Salt Marsh Vegetation and Shoreline Condition along Great Bay Blvd, Tuckerton, NJ

A Barnegat Bay Partnership report to Stockton University Coastal Research Center

in relation to the grant

"Quantification of Flood Event Forcing and the Impact of Natural Wetland Systems "

Erin Reilly, Martha Maxwell—Doyle, James Vasslides

Barnegat Bay Partnership

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Objective

The objective of the overall "Quantification of Flood Event Forcing and the Impact of Natural Wetland Systems" study was to provide recommendations for the use of green infrastructure solutions to lessen the frequency and severity of flooding along Great Bay Boulevard. Thus, project partners conducted a baseline investigation that included three goals:

1. Defining the physical parameters that initiate flooding along Great Bay Boulevard to ascertain how extreme coastal events (*e.g.*, northeast storms and spring high tides) affect roadway flooding;
2. Describing the overall condition and influence of a natural wetland system in buffering high water events; and
3. Determining if there is a minimum marsh width necessary to protect the roadway during high water events.

The information, once compiled, will be used to provide recommendations for marsh restoration or living shoreline projects, which may include the use of dredged or combined disposal facility (CDF) material readily available in the vicinity of the project.

To determine the suitability of potential green infrastructure options to the wetlands themselves, the Barnegat Bay Partnership (BBP) evaluated the condition of the marsh surface within the study area using established *Mid-Atlantic Coastal Wetlands Assessment* (MACWA) metrics and protocols (*i.e.*, MidTRAM v3.0) and shoreline condition using the protocols developed as part of the BBP's *Paddle-For-The-Edge* program.

Methodology

Marsh SurfacePlatform

To assess the condition of the marsh surface, the BBP established a total of six transects crossing Great Bay Boulevard equally divided between two sections of marsh (Figure 1). Great Bay Boulevard users had identified these sections as areas that flood frequently. The first section was located immediately south of the first bridge travelling south from Tuckerton. The second section was located to the north of Captain Mike's Marina, approximately midway down the Tuckerton peninsula (39.533889 latitude, -74.321667 longitude). Each transect consisted of a minimum of seven (maximum 9) 1-m^2 sampling plots placed such that plots were not located within open waters. These plots were established to capture the overall condition of the saltmarsh on the platform (n=24), both near the road (n=12) and along the shoreline edge (n=12).

