QUANTIFICATION OF FLOOD EVENT FORCING AND THE IMPACT OF NATURAL WETLAND SYSTEMS: GREAT BAY BOULEVARD, OCEAN COUNTY, NEW JERSEY

This report was developed by the U.S. Army Corps of Engineers Institute for Water Resources in partnership with the U.S. Army Corps of Engineers Philadelphia District, Stockton University Coastal Research Center, and Barnegat Bay Partnership in accordance with a grant from the Federal Highway Administration (FHWA), Green Infrastructure Techniques for Coastal Highway Resilience, 2016-2017 Pilot Program. The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of FHWA or the U.S. Department of Transportation.

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This report documents a pilot project sponsored by the Federal Highway Administration (FHWA) in partnership with the US Army Corps of Engineers, Stockton University, and the Barnegat Bay Partnership. It is one of five pilot projects FHWA sponsored to assess the potential for natural infrastructure to protect specific locations along coastal roads and bridges. More information can be found at: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/index.cfm</td></tr>
<tr><td colspan="4">16. Abstract
Great Bay Boulevard, located on the Tuckerton Peninsula in Ocean County, NJ, is a coastal roadway experiencing increased closures due to flood events. The project team explored the use of green infrastructure solutions that could simultaneously mitigate future roadway flooding and maintain marsh health over time. Thin layer placement of sediment could raise the marsh platform elevation in vulnerable locations along the road. A combination of oyster beds and native plants could be placed along the marsh edge to reduce overall wave energy at the site.</td></tr>
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EXECUTIVE SUMMARY

In July 2016, the U.S. Army Corps of Engineers Institute for Water Resources (USACE-IWR) was awarded a Federal Highway Administration (FHWA) grant to analyze how green infrastructure, or nature-based infrastructure, can help protect Great Bay Boulevard in Ocean County, New Jersey from flooding due to severe storms and sea-level rise. This study builds upon coordination done by the Systems Approach to Geomorphic Engineering (SAGE) program, which convened stakeholders and identified locations within the Barnegat Bay region that could benefit from nature-based infrastructure. Great Bay Boulevard was one of those locations.

Results from the study include an empirical understanding of what causes Great Bay Boulevard to flood, a survey of the surrounding salt marsh ecosystem, and two conceptual designs that intend to simultaneously reduce flood risks and improve ecosystem functions. The designs were evaluated relative to anticipated protection against future coastal impacts, implementation benefits and challenges, and lessons learned from prior marsh management studies and USACE green infrastructure projects in New Jersey.

This project was led by a multidisciplinary team from the USACE Institute for Water Resources (IWR), USACE Philadelphia District, Stockton University Coastal Research Center (CRC), and Barnegat Bay Partnership (BBP), with the support of several other partners.

Problem and Context

New Jersey's coastal bay shorelines are susceptible to flooding and storm surge. In 2012, Hurricane Sandy demonstrated this vulnerability by inundating many back-bay communities and causing significant structural damage. Communities within the Barnegat Bay watershed are still recovering five years after Sandy's landfall. Since the historic storm, these communities have sought techniques for reducing their vulnerability by preparing for anticipated climate change and the possibility of more frequent and intense flooding.

Coastal roadways often serve as evacuation routes, so protecting them from severe storms is critical to human safety. However, due to local sea-level rise, New Jersey's coastal roads are flooding even during routine events such as northeasters and high tides. In addition to safety concerns, frequent loss of access hurts local economies by limiting activities such as fishing, recreation, and research.

Great Bay Boulevard, located on Tuckerton Peninsula in Ocean County, is a coastal roadway experiencing increased closures due to flood events. Great Bay Boulevard extends approximately five miles along the peninsula, surrounded by a natural salt marsh ecosystem on both sides. Great Bay Boulevard provides access to several popular marinas, the Great Bay Boulevard Wildlife Management Area, and the Rutgers University Marine Field Station. This study focused on identifying factors that cause Great Bay Boulevard to flood and determining how the marsh can provide natural protection to the road. Through this research, the project team explored the use of green infrastructure solutions that could simultaneously mitigate future roadway flooding and maintain marsh health over time.

Methods

Field research was conducted at two sites along Great Bay Boulevard that flood regularly during storm events. Data collection included local meteorological information, wave spectra in nearby bays, water levels on the marsh surface, sediment cores, plant density and diversity, marsh bearing capacity, and density of faunal species known to disturb the marsh surface.

The project team presented results from the field research at a Partnership Workshop in September 2017. Partnership members included federal, state, and local planners, regulators and resource managers, dredging experts, academic scientists, and consulting engineers. Based on the research results and knowledge of the area, workshop participants discussed opportunities and challenges for using green infrastructure at the Great Bay Boulevard site. Workshop feedback led to the development of two concepts designed to protect the roadway and marsh together as a unified system. These concepts intend to re-establish natural coastal processes and become self-sustaining over time.

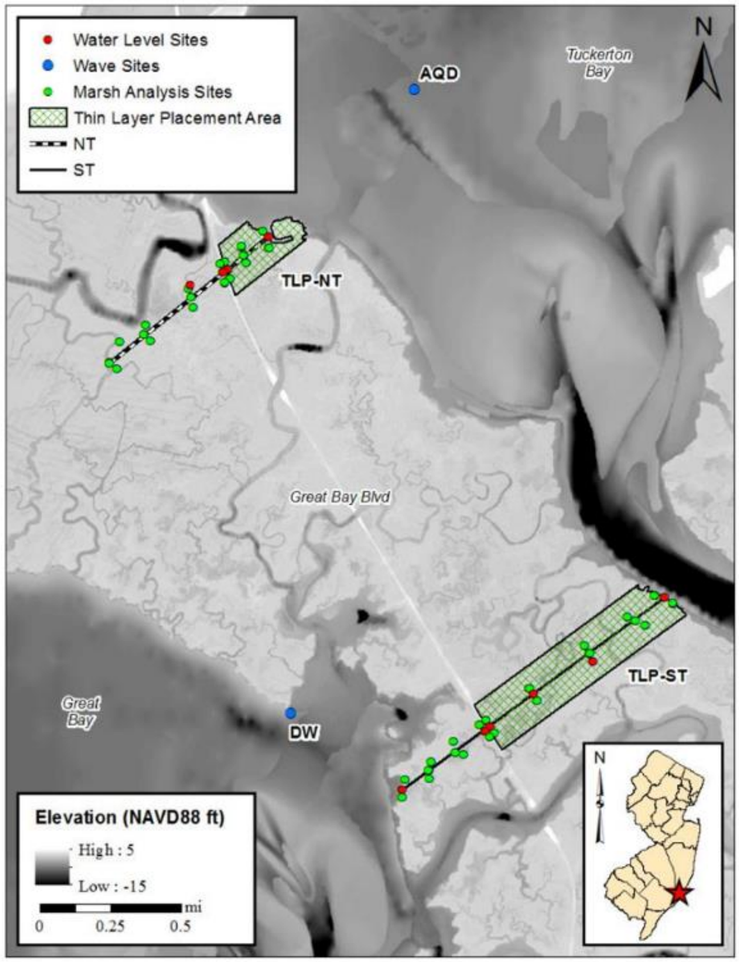
Adaptation Options

<u>Thin Layer Sediment Placement</u>: Thin layer placement of sediment could raise the marsh platform elevation in vulnerable locations along Great Bay Boulevard. Because of low tidal range at the site, raising the marsh platform can reduce the frequency and duration of flooding by shifting Mean High Water and Mean Higher High Water elevations. Sediment placement may also reduce marsh edge erosion and help the marsh keep pace with sea-level rise. This design would incrementally place dredged material in two areas adjacent to Great Bay Boulevard. The placement would eventually achieve a cumulative thickness of 1.00 ft in each area, with total volumes of 44,000 cubic yards (CY) and 150,000 CY respectively. Replenishment would be required periodically to keep up with trends in sea level.

<u>Natural Sill or Living Reef and Marsh Plantings</u>: A combination of nature-based barriers and native plants could be placed along the marsh edge to reduce overall wave energy at the site. Nature-based barriers may include marsh sills, oyster and clam beds, or concrete oyster castles (living reefs). Wave attenuation provided by this hybrid green and gray approach could reduce both marsh edge erosion and water levels at the roadway, while providing a secondary benefit for aquaculture.

Conclusions and Next Steps

This study was a valuable exploration of nature-based design solutions to protect a coastal roadway from flooding hazards that will likely worsen with the effects of climate change. The project benefitted from taking a systems approach to coastal resilience, which sought to understand the relationship between the road and surrounding ecosystem and create options that could sustain them both over time. The experiences and perspectives of regional experts were extremely helpful in building community support and deciding among design options. While there are challenges for implementing coastal green infrastructure in New Jersey, the concepts developed and stakeholder outreach initiated during this study will help inform decisions for how this and similar sites are addressed in the future.



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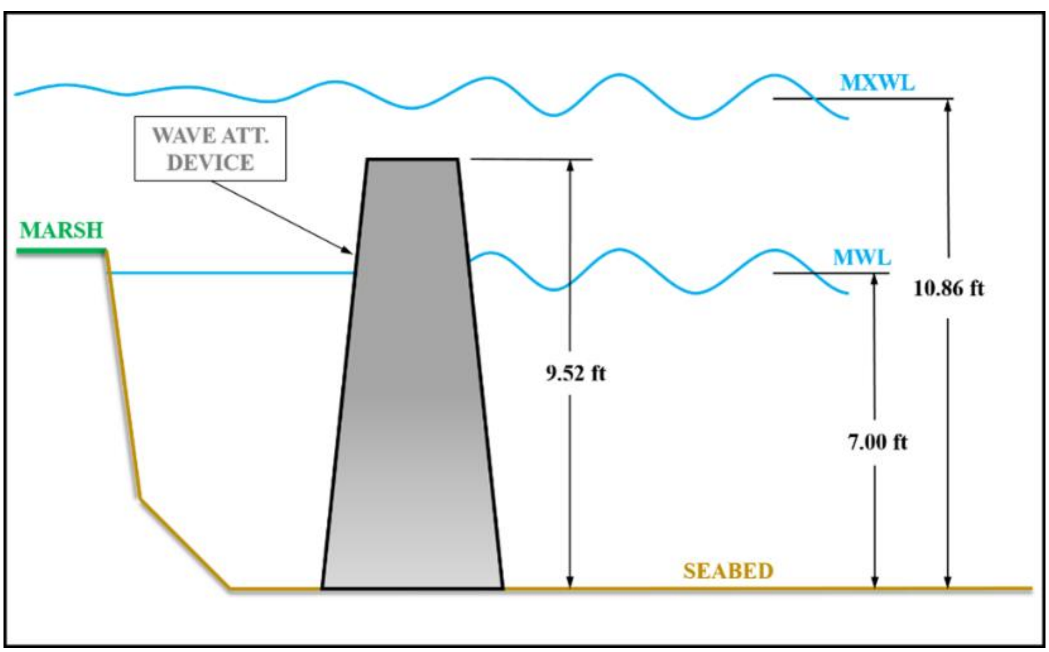

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ES 1a and 1b. Conceptual green infrastructure design options for Great Bay Boulevard to address roadway flooding, marsh erosion, and sea level rise.

INTRODUCTION

New Jersey's coastal bay shorelines are susceptible to flooding and storm surge. In 2012, Hurricane Sandy demonstrated this vulnerability by inundating many back-bay communities and causing significant structural damage. Communities within the Barnegat Bay watershed are still recovering five years after Sandy's landfall. Since the historic storm, these communities have sought techniques for reducing their vulnerability by preparing for anticipated climate change and the possibility of more frequent and intense flooding.

Coastal roadways often serve as evacuation routes, so protecting them from severe storms is critical to human safety. However, due to local sea-level rise, New Jersey's coastal roads are flooding even during routine events such as northeasters and high tides. In addition to safety concerns, frequent loss of access hurts local economies by limiting activities such as fishing, recreation, and research.

Great Bay Boulevard, located on Tuckerton Peninsula in Ocean County, is a coastal roadway experiencing increased closures due to flood events. Great Bay Boulevard extends approximately five miles along the peninsula, surrounded by a natural salt marsh ecosystem on both sides. Between 2002 and 2012, the annual number of hours of roadway flooding increased, ranging from 25 hours in 2002 to over 100 hours in 2009 (Howell, 2017). Great Bay Boulevard provides access to several popular marinas, the Great Bay Boulevard Wildlife Management Area, and the Rutgers University Marine Field Station – road closures inhibit this access and prevent activities that are important to the local community.

Great Bay Boulevard was selected for this study because it provides an opportunity to explore a systems approach to coastal resilience, which seeks to maintain and enhance the functions of both our built infrastructure and the surrounding ecosystem. At Great Bay Boulevard, a healthy marsh is critical for long-term maintenance of the road. The marsh buffers flooding, and where the marsh collapses, the road may be undermined. Mitigating floods with traditional protection techniques, such as elevating the road, may harm the surrounding ecosystem by altering hydrology or degrading the marsh surface. Instead, we pursued a flood risk reduction strategy that considers the relationship between the road and marsh, and seeks to reduce the overall vulnerability of both.

In that regard, this study focused on identifying factors that cause Great Bay Boulevard to flood and determining how the marsh can provide natural protection to the road. Through this research, the project team explored the use of green infrastructure solutions that could simultaneously mitigate future roadway flooding and maintain marsh health over time.

