 10, 2022.

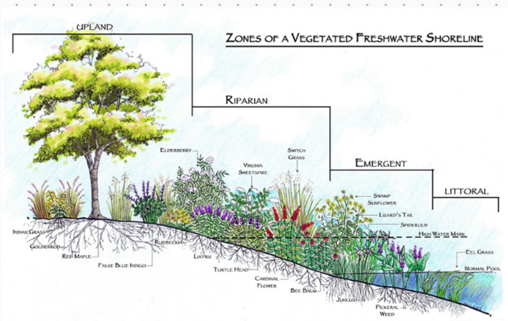
Guan, N. Rising waters: Tybee's Back River neighborhood is ground zero for flooding, sea-level rise (viewable to subscribers only). Savannah Morning News. March 15, 2022.

Tybee Island residents see more flooding as sea levels rise. Yale Climate Connections radio series. Yale University. February 7, 2022.

Pomerleau, L. UGA Project Profile: Flood Resilience for the City of Tybee Island University of Georgia College of Environment and Design. August 16, 2021.

Examples from Design Charrette Mural Boards

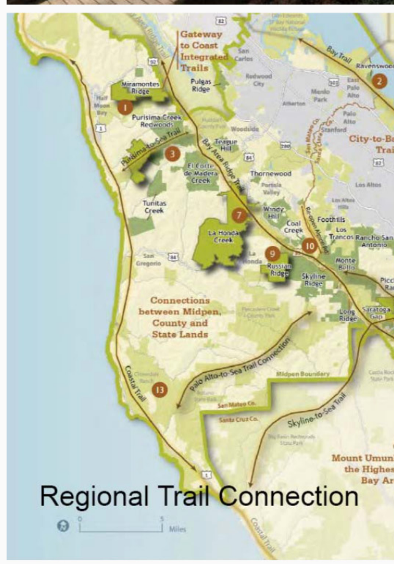
Enhancing Shoreline



Enhancing shoreline adjacent to homes allowing for marsh growth

Allowing for shoreline restoration to exemplify storm surge + ecological protection

Extension of Greenway



Extending existing greenway along highway 88 into marshland

Acquiring property to create greater extension may be necessary

Bike and Pedestrian access via boardwalks and/or elevated walks

Opening Waterway

Allowing more movement for waterway access

Boating opportunities and allowing more water onto site

APPENDIX D: COASTAL EMPIRE ADAPTATION SURVEY

	MEAN/PROP.	MEDIAN	SD
age	57.62	63.00	16.60
female	.55	1.00	.50
high_school	.11	.00	.31
vocation	.02	.00	.15
some_college	.16	.00	.37
assoc_degree	.04	.00	.20
college_grad	.28	.00	.45
prof_degree	.10	.00	.30
grad_school	.29	.00	.45
emp_ft	.35	.00	.48
emp_pt	.13	.00	.33
work_in_home	.01	.00	.08
not_emp	.05	.00	.21
retired	.44	.00	.50
student	.01	.00	.11
white	.76	1.00	.43
hispanic	.03	.00	.17
black	.12	.00	.33
native_am	.01	.00	.08
pac_isl	.00	.00	.00
indian	.01	.00	.08

	MEAN/PROP.	MEDIAN	SD
chinese	.00	.00	.00
filipino	.00	.00	.00
japanese	.01	.00	.08
korean	.01	.00	.08
vietnamese	.01	.00	.08
asian_other	.01	.00	.08
Income*	114.85	87.50	87.83
reg_voter	.89	1.00	.31
conserv_very	.15	.00	.36
conserv	.20	.00	.40
moderate	.28	.00	.45
liberal	.17	.00	.38
liberal_very	.11	.00	.32
tybee	.41	.00	.49

N=176, except for income_cateogory (n=175)

Table D.1. Descriptive Statistics – Demographics

	MEAN/PROP.	MEDIAN	SD
coast_reside	18.96	15.00	12.71
primary_res	.94	1.00	.23
clear_title	.76	1.00	.43
heirs_prop	.03	.00	.18
renter	.20	.00	.40
own_residence	.78	1.00	.42
own_biz	.03	.00	.18
own_leasep	.05	.00	.22
own_other	.03	.00	.18
county_time	47.09	50.00	10.19
ft_res	.94	1.00	.24
pt_res	.05	.00	.22
not_res	.01	.00	.11
length_res	17.59	15.00	12.45
plan_move5	.10	.00	.30
plan_move10	.07	.00	.26
plan_move20	.02	.00	.15
plan_moveno	.80	1.00	.40

N=176

Table D.2. *Descriptive Statistics – Residency and Property Ownership*

	FLOOD_INS	WIND_INS
higher_edu	0.3808	1.3609***
	(0.4247)	(0.3605)
conservative	-0.8487**	0.2838
	(0.3952)	(0.3232)
gamble_fal	0.2192	0.4269
	(0.5162)	(0.4767)
avail_heur	-0.3300	0.0706
	(0.4740)	(0.3581)
deduct_understand	-0.1996	-0.0083
	(0.3976)	(0.3223)
charity_grant	-0.6075	0.5879**
	(0.3779)	(0.2970)
inc	0.0177**	0.0088
	(0.0086)	(0.0069)
Ln(wealth)	-0.5637*	0.1843
	(0.3144)	(0.2287)
zip=31404	-2.7937***	-1.7422**
	(0.7926)	(0.7971)
zip=31410	-0.7050	0.0183
	(0.6151)	(0.4837)
zip=31411	-0.1663	-0.8426**
	(0.6280)	(0.3983)

	FLOOD_INS	WIND_INS
zip=31419	-1.8881***	-0.3662
	(0.5029)	(0.3949)
Constant	8.4457**	-4.2174
	(4.1446)	(3.0333)
athrho	1.0031**	
	(0.4114)	
Observations	115	

** p<0.10; ** p<0.05; *** p<0.01* *Standard errors in parentheses*

Table D.3. Flood and Wind Insurance Bivariate Probit

TIME FRAME	FORMAT	INSTRUMENT
12 Months	Open-ended, percentage	In the next 12 months, what do you think the percentage chance is that your home will flood from any weather related event (for example, rain, storm surge, hurricane, etc.). __________%
12 Months	Multiple Choice	In the next 12 months, what do you think the chances are that a major hurricane (Category 3 or greater, with winds of 111 mph or greater, possibility of tornadoes, and storm surge of at least 10-12 feet) will pass within 60 miles of Chatham County? a) 0% - 5% chance b) 6% - 10% chance c) 11% - 20% chance d) 21% - 50% chance e) greater than 50% chance
25 Years	Likert Scale	In general, how likely is it that your property/current home will be flooded over the next 25 years? a) Very likely b) Likely c) Somewhat likely d) Somewhat unlikely e) Unlikely f) Very unlikely g) Don't know
50 Years	Open-ended, count	How many major hurricanes (Category 3 or greater, with winds of 111 mph or greater, possibility of tornadoes, and storm surge of at least 10-12 feet) do you expect to pass within 60 miles of Chatham County over the next 50 years? Minimum ________ On Average ________ Maximum ________

Table D.4. Risk Perception Instruments

FLOOD_PROB	COEFF	S.E.
vzone	0.4881*	(0.2514)
azone	0.4895***	(0.1854)
xzone	0.0330	(0.1697)
dk_fzone	0.4402**	(0.2035)
higher_edu	0.2162	(0.1444)
Conservative	0.0068	(0.1589)
liberal	-0.3850**	(0.1588)
gamble_fal	-0.0129	(0.2462)
avail_heur	0.5002***	(0.1584)
deduct_understand	-0.0591	(0.1349)
past_floods	0.0112**	(0.0045)
d_days	0.0012	(0.0015)
Constant	-1.4558***	(0.1933)
Observations	176	