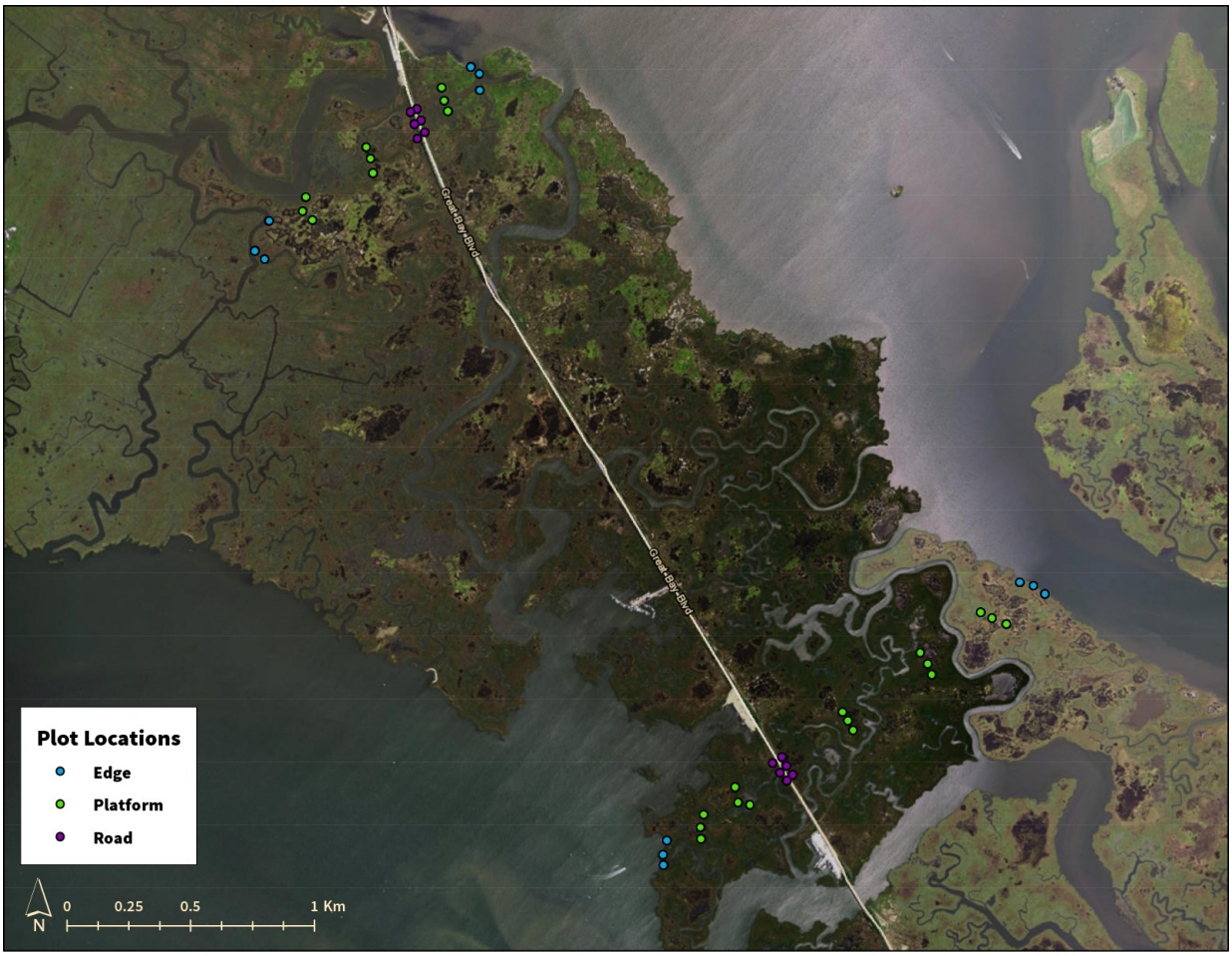

Figure 1: Plot location and type along Great Bay Boulevard

Each plot was evaluated for measures of plant density and robustness, faunal influence, and soil cohesiveness over the course of 3 days; September 27th, September 28th, and October 3rd of 2016. RTK GNSS was used to obtain GPS coordinates and elevation data (±0.02m) for the four corners and middle of each plot, from which an average plot elevation was calculated. Following elevation and location data collection, BBP ecologists collected the following data using MACWA protocols: light attenuation, horizontal vegetation obstruction, stem heights, bearing capacity, number of mussels, and number of fiddler crab burrows (Figure 2). In addition to these metrics, a species list was compiled for each of the quadrants.

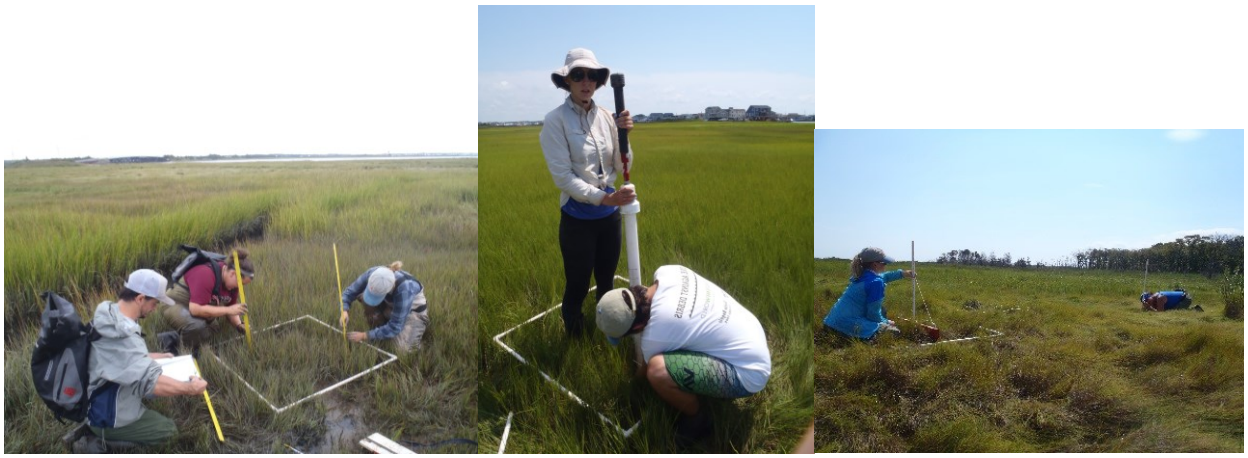

Figure 2. Photos demonstrating the collection of field data. A) Stem Heights, B) Bearing Capacity, C) Horizontal Vegetation Obstruction.

Light attenuation is a vegetation metric that is a proxy for vertical denseness of the plant canopy, where higher values indicate a more dense canopy. Light attenuation was measured by recording the amount of light above the canopy (ambient light) and on the ground (penetrative light) at each corner and the middle of a plot using a digital light meter. Higher values indicate greater density. Values are given by the equation:

$$\boldsymbol{Light\ Attenuation} = \left(\mathbf{1} - \frac{\boldsymbol{average\ penetrative}}{\boldsymbol{average\ ambient}}\right) * \mathbf{100}$$

Horizontal vegetation obstruction measures horizontal vegetative density across multiple levels. A 1-m board divided into 10 equal sections was observed at 0.25m, 0.5m and 0.75m from the ground at a distance of 4 meters. At each height, the total number of squares seen was recorded, so that higher scores indicate less density. Horizontal vegetation density was then calculated via the equation:

$$\boldsymbol{Horizontal\ Vegetation\ Density} = \frac{\boldsymbol{number\ of\ bars\ available} - \boldsymbol{number\ of\ bars\ visible}}{\boldsymbol{number\ of\ bars\ available}}$$