PROJECT TEAM

This study was a collaborative effort between USACE-IWR, USACE Philadelphia District, Stockton University CRC, and the BBP. USACE staff managed the project, while CRC and BBP staff conducted field research and analysis. The team jointly prepared this report, with input from other partners and regional stakeholders.

The internal project team included:

- Bari Greenfeld, USACE-IWR
- Heather Jensen and Jeffrey Gebert, USACE Philadelphia District
- Kimberly McKenna and Nicholas DiCosmo, Stockton University CRC
- Martha Maxwell-Doyle, James Vasslides, and Erin Reilly, BBP

The full group of project partners included representatives from:

- Barnegat Bay SAGE Community of Practice
- US Fish and Wildlife Service (USFWS)
- New Jersey Department of Environmental Protection Divisions of Fish and Wildlife and Land Use Management, (NJDEP-F&W; -Land Use)
- New Jersey Department of Transportation Office of Maritime Resources (NJDOT-OMR)
- Jacques Cousteau National Estuarine Research Reserve (JCNERR)
- Rutgers University Marine Field Station (RUMFS) and Center for Remote Sensing and Spatial Analysis (CRSSA)
- County and municipal agencies (Ocean County Mosquito Extermination Commission and Township of Egg Harbor)
- Consulting firms (T&M Associates)
- North Jersey Transportation Planning Authority (NJTPA)
- FHWA-New Jersey

PROJECT SCOPE & GOALS

This study identified physical factors that initiate flooding on a low-lying coastal roadway and evaluated the suitability of natural and nature-based solutions. The project site was selected in an area that is currently experiencing impacts from storm surge and nuisance flooding. The project team conducted field research at two locations along the road that are known to flood, collecting data on conditions during flood events and surveying the health of the surrounding marsh. The project team presented analysis of this data to a group of regional experts and stakeholders at a Partnership Workshop, where the team collected feedback from participants regarding the opportunities and obstacles for using green infrastructure at the site. This feedback informed the development of design concepts intended to simultaneously reduce flooding hazards and provide resilience benefits for the marsh. Four conceptual green infrastructure design concepts were developed for Great Bay Boulevard, and based on an initial feasibility analysis, two were selected for further evaluation. The result of this study is an overview of the two selected design options. The two selected options were evaluated relative to anticipated protection against future coastal impacts, implementation benefits and challenges, and lessons learned from prior marsh management studies and USACE green infrastructure projects in New Jersey.

The overall goal of the project was to provide recommendations for the use of green infrastructure solutions to lessen the frequency and severity of flooding along Great Bay Boulevard. To meet this goal, the project team achieved the following objectives:

a. Determined the physical parameters that initiate flooding in order to ascertain how extreme coastal events (e.g. northeast storms and spring high tides) affect roadway flooding;
b. Described the overall condition and influence of a natural wetland system in buffering high water events;
c. Determined if a minimum marsh width is necessary to protect the roadway during high water events; and
d. Considered green infrastructure options to protect the roadway from flooding and maintain marsh health.

STUDY AREA

Great Bay Boulevard is located on Tuckerton Peninsula in Little Egg Township, Ocean County, New Jersey. The State of New Jersey constructed this two-lane road in 1931, and it is now under Township jurisdiction. Great Bay Boulevard extends approximately five miles along the peninsula, surrounded by a natural salt marsh ecosystem on both sides. County-owned bridges span several tidal creeks that intersect the roadway. Great Bay Boulevard provides access to several popular marinas, the Great Bay Boulevard Wildlife Management Area (total acreage = 5,976.43), and the Rutgers University Marine Field Station. Roadway elevations are only slightly higher than marsh elevations, so much of the area becomes flooded during high water levels (Figures 1 and 2).

Figure 1. View of Great Bay Boulevard from Big Thorofare bridge on November 9, 2016 during normal tidal conditions and showing a dry (not flooded) roadway.

Figure 2. View of Great Bay Boulevard roadway flooding and flooded marsh from Big Thorofare bridge one day after the passage of a northeast storm (January 24, 2017).

Tuckerton Peninsula is located at the southern extent of the Barnegat Bay watershed, which the U.S. Environmental Protection Agency has designated as an Estuary of National Significance. Tuckerton Peninsula is also located within the Jacques Cousteau National Estuarine Research Reserve (JCNERR), which is a sentinel site for monitoring the effects of climate change (Kennish et al, 2014a; Kennish et al, 2014b). The tidal marshes on either side of Great Bay Boulevard vary in width from less than 0.3 miles (mi) to nearly 1.25 mi. The marsh plant community is *Spartina* dominated, with *Phragmites* and cedar present along the roadway edge (Figure 3). The northern third of the peninsular wetland was extensively grid-ditched for mosquito control in the mid-20th century, and the central portion of the marsh has been the recipient of Open Marsh Water Management (OMWM) activity in recent history.

OMWM involves the creation of small ponds in the marsh platform in order to increase hydrological connectivity and allow greater access for juvenile fish to consume larval mosquito eggs. When done effectively, OMWM reduces the need for larvicides. While this practice has critical public health implications, it raises potential issues regarding marsh elevation changes and placement of dredged materials. (Elsey-Quirk, 2015). BBP researchers are concerned about alteration of the wetland surface due to OMWM. Their concerns include placement of the ponds, loss of biomass and root structure both above and below ground, and the relationship of OMWM to accelerated shoreline erosion rates. As the shoreline erodes back toward an OMWM pond, there is potential for increased erosion if the pond is breached. OMWM is currently practiced in the state-owned marshes adjacent to Great Bay Boulevard, however OMWM activities have been suspended on U.S. Fish and Wildlife Service properties pending more study.

Field assessments of wetland conditions in the southern portion of the peninsula conducted over the past few years identified the marshes as ranging from good to moderately degraded, with degradation due mainly to ditching and filling (Barnegat Bay Partnership, unpublished data).

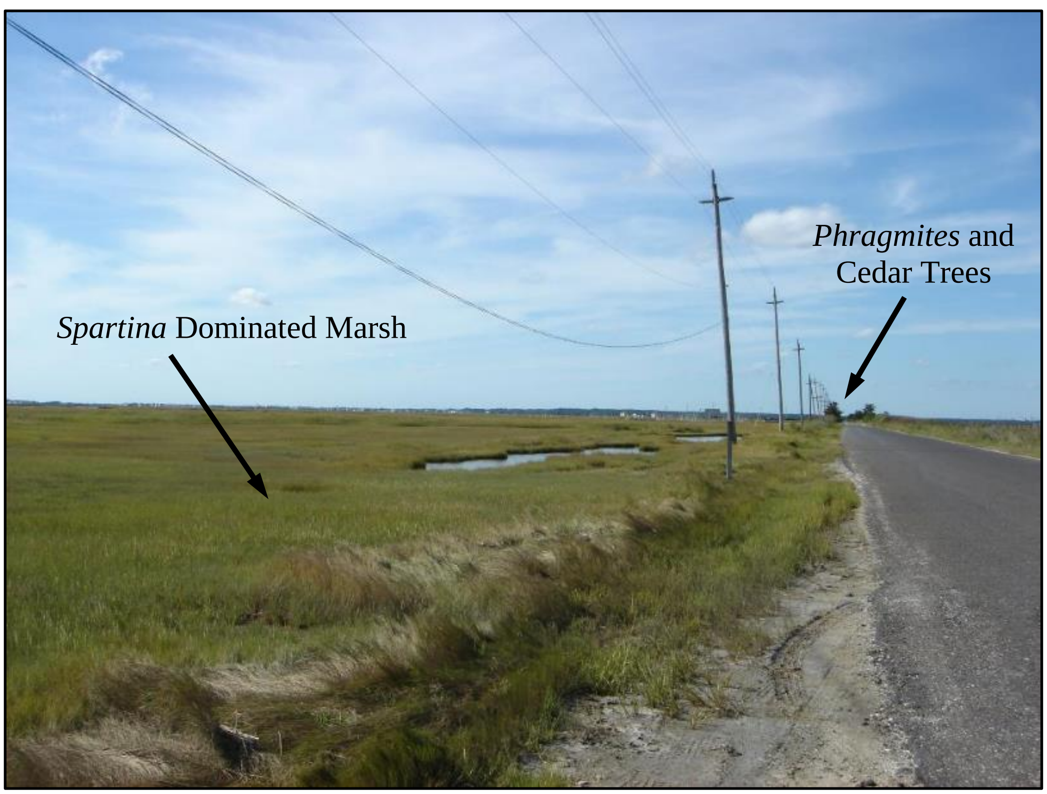

Figure 3. View of a portion of Great Bay Boulevard, with *Spartina* dominated marsh bordering the roadway on both sides, and *Phragmites* and cedar trees visible along the roadway edge off in the distance.

At current Mean Higher High Water (MHHW) levels – the average of the higher high water elevations (NOAA, 2013) - most of the marsh adjacent to the roadway becomes inundated, but the roadway itself is not. However, the roadway typically floods in multiple locations during astronomical high tides, northeasters, and other extreme high water events. Roadway flooding temporarily closes access and affects evacuation measures. Relative sea level projections could also pose a threat to the marsh system. The USACE Sea-Level Curve Calculator estimates relative sea level changes for Atlantic City, New Jersey of 1.41 feet (ft) at the *Low* rate, 2.45 ft at the *Intermediate* rate, and 5.7 ft at the *High* rate by the year 2100 (USACE, 2017). Another tool for displaying potential sea level scenarios is the New Jersey FloodMapper that was developed by Rutgers University. This visualization tool shows that under a 1-foot sea-level rise scenario, multiple portions of Great Bay Boulevard would be inundated during an average high tide (njfloodmapper.org). Under a 2-foot sea-level rise scenario, the entire roadway, with the exception of the bridges, would be underwater at high tide (Figure 4). With regard to flooding from storms, the National Hurricane Center's *Sea, Lake, and Overland Surges from Hurricanes* (SLOSH) model indicates 3-6 ft of water across the marshes and roadway under a Category 1 hurricane scenario. In addition, staff from the Rutgers University Marine Field Station (RUMFS) analyzed flood data for the area near Little Egg Inlet and documented an increase in the number of hours that the roadway was flooded between 2002 and 2012 (Howell, 2017).

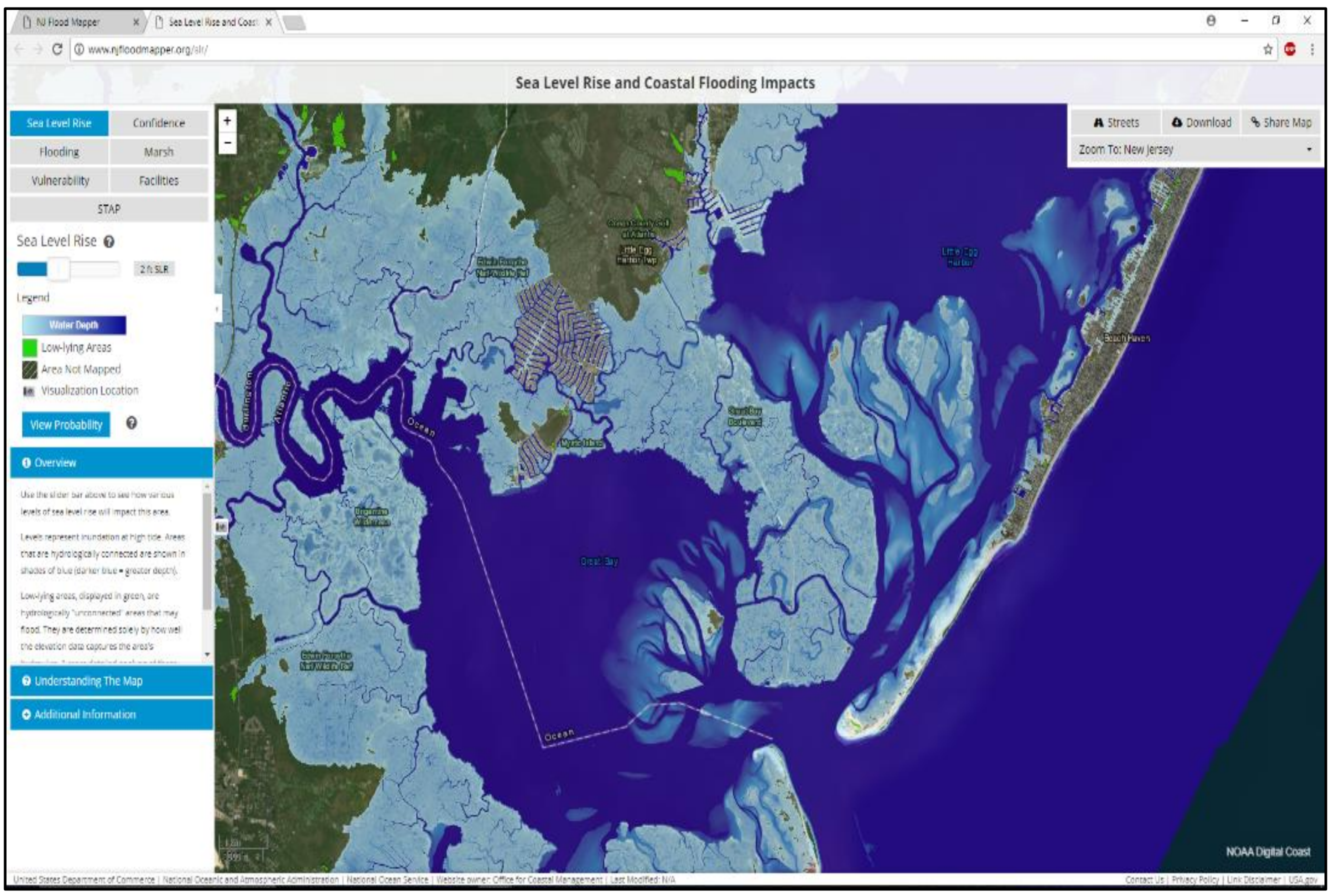

Figure 4. Coastal flooding impacts of the Tuckerton Peninsula and surroundings under a 2-foot rise in sea level presented by *NJ FloodMapper*.