** p<0.10; ** p<0.05; *** p<0.01*

Table D.5. Perception of Flood Risk Over next 12 Months

Random Utility Model

Consider the satisfaction (or utility, *U*) that an individual gets from public investments in riverine flood management infrastructure:

$$U_{nht} = V_{nht} + \epsilon_{nht} \tag{1}$$

where $V_{nht} = \alpha_{nht} + \beta_{nh-sf}x_{sf} + \beta_{nh-nf}x_{nf} + \beta_{nh-hab}x_{hab} + \gamma_n(y - cost_{nh})$ is the deterministic portion of utility (where x_{sf} = the level of storm flooding risk, x_{nf} = the level of nuisance flooding, x_{hab} = the level of coastal habitat, and $cost_{nh}$ is the associated SPLOST cost for the project), with infrastructure fixed effects α_h (reflecting the utility associated with "brands" h = "Gray", "Hybrid", and "Green" relative to the "Status Quo"), utility parameters β that reflect the relative importance of project features, and marginal utility of income γ(where y is household income). Utility varies across respondents (n), infrastructure project type (h), and choice occasion (t). The random variable ϵ_{nht} is assumed to follow a type I extreme value distribution (McFadden 1974). Since the random error is unobserved by the researcher, the plan specifies the probability of a particular choice in the data as:

$$Pr(choice = h) = Pr(V_{nht} + \epsilon_{nht} > V_{nkt} + \epsilon_{njk}) \text{ for } \forall\, k \neq h \tag{2}$$
$$Pr(choice = h) = Pr(\epsilon_{nkt} - \epsilon_{nht} < V_{nht} - V_{nkt}) \text{ for } \forall\, k \neq h$$

The difference in Type I extreme random variants is distributed logistic, so the logit model can be used to estimate this probability. Ignoring the panel dimension of the data (repeated choices by each respondent), the researchers can recover representative parameters for the utilities in (1) by estimating the standard conditional logit model:

$$\mathrm{Pr(choice}\frac{\exp(x'_{nht}\theta)}{\exp\sum_{k\epsilon C}(x'_{nkt}\theta)'} \tag{3}$$

where $\theta = [\alpha'\beta'\gamma]$ is a vector of model parameter estimates. Model estimation of equation (3) permits exploration of basic parameters of riverine infrastructure choice, but does not incorporate individual heterogeneity and imposes potentially unrealistic substitution effects (known as "Independence of Irrelevant Alternatives"). The researchers use estimates from (3) as a baseline for further modeling decisions.

Introducing preference heterogeneity, the project employs the Mixed Multinomial Logit (MMNL) model which provides a flexible specification for parameters for population moments as:

$$\theta_{nj} = \underline{\theta_j} \pm\blacksquare\, \psi_j q_n, \tag{4}$$

where $\underline{\theta_j}$ represents the mean parameter for project attribute *j*, $\psi_j$represents the spread of the distribution around the mean, and q_n represents random draws from a pre-determined distribution for each respondent *n*. When ψ_j is either not specified or not statistically significant, one interprets preferences as fixed parameters. To estimate MNNL, it is necessary to simulate the integral for the distribution of random preferences:

$$P_{nht} = Pr(choice = h) = \int_{\blacksquare}^{\blacksquare} \blacksquare \frac{exp(x'_{nht}\theta)}{exp\sum_{k\epsilon C}(x'_{nkt}\theta)} g(\theta)d(\theta) \tag{3'}$$

The integral of random preferences is simulated using Halton draws. Given the panel structure, log-likelihood function for the choice experiment data is:

$$log\ E(L) = \sum_{n=1}^{N} logE(P_n{}^*) \quad (5)$$

with

$$P_n{}^* = \prod_{h\epsilon 1}^{H} \prod_{t\epsilon 1}^{T} (P_{nht})^{y_{nht}} \quad (6)$$

where P_{nht} is probability of individual *n* choosing option *h* at time *t*.

	MODEL (1)		MODEL (2)	
CHOICE				
gray	-0.1352	(0.5087)	-0.1352	(0.4249)
hybrid	0.5539	(0.4923)	0.5539	(0.4039)
green	0.7162	(0.4828)	0.7162*	(0.3966)
storm_flood	-0.0121***	(0.0036)	-0.0121***	(0.0033)
nflood_days	-0.0033	(0.0023)	-0.0033*	(0.0020)
good_hab	0.6886***	(0.1819)	0.6886***	(0.1542)
best_hab	0.9095***	(0.2231)	0.9095***	(0.2010)
splost_cost	-0.0009***	(0.0003)	-0.0009***	(0.0003)
Clustered SE	YES		NO	
Observations	2112		2112	

** p<0.10; ** p<0.05; *** p<0.01* *Standard errors in parentheses*

Table D.6. Conditional Logit Models for Riverine Infrastructure

Table D.6 presents results for the basic logit model (equation 3). Model (1) clusters standard errors at the individual level (to permit correlation among error term), while Model (2) employs robust standard error estimates. In both models, "Hybrid" design has the highest utility (relative to "Status Quo" – omitted category) followed by "Green" (which is statistically significant in model (2)). "Gray" is positive (relative to "Status Quo)), but much smaller in magnitude (and not statistically significant). Increasing flood risk probability has a significant and negative effect, while the influence of nuisance flooding is negative, but not significant. "Good" and "Best" habitat provision coefficients are positive (relative to "Poor" – excluded category) and statistically significant. The SPLOT cost parameter is negative and statistically significant.

To provide a quick snapshot of WTP, the researchers can calculate the marginal rate of substitution among risk reduction, habitat provision, and money. This provides the following results:

$MWTP_{storm\_flood}$ = = \$13.38 [95% C.I.: \$4.44 – \$22.33]
$MWTP_{nuisance\_flood}$ = = \$3.68 [95% C.I.: -\$0.61 – \$7.98]
$MWTP_{good\_hab}$ =- = \$761 [95% C.I.: \$249 – \$1270]
$MWTP_{best\_hab}$ =- = \$1010 [95% C.I.: \$400 – \$1610]

On average, subjects are willing-to-pay \$10.63 to reduce the risk of storm-flooding in low-lying areas over the next 30 years by 1%., whereas infrastructure projects that provide for good (best) coastal habitat (relative to poor) are worth \$676 (\$701), on average, per household. Confidence intervals for MWTP are estimated using the Delta Method (2nd order approximation using Taylor series expansion). WTP for a particular infrastructure design can be estimated using the ln-SUM procedure (TBD). **Table D.7** presents estimates for the mixed logit model (which allows the coefficients for "Gray", "Hybrid", and "Green" to vary within the sample of respondents and estimates a 33 variance-covariance matrix for these parameters – thus also permitting correlation).

	MODEL (1)		MODEL (2)	
MEAN				
storm_flood	-0.0170***	(0.0053)	-0.0170***	(0.0049)
nflood_days	-0.0053*	(0.0031)	-0.0053*	(0.0030)
good_hab	1.0951***	(0.2574)	1.0951***	(0.2287)
best_hab	1.3540***	(0.3350)	1.3540***	(0.2988)
splost_cost	-0.0017***	(0.0004)	-0.0017***	(0.0004)
gray	2.1156	(1.4420)	2.1156	(1.3672)
hybrid	3.4356***	(1.2557)	3.4356***	(1.2306)
green	3.5492***	(1.2414)	3.5492***	(1.2100)
Clustered SE	YES		NO	
l11				
Constant	4.8239***	(0.9265)	4.8239***	(0.8152)
l21				
Constant	3.9438***	(0.7137)	3.9438***	(0.7884)
l31				

	MODEL (1)		MODEL (2)	
MEAN				
Constant	3.2181***	(0.6349)	3.2181***	(0.7430)
l22				
Constant	-1.5992***	(0.3540)	-1.5992***	(0.3682)
l32				
Constant	-1.0129***	(0.3693)	-1.0129*	(0.5230)
l33				
Constant	2.3357***	(0.3831)	2.3357***	(0.3721)
Observations	2112		2112	

** p<0.10; ** p<0.05; *** p<0.01* *Standard errors in parentheses*

Table D.7. Mixed Logit Models for Riverine Infrastructure

Preliminary results for marginal WTP from the mixed logit models are:

$MWTP_{storm\_flood}$ = = $10.21 [95% C.I.: $3.85 – $16.57]

$MWTP_{nuisance\_flood}$ = = $3.17 [95% C.I.: -$0.33 – $6.68]

$MWTP_{good\_hab}$ =- = $658 [95% C.I.: $271 – $1050]

$MWTP_{best\_hab}$ = - = $814 [95% C.I.: $375 – $1250]

Natural Infrastructure Design Details:

1. Permeable Pavers: The plan suggests using the PowerBlock® Pervious Paver from ACF Environmental. This permeable paver is designed with 0.25 in gaps between the pavers that can still infiltrate water even when clogged. This is important on Tybee where sand from the beach might fill the gaps in the pavers. Permeable pavers are distributed across the island in parking areas based on the different scenarios.