Measuring stem heights provides an indication of the vertical height of the vegetative canopy. Plant growth forms (*i.e.*, stem heights) are affected by inundation times; salt marsh plants tend to grow taller with longer hydroperiods. In *Spartina alterniflora,* this is much more

pronounced than in other species; it grows in both a tall form and short form. Tall-form *Spartina alterniflora* is found along the edges of creeks and ditches and in other low-lying areas. It is able to grow taller because the longer hydroperiods allow for greater oxygen exchange and lower levels of soil toxicity. When *Spartina alterniflora* has a decreased hydroperiod, it grows shorter, concentrating its growth in an extensive root system that is better able to scavenge nutrients and survive in an area with less favorable soil chemistry. Stem heights were measured for the first 25 stems of a given species in each plot, starting at a corner closest to the water's edge and working diagonally towards the opposite corner.

Bearing capacity is a metric that assesses the below-ground stability of the wetland by measuring soil resistance using a slide hammer and PVC pipe. It is comprised of two metrics, immediate loading response (how far the pipe sinks once the hammer is placed on top of the pipe), and penetration depth (the depth the pipe penetrates into the soil after 5 blows). Changes to below-ground organic material may occur before there are visible above-ground changes in the plant community and other indicators of stress. Bearing capacity values tend to be higher closer to creeks and larger sources of water. Bearing capacity was measured in a random location within the plot using an 18-pound slide hammer.

The presence or absence of ribbed mussels provides information regarding the erosional forces acting along marsh edges. Mussels found at lower elevations near the main body of water and internal creeks and ditches act as a wave-attenuating device, lessening the erosional forces at the marsh edge. However, in areas exhibiting high levels of erosion, mussels are unable to dampen wave energy and their attachment points often erode away, making it difficult for large groups of mussels to grow. The number of ribbed mussel (*Guekensia demissa*) lips within each sample plot were counted to determine the mussel density.

The density of fiddler crab (*Uca pugnax*) burrows can give a clue to the subsurface vegetation and soil conditions, as well as hydroperiod within a marsh. Fiddler crabs prefer to burrow in areas with a medium root mat density; however, areas with soft muds that are frequently flooded are unable to support the crab's burrow structure, while infrequently flooded hard sediments are too difficult for crabs to dig in (Bertness and Miller 1984). Furthermore, the crabs' behaviors can impact vegetation growth and subsurface processes within the marsh. Burrows have been shown to change the sediment chemistry in ways that influence emergent vegetation growth (Bertness and Miller 1984); however, their impact on the 'cohesiveness' of the

marsh has not been studied extensively. The number of fiddler crab burrows within each sample plot were counted.

Marsh Edge

For the past two years, the Barnegat Bay Partnership has conducted a citizen scientist-based shoreline assessment called *Paddle-for-the-Edge*. Utilizing the ESRI Collector application (Redlands, California) for smart phones, volunteer kayakers, canoers, and standup paddle boarders evaluate marsh shorelines at 30-m increments.

For QA/QC purposes, the BBP staff conducts an annual group training session held in each spring. Trained citizen scientists are assigned a section of marsh edge to evaluate. Once in the field, they answer questions about land use, flora, fauna, signs of erosion, and recreational use, and then attach a picture of the associated shoreline (Table 1). BBP staff then compares the photos and survey answers for a selection of the data. For this project, we utilized data collected from the project area during the 2016 June survey (no points were taken in the project area in 2015), as well as from a second collection in October targeting the Tuckerton peninsula. All data were assessed for quality according to the Paddle for the Edge Quality Assurance Project Plan.

Question	Type	Answers
Date	Date	Auto fill
What is the Tidal Stage	Categorical	Slack High; Ebb; Slack Low; Flood
Land use behind assessment point is	Categorical	Undeveloped; Mostly Residential, Mostly Commercial
How high is the bank	Categorical	0-5 ft; 5-10 ft; >10 ft
Edge vegetation density at your assessment point is.	Categorical	> 75% Vegetated; 50 – 75% vegetated; Mostly bare soil/sand; mostly hardened
Describe the predominant edge plants	Categorical	Reeds; Short Grass; Tall Grass; Trees/bushes
Is the type of soil do you see	Categorical	Sandy Soil; Mucky Soil
How many mussels do you see	Categorical	0; 1 – 10; 10 – 100; 100- 1000
How are the mussels distributed	Categorical	Singles, Clumped, Continuous
How many Fiddler Crab burrows do you see	Categorical	0; 1-2; up to 10; Looks like Swiss Cheese
Describe the slope of the bank	Categorical	Perpendicular; Gradual Slope; Undercut
Do you see exposed roots	Y/N	Yes; No
Is the bank cantilevered	Y/N	Yes; No
Is the bank tiered or step-like	Y/N	Yes; No
Are there chunks or pieces of marsh in the water	Y/N	Yes; No
Have you passed any ditches since your last point	Y/N	Yes; No
How many people do you see	Integer	
What are they doing	Text	
What type of structures do you see in the water	Categorical	None; Unidentifiable/Remnant; Riprap; Bulkhead; Gravel/Cobblestone; Groin/Jetty; Pilings; Pier/Dock; Marina; Boat Ramp