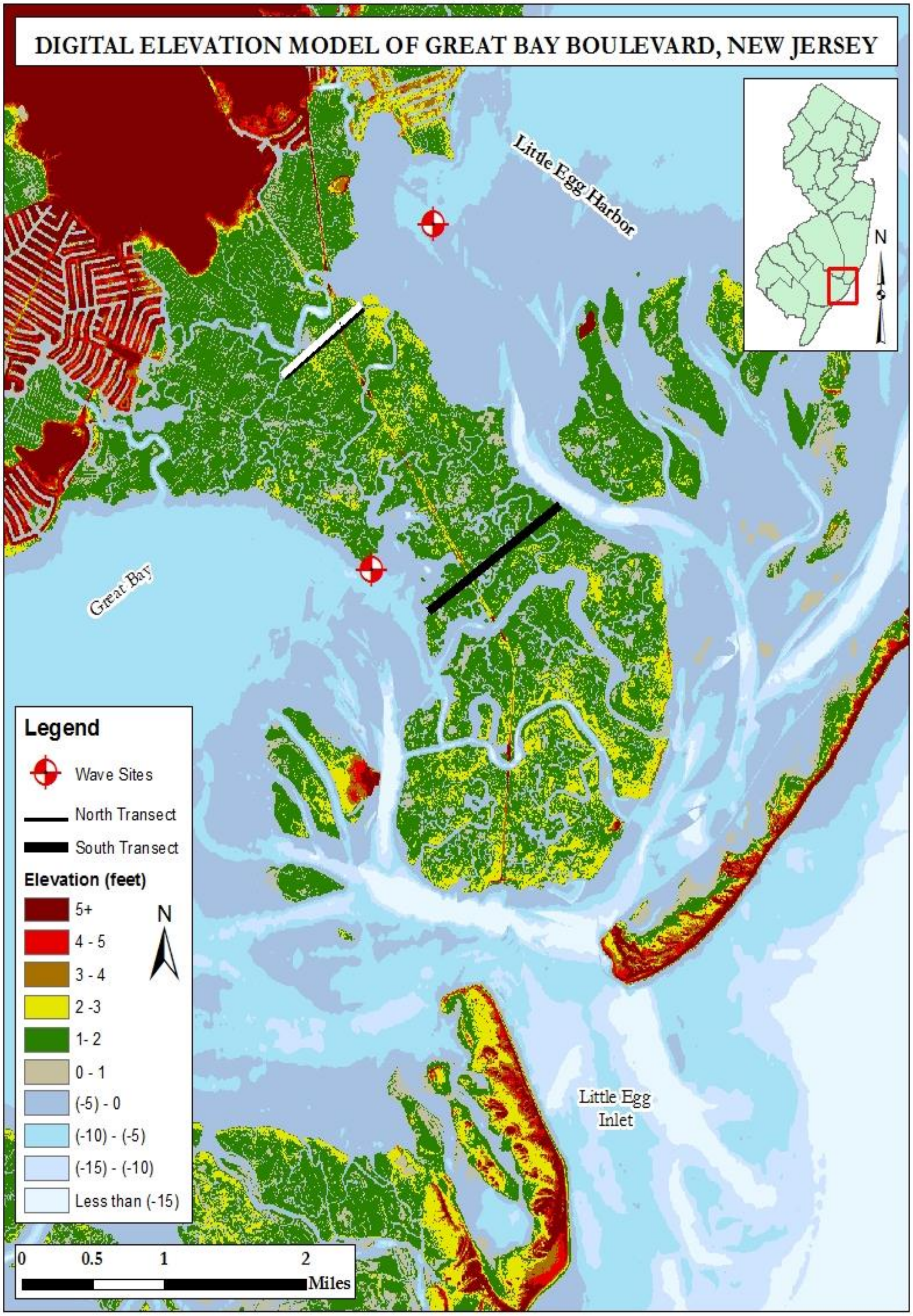

Figure 5. Site map and digital elevation model of Tuckerton Peninsula, bathymetry, developed upland, and surrounding geomorphic features. A predominantly yellow line that generally bisects the peninsula represents Great Bay Boulevard.

METHODS

This section describes the methods taken to select sites, and collect and analyze data. CRC staff conducted a baseline study of hydrodynamic conditions at Great Bay Boulevard, while researchers from BBP completed analyses to determine the health of the surrounding marsh ecosystem. The study approach involved:

- Site selection and existing data compilation
- Sensor deployment
- Marsh thickness and sediment texture measurements
- Marsh condition surveys
- Data analysis and modeling

Site Selection

CRC and BBP chose two locations, the North Transect (NT) and South Transect (ST), in which to collect data (Figures 5 and 6). The transect locations were selected based upon roadway users' knowledge of areas where flooding is most common. BBP conducted surveys of marsh health at designated sampling plots along each transect, while CRC collected water level data and sediment cores at corresponding sites. The NT and co-located sample and water level sites were located just south of Big Thorofare. The ST and co-located sample and water level sites were located just north of Big Sheepshead Creek. The CRC and BBP coastal analysis teams also established sites for measuring wave heights in Great Bay (DW) and Tuckerton Bay (AQD).

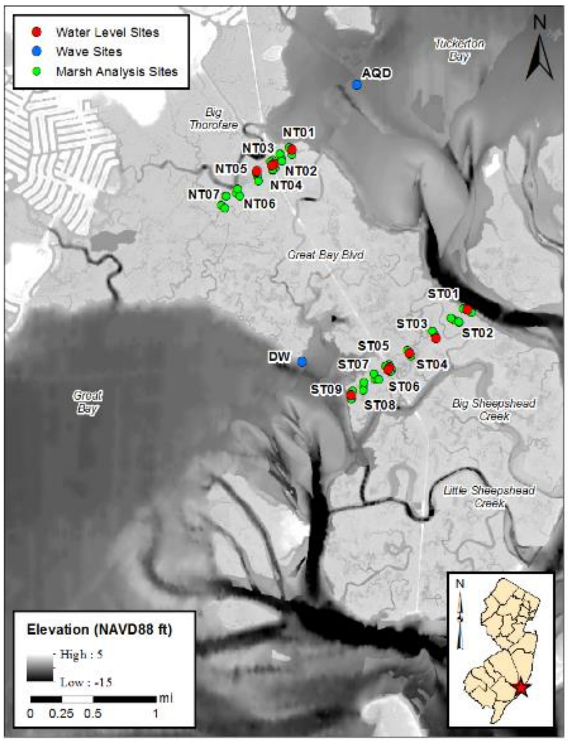

Figure 6. Digital elevation model showing Great Bay Boulevard (white line through center of peninsula) and locations of North and South marsh condition transects (green dots), water level loggers and cores (red dots), and wave recorders (blue dots).

Existing Data Compilation

CRC staff began by reviewing existing information related to the location and history of flooding near Great Bay Boulevard. High-resolution topographic and bathymetric data for the Tuckerton Peninsula were compiled from existing United States Geological Survey (USGS) digital elevation models. Coastal elevation data were extracted from the 2015 Coastal National Elevation Database (CoNED) Project, which contains data for New Jersey in spatial resolutions varying from 3.28-13.12 ft (1.00-3.00 m). For this project, CRC staff extracted CoNED data for a region extending from Atlantic City to the south, the northern side of Barnegat Light Inlet to the north, offshore to 60.00 ft depth, and 15.00 mi inland. Meteorological data, such as barometric pressure, wind speed, and wind direction, were collected during the study from the Nacote Creek Station located in JCNERR.

Sensor Deployment

In order to quantify the physical hydrodynamic parameters that cause Great Bay Boulevard to flood, CRC researchers deployed wave and water level sensors along the marsh and in the bays adjacent to the marsh peninsula to the northeast and southwest. The R/V Osprey, Stockton University's research vessel, was used to deploy the instruments (Figure 7). Instruments were deployed during spring high tide and winter northeast storm events. In addition to collecting data during the high water events, the instruments also measured baseline conditions through the duration of the study.

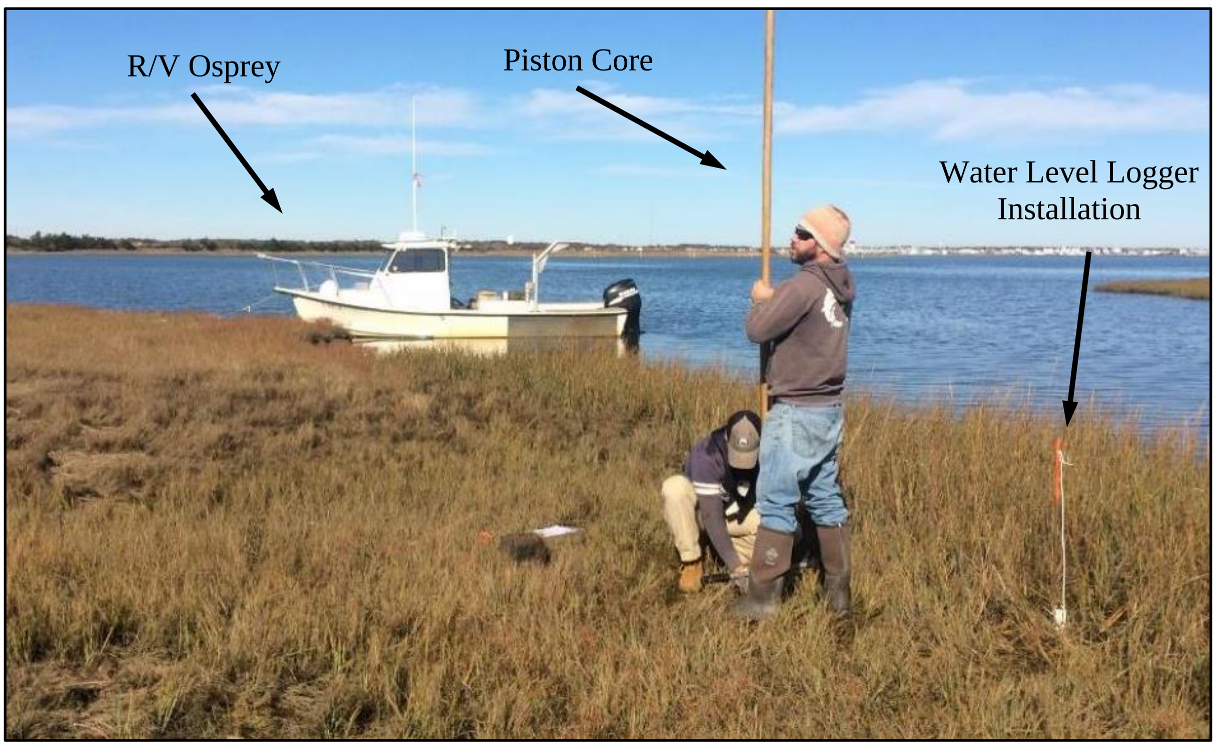

Figure 7. Marsh edge site that was accessible only by the R/V Osprey. This image shows the vessel moored to the marsh edge, CRC researchers extracting a marsh core, and a water level logger installation (instrument mounted on a rebar spike driven into the marsh).

Two oceanographic instruments were used to measure waves and water levels in the bays adjacent to Great Bay Boulevard. A NortekUSA 2 MHz Aquadopp Profiler (AQD in Figure 6), was used to measure waves and water levels on the northeast side of the roadway in Tuckerton Bay. The Aquadopp Profiler is an Acoustic Doppler Current Profiler (ADCP) that utilizes the PUV processing technique, based on pressure (P) and wave orbital velocity measurements (U and V for the x and y directions), to calculate the full directional wave spectra from measured velocity and pressure time series. The full spectra includes the significant wave height (Hs), peak wave period (Tp), and peak wave directions (DirTp). A second type of instrument, the RBR Limited RBR*solo* DWave (DW in Figure 6), was used to measure waves and water levels in Great Bay on the southwest side of the roadway. The DWave is a compact wave and tide logger that records pressure at high sampling rates in order to measure and calculate significant wave height (Hs) and significant wave period (Ts). The DWave does not have the capability of measuring wave direction. However, the study site's location in a back-barrier bay system means that waves are generated very locally and refraction due to bathymetric changes is minimal. Therefore, it is valid to assume that wave direction will closely mimic wind direction (wave direction from site DW is represented by WDir, which is the measured wind direction). In this report, wave direction is defined as the direction from which waves are traveling.