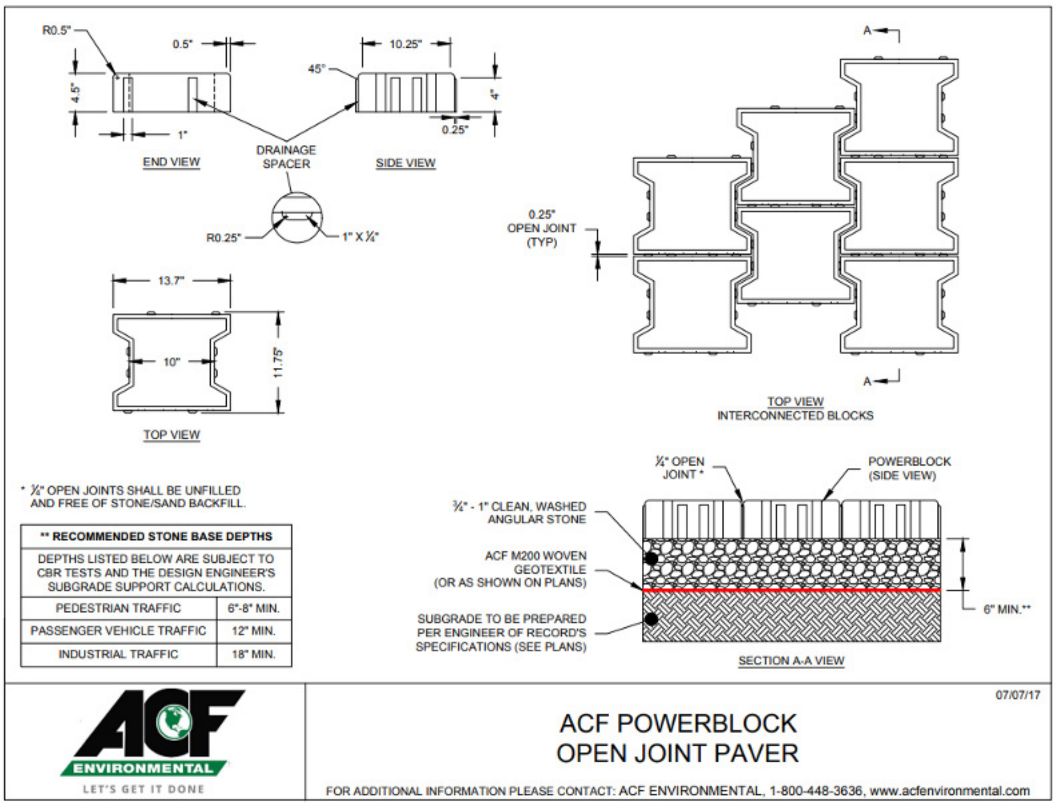


Figure E.1. Design details of the recommended permeable paver from ACF Environmental (ACF Environmental, 2022).

2. 14th Street Bioswale: The swale along 14th street was designed based on recommendations from the Georgia Stormwater Management Manual and the constraints of available space (Atlanta Regional Commission, 2016). The swale is trapezoidal and segmented into 8 sections along 14th Street to accommodate for the connecting roads. The depth of the swale varies according to the depth of the existing stormwater pipes and ranges from 0.8 to 2 ft. The top width was designed based on the available space in the Tybee-owned right-of-way and is 20 ft. The side slopes of the swale segments range from 1:3 to 1:7.5 due to the varying depths.

SECTION	DEPTH	SIDE SLOPE
1	2	1:3
2	0.8	1:7.5
3	1.5	1:4
4	1.5	1:4
5	1	1:6
6	1.5	1:4
7	2	1:3
8	2	1:3

Table E.1. The depths and side slopes of the different sections of the 14th Street Swale.

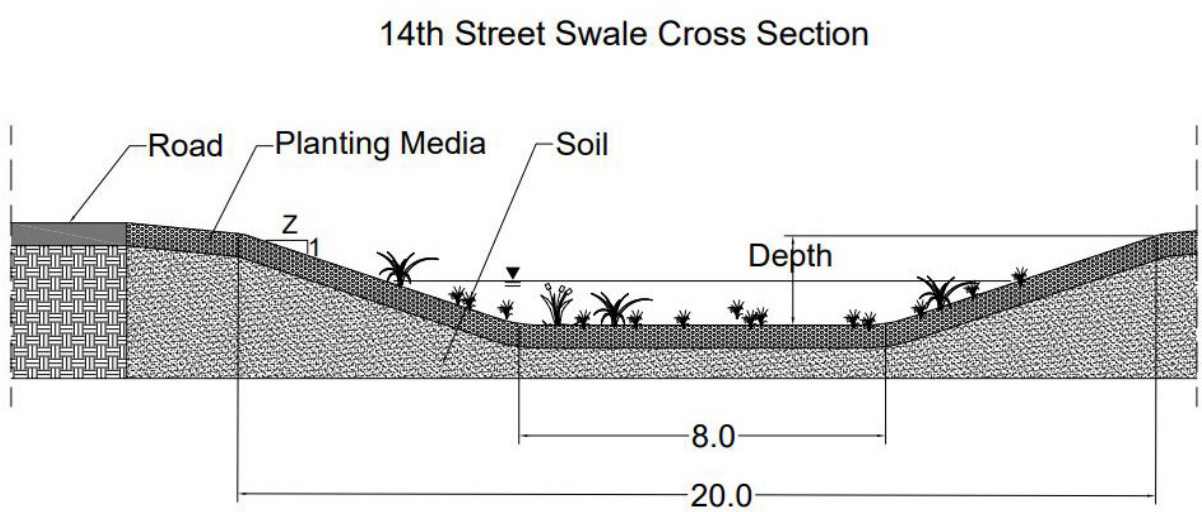


Figure E.2. The depths and side slopes of the different sections of the 14th Street Swale.

3. Curb cut rain garden Design Specifications: The project team has designed rain gardens along both sides of Butler Avenue from 1st Street to Tybrisa Street. The rain gardens are flush with the ground with cuts in the curb that act as inlets that allow flow to enter the area and infiltrate. The curb cut rain gardens provide storage in the form of infiltration, and they can reduce flow velocities by increasing roughness by including vegetation. The plan recommends using modular, prefab HydroPlanter™ rain gardens from GreenBlue Urban. These modular rain gardens are 28 ft. 3 in. size with a three-foot width which is the available space between the sidewalk and road (GreenBlue Urban Limited, 2021). The curb cuts are sized based on the Georgia Stormwater Management Manual

Technical Handbook sizing procedures for a curb-opening inlet (Haubner et al., 2001). Each section of the rain garden has a recommended curb cut length to accommodate the 1-yr flow based on location in **Table A.2**

LOCATION (STREET NAME)	CURB CUT LENGTH (FEET)
Tybrisa to 15th	4
15th to 14th	5
14th to 13th	6
13th to 12th	5
12th to 11th	4
11th to 10th	3
10th to 9th	3
9th to 8th	3
8th to 7th	3
7th to 6th	4
6th to Center St.	4.5
Center St. to 4th	4
4th to 1st	4

Table E.2. The length of curb cut for each section of curb cut rain garden based on location to accommodate the 1-year flow.

4. Horizontal Levee Design specifications: The horizontal levee along Venetian Drive is designed for the purposes of marsh migration and flood protection. The levee begins 20 ft past the outfall at AJ's so that the outfalls were not impaired by the levee. It extends along the road until Venetian turns into 12th Street. In the design, Venetian has raised 1 ft and crowned, and the levee extends approximately 300 ft into the marsh from the edge of Venetian. It impacts 284,874 square feet of the marsh. For horizontal levees, steeper slopes provide more flood protection, but shallow slopes are better for marsh migration. The team opted to use a slope of 1:50 to balance both the flood and marsh protection. **Figure A.3** show the changes to a select cross-section and the extents of the levee.