Table 1: Questions on the Paddle for the Edge Survey

Data Analyses

Data analyses were conducted using the R statistical package (R Core Team 2013). For the marsh surface metrics, averages and standard deviations were calculated by type of plot (Road, Edge, or Platform), by the side of the road (North or South) and by marsh section (near the bridge or the marina). To determine how the marsh surface may differ spatially, multi-way Analysis of Variance (ANOVAs) were run on each metric for the three factors listed above. For ANOVAs that had significant values ($p < 0.05$), a Tukey test for Highly Significant Differences (HSD) was conducted. Additionally, the averages for each metric were compared against

MACWA reference values (the same metrics collected throughout the Barnegat Bay watershed from 2010-2015 [BBP unpublished data]) to compare this marsh complex to others within the watershed.

The shoreline data were combined into a single erosional level ("High Erosion", "Low Erosion", "Transitional Edge", or "Accretion") based on the VIMS CCRM shoreline rubric (Berman and Hershner 1999). The calculated erosion levels were then compared to the accompanying photographs for 20% of the points to determine how well the volunteer-collected data corresponded to an assessment conducted by an experienced data-collector. The erosional level for each point was then color-coded and displayed in ArcGIS to visually ascertain spatial patterns in erosion along the project area.

Results and Discussion

Marsh Surface

Elevation

Mean elevations ranged from a low of -0.2606 m (NAVD 88) to a high of 0.711 m (NAVD 88). As none of the NOAA tidal stations near the site have NAVD-88 values, local values for Mean Higher High Water (MHHW), Mean High Water (MHW), and Local Mean Sea Level (LMSL) were calculated for four points at the edge of the Tuckerton Peninsula using NOAA's vDatum software tool (https://vdatum.noaa.gov/) and then averaged (Table 2).

Point	1	2	3	4	Mean
Latitude	39.564043	39.543787	39.534436	39.544343	
Longitude	-74.332028	-74.308354	-74.334049	-74.358877	
MHHW (m in NAVD 88)	0.3547	0.3568	0.541	0.5584	0.4527
MHW (m in NAVD 88)	0.2757	0.2766	0.4325	0.4503	0.3588
LMSL (m in NAVD 88)	-0.0451	-0.0605	-0.0624	-0.0449	-0.0532

Table 2: Locations and tidal datums at 4 points around the Tuckerton Peninsula from vDatum. These values were then averaged to calculate local values for MHHW, MHW and MSL in NAVD 88.

The mean plot elevations were then placed in four categories: "MHHW and above", "MHW to MHHW", "LMSL to MHW", and "LMSL and below." Only one plot had an elevation lower than LMSL, 46% of the plots were located between LMSL and MHW, 13% were located between MHW and MHHW, and 40% of the plots were located at MHHW or

above. It is encouraging that the majority of the plots were found between LMSL and MHHW, the optimal growing range for marsh plants (Morris 2002). However, the fact that 40% of the plots were found at MHHW or above is a concern in the context of a thin layer deposition restoration project, as additional elevation would put these areas at risk of becoming too high for marsh plants to grow successfully.

Light Attenuation

There were no significant differences in light attenuation between plot type, section, side of the road, or interaction terms (Figure 3). Average light attenuation for all combinations was greater than the reference value of 50%, suggesting a vegetation canopy that is more dense within the project area compared to the wider watershed.

Horizontal Vegetation Obstruction

There was a significant difference between the mean values for the marsh edge and marsh platform ($p=0.016$), but the pattern was not consistent across section or side. The mean horizontal vegetation obstruction values for all factors are within one standard deviation of the MACWA mean, though some subsets fall above the reference mean and others below (Figure 3).