Multi-purpose water level loggers were used to measure water levels on the marsh platform and near the roadway. Ten (10) Onset HOBO U20L Water Level Loggers (NT01, NT03, NT04, NT05, ST01, ST03, ST04, ST05, ST06, and ST09 in Figure 6), were deployed along the marsh platform at the NT and ST locations. The instruments measure absolute barometric pressure by extracting water levels from the data through a multi-step process in which air pressure must be isolated and removed from the measured signal. Each water level site was co-located with a BBP marsh analysis site along each of the two transects in order to stay consistent with measurement locations. The loggers were also deployed at the marsh edge where possible (NT01, ST01, and ST09) and adjacent to the roadway (NT03 and NT04 on the NT and ST05 and ST06 along the ST).

Two separate deployments were conducted during the study in order to collect data during baseline conditions and a northeast storm event. The first deployment occurred from November 8, 2016 to January 13, 2017 (66 days) and captured baseline conditions in the area. The second deployment occurred from January 19, 2017 to January 31, 2017 (12 days), focused on the northeast storm that occurred from January 22, 2017 to January 24, 2017. The second deployment was a rapid, pre-storm deployment intended only to capture the conditions during the storm. This deployment contained all previously described instruments, except for the DWave, because the rapid nature of the deployment did not allow for two instruments to be deployed in the bays. This deployment was extended to January 31, 2017 because this was the earliest time after the storm that weather conditions and schedules allowed for instrument retrieval (Appendix B).

Marsh Thickness and Sediment Texture

CRC collected ten sediment cores to determine sediment characteristics, erosion potential, and thickness of the marsh (Figure 6, red dots). The cores were extracted from November 8-10, 2016 using piston coring techniques to minimize the impact to the marsh platform (Figure 8). Marsh thickness was measured concurrently at each of the piston core locations using a soil probe. The cores were processed at the CRC's Sediment Laboratory. Selected organic samples were sent to Beta Analytic Inc. in Miami, Florida for radiometric (Accelerator Mass Spectrometry [AMS]) dating analysis.

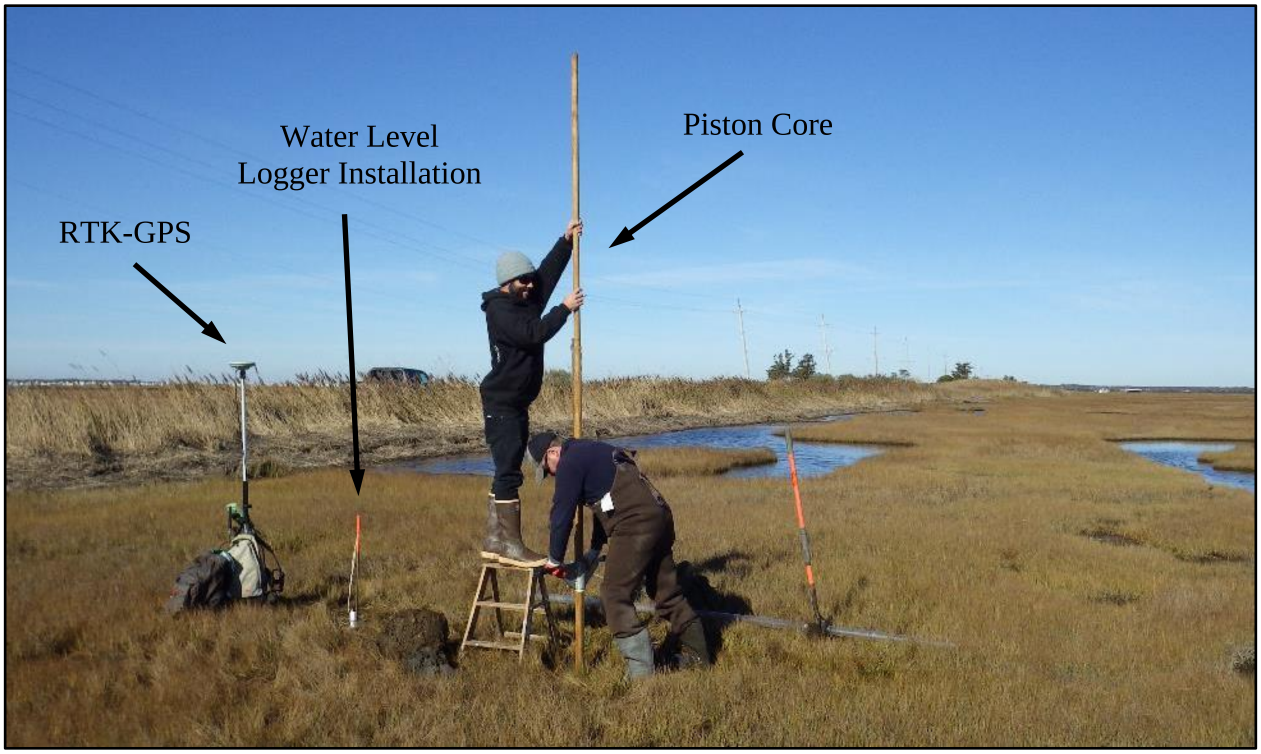

Figure 8. CRC researchers using the piston coring technique to extract a marsh core during the data collection phase of the project. RTK-GPS unit and water level logger installation can also be seen in this image.

Marsh Condition Surveys

BBP researchers evaluated conditions at both the marsh surface and marsh edge by conducting field surveys at the NT and ST. Conditions at the marsh surface were evaluated using established Mid-Atlantic Coastal Wetlands Assessment (MACWA) metrics and protocols (i.e., MidTRAM v3.0). Conditions at the marsh edge were evaluated using protocols developed by BBP's Paddle-For-The-Edge program. Paddle-For-The-Edge organizes events where citizen scientist volunteers travel through the marsh in canoes and kayaks to collect data about shoreline features and key biotic indicators of health in the ecosystem. At the Great Bay Boulevard site, BBP researchers and Paddle-For-The-Edge volunteers observed and documented plant density and diversity, mussel and crab distribution, soil cohesiveness, land use and recreational activity, and signs of erosion (Figure 9). Methodology for describing marsh surface and edge conditions is included in BBP's marsh condition report (Appendix A).

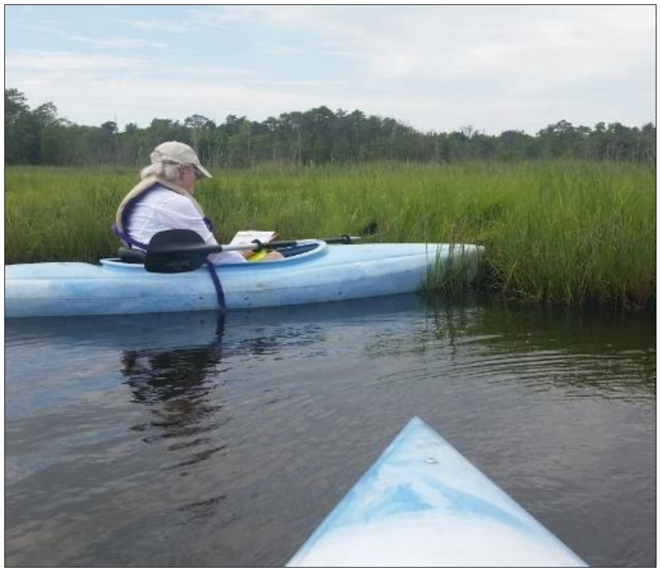

Figure 9. Paddle-For-The-Edge volunteer collecting data at the project site.

Data Analysis & Modeling

Wave and water level data were post-processed, quality controlled, and analyzed using a combination of software provided by each instrument company and a suite of in-house software codes developed in MATLAB (a scientific computing language).

Post-processing and quality control was minimal for the AQD and DW wave and water level data. Full directional wave spectra were calculated from Aquadopp Profiler data using Quickwave (a program purchased from NortekUSA). The program utilizes the PUV method, combined with spectral analysis methods, to compute wave heights, wave periods, and wave directions from measured pressure and velocity data. Wave heights and wave periods were calculated from DWave in Ruskin, which is the instrument communication program provided by the manufacturer. Ruskin uses a zero up-crossing method in order to calculate wave heights and wave periods. CRC's suite of MATLAB codes were used to verify the data, eliminate abnormalities, and compile the information into a usable format.

Water level data recorded by HOBO U20L Water Level Loggers required thorough post-processing using MATLAB. Since the instruments measure absolute pressure, the barometric pressure had to be removed from the signal in order to achieve data associated with water depth only. After isolating water depth data, time series from all of the sites were analyzed in conjunction with each other to isolate data from flooding events. The instruments deployed on the marsh platform remained dry most of the time and only measured water depth data during episodic flooding events. The episodic nature of the flooding events resulted in long periods of uninteresting (zero water depth) data that needed to be removed. In addition, not every flooding event registered at every site (due to elevation differences) and flooding events that did register were not necessarily large enough to be significant to this study. Water level data was considered significant if it met the following two requirements: 1) the value of the pressure signal had to peak above a specified minimum value and 2) this peak had to be observed at all sites. Once all insignificant data were eliminated, the significant data were converted from units of pressure (mbar or psi) to units of water depth (m or ft). Finally, the water depth data at each site was adjusted relative to the North American Vertical Datum of 1988 (NAVD88) based on the measured elevation value of each instrument at each site.

The study site was numerically modeled using *Delft3D* (an open source software developed by Deltares) in an attempt to get a better spatial coverage of hydrodynamic and flooding data during the storm event that occurred from January 22-24, 2017, and to model the anticipated effect of the proposed adaptation options (see Appendix C for model details). In order to evaluate the effect of the proposed adaptation options, the model had to be validated to be sure that modeled data mimicked measured data within a specified margin of error, specifically for the water level elevation. Validating the model, however, proved to be a very difficult task and was unsuccessful (see Appendix C for discussion on model).

RESULTS

This section describes results of the field research conducted by CRC and BBP staff and volunteers. The results include findings related to the health of the marsh surrounding Great Bay Boulevard, physical conditions within the marsh that relate to roadway flooding, and hydrodynamics that occur at the site during flood events.

Marsh Condition

Marsh surface data indicated that the marshes adjacent to Great Bay Boulevard are similar in condition, and in some ways healthier, compared to Barnegat Bay wetlands on average. It is worth noting that the reference data used to make these comparisons measure conditions at sites characteristic of all Barnegat Bay salt marshes, not just pristine sites. Thus, comparing project data to the reference data does not mean that the areas we surveyed were in pristine condition, just that they were not more degraded than other marshes in Barnegat Bay. Given that this marsh complex has been subject to less human development than other marshes included in the MACWA dataset, these findings are not surprising.

The marsh along the transects was identified as moderately to severely stressed. The overall stress score includes several factors (Appendix A). Our assessment determined that the marsh edge was highly stressed, while the marsh platform had moderate scores (Appendix A, Figure 7). These scores should inform how practitioners identify areas for intervention, as a healthy marsh does not need restoration. Marsh vegetation along the NT and ST appears to be within the normal growth range for Barnegat Bay marshes. Light attenuation and horizontal vegetative obstruction, both indicators of overall vegetative robustness, are within the normal ranges expected for each parameter. Soil stability is within the range associated with minimally stressed marshes in the mid-Atlantic. Because there is more potential high marsh habitat in the current project dataset, we found that the average stem height was below the Bay-wide average. A relatively high level of observed biodiversity shows the marsh has a mosaic of areas displaying characteristics of both high and low marsh.

Our research indicated that 60% of *Spartina alterniflora* plants were situated within their optimal growth range. Optimal growth ranges are determined by the tidal conditions and the species composition relative to marsh type (e.g. high marsh or low marsh). The data from our site indicates that the marsh has high elevation capital, defined as the position of a marsh relative to the lowest elevation at which plants can survive (Cahoon and Guntenspergen, 2010). When the elevation of a marsh changes, wetland plants can be shifted outside of their optimal growth ranges. If marsh elevation increases above *Spartina alterniflora*'s optimal growth range, other plant communities will take over. If elevation decreases below the optimal growth range, the marsh will convert to mud flats.

The 40% of *Spartina* outside their optimal growth range may not be unhealthy, potentially just in transition to a new community type such as upland or open water. Because this study was a snapshot in time, there are insufficient data to determine the long-term trend. However, this does demonstrate that marsh restoration practitioners can target a specific habitat type and attempt to create optimal vegetation zones either by changing elevation to suit particular species or by planting species that are elevation specific (Morris et al, 2002). It is important to note that if an application of sediment to raise marsh elevation exceeds 15 cm (0.5 ft), there is a good chance that the existing marsh plants may not be able to recover and supplemental planting will be necessary. The current accepted practice for thin layer sediment placement cites 10-15 cm (0.33-0.5 ft) as the optimal amount for marsh enhancement. In addition, filling the lower sections of the marsh platform would be preferred over filling marsh pools and ponds. A full assessment of current wetland function and conditions should be completed before commencing this type of activity.

Because the optimal growth range for *Spartina* in Barnegat Bay is smaller than other areas of New Jersey, these marshes may be more vulnerable to elevation shifts. Almost all of the plots were at or higher than optimal elevations for marsh vegetation growth. Healthy tidal marshes are able to build enough elevation to maintain their vertical position as sea levels rise. The MACWA data from BBP's Site Specific Intensive Monitoring (SSIM) Station at Horse Point show an average accretion rate of 6.17 mm (0.02 ft) per year (BBP unpublished data). The Horse Point site is located just north of Great Bay Boulevard, and within the same marsh complex. This accretion rate is greater than the 4.07 mm (0.01 ft) per year observed sea-level rise for Atlantic City (NOAA 2015), suggesting that these marshes should be able to maintain their elevation relative to sea-level rise, provided other conditions remain similar. The accretion rate is comparable to the USACE *Low* rate estimate of future sea-level rise (3.96 mm [0.013 ft] per year) (USACE, 2017).