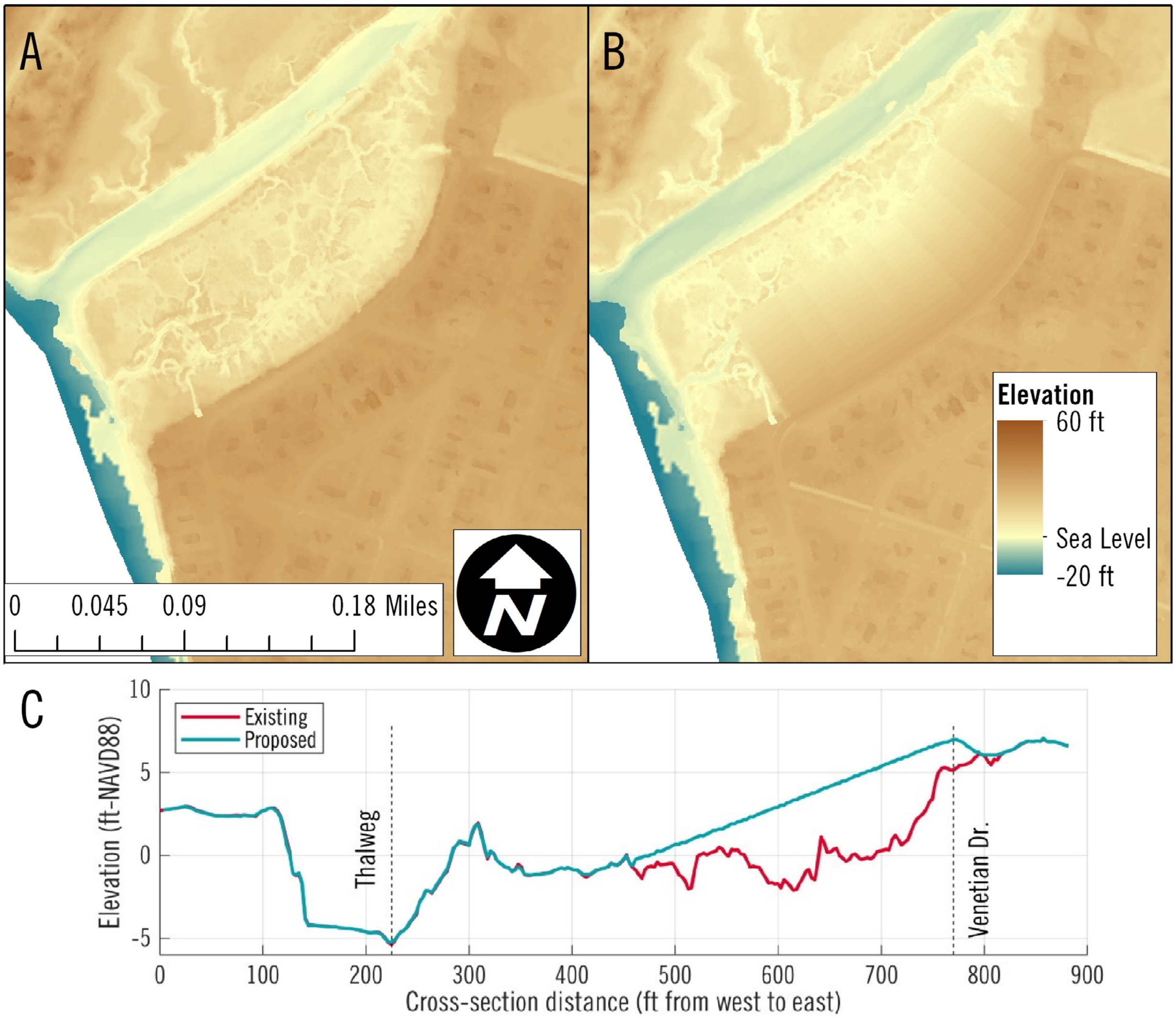


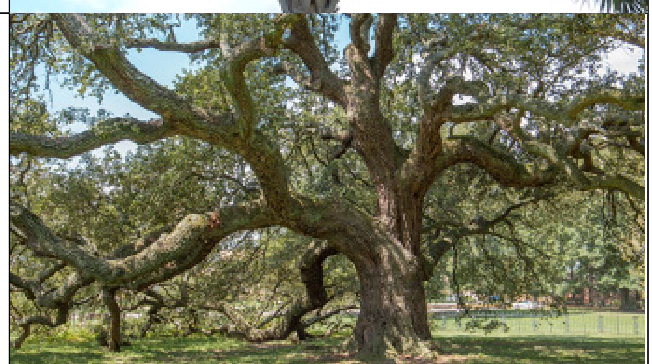
Figure E.3. Aerial view of the marsh under current conditions and with the horizontal levee with the corresponding changes to the drawn cross-section.

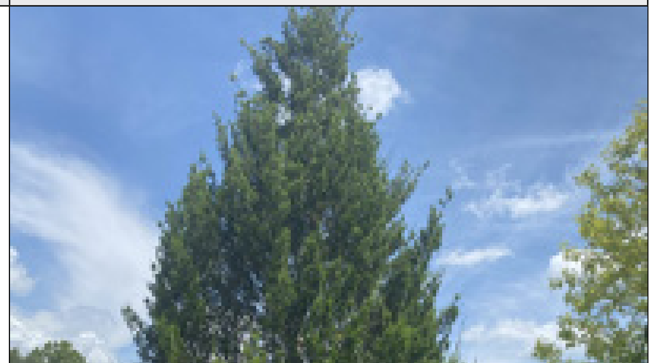
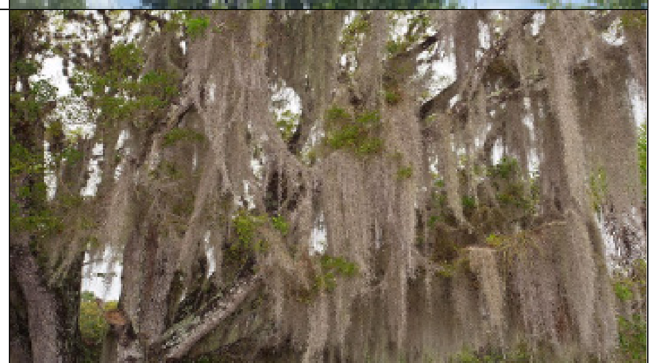
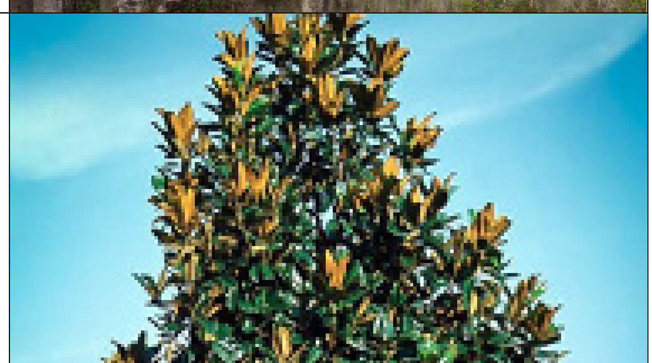
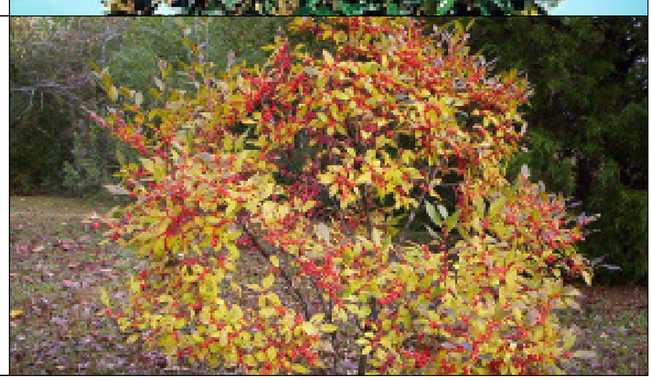
5. 6th street culvert Design: The plan proposes increasing the sizes of the current culverts at 6th Street that connects both marsh regions of Horsepen Creek. It would increase the size from two 30-in-diameter pipe culverts to two rectangular box culverts with dimensions of 8 ft height by 10 ft wide.

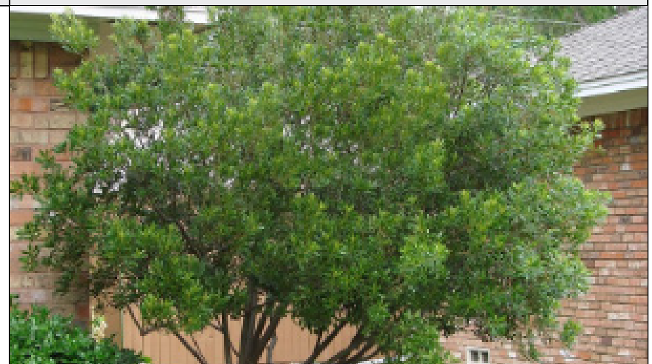
6. Rain harvesting design details: For rain harvesting, the plan recommends storage to accommodate a 0.25 in of rainfall that falls on each building. Based on the average residential roof area, this comes to an average storage amount of 36 cubic feet, corresponding to 5 of 55-gallon containers. For the commercial buildings, the 0.25 in of storage corresponds to 1,300 gallons of storage. For the public buildings, the 0.25 in of storage corresponds to 1,518 gallons of storage. Rain harvesting is distributed across the island based on the different scenarios. However, the residential rain harvesting is centered around 14th Street since this is a low spot prone to nuisance flooding.