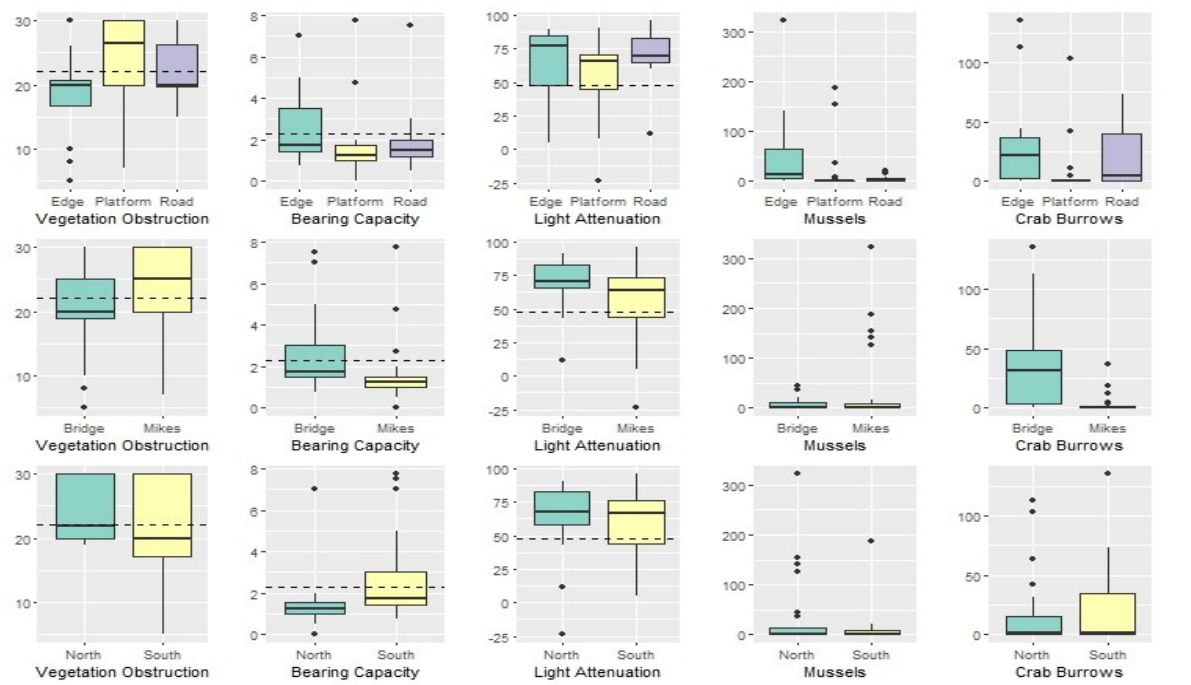

Figure 3. Average values for each metric by plot type, marsh section, and side of the road. The black dotted line indicates the MACWA reference average where applicable.

Stem Heights

Spartina alterniflora was the dominant species present in the vegetation plots, with *Spartina patens*, *Distichilis spicata*, *Limonium carolinianum*, and *Salicornia* sp. also present, but far less abundant (Figure 4). Because the minor plant constituents were found unevenly across the plots, we opted to focus on *Spartina alterniflora* as a metric for marsh health given its wide-spread distribution throughout Barnegat Bay tidal wetlands.

The mean height of *Spartina alterniflora* fell within one standard deviation of the Barnegat Bay MACWA reference data across all three factors (plot type, wetland section, and side of road; Figure 5). The mean height of the *Spartina alterniflora* in the edge plots was taller than the

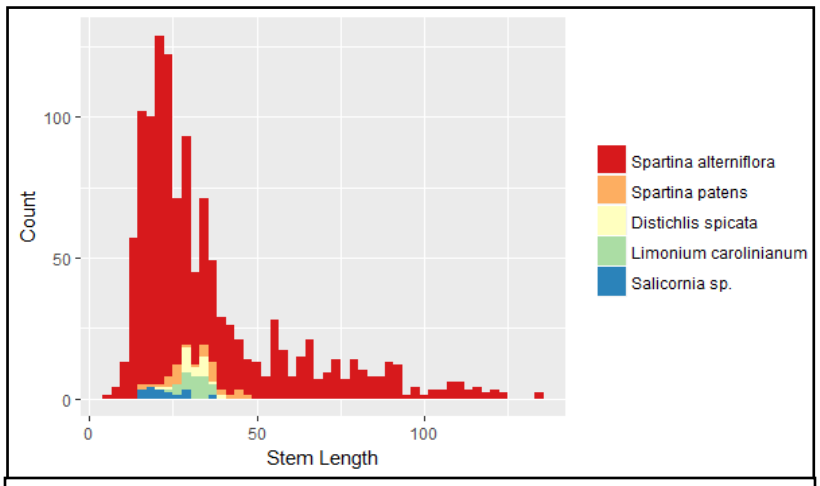

Figure 4: Histogram of stem heights by species.

mean height of the platform and road plots ($p < 0.001$), following the pattern of taller plants near the creek edge described previously. *Spartina alterniflora* stem heights across plot type were found to be significantly shorter north of the road near Captain Mike's Marina than the other three section/road combinations ($p < 0.001$). The stem heights in the other section/road combinations were not significantly different from each other.