Neither sediment deposition nor in situ bio decomposition were measured at the transect locations. Sediment elevation tables (SET) and marker horizons (MH) are used for long-term monitoring at West Creek and Horse Point, both located north of this study site. Researchers from JCNERR maintain long-term wetlands monitoring sites on the peninsula, which will yield critical data in the future. Table 1 provides accretion rates for marshes near the study site. The Barnegat Bay ecosystem is generally sediment starved. Thus, it would be difficult to redirect stream flows into the system to provide sediment, as the amount of sediment needed is likely greater than the area could naturally provide. Manipulating hydrology could stem future sediment losses, but it could not bring back enough sediment in a short range of time. Since Barnegat Bay is a microtidal estuarine system with minimal sediment input, both biomass and sedimentation are crucial to maintaining marsh elevations.

Table 1. SET sites and accretion rates from other Barnegat Bay locations.

Station	Days since Installation	Accretion Rate (mm/yr)	Elev. Change (mm/yr)	SS (mm/yr)	LSLR (mm/yr)	Keeping pace?
Reedy	1500	5.03	5.62	-0.6	4.07	Yes
Island Beach	1459	1.04	-1.20	2.24	4.07	No
Horse Point	1113	5.18	4.16	1.02	4.07	Yes
West Creek	1433	22.6	19.7	2.9	4.07	Likely*

The collected wave data lends itself to the most efficient and effective restoration tactics. If waves are most intense from a specific direction, that area will need the most shoreline protection (armoring, breakwaters, or other tactics). Shoreline protection features can be placed at a specific angle for the most wave energy dissipation or blockage. The wave climate also affects plantings, with regard to how quickly an area should be planted, or if plants can survive in a given area. Similarly, projects should be designed so that the restoration is large enough to anticipate waves, but small enough to have the minimum negative environmental impact.

Based on this study, erosion of the marsh edge is of particular concern, especially during strong northeast storm events (Appendix A, Appendix B). Figure 10 show areas of the marsh edge (in red) where erosion levels are the highest. At these locations, strategic sediment placement would be optimal. The best methods for keeping pace with existing sea level include marsh edge protection, banking of sediment in the nearshore, control of biogeochemical factors (i.e. nutrient input), and planting native marsh vegetation. Therefore, marsh platform restoration could be a viable option.

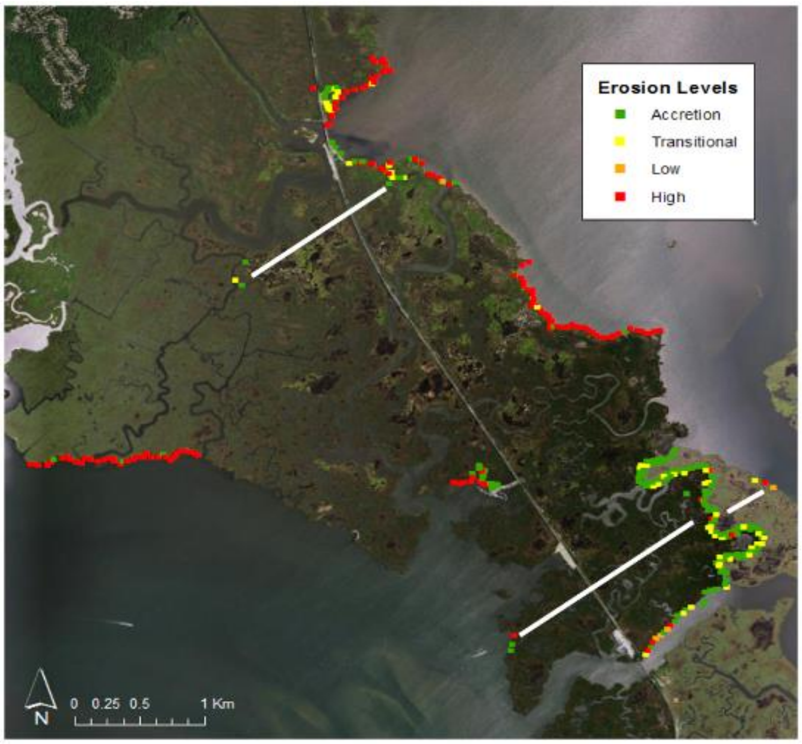

Figure 10. Map depicting relative levels of marsh erosion and accretion, as observed and documented by BBP researchers and Paddle for the Edge volunteers.

The research team also observed a large number of natural and man-made pools found throughout the marsh, although this stressor was not captured in the data analysis. The pools are common in Barnegat Bay marshes, though maybe not to the extent found at this site. Marshes in Barnegat Bay have been managed for many uses over the last century, including duck hunting, salt hay farming, and Open Marsh Water Management (OMWM) for mosquito control. In general, the excavated OMWM pools do not appear to be causing the marsh to fragment or break apart. However, there is concern that the effects of shoreline erosion may intensify as the marsh edge continues to accelerate inland and reaches these ponded areas. In addition, BBP observed some deterioration between OMWM dredged ponds along the southern transect. Some of the adjoining pond walls were undermined to the point of breaking through, with only the upper level of root mat and soil remaining intact. Further assessment of these pools and their impact on the marsh would provide valuable insight into the functioning of this marsh. At a marsh located approximately seven miles northeast of our project site, a decrease in vegetative cover was observed after Open Marsh Water Management (OMWM) activities increased the elevation by approximately 20 cm [0.65 ft] in 2011. Since that time, little vegetation returned to those areas (BBP, unpublished data).

Marsh Thickness and Sediment Texture

Soil probes indicated that the marsh thickness was greater than 16 ft at each of the core locations, except for the two sites closest to Great Bay Boulevard (#NT04 and #ST06), where cores contained coarse sand and crushed concrete fragments. At all other sites sampled, the subsurface sediments were comprised of silts and organic material (including roots from former marsh plants). This indicates that the marsh has been in existence without significant sandy overwash material. Radiometric dating was conducted on organic materials that were sampled from two cores on the southern transect (#ST01 at the eastern marsh edge and #ST09 at the western marsh edge). A marine shell layer sampled from #ST01 at -7.6 ft dated at 1540 +/- 30 BP. Organic peat from ST09 sampled at -5.7 ft dated at 1090 +/-30 BP. Cores extracted from the marsh did not contain deep marine or terrestrial sediments. Thus, the dated samples indicate that, at these locations, the marsh has been in existence and growing upward with sea level. Stratigraphic log descriptions are provided in Appendix D.

Hydrodynamic Analysis

This section summarizes the results and analysis for measured hydrodynamic data, while in-depth details are provided in Appendix B (Hydrodynamic Analysis). Baseline hydrodynamic parameters were measured during two deployments of field equipment at the site. During Deployment 1, CRC researchers measured water levels along each transect and calculated the average erosion rate at the marsh edge. During Deployment 2, which captured data during a northeast storm event, CRC researchers measured flood height and duration along each transect, spatially analyzed roadway flooding, and determined the average erosion rate at the marsh edge during the storm.

Deployment 1 was conducted from November 8, 2016 to January 13, 2017. During this time, waves in Tuckerton Bay and Great Bay can be classified as small, short period, and locally generated. At the AQD site in Tuckerton Bay, the average wave height was 0.19 ft, the average peak wave direction was 172° (south-southeast), and the average peak wave period was 1.57 s (Table B1). At the DW site in Great Bay, the average wave height was 0.10 ft, the average wave direction was 241° (southwest), and the average peak wave period was 2.47 s (Table B2). The peak in wave energy at the AQD site was observed from the east-northeast direction, with a secondary peak from the northwest direction (Figure B2). Waves at the DW site were observed from the southwest to northwest directions, with none observed from the northeast to southeast directions. On average, wave heights were larger at the AQD site than the DW site. This difference is most likely attributed to fetch, as the possible fetch in Tuckerton Bay is about 4.50 mi longer than that in Great Bay (Figure B4). This shows that the northeast side of the marsh peninsula is the most vulnerable to impacts from waves.

Several small-scale storm events were observed during Deployment 1. The events were classified as west (W) and northeast (NE) wind storm events, and two of each were isolated and analyzed (S1 and S2 in Figures B5-B6). The analysis showed a significant difference in average wave height between both sites during NE storm events. The average wave height at the AQD site was much larger than the DW site, as the DW site displayed little to no wave activity at all (Tables B3-B4). The analysis also showed that NE storms were responsible for producing the largest waves during the deployment. Unlike the NE storm events, waves at both sites were relatively consistent during the W storm events. In addition, water level elevations were observed above predicted values at both sites during the NE storm events, but not during the W storm events. This shows that the NE storms pose a larger threat to the Tuckerton Peninsula, because they produce high water levels in conjunction with large waves. These observations also reiterate the fact that the northeast side of the peninsula experiences the greatest impacts during such events, as the AQD site was the only site that displayed a combination of increased water levels and increased wave heights during the NE storm events. Six minor flooding events were recorded in the marsh platform during the first deployment, but none of these events caused flooding on Great Bay Boulevard (Figures B7-B8). During these events, water levels at the ST were higher than those at the NT.

During Deployment 1, CRC researchers also calculated the average erosion rate at the marsh edge. Calculations were made using the Digital Shoreline Analysis System (DSAS) and a linear regression method (Theiler et al, 2009). Digital shoreline maps from the years 1977 to 2015 were used to calculate an erosion rate at the northeast and southwest edges of both transects (Figure B9). Annual erosion rates were then averaged together to produce an average erosion rate of about 0.80 ft/year (0.002 ft/day). The average erosion rate suggests that about 30 ft of marsh edge has eroded over the 38-year analysis period.

During Deployment 2, CRC researchers measured hydrodynamic data at the AQD site in Tuckerton Bay during a significant northeast storm that occurred from January 22-24, 2017. Water levels were also measured along each transect. The storm lasted for 43 hours, with maximum sustained winds of 36.46 mph from the northeast and a minimum barometric pressure of 991 mbar (Figure B12). The average peak wave height during the storm was 1.73 ft, the average peak wave direction was 71.82° (east-northeast), and the average peak wave period was 2.92 s. The maximum wave height was 3.12 ft with an associated wave direction of 78.13° (east-northeast) and wave period of 3.71 s (Table B5). Throughout the storm, the majority of peak wave heights and the highest concentration of wave energy came from the east-northeast direction (Figure B10). Wave energy was focused within the wave period bands of 3.00-5.00 s (Figure B11), showing that these waves were larger and more powerful than those measured during Deployment 1. Tidal water surface elevations at the AQD site during the storm peaked almost 4.00 ft above the predicted tide. The water surface elevations remained at almost 4.00 ft above predicted values for two tidal cycles, and over 2.00 ft above predicted values for three tidal cycles (Figure B12).

Two flooding events occurred during Deployment 2, with the major northeast storm event being of primary interest to the research team. This event caused the most severe flooding during the study, and dwarfed all other events with regard to duration and flood height (Figures B13-B14). The event lasted two days, causing flooding at both the marsh platform and Great Bay Boulevard. Great Bay Boulevard was flooded by almost 0.50 ft at the NT, and almost 2.00 ft at the ST. Individual flood heights ranged from 0.25 ft to 0.51 ft at the NT, and 0.49 ft to 1.73 ft at the ST (Table B6). Individual flood durations ranged from 2.93 hrs to 5.60 hrs at the NT, and 4.00 hrs to 8.80 hrs at the ST (Table B6). The average flood height was 0.40 ft for the NT and 1.14 ft for the ST. The average flood duration was 4.15 hrs for the NT, and 6.44 hrs for the ST. On average, the ST displayed larger flood heights and longer flood durations than the NT.

CRC researchers performed additional analyses to determine why the ST displayed larger flood heights and longer flood durations during the northeast storm. Along the NE side of the peninsula, the marsh platform is wider and higher in elevation at the ST than the NT (Table B6 and Appendix B). However, roadway flooding was most severe at the ST, showing that marsh width and marsh elevation did not act to protect Great Bay Boulevard during the storm. This suggests that roadway flooding is more related to road elevation, as the elevation of Great Bay Boulevard is higher at the NT than the ST. There is also evidence to suggest that flooding was more severe at the ST due to its closer proximity to Little Egg Inlet (see Appendix B). While this particular storm raised water levels past a critical elevation where the marsh could have protected the roadway, the current marsh width and elevation may still reduce flooding during smaller, less energetic northeast events.

The CRC also performed a proximity analysis to estimate maximum flooding heights along the entire roadway. This also evaluated the effect of marina boat ramps on roadway flooding. During the northeast storm, maximum flood heights at each transect were used to calculate flood heights along the entire length of the roadway (Figure B16). This analysis reiterated the difference in flood heights between the NT and ST, as previously shown. The flood heights where the ST intersected the roadway (represented by the red colors) were noticeably higher than the flood heights where the NT intersected the roadway (represented by the blue colors). Flood height varied along the roadway, with an overall decrease observed from just north of Little Sheepshead Creek to the southern end of the peninsula. Again, this demonstrates that roadway elevation appears to be a controlling factor with regard to flood height. Increased elevation along this section of Great Bay Boulevard was enough to counteract some of the flooding, but not enough to entirely overcome the increased water levels resulting from proximity to the inlet. Analysis of the boat ramps showed that the ramps also appeared to intensify roadway flooding. Boat ramps BR01 and BR02 may have contributed to roadway flooding because high flood heights were present within 40 ft of both ramps. Boat ramp BR03 appeared to directly cause flooding because one of the highest flood heights in the area was located directly adjacent to the ramp (Figures B17-B18). We hypothesize that boat ramps may be a main factor of roadway flooding because they could be acting as entranceways for water to easily flow through and flood the road.