7. Pocket Park Design: The pocket park is a location-specific feature and not a distributed one like the others. It is located near the intersection of 15th Street and Butler Avenue. This lot has an unused go-kart track that the plan proposes to be removed, and the land converted to a park that can include local vegetation and increased tree cover. The park is designed to be concave so that any precipitation that falls on it will not flow elsewhere. It has a slope of 0.0015.

Urban Canopy Cover

TREE NAME	IMAGE OF TREE
Cabbage Palm	
Live Oak	
Longleaf Pine	

TREE NAME	IMAGE OF TREE
Southern Red Cedar	
Spanish Moss	
Southern Magnolia	
Sparkleberry	

TREE NAME	IMAGE OF TREE
Wax Myrtle	
Yaupon Holly	

From https://www.tybeemarinescience.org/portfolio_category/plants/

Table E.3. Examples Of Native Trees That Can Be Implemented In Urban Canopy Cover

Bird Species that travel through Tybee as part of migration

From this, try and look into calculations of % endangered population compared to all birds visited.

As of Nov. 27, in a list with all birds, 255 unique species were tracked to have visited Tybee Island. This table is tracking those which are of ecological concern

COMMON BIRD NAME	SCIENTIFIC NAME	CONTINENTAL IMPORTANCE	IUCN RED LIST CATEGORY
Black Rail	*Laterallus jamaicensis*	Red Watch List	Near Threatened
Black Scoter	*Melanitta americana*		Near Threatened
Black-legged Kittiwake	*Rissa tridactyla*		Vulnerable
Blackpoll Warbler	*Setophaga striata*	Common Birds in Steep Decline	Near Threatened

COMMON BIRD NAME	SCIENTIFIC NAME	CONTINENTAL IMPORTANCE	IUCN RED LIST CATEGORY
Buff-breasted Sandpiper	*Calidris subruficollis*		Near Threatened
Chimney Swift	*Chaetura pelagica*	Yellow Watch List D	Vulnerable
Chuck-will's-widow	*Antrostomus carolinensis*	Common Birds in Steep Decline	Near Threatened
Common Eider	*Somateria mollissima*		Near Threatened
Common Grackle	*Quiscalus quiscula*	Common Birds in Steep Decline	Near Threatened
Eastern Meadowlark	*Sturnella magna*	Common Birds in Steep Decline	Near Threatened
Golden-winged Warbler	*Vermivora chrysoptera*	Red Watch List	Near Threatened
Horned Grebe	*Podiceps auritus*		Vulnerable
King Rail	*Rallus elegans*	Yellow Watch List D	Near Threatened
Loggerhead Shrike	*Lanius ludovicianus*	Common Birds in Steep Decline	Near Threatened
Long-tailed Duck	*Clangula hyemalis*	Common Birds in Steep Decline	Vulnerable
Piping Plover	*Charadrius melodus*	Red Watch List	Near Threatened
Red Knot	*Calidris canutus*	Yellow Watch List D	Near Threatened
Reddish Egret	*Egretta rufescens*	Yellow Watch List R	Near Threatened
Rufous Hummingbird	*Selasphorus rufus*	Yellow Watch List D	Near Threatened
Rusty Blackbird	*Euphagus carolinus*	Common Birds in Steep Decline	Vulnerable
Saltmarsh Sparrow	*Ammospiza caudacuta*	Red Watch List	Endangered
Semipalmated Sandpiper	*Calidris pusilla*	Yellow Watch List D	Near Threatened
Wood Thrush	*Hylocichla mustelina*	Yellow Watch List D	Near Threatened

From https://www.tybeemarinescience.org/portfolio_category/plants/

Table E.4. Bird Species that travel through Tybee as part of migration

Note: This list only includes the birds whose IUCN Red List Categories exceed those of Least Concern

With that being said, many birds listed as Least Concern may also show high Climate Vulnerability and/ or have notes on Continental Importance

Statistics:

23/255 birds (9%) of the birds that pass through Tybee Island are listed in the International Union for Conservation of Nature's Red List of Threatened Species. This is a marker of a decline in biodiversity, and the need for wide-scale action to protect these species.

This does not include birds considered "Least Concern" but were listed on the National Audubon Society's database as "Climate Vulnerable" or threatened as on the Partners in Flight Avian Conservation Assessment Database. Therefore, the number of birds that are of concern is much greater.

APPENDIX F: MULTI CRITERIA DECISION ANALYSIS (MCDA) DETAILS

Flood Performance

Flood conditions for the different alternatives were evaluated at each building for the various hydroclimatic combinations. Weights were assigned to each combination based on its frequency of occurrence (e.g., the mean tide with 3 inches of rain was given a much larger weight than the king tide with 7.5 inches of rain). A performance index was calculated by multiplying the maximum depth of inundation and the duration of inundation at each building, then averaging across all buildings. The total percentage of buildings that were inundated was also calculated. These calculations were repeated for each hydroclimatic combination, weighted as described above, and summed for all combinations. Performance indices were computed for both current and projected (those with sea-level rise) conditions. Calculations were repeated to assess flood conditions at critical infrastructure, which included essential public properties such as the police and fire stations, city hall, the public works department, YMCA, 4-H club, and more. Within the relative importance of 0.25 for flood reduction in the entire MCDA, normalized weights were assigned to each of the above sub-criteria as follows: 0.25 each for the performance index and percent of all buildings flooded under current conditions, 0.1 each for the performance index and percent of critical infrastructure flooded under current conditions, and 0.1 and 0.05 for the same sub-criteria, respectively, under future climate conditions.

Habitat Performance

The habitat performance score considers the improvement in connectivity, diversification of habitat, and the total freshwater towards the marsh. The alternatives were assigned a value of 1 if connectivity is worse and a value of 3 if connectivity is better. Alternatives A-D improved connectivity because of the 6th street culvert and were assigned scores of 3 while the X and E alternatives did not improve connectivity and were assigned values of 1. Diversification scores were based on the inclusion of additional habitat for the alternatives and these scores ranged from 1 to 5 where 1 is 'Bad,' 2 is 'Fair,' 3 is 'Good,' 4 is 'Very Good,' and 5 is 'Excellent.' The X alternative was assigned a score of Fair based on current conditions. The A-D scenarios were all assigned a value of Excellent because the features that provide habitat, 14th Street swale and curb cut rain gardens, are included in each of these four alternatives. The E alternative was assigned a score of Fair because there is no increase in habitat with improvement only the gray features. The freshwater towards the marsh criterion quantifies the amount of rainfall-runoff that enters the marsh system during a rainfall event. The outflow from 14 different stormwater outfalls was considered for the different alternatives using the various rainfall events and mean tidal conditions. These outfalls are located on the back end of the island going from Venetian Dr. to Butler Ave. Scores closer to 1 represent that the alternative delivers the most freshwater to the marsh ecosystem, thus altering the health of the system by potentially introducing inland pollutants, such as oil, debris, and waste. Conversely, scores closer to 5 represent that the alternative delivers less rainfall-runoff to the marsh system.

Cost

For the MCDA approach, the same coastal features and gray infrastructure improvements were included in each alternative. Therefore, the project team estimated the cost to implement the inland natural infrastructure for the MCDA since this is what changed among the scenarios. For the cost of rain harvesting, the project team used the average rainfall storage volume to determine the number and size of rain barrels required. For the residential area, this came to five 55 gallon containers which cost $160 per barrel (National Tank Outlet, 2022). For the public and commercial areas, the project team used just one large storage container which cost $1,500 and $1,400 respectively (National Tank Outlet, 2022). For the cost of implementing the pocket park and the swale, the project team estimated the cost to excavate the land to provide the additional surface storage. The project team used a cost value of $2.33/ft3 of earth moved (USDA FOREST SERVICE NORTHERN REGION ENGINEERING, 2020). To estimate the cost of permeable pavers, the project team considered the cost of excavation, permeable pavers, and underlying aggregate. These costs were calculated per square foot and were $1/ft2, $7.5/ft2, and $3.67/ft2, respectively (CTC & Associates LLC & WisDOT Research & Library Unit, 2012). To calculate the cost of implementing the curb cut rain gardens, the project team researched the average costs of rain gardens in the literature. They found a cost of $1.09/ft3 for installation and operation and maintenance (Nordman et al., 2018). They applied a factor of 1.4 to account for the cost of modifying the curbs and sidewalks in construction. These cost estimates are preliminary and were used as a comparison in the MCDA approach. The specific costs associated with each scenario are expected to change as the designs become more detailed in future phases of the project.