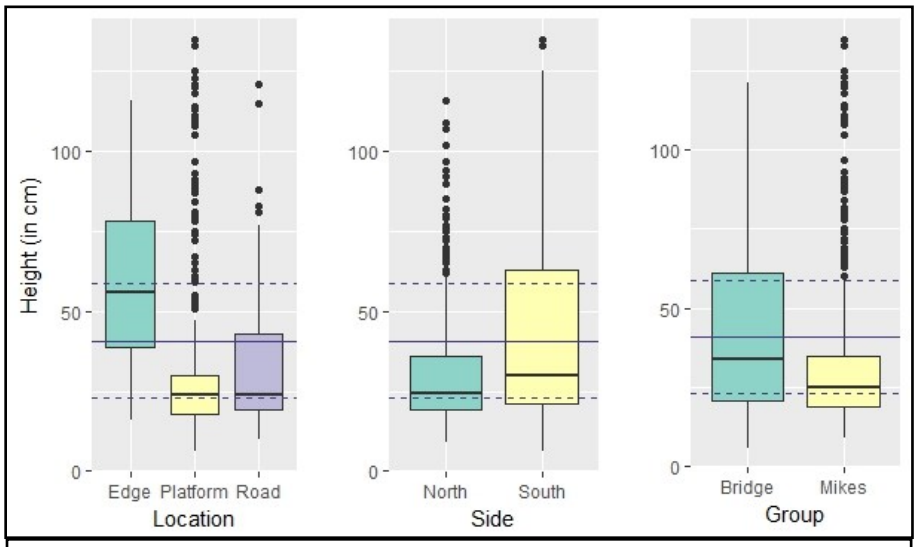

Figure 5: *Spartina alterniflora* stem heights shown by location of plot, side of the road, and group of transects. The solid line is the mean stem height for *Spartina alterniflora* in Barnegat Bay from MACWA data (40.77). The dashed lines represent one standard deviation from the mean (±17.81).

Bearing Capacity

The average bearing capacity by plot type, section, and side of the road, were all below the MACWA average for Barnegat Bay (Figure 3), indicating a slightly firmer substrate than the watershed average. Bearing capacities were significantly different between the north and south side of the road ($p = 0.02$) as well as between the group of transects by the bridge and the group of transects by Captain Mike's Marina ($p = 0.04$). While there were statistically significant differences, biologically the differences were unlikely to have a substantial impact on plant survival. The difference between means in both cases was less than 1.5 cm, which is less than the binning system used in the MACWA MidTRAM 3.0 protocol to score bearing capacity (2 cm bins). All three means (plot location, section, and side of road) were within the top two tiers of the MACWA protocol, which are indicative of minimally stressed marsh systems.

Mussel Density

Mussel densities were not different across plot type, section, or side of road (Figure 3), but the interaction of these factors did lead to significant differences in densities. There were significantly more mussels at the North Edge plots (mean differences ranged from 90 to 105 more mussels, $0.023 < p < 0.046$) compared to the North and South Platform and Road plots and the South Edge plots. It is possible that the larger number of mussels found at the northern edges are due to the protection provided by the series of small islands along the northern side of the peninsula. Additionally, conditions at the southern edges may not be as favorable to mussel growth. The southern edge plots near the first bridge tended to show signs of accretion; higher sediment accumulation would bury mussels and make it difficult for them to feed. Conversely, higher erosion near Captain Mike's Marina at the southern edge may not be conducive to mussel recruitment.

Fiddler Crab Burrow Density

There were significant differences between the plot types ($p = 0.0369$) and between wetland sections ($p < 0.0001$), but not side of road (Figure 3). There were significantly more crab burrows along the edges than on the marsh platform (p=0.008), which is not unusual in New Jersey salt marshes, and may indicate that the platform elevation is sufficiently high enough that it is difficult for the crabs to dig. There were also significantly more burrows near the bridge than near Captain Mikes Marina.

South Side of the Road, Transects near the Bridge	**North Side of the Road, Transects near the Bridge**
Baccharis halimifolia Distichlis spicata Iva frutescens Juniperus virginiana Limonium caroliniaum Phragmites australis Salicornia spp. Solidego sempervirens Spartina alterniflora Spartina patens	Atriplex prostrata Baccharis halimifolia Distichlis spicata Iva frutescens Juniperus virginiana Limonium caroliniaum Phragmites australis Salicornia spp. Solidego sempervirens Spartina alterniflora Spartina patens Symphyotrichum tenuifolium
South Side of the Road, Transects near Captain	**North Side of the Road, Transects near Captain**
Distichlis spicata Iva frutescens Limonium caroliniaum Phragmites australis Salicornia spp. Spartina alterniflora Spartina patens	Distichlis spicata Iva frutescens Limonium caroliniaum Phragmites australis Salicornia spp. Spartina alterniflora Spartina patens Sueda spp. Symphyotrichum tenuifolium

Figure 6: List of species found per quadrant. Red indicates an invasive species.

Biodiversity

These marshes are dominated by *Spartina alterniflora,* which is typical for tidal salt marshes along the New Jersey Atlantic coast. However, in each of the 4 wetland section/side of road combinations, between 6 and 12 species were found, indicating a healthy mosaic of species across the marsh. This was not a comprehensive survey to identify all of the species in a defined area, but rather a list of species observed while walking or boating to each of the plots. The species list for each quadrant is shown in Figure 6. Species in Red are considered invasive species. The MidTRAM 3.0 protocol gives any site with five or more species the highest rating for species richness.