Lastly, the CRC quantified the erosional effect of the northeast storm. CRC researchers calculated the marsh edge erosion rate on the northeast side of the peninsula, because that side of the marsh was directly influenced by the large storm waves. Using equations B1 and B2 (Appendix B), the average marsh edge erosion rate during the storm was calculated as 0.01 m/day (0.05 ft/day [18.70 ft/year]). This translates into approximately 0.02 m (1.10 in [0.09 ft]) of marsh edge erosion during the 43-hour storm. The erosion rate during the storm was about twenty times greater than the background erosion rate, which demonstrates the erosive potential of northeast storms. Since this type of storm occurs several times per year, the data suggest that northeast storms are the main drivers of marsh edge erosion in this region, and that the primary erosional events tend to occur in an episodic manner.

Partnership Workshop

The project team held a one-day workshop at the Jacques Cousteau National Estuarine Research Reserve (JCNERR) Coastal Education Facility on September 21, 2017. The purpose of the workshop was to engage regional stakeholders and obtain their input on green infrastructure options that could be implemented at the project site. The workshop participants included marsh and dredging experts, state and federal regulators and planners, engineering consultants, and public educators (Appendix E). All of the participants were familiar with green infrastructure, and many had first-hand knowledge of permitted or completed projects along the New Jersey coast.

Following a presentation of the study goals, field research, and results, the project team asked the participants for their opinions on the following categories of coastal protection techniques:

a. Marsh restoration using thin layer placement of sediment and native plantings
b. Living shoreline composed of rock sill and native plantings
c. Traditional gray approaches, including elevating the roadway and installing rip rap

The discussion immediately focused on regulatory questions regarding the challenge of receiving permits for coastal green infrastructure projects. In New Jersey, the purpose and need for a shoreline project drives the permitting process, and the group's discussion highlighted the importance of clearly defining the goal of our project. The group also noted that there are limitations for implementing any project without a thorough understanding of the marsh system and its interaction with the roadway. However, group consensus agreed with our proposition to consider protection for the marsh and roadway as a holistic system, rather than focusing solely on the roadway. Participants agreed that the project should include some form of marsh restoration, which could entail raising the marsh platform, protecting eroding marsh edges, or placing sediment upstream to replenish the marsh via natural sediment transport. However, when selecting the preferred alternative, the group strongly encouraged consideration of ecosystem services that the project will provide (fisheries, recreation, coastal protection, habitat, pollutant removal).

The workshop also underscored the importance of interagency cooperation in selecting locations, evaluating designs, permitting, and constructing potential green infrastructure projects. In a relatively pristine location such as Tuckerton Peninsula, coordination with federal and state resource agencies should be the first step in developing a green infrastructure project.

ADAPTATION OPTIONS

Based on study findings and feedback from the workshop, the project team considered a range of solutions for the Great Bay Boulevard site. CRC staff researched design concepts to protect the roadway and marsh as a unified system, addressing the issues of flooding, erosion, and long-term sea-level rise. The intent of green infrastructure would be to re-establish natural processes within the marsh, which would reduce flood risks for the road and allow the system to become self-sustaining over time.

CRC staff developed two potential adaptation options for Great Bay Boulevard, which are presented for consideration below. We also propose that either of the options be implemented and monitored at the study transect sites (Figures 5 and 6). Since northeast storms tend to have the greatest impact on Tuckerton Peninsula, the options were sited on the northeast ends of each transect to provide enhanced protection. CRC staff evaluated the anticipated protection each option would provide against future roadway flooding using a coastal hydrodynamic, sediment transport, and morphology model (Deltares Open Software *Delft3D*). The team estimated flood reductions based on how each option would affect the marsh system. The options do not consider elevating the roadway in determining potential flood reductions. Because the options are conceptual in nature, the project team did not provide site drawings, cost estimates, anticipated protection from sea level rise, and economic analyses.

Option 1 – Thin Layer Sediment Placement and Vegetation

Because of the low tidal range, raising the marsh platform adjacent to vulnerable sections of Great Bay Boulevard could shift MHW and MHHW elevations and reduce future flood risks. Raising the marsh platform could be accomplished using thin-layer placement (TLP) of dredged sediment material. We propose implementation of TLP on the northeast side of the marsh platform at both transect locations (NT and ST). The material would be incrementally placed to achieve a cumulative thickness of 1.00 ft. Proposed placement areas are 1000 ft wide and centered along each transect line. Sediment placement would begin adjacent to the roadway and extend northeast to the marsh edge, with the north and south edges of the placement areas parallel to each transect line (Figure 10). The total volume of material would be approximately 44,000 cubic yards (CY) at the NT and 150,000 CY at the ST.

CRC selected a cumulative thickness of 1.00 ft (30 cm) to achieve maximum flood protection benefits with minimal negative impacts to the ecosystem. By definition, TLP has a maximum thickness of 6.00 in (0.50 ft) [0.15 m] for each application, with less being preferable. A cumulative thickness of 1.00 ft would require a minimum of two applications of material, placing a maximum of 22,000 CY at the NT and 75,000 CY at the ST during each application. Areas previously devoid of vegetation would be planted with the predominant native species on the peninsula (*Spartina alterniflora*).

Similar marsh system TLP projects have been completed along the east coast of the United States, with total placement values ranging from ~7,000 CY to ~60,000 CY (Whitin, 2017). USACE, USFWS, and USGS have supported and facilitated these projects in partnership with state agencies. The total proposed volume at the NT is comparable to the projects described by Whitin, while the total proposed volume at the ST is higher. However, the proposed incremental application volumes for the NT and ST appear to be feasible because they are comparable to those described by Whitin for several successful projects.

Although a 1.00-ft elevation gain would not raise the marsh above the maximum water levels observed during the January 2017 storm, it would eliminate a significant amount of roadway flooding during lesser storms. While we have proposed two initial placement areas to demonstrate the feasibility of TLP, it is important to note that TLP would need to occur along the entire length of the roadway to effectively decrease flooding. Otherwise, high water levels might be able to circumvent the higher elevation areas and still flood the roadway. If 1.00 ft of TLP was implemented along the entire length of the roadway, the added elevation would reduce roadway flooding by approximately 54% during a future storm comparable to the January 2017 storm. This flood reduction was determined by using the maximum water elevations observed during the January 2017 storm to calculate the percentage of road that experienced less than 1.00 ft of flooding. The added TLP would potentially eliminate roadway flooding with flood heights equal to or less than the added TLP elevation. Therefore, the flood reduction percentage equals the percentage of roadway flooded by the amount of elevation gained through TLP.

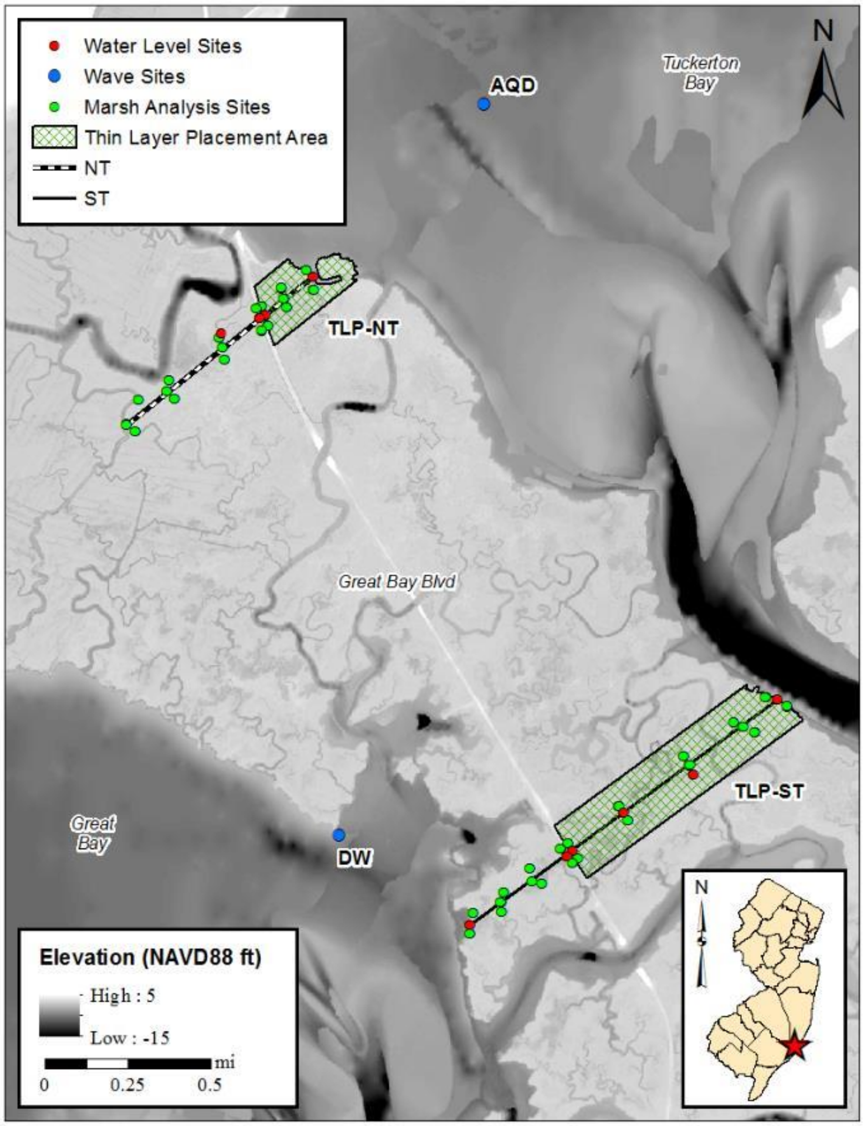

Figure 11. Digital elevation model showing Great Bay Boulevard (white line through center of peninsula) and locations of marsh condition transects (green dots), water level loggers and cores (red dots), wave recorders (blue dots), and the proposed TLP areas TLP-NT and TLP-ST. Each area is 1000 ft wide, centered on each transect, and extends from the roadway to the marsh edge at that location.

The sediment chosen for thin layer placement should match the textures of the existing marsh platform surface (very fine sand and silt). Sediment cores extracted along the transects showed, on average, that the top 3.00 ft was composed of fine salt marsh sediments and organic material. This suggests that a similarly organic and muddy sediment type should be used for TLP at this site. Potential sediment sources include nearby navigation channels or confined disposal facilities. Beneficial use of dredged material at Great Bay Boulevard could also help solve an ongoing problem of where to place dredged material produced by maintenance operations at federal and state channels. While there is high demand to dredge lagoons and channels for navigation, there are very few suitable areas for placement of dredged material. TLP on the marsh would be a beneficial alternative to the restoration of submerged borrow sites (dredged holes) in the back barrier bays, which has recently been suggested (Howard et al, 2015). However, it is important to note that incremental TLP does not provide an immediate solution to roadway flooding, as it will take several years to achieve the desired elevation.

Thin layer placement on an existing marsh system should prevent overburden of the marsh plants, therefore no more than 10 cm (0.32 ft) of compatible material should applied every few years. This amount was determined from local conditions and data collected under MACWA protocols (Appendix A). In other areas of the mid-Atlantic region, up to 46 cm (1.5 ft) of dredged material was placed on marshes with successful vegetative recovery; although sediment texture (% sand and % silt content) plays an important role in biomass production (Mohan, 2016; Ray, 2007; BBP personal communication, 2018)

Maintenance of a TLP project will be minimal after the desired elevation has been reached. The goal of TLP is to build up marsh elevation, but still allow the marsh to remain in a quasi-natural state. Once the material and initial native plantings are installed, the marsh will be left alone and allowed to respond and develop naturally. If storm events move or erode material, the material will not be replaced, and the marsh will simply be left alone. We recommend ongoing monitoring of vegetation and marsh platform elevations in order to determine project success.

The New Jersey Coastal Management Rules (N.J.A.C. 7:7-6.24) allow both federal and state agencies to beneficially use dredged material to create, restore, or enhance habitat. Projects must also abide by other state laws (Wetlands Act of 1970, the Waterfront Development Law, the Coastal Area Facility Review Act) and undergo regulatory review for impacts to habitat and wildlife. Obtaining permits for beneficial use can be challenging, but there are efforts underway to streamline the process.

TLP would benefit the roadway and marsh system in several ways. First, TLP would reduce future roadway flooding and preserve access to boat ramps, outdoor recreation areas, and research stations. Second, it would help the marsh keep pace with long-term sea-level rise. More broadly, if the entire peninsula becomes more resilient, then it can serve as buffer to protect adjacent areas and mainland communities during high water events. We also suggest calculating the monetary value of human activities that utilize Tuckerton Peninsula resources, as well as qualifying ecosystem services that the marsh provides to the region. Preserving the economic value of the peninsula is critical for local communities, and should be included in the decision-making process for selecting a preferred option.