Aesthetics

The improvement to aesthetics from the features in each alternative was scored from 1 to 5 where 1 is 'Bad,' 2 is 'Fair,' 3 is 'Good,' 4 is 'Very Good,' and 5 is 'Excellent.' The do nothing alternative (X) was given a score of Fair based on current conditions. The A alternative was assigned a score of Very Good because it includes the swale and permeable pavers along 14th Street and the curb cut rain gardens down Butler which include vegetation that would improve the aesthetics. The B alternative was assigned a score of Good because while the features in A are included and would improve aesthetics, the rain barrels required for rain harvesting would reduce the aesthetics of the residential area. The C alternative was given a score of Excellent because the commercial harvesting would only be on a few buildings and the addition of permeable pavers in commercial parking lots would be an aesthetic improvement from the asphalt in addition to the features in the A alternative. The D alternative also has a score of Very Good because it includes the residential rain harvesting barrels. The E alternative was given a score of Bad because the proposed gray includes an exposed pump on 14th St that would be visible to residents.

Feasibility

The feasibility scores are based on the cost of implementation and the property type considered in each scenario. Feasibility scores range from 1 to 5 where 1 is 'Unlikely,' 2 is 'Less Likely,' 3 is

‘Somewhat Likely,’ 4 is ‘Likely,’ and 5 is ‘Very Likely.’ The X alternative was assigned a score of ‘Unlikely’ because the City of Tybee is committed to protecting the island and its residents from the threat of flooding and sea-level rise. The A alternative scored Very Likely because all of the inland green infrastructure features are on public-owned property where there are few barriers to implementation. The B and C alternatives scored Somewhat Likely because both scenarios involve persuading property owners, either residents or owners of commercial property, to implement inland features. The D alternative scored Less Likely because convincing both residents and owners of commercial properties to implement the inland features will be more difficult. The E scenario scored Likely because the proposed gray improvements are likely to occur as a part of Tybee’s Stormwater Master Plan.

Modeling Description:

Environmental Conditions

Alternatives were tested across various combinations of rainfall depths, tides, and a future projection for sea-level rise (**Table A3**). Rainfall depths included 3, 4.5, 6, 7.5, and 9 inches and were applied as 24-hour, SCS Type-III storms, consistent with typical conditions along the Georgia coast (USACE, 2000). These storms correspond to approximately >100%, 100%, 20%, 10%, and 4% annual exceedance probabilities, respectively, under current conditions (NOAA, 2017). Four different tidal conditions were considered: neap, average, spring, and perigean spring tides (a.k.a., king tides). The mean tide condition represents the average tidal amplitude within a 14-day tidal period. The spring and neap tidal conditions are related to the new or full mone once every 14 days, with the spring tide being the highest tidal amplitude and the neap the lowest, while the perigean spring tides occurs when the moon is either new or full and closest to Earth. Mean and spring tides (amplitudes 3.85 and 5.81 feet, respectively) were simulated for all storm depths, with peak tide and rainfall occurring simultaneously. Neap and perigean spring tidestides (amplitudes 2.77 and 6.63 feet, respectively) were simulated for the 7.5 inch storm to investigate marsh connectivity across a broader range of tides. The perigean spring tide value was obtained from the most recent event at the Ft. Pulaski tide gauge (November 4-6, 2021). Sea-level rise was applied to select mean and spring tidal conditions using the intermediate projection for the Southeast US in 2050 (1.18 feet; Sweet et al., 2022). **Figure F.1** summarizes all the coastal boundary conditions utilized in this study.

RAINFALL DEPTH (IN.)	TIDES				SEA LEVEL RISE	
	NEAP TIDE	MEAN TIDE	SPRING TIDE	PERIGEAN SPRING TIDE	MEAN + SLR	SPRING + SLR
3		x	x		x	
4.5		x	x		x	
6		x	x		x	
7.5	x	x	x	x	x	x
9		x	x		x	x

Table F.1. *Summary of rainfall and coastal conditions that were simulated for the existing infrastructure system and each selected alternative*

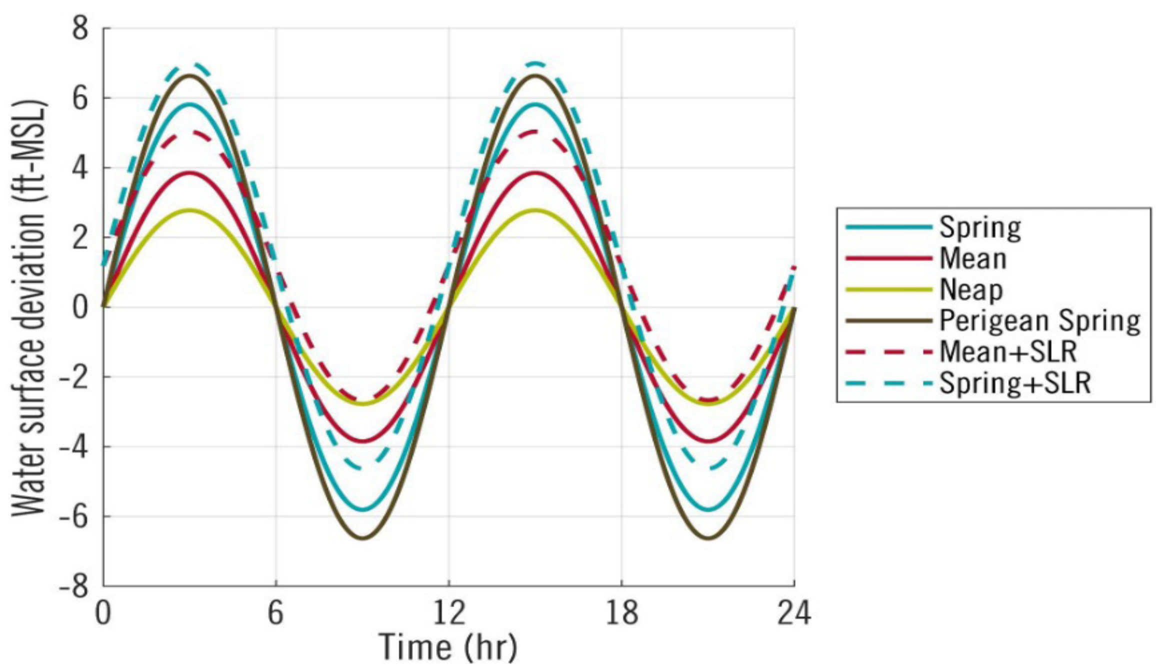


Figure F.1. *Graphical illustrations of the coastal forcings employed at the hydrodynamic model.*

Hydrodynamic Model

Hydrodynamic models for each of the described alternatives were prepared with the computer software Interconnected Channel and Pond Routing (ICPR). ICPR is a parameterized and integrated hydraulic and hydrologic modeling software capable of simulating compound flooding from rainfall and tidal forcing conditions. Rainfall was spatially invariant throughout the domain and tidal flux was applied at model boundaries. Models include a 2D overland flow region with mesh of the island and marsh topography parameterized by land use and soil conditions. Stormwater sewers are integrated into the overland mesh with link-node networks. Models also include a 2D groundwater region with meshes for a bedrock confining layer and water table. Infiltration was modeled with the Green-Ampt equation and the conservative assumption of no leakage through a bedrock confining layer.

Two different sets of initial conditions were applied depending on whether or not sea-level rise was considered. In the case of current environmental conditions, models were initialized with a mean sea level stage in the marsh, groundwater table, soil hydraulic conductivity, and soil porosity index. All of which change dynamically with space and time during a simulation. Sea-level rise simulations differ with a higher initial stage in the marsh; however, the water table elevations and soil properties were not updated with different initial conditions.