Marsh Edge

A total of 345 points were utilized in the marsh edge analysis. Approximately 40% of the points were classified as High Erosion, 2.0% as Low Erosion, 15% as Transitional Edge, and 43% as Accretion (Figure 7). The accreting and transitional edges tended to be within interior marsh creeks or sheltered shorelines, while the exposed marsh edges were predominately highly erosional. The calculated erosion level and photo determined erosion level were the same for 75% of the points.

In most of the cases where there was disagreement, the photos showed shorelines at high tide. Previous data analyses have indicated that citizen data collectors find it challenging to answer the survey questions when they cannot see the entire edge.

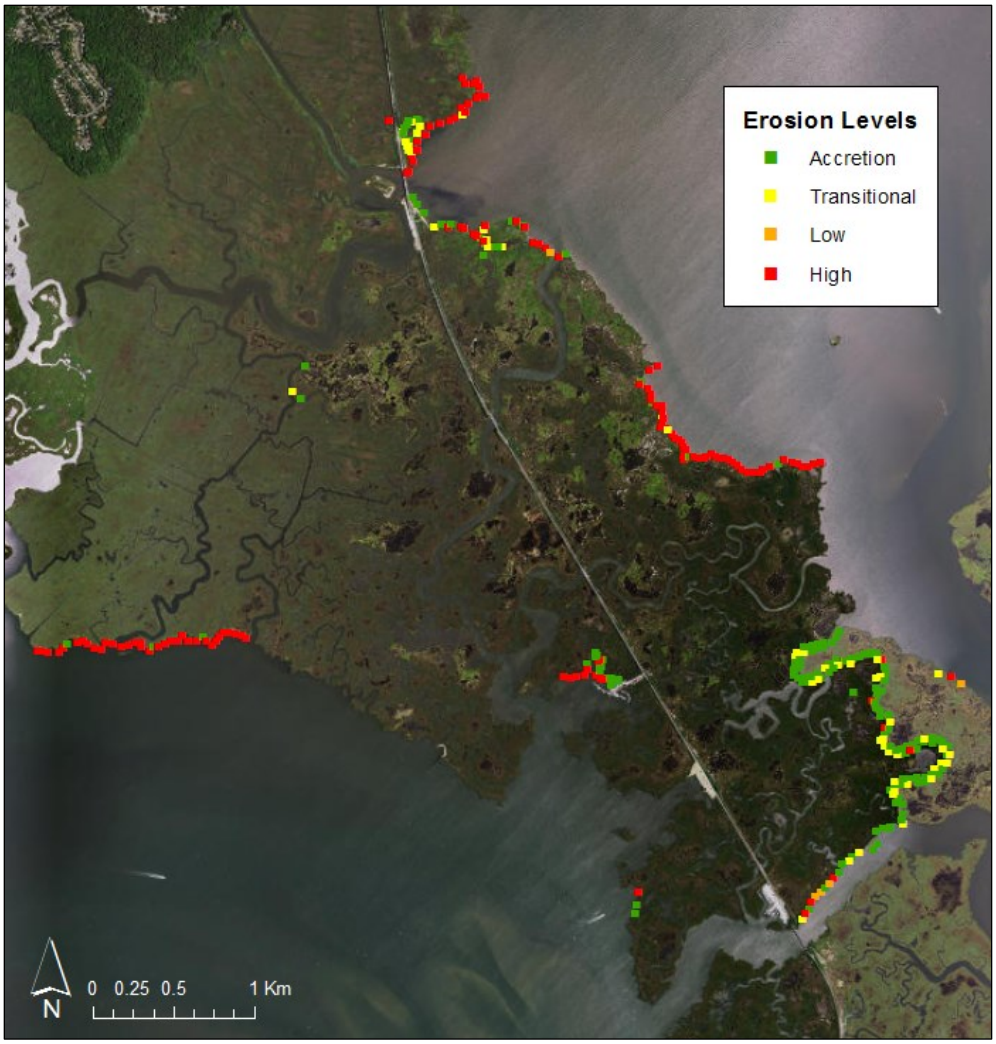

Figure 7: Calculated shoreline erosion levels along the Tuckerton Peninsula as determined by the citizen-science based Paddle For The Edge program.

Conclusions

The marsh surface data indicated that these marshes are similar in condition, and for some metrics better than, Barnegat Bay wetlands as a whole. It is worth reiterating that the reference data used to make these comparisons do not measure conditions at solely pristine sites, but rather sites characteristic of Barnegat Bay salt marshes at-large. Thus, comparing the project data to the reference data does not mean that the areas surveyed as part of this project were in pristine conditions, rather that they were not in worse condition than other marshes in Barnegat Bay. Given the lesser degree of development immediately adjacent to and surrounding this marsh complex, as compared to other marshes included in the MACWA dataset, these findings are not surprising.

Marsh vegetation along the transects appears to be growing within the normal 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. The dataset that forms the basis for the Barnegat Bay MACWA reference average contains more edge measurements than platform measurements, whereas the marsh surface portion of the project focused more on platform measurements than edge measurements. Because there is more potential high marsh in the current project dataset, you would expect the average stem height to be below the baywide average, which was the case. The relatively high level of biodiversity shows the marsh has a mosaic of areas displaying characteristics of both high and low marsh and is in the minimally stressed range for mid-Atlantic marshes.