A significant challenge in implementing TLP is the operating cost for incremental applications of material. Acquiring 97,000 CY of material is not likely to be a problem, since navigation channels in the area need to be routinely dredged in order to maintain safe passage. However, the cost of placing the material may be high. The high mobilization cost for dredging operations may be considered excessive relative to the small amount of material required for incremental placement. In addition, this high cost will need to be funded for multiple years in order to achieve the cumulative thickness. A cost/benefit analysis should be completed in order to justify the placement of material if this project is to move forward.

Option 2 – Natural Sill or Living Reef and Vegetation

Directly addressing the issue of marsh edge erosion is another strategy for increasing resiliency of the roadway and marsh system. This option would include a combination of nature-based armoring and native plantings along the marsh edge. The plantings would be located behind strategically placed wave attenuation devices such as marsh sills, oyster or clam beds, and oyster castles (living reefs). In addition to preventing further marsh erosion, this option intends to increase the capacity of the marsh to act as a buffer against future roadway flooding. CRC staff observed that waves during the January 2017 northeast storm caused significant marsh erosion. Wave attenuation devices are designed to intercept and decrease the energy of approaching waves in order to reduce damage to habitat or development. Reducing wave energy over the marsh will reduce wave setup that approaches Great Bay Boulevard, decreasing future flood risks.

Wave attenuation devices would consist of structures placed on the bay floor offshore from the marsh edge. These structures will extend to a height sufficient to influence waves caused specifically by northeast storms. Waves associated with northeast storms have been deemed the primary focus of these structures because these waves were shown to be highly destructive to the marsh edge, producing an erosion rate of almost twenty times that of the background erosion rate. The background erosion rate was only 0.80 ft/year, as compared to the 18.70 ft/year erosion rate of the northeast storm, which shows that waves associated with typical conditions do not seem to be as much of a problem.

Linear wave theory states that the energy associated with a wave propagates farther towards the sea bed from the water surface, for a given water depth, as the wave height and period increase. In order to target the larger and more powerful waves associated with a northeast storm, the attenuation devices would need to have a lower height above the bed (HAB) than if they targeted smaller waves associated with background conditions. However, since water levels increased by almost 4.00 ft during the observed northeast storm, the attenuation devices would have to be built to an elevation in order to account for this increase in depth so that they can work as intended during a high water event.

To determine an estimated HAB for attenuation devices at the NT and ST, the project team assumed that the devices' main purpose would be to force approaching waves to break. The forced breaking wave height was assumed to be the average wave height during the January 2017 northeast storm at the AQD site (Table B5) and the associated breaking depth was then calculated for this wave height. Once the breaking depth was calculated, the value was subtracted from the maximum measured water depth at the AQD site in order to determine the estimated HAB (a final HAB would need to be refined for the water depth at the exact proposed locations for the attenuation devices). The following equation (taken from Munk, 1949):

$$\frac{H_b}{h_b} = 0.78$$

in which H_b is the breaking wave height, h_b is the breaking depth, and 0.78 is an accepted value for the wave breaking index, was used to calculate a breaking depth of 1.34 ft for a breaking wave height of

1.73 ft (the average wave height during the northeast storm). Subtracting the breaking depth from the maximum measured water depth at the AQD site of 10.86 ft produced a HAB of 9.52 ft (Figure 12).

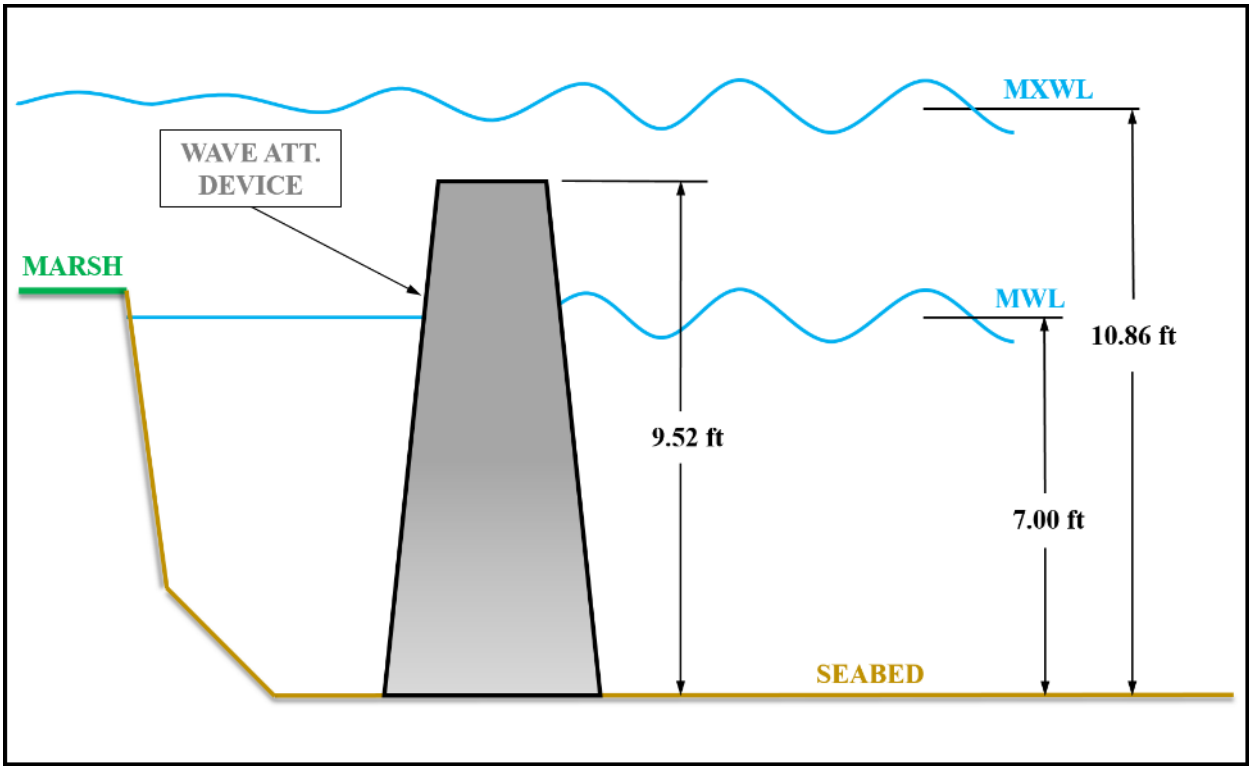

Figure 12. Example schematic of a living reef or wave attenuation device proposed for Adaptation Option 2. Water depth values are based on measurements at the AQD site. The mean water level (MWL) and the maximum water level during the northeast storm (MXWL) are also shown.

Designing the devices for the elevated water levels associated with a northeast storm manifests both positive and negative impacts. In addition to preventing marsh edge erosion and decreasing water levels on the roadway, the wave attenuation structures may serve as habitat for various shellfish species, such as oysters, and increase the aquaculture productivity of the area. Preventing marsh edge erosion will help to preserve habitat, and the reduction in roadway flooding allows access to the area. As previously mentioned, preserving marsh habitat also preserves the peninsula's economic value by preventing the loss of an area important for many types of outdoor activities. In addition, devices designed for high water events will block the energy associated with waves during background conditions. Thus, this option could potentially prevent all wave-induced marsh edge erosion and reduce flooding due to wave setup under all conditions.

However, there are some tradeoffs to this approach. The attenuation devices will be visible above the water surface during typical, non-northeast storm conditions because the average depth at the AQD site is 7.00 ft, while the estimated HAB is 9.52 ft. The attenuation devices may pose a navigational hazard to boat traffic and will need to be marked accordingly. In addition, a hard structure protruding above the water surface nearly all the time be may not be considered a "green" option by federal and state environmental agencies.

The Nature Conservancy installed this type of structure along the New Jersey Delaware Bay shoreline (The Nature Conservancy, accessed 2017). The estimated cost of wave attenuation devices is less than thin layer sediment placement, although structures may need periodic maintenance if they are damaged from abnormally large waves or accidental boat crashes. Monitoring is equally important for this option, where the adjacent bay bottom and marsh elevations would determine project success.

Alternative Adaptation Options

Following the Partnership Workshop, the project team considered two other options for Great Bay Boulevard, but determined that they did not merit further modeling and analysis:

a. *Detached nearshore sediment berm* – This option entails placement of sediment as a detached submerged berm at a short distance offshore from the marsh edge. The nearshore berm acts to deter wave action and mitigate marsh edge erosion. This method would rely on waves to re-suspend sediment and eventually deposit it on the marsh platform during extreme weather events. This natural sediment transport could potentially elevate the marsh over time. Nearshore sediment berms are in place to mitigate shoreline erosion on the open coasts of Florida, Texas, and the Long Island Sound; and the USACE Regional Sediment Management Program is fostering further development of the practice (Woods Hole Group, 2012; Martin, 2002). This option could also utilize dredged material to create the nearshore berm. Modeling sediment mobility from the berm to the marsh requires a greater understanding of the wave climate, near-bottom velocities, and sediment textures. USACE is leading efforts to develop an interactive web tool that can estimate sediment mobility (McFall et al, 2016), although it is not yet complete. The feasibility of this option at Great Bay Boulevard is difficult to evaluate, since this type of project has not yet been implemented in New Jersey.

b. *Traditional riprap* – This option entails placement of rock at the base of the marsh edge or along the roadway, and is not a considered a green infrastructure project. While this option would be feasible for specific marsh erosion areas or vulnerable sections of the roadway, it does not provide environmental benefits or protection for the marsh as a whole.

DISCUSSION

Moving forward with either of the proposed adaptation options would require full design drawings, cost estimates, and consideration of permitting and regulatory requirements. We would also encourage future decision-makers to incorporate lesson learned from similar projects that USACE and others have planned and implemented in New Jersey. These topics are described in the sections below.

Design Guidance

The use of living shorelines and other natural and nature-based infrastructure for shoreline protection is relatively new to New Jersey, although these techniques have gained popularity since Hurricane Sandy. In 2016, the New Jersey Department of Environmental Protection commissioned state-specific design guidance for coastal green infrastructure projects. The guidance, produced by the Stevens Institute of Technology, identifies the parameters necessary for planning and designing a project and provides engineered examples (Miller et al, 2016). USACE also provides a framework for assessing and ranking coastal protection techniques, including the beneficial use of dredged materials to achieve coastal resiliency (Bridges et al, 2015).

Accounting for Ecosystem Services

When selecting a preferred design alternative, the Partnership Workshop participants strongly encouraged consideration of ecosystem services that the project will provide, including benefits to fisheries, recreation, coastal protection, habitat, and pollutant removal. While USACE does not formally include the value of ecosystem services in their cost/benefit analysis for funding shoreline protection projects, they do require projects to demonstrate environmental benefits above projected future conditions if no action was taken. For decision-making about green infrastructure projects, where environmental benefits are intended to be of approximately equal value to economic and flood risk reduction benefits, the project team recommends a more robust approach for capturing ecosystem services.

Regulatory Requirements

New Jersey's Coastal Zone Management Rules (N.J.A.C. 7:7) govern the implementation of living shoreline projects that include strategic placement of sediment and vegetation. N.J.A.C. 7:7-12.23 governs living shoreline projects that fall under the jurisdiction of an individual permit. N.J.A.C. 7:7-6.24 governs living shoreline projects that fall under the jurisdiction of a general permit. New Jersey claims ownership over tidelands, and holds them in trust for the people of the state. Tidelands are defined as property where any portion of the upland is flowed by the mean high tide of a natural waterway, or has been in the past. The Tidelands Resource Council, appointed by the Governor, makes the final decision on tidelands applications. Projects must also receive federal permits through the processes established by Section 10 of the Rivers and Harbors Act of 1899 (33 U.S.C. 403) and Section 404 of the Clean Water Act (33 U.S.C. 1344).

USACE Green Infrastructure Projects in New Jersey

The USACE Philadelphia District performs maintenance dredging of the New Jersey Intracoastal Waterway (NJIWW), which transits from east to west adjacent to the southern end of the Tuckerton (Great Bay) Peninsula. The most recent USACE dredging at this site occurred in 2013, when the hopper dredge, Currituck, removed approximately 20,000 CY of sand and bottom dumped the material offshore of the Holgate spit. Bottom dumping is the only disposal method available to the Currituck. The closest USACE dredged material placement site to Tuckerton Peninsula is an open water disposal site that is no longer used, and probably could not be mined. The nearest USACE confined disposal facilities (CDFs) are about 5 miles away on the Forsythe Refuge (Shad Island and Black Point) to the south and Parker Island near Mordecai Island to the north.

USACE Philadelphia District has conducted several projects involving the beneficial use of dredged material along the NJ Intracoastal Waterway over the past 5 years. The projects include:

a. Mordecai Island, located west of Beach Haven on Long Beach Island. 30,000 CY of material, consisting of 80% sand, was dredged from the NJIWW. The material was placed for restoration purposes in a previously breached area of Mordecai Island.
b. Ring Island, near Avalon, New Jersey. Dredged material from the NJIWW, consisting of 96% sand, was used to create habitat for the black skimmer and other bird species on Ring Island. The NJ Division of Fish and Wildlife owns and manages Ring Island. In addition, a small demonstration project adjacent to the black skimmer habitat used thin layer placement technique with approximately 500 CY of sand.
c. Stone Harbor and Avalon, New Jersey. In 2014, thin layer placement (TLP) of 5,000 CY of dredged sediment raised low-lying areas and restored wetland integrity. Philadelphia District incorporated lessons learned from this pilot project into larger-scale dredging and placement operation, placing approximately 45,000 CY of material into designated marsh areas between November and February 2016.