All simulations can be divided into pre-rainfall, rainfall, and post-rainfall time periods. The pre-rainfall time period allows for multiple tidal cycles and the post rainfall time period allows for extended hydrologic response times. In total, each simulation lasts for eighty-seven hours or 3.625 days. Twenty-seven hours of tides moved through the system before rainfall began to establish antecedent conditions. Rainfall occurred for 24 hours, then the simulation continued for 36 hours after the end of rainfall. Model data are recorded at 15-minute intervals throughout a simulation.

The coastal processes were imposed into the hydrodynamic model by a time-varying water level boundary condition. To simplify the complex behavior of the tides, a sinusoidal tide was created with a constant-amplitude, single-frequency signal. This was achieved by using a tidal resynthesis analysis of observed data from a complete tidal cycle (e.g., approximately 14 days) at the NOAA Fort Pulaski tidal gauge. This technique recreates the water surface elevation due to the amplitude, phase, and speed of several (e.g., 37) harmonic tidal constituents (Pugh and Woodworth, 2014). Tidal amplitudes were computed as one-half of the daily tide range (i.e., maximum daily level minus minimum daily level). The amplitude and diurnal tide behavior typify conditions of the Southeastern and Georgia coast, respectively (Davies, 1964).

Modeling Results

Alternative B improved flood protection over the existing stormwater infrastructure, which the project team quantified as the number of fewer houses flooded. They subset results by inundation depth and duration and focused on the first 1.5 inches of flooding. For maximum inundation depth, minor improvements (up to 15 buildings, 4.8% improvement from base flooding) occurred for buildings with minor improvements (up to 15 buildings, 4.8% improvement from base flooding) occurred for buildings with 0.5 to 1.5 inches of inundation. Compared to the base scenario, the number of buildings with up to 0.5 inches and 0.5 to 1.5 inches of inundation was reduced by 130 and 51 (8.0% and 13.8% improvement), respectively, during a spring tide with sea-level rise. However, there was a reciprocal increase in the number of buildings with more than three inches of inundation, indicating that the spring tide with sea-level rise may have overwhelmed the hybrid stormwater infrastructure, exacerbating flooding at some locations (Figure F.2b). For flooding duration, the number of buildings flooded for up to one hour during a mean tide with sea-level rise was reduced by 70 (13.3% improvement; Figure F.2d). Most of the flood improvements occurred in buildings on the southern portion of the island, with 63 fewer buildings (20.3% improvement in that portion) inundated up to 0.5 inches during a 6 inch storm (Figure F.3). The flooding improvements in the southern portion accounted for 90% of island-wide benefits for that scenario. This indicates potential promise for flood protection since most hybrid infrastructure was implemented in the southern portion of Tybee Island to target flood-prone areas. Some buildings did experience increased flood duration in the mean tide and sea-level rise scenario, as evidenced by the negative bars in the other duration classes (Figure F.2c,d). However, these were often fewer than the improvements to flooding up to one hour, meaning alternative B provided a net reduction in the number of flooded houses. Future modeling will use locations of the buildings with worsened flooding to integrate additional natural infrastructure to mitigate these impacts.

The previous results have discussed flood improvements for the hybrid alternative B, not isolating the individual effects of natural infrastructure. Compared to the gray infrastructure (alternative X), alternative B provided similar trends in improvements as to the base condition, with the greatest benefits occurring for buildings inundated up to one inch or for up to one hour. The hybrid system was most beneficial for maximum depth during the 6 inch storm (75 fewer houses with up to 1 inch inundation; 3.9% improvement) and for flood duration during the 7.5 inch storm (113 fewer hours with up to an hour inundation; 8.3% improvement). Alternative B provided similar benefits among all tidal conditions, reducing the number of buildings inundated up to 1 inch by about 50 (2.5% improvement) and the number of buildings flooded up to one hour by 105-114 (8.1-8.8% improvement). Similar to the prior comparisons to the base condition, some buildings did experience increased flood duration, although these were fewer and in the more extreme classes. These buildings will be identified as target locations for subsequent modeling and refinement of natural infrastructure.

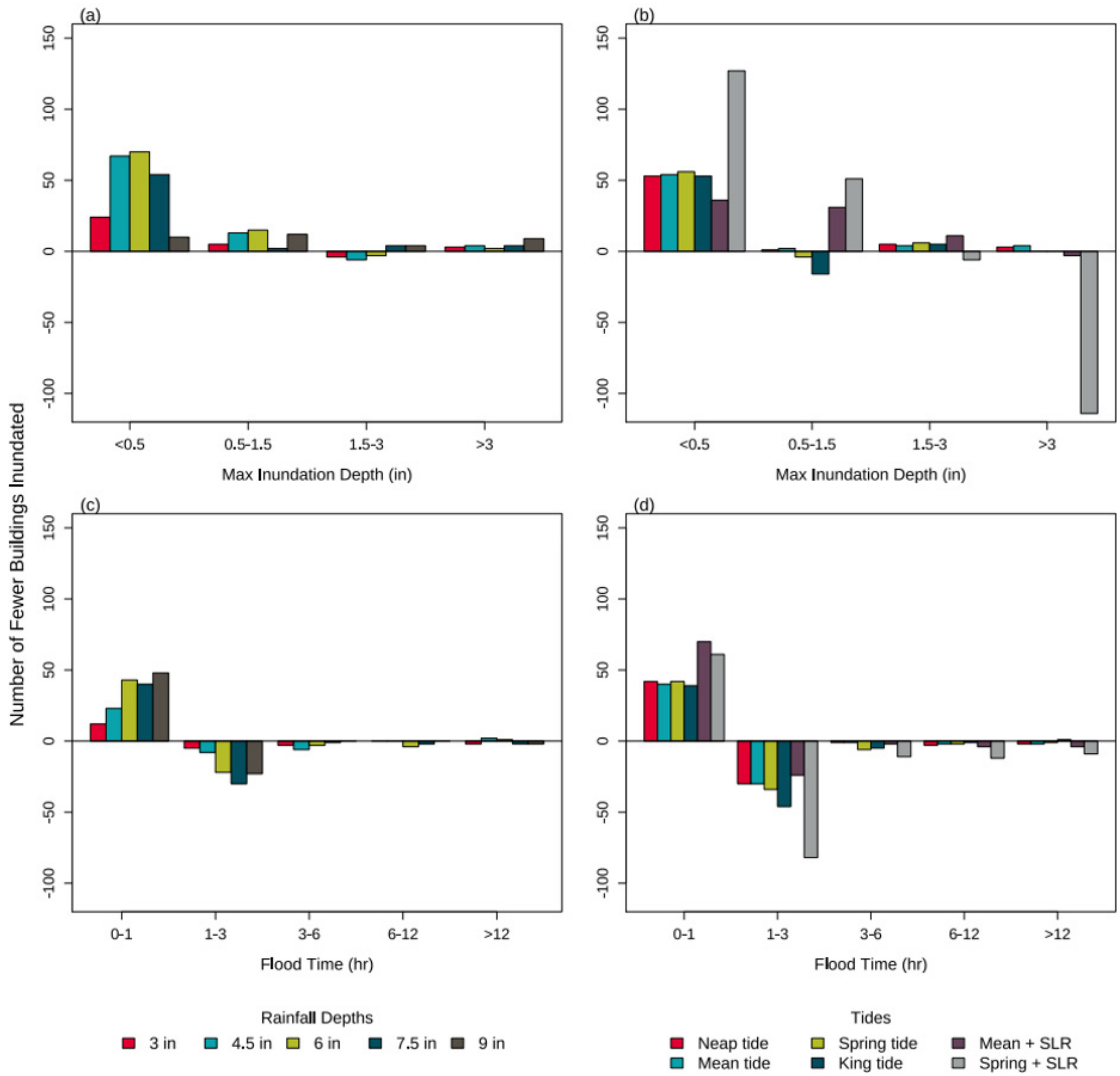


Figure F.2. Flood performance of alternative B compared to the base condition X, as the number of fewer buildings inundated in each class of flood depth (a-b) and flood duration (c-d). Panels (a) and (c) show results for the mean tide at various rainfall depths, while panels (b) and (d) show results across the different tidal conditions for 7.5 inch storms. Flood duration was counted only for buildings with 0.5 to 1.5 inch of inundation. Negative values indicate an increase in the number of buildings inundated.