Initial monitoring by the Stone Harbor Wetlands Institute confirms that a number of shorebirds, horseshoe crabs, and terrapins are now using the Stone Harbor site. Preliminary reports indicate placement activities have also been successful on the Avalon marsh site, however monitoring will continue for several years to document the outcome of this project.

The three USACE beneficial use projects in New Jersey demonstrated the importance of utilizing proper dredges and personnel experienced with TLP. Thin-layer placement is relatively new and a very different process from conventional pipeline dredging, where dredged material is pumped at the maximum volumetric production rate into a confined upland disposal site. In contrast, thin-layer placement requires specialized, custom-made discharge nozzles that have only recently been developed and tested. Because only a few contractors are doing TLP, there is no "industry standard" for some of the dredging hardware yet. As more contractors gain experience with TLP, it should become easier to identify the optimum equipment. Likewise, the discharge and placement process for TLP has a different purpose than routine maintenance dredging. The goal of routine maintenance dredging is to remove material from a channel as quickly and cost-effectively as possible, while thin-layer placement transports material into an area that needs sediment to accomplish a specific objective, typically habitat restoration. Accomplishing restoration objectives requires much more finesse than pumping sediment into a confined disposal facility. TLP also requires some experimentation to identify which placement techniques are most effective at a particular site, and monitoring to evaluate effectiveness over time.

Today, there only are a limited number of contractors with the requisite experience. If this method is to continue in other areas of the state, more contractors will need proper training. In addition, New Jersey needs a regional sediment management plan to identify potential sediment sources and critical wetlands that could benefit from future projects.

Lessons Learned from New Jersey Marsh Studies

New Jersey marshes have historically been managed for multiple uses, including salt hay farming, mosquito control, and dredging/filling for development purposes. Human activity in New Jersey coastal wetlands dates back to the 1700s, meaning that the majority of wetlands have been altered.

The marsh ecosystem within Tuckerton Peninsula is largely intact because of protection under the New Jersey Wetlands Act of 1970 and management techniques used by the state Wildlife Management Area. Previous studies have mapped marsh habitat and evaluated biological systems, including habitat use and loss on the peninsula and within nearby bays (Montgomery and Newcomb, 1975; Able et al, 1999; Kennish, 2001; Lathrop and Bognar, 2001; Kennish et al, 2014a; Kennish et al, 2014b). Kana and others (1988) measured vegetation types and Tuckerton Peninsula marsh elevations to determine vulnerability with respect to accelerated sea-level rise. While the marsh system appeared to keep up with past changes in sea level, a three-foot rise could convert 90% of the area's marsh from high marsh to low marsh, and existing tidal flats to open water. Continuing changes in climate patterns have sparked interest among local researchers to designate the Tuckerton Peninsula marsh as a sentinel site for collecting data to calibrate sea level models and predict future changes (Kennish et al, 2014 b). Staff from JCNERR use these data and study results to advise coastal communities with regard to climate adaptation and mitigation strategies.

Open marsh water management (OMWM) is used for local mosquito control in the northeast section of the peninsula (Figure 12). This method of salt marsh manipulation has been found to benefit salt marsh productivity (vegetation, invertebrates, fish, birds) and the movement of organic carbon (Shisler and Schulze, 1981). From a human health standpoint, the altering of marshes to control mosquito populations has been successful in reducing the amount of pesticides used. However, there is some concern regarding expansion of the OMWM sites and erosion of the marsh platform as sea level rises. Researchers are presently collecting quantitative data on the long-term effects of OMWM and the impacts on marsh fragmentation. Qualitative observations indicate that this type of marsh management decreases marsh integrity by creating ponding and unvegetated areas that are subject to expansion. It is believed that OMWM fragments formerly whole marsh systems, disrupting rooting and the cohesiveness of the marsh platform. Some deterioration of the OMWM dredged ponds were observed along the northern transect during this study (Appendix A).

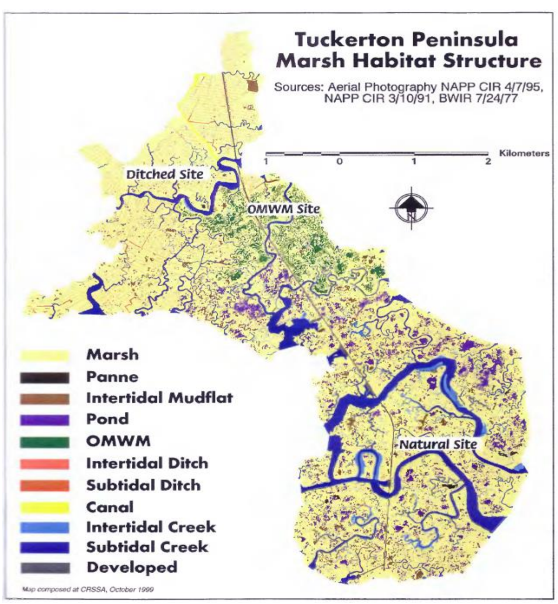

Figure 13. Marsh habitats of Tuckerton Peninsula (Able et al, 1999).

After Hurricane Sandy, shoaling in many New Jersey coastal waterways limited navigation. As mentioned earlier, the USACE Philadelphia District implements Regional Sediment Management practices along the coast to beneficially reuse dredged sediment, and some of the shoaled material was used for marsh habitat restoration through sediment thin-layer placement. Development of a thin-layer marsh restoration program is in its infancy stage in New Jersey as processes for identifying degraded marsh, permitting, and follow-up assessments are still being worked out through pilot studies conducted by the USACE and The Nature Conservancy (Chasten et al, 2016; Yepsen, 2016). The majority of the post-Sandy marsh restoration projects are still in the permitting process and have yet to be implemented. The USFWS Edwin B. Forsythe National Wildlife Refuge is seeking to carry out a thin-layer sediment project in the Reedy Creek section of the refuge. Several sediment placement projects in Cape May County may provide lessons learned regarding the depth of placement and soil acidification.

Little Egg Harbor/Tuckerton Borough Marsh Restoration Project

The nearby Township of Little Egg Harbor initiated an effort to address shoaled channels and marsh restoration after receiving a National Fish and Wildlife Foundation (NFWF) Hurricane Sandy Response Fund grant in 2014. The project involves dredging sections of seven nearby manmade lagoons and channels and placing over 150,000 CY of dredged material into 50.46 acres of the marsh platform adjacent to Great Bay Boulevard. The dredged sediment would be pumped from a barge and pipelined over the existing marsh platform in order to reach the designated restoration location. The marsh placement sites were selected by a consulting team via desktop analysis of aerial photographs and on-site visual inspections of open water pooling, presence of salt pans, sloughing, and saturation. As of September 2017, the project had not received permits to begin implementation.

Based on the results from this study and previous studies of the area, including information gathered during the workshop, the Township project would have benefitted from consultations with local marsh vegetation, mosquito control, and natural resource permitting experts prior to project design. While the Township's potential restoration sites do not overlap with our study, the data we collected can provide correlations between elevation, vegetation type, and the appropriate densities for planting new native vegetation. In addition, the present study found that erosion of the marsh edge is more of a threat than marsh platform erosion, and placement of sediment on the marsh platform should be in small increments to minimize impacts to existing healthy vegetation. Post-project monitoring is necessary to note changes in vegetation and hydrology, and should be coordinated with existing research efforts. The Township project has potential to be successful in restoring degraded marsh, but under present permitting circumstances may take longer to complete than expected.

SUMMARY OF KEY FINDINGS

- Maintaining a healthy marsh ecosystem and access to the natural resources of Tuckerton Peninsula is vital to the local economy.
- The marsh areas surveyed are moderately to severely stressed, although less degraded overall than other marshes in Barnegat Bay.
- Marsh edge erosion is a significant concern at the study location. The marsh edge is eroding at an average rate of 0.8 ft/year (measured between 1977 and 2015).
- A large number of human-created pools for mosquito control are located throughout the marsh. As marsh edge erosion accelerates inland and reaches the pooled areas, the erosion impacts could intensify.
- Barnegat Bay is a microtidal system, having a tidal range less than 2 m (6.5 ft). Because of this, small changes in marsh elevation can influence flooding. At the study site, adding only 10 cm [0.032 ft] of sediment would shift the site elevation from a location between MHW and MHHW to being above MHHW. This could significantly affect flood durations.
- The northeast sections of Tuckerton Peninsula and Great Bay Boulevard are susceptible to high waves from the east-northeast direction during storm conditions. Storms from the west had no effect on flooding during the period of study.
- Northeast storms are the main driver of marsh edge erosion.
- Low barometric pressure (990 mbar) increases water levels on Tuckerton Peninsula.
- Southern Great Bay Boulevard is surrounded by higher and wider marsh, but this part of the roadway is more prone to flooding than the northern section. This is due to lower roadway elevations and closer proximity to Little Egg Inlet, which channels tidal flow from the Atlantic Ocean.
- While federal and state resource agencies are most concerned with marsh edge erosion, they would consider projects that elevate the marsh platform to offset sea-level rise.
- Adaptation options considered in this study are thin-layer placement of dredged sediment (Option 1) and installation of a detached nearshore living reef (Option 2).
- Option 1 would require incremental placement of dredged sediment on low-lying sections of the marsh surface at the north and south transect locations (NT and ST).
- Thin-layer placement of sediment should not apply more than 10 cm (0.32 ft) of material every few years to prevent plant overburden.
- Increasing the marsh elevation by a total of 30.5 cm (1.00 ft) would reduce roadway flooding during a storm comparable to the January 2017 northeaster.
- Option 2 would place a wave attenuation device (marsh sill or living reef) seaward of the marsh edge to reduce wave energy brought on by northeast storms and protect against erosion.
- The wave attenuation device should be visible above the water surface, although this could pose a navigational hazard.
- Each project should include an adaptive management plan, long-term monitoring, and maintenance program.

TAKEAWAYS & NEXT STEPS

This study was a valuable exploration of nature-based design solutions to protect a coastal roadway from flooding hazards that will likely worsen with the effects of climate change. The project benefitted from taking a systems approach to coastal resilience, which sought to understand the relationship between the road and surrounding ecosystem and create options that could sustain them both over time. The experiences and perspectives of regional experts were extremely helpful in building community support and deciding among design options. While there are challenges for implementing coastal green infrastructure in New Jersey, the concepts developed and stakeholder outreach initiated during this study will help inform decisions for how this and similar sites are addressed in the future. Our takeaways and next steps include:

Systems approach to coastal resilience:

- Shoreline landscapes, such as this one, are often a patchwork of existing infrastructure and sensitive ecosystems. In order to build regional resilience to coastal hazards, the human and natural features must be considered together as components of a larger system.
- A systems approach requires an understanding of natural processes and hydrodynamics before proposing solutions.
- Applying a systems approach to coastal resilience at Great Bay Boulevard led to project designs that could protect both the roadway and surrounding marsh from future hazards.

Early and continued collaboration:

- Designing, permitting, and implementing green infrastructure along Great Bay Boulevard will require interagency cooperation.
- Engagement with regional stakeholders from the beginning of the process, including regulators and resource agencies, was extremely beneficial to this project. Early consultations and feedback during the Partnership Workshop provided the project team with valuable expertise and buy-in from the community. Collaboration with regulators helped to narrow down our list of design alternatives and set the foundation for a positive working relationship moving forward.
- The project team, through the Barnegat Bay SAGE Community of Practice, will continue coordinating with stakeholders to develop a sequence for proceeding with the project.

Regional sediment management:

- In coastal New Jersey, the beneficial use of dredged material can be an effective technique for marsh restoration. Healthy coastal marshes, in turn, provide flood protection to adjacent infrastructure and development.
- However, sporadic funding and the timing of dredging events can be obstacles to implementing beneficial use projects. Due to this, we observe that beneficial use projects are more feasible in areas with identified nearby sources of sediment.
- The project team recommends development of a regional sediment management plan for coastal New Jersey, similar to the product developed for the Delaware Estuary (Delaware Estuary Sediment Management Plan Workgroup, 2013). The plan should provide information about types and sources of sediment, and identify vulnerable coastal wetland areas that would benefit

from the sediment. The identification of candidate wetlands should use existing assessment tools, like the protocols established by The Nature Conservancy (Yepsen, 2016).

Monitoring:

- Since there are few studies documenting the ecological impacts of green infrastructure projects, any project should include a plan for long-term monitoring of marsh health.
- Long-term monitoring would also increase the collective knowledge of green infrastructure techniques that will and will not work in the New Jersey coastal environment.

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TECHNICAL APPENDICES

APPENDIX A
Task Report by Barnegat Bay Partnership – *Salt Marsh Vegetation and Shoreline Condition along Great Bay Boulevard, Tuckerton, NJ*

APPENDIX B
Task Report by Coastal Research Center – *Hydrodynamic Analysis*

APPENDIX C
Task Report by Coastal Research Center – *Delft3D Model Details*

APPENDIX D
Task Report by Coastal Research Center – *Geotechnical Report*

APPENDIX E
Task Deliverables – *Webinars & Partnership Workshop*