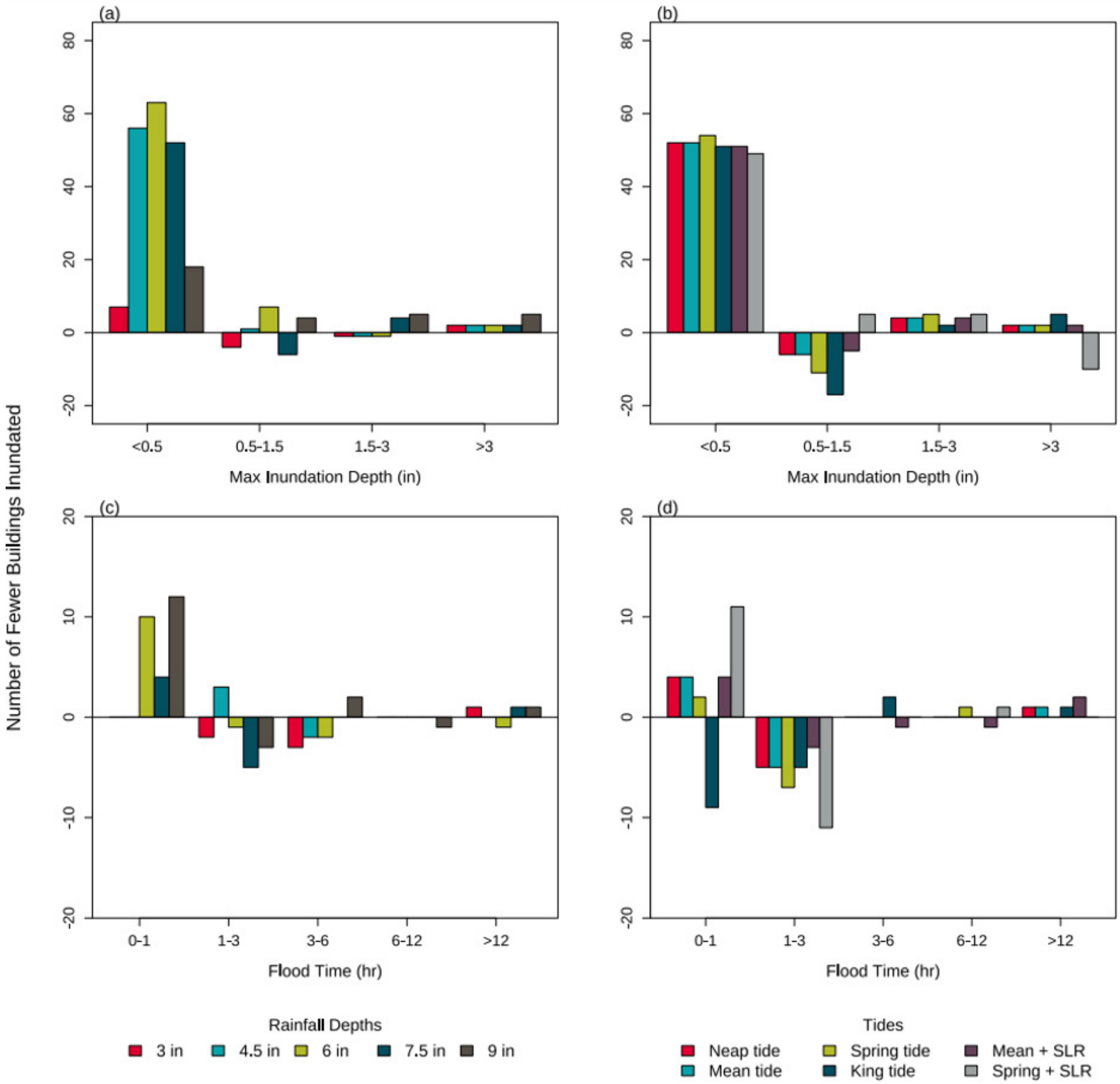


Figure F.3. Flood performance of alternative B compared to the base condition (X) for the southern portion of the island, as the reduction in the number of buildings in each class of flood depth (a–b) and flood duration (c–d). els (a) and (c) show results for the mean tide at various rainfall depths, while panels (b) and (d) show results across the different tidal conditions for 7.5 inch storms. Flood duration was counted only for buildings with 0.5 to 1.5 inch of inundation. Negative values indicate an increase in the number of buildings inundated.

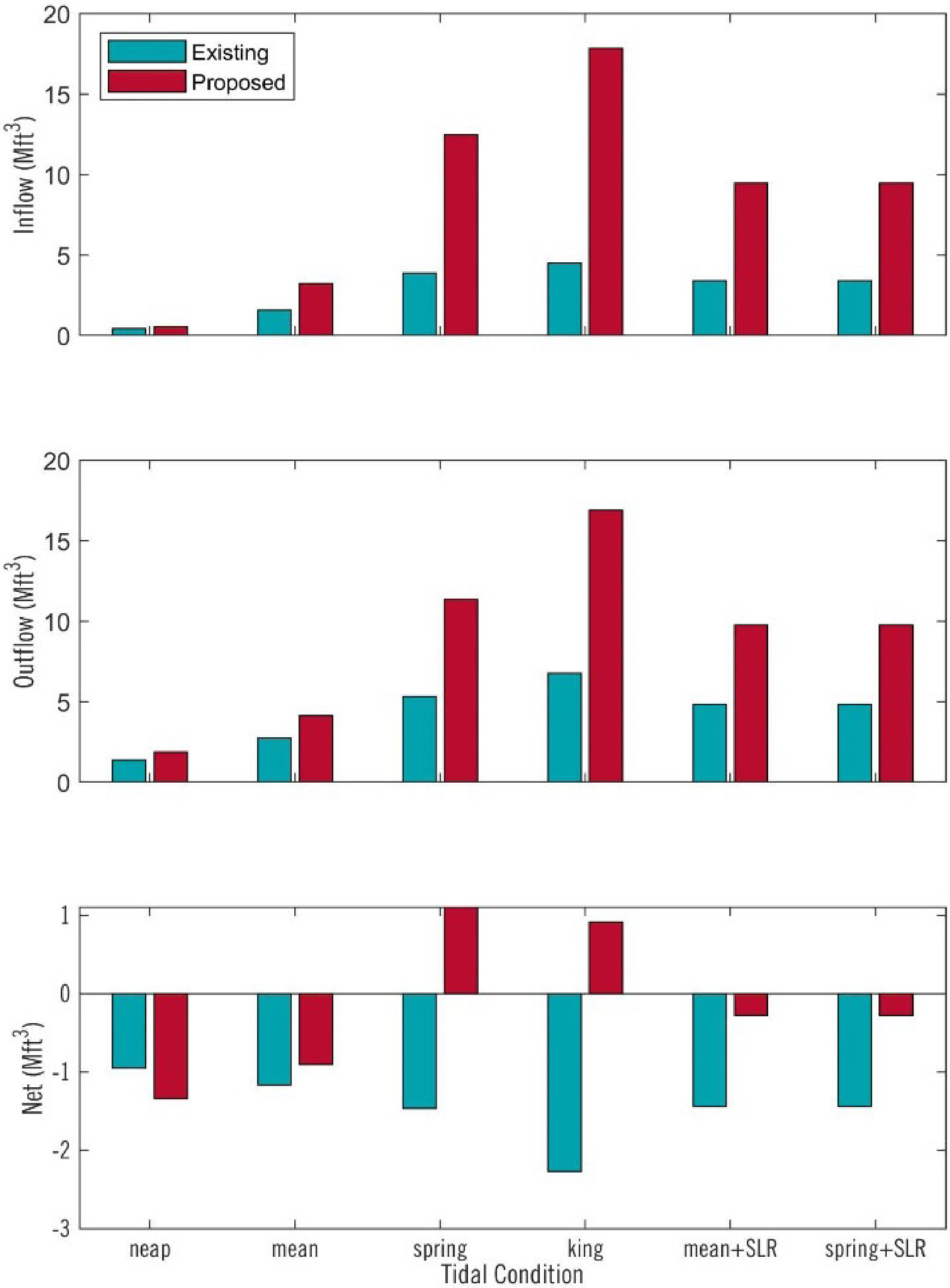


Figure F.4. Average net volume through the downstream and upstream end of the culvert at 6th Street for different tidal conditions using a 7.5 inch rainfall event. The different color bars represent the different alternatives. A negative net volume represents that water is moving out of the system, while a positive that water is moving into the system.

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