In general, it may seem like Barnegat Bay marshes are more vulnerable to SLR than other marshes in the state of New Jersey because of their lower elevation in NAVD 88. However, Barnegat Bay marshes tend to have higher elevation capital (especially at the southern end) because of local tidal conditions. Elevation capital is the position of a marsh relative to the lowest elevation at which plants can survive (Cahoon and Guntenspergen 2010). In general, wetlands with large tidal ranges have large growth ranges, and subsequently more potential to accumulate minerals and organic matter. Wetlands with small tidal ranges like those found in Barnegat Bay have smaller growth ranges, and as a result, small changes in elevation can have larger impacts. Wetlands considered to have large elevation capital are generally more resilient to the effects of relative sea level rise. The marshes for this study are situated within and towards the upper end of their optimal growth ranges, indicating higher elevation capital, however because the growth range is smaller than other areas of New Jersey, they may be more vulnerable to elevation shifts.

Almost all of the plots were at elevations that were optimal for marsh vegetation growth or higher. Healthy tidal marshes are able to build enough elevation relative to current sea level to maintain their vertical position as sea level rise increases. The MACWA data from the nearby Site Specific Intensive Monitoring (SSIM) Station at Horse Point show an average accretion rate of 6.17 mm per year (BBP unpublished data); this is larger than the 4.27 mm per year projected 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.

Because Barnegat Bay is a microtidal system, small changes in elevation can have larger impacts than they would in systems with a larger tidal range. At this site for example, just 10 cm (4 in) of sediment added would move the site from being between MHW and MHHW to being above MHHW, dramatically shifting hydroperiods. At a marsh neighboring the Horse Point site, we observed a decrease in vegetative cover after Open Marsh Water Management (OMWM) spray increased the elevation by approximately 20 cm (approximately 8 in) in 2011; little vegetation has returned to these areas to date.

One stressor observed, but not captured in the data collected, was the large number of man-made pools found throughout this marsh. These 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 including duck hunting, salt hay farming, and mosquito control since before the 1930s. In general, the pools that have been excavated do not appear to be causing the marsh to fragment or break apart. However, there is concern as shoreline erosion continues to accelerate inland that once they reach these ponded areas erosion will be more dramatic. In addition, we also observed some deterioration between OMWM dredged ponds along the northern transect closest to Capt. Mike's. Some of the adjoining ponds walls were beginning to be severely 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.

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APPENDIX B – HYDRODYNAMIC ANALYSIS

The results section for the sensor deployments is broken up into two main sections based on the two instrument deployments that were conducted. The first section explains the results from the first deployment. The baseline hydrodynamic parameters are highlighted, several small storms that occurred during that deployment are analyzed, water levels along each transect are displayed, and the average background marsh edge erosion rate is calculated. The second section explains the results from the northeast storm that was measured during the second deployment. The hydrodynamic parameters associated with the storm are highlighted, water levels along each transect are analyzed in terms of flood height and flood duration, roadway flooding is analyzed in a spatial sense along the entire peninsula, and the average marsh edge erosion rate during the storm is calculated. Please note that the wave directions, as referenced in this report, refer to the directions that waves were traveling from (as is convention).

Deployment 1 Results

Results from the first deployment show that waves in both Tuckerton Bay and Great Bay can be classified as small, short period, and locally generated waves. The average Hs was 0.19 ft, the average DirTp was 172° (south-southeast), and the average Tp was 1.57 s at the AQD site in Tuckerton Bay. The minimum Hs was 0.03 ft with an associated DirTp of 159° (southeast) and Tp of 1.43 s, and the maximum Hs was 1.48 ft with an associated DirTp of 311° (northwest) and Tp of 1.89 s (see Table B1 for a tabular format of the statistical wave parameters). The wave rose plot of deployment 1 shows that wave heights were typically between 0.00-1.00 ft, and distributed somewhat uniformly in terms of direction. Even though the average DirTp is southeast, the wave rose displays a concentration of wave heights in a narrow directional band around the east-northeast direction and shows that the larger wave heights tend to come from the northwest and northeast direction (Figure B1). The wave energy spectrum plot reiterates the fact that the waves during the first deployment were, on average, short period waves because all wave energy falls within the wave period bands of 3.00 s or less, with the majority falling within the wave period band of 2.00 s. The plot also shows that the highest concentration of wave energy was from the east-northeast direction, with secondary peaks in wave energy being concentrated from the west-northwest and a tertiary peak from the southwest direction (Figure B2). This shows that waves from the east-northeast direction are of the main concern along the northeast side of the roadway during normal conditions because this direction displayed the highest concentration of wave energy and the largest wave heights that were directed towards the marsh edge.

Table B1. Statistical wave parameters from deployment 1 for the AQD site.

AQD - Wave Parameters (Dep. 1)				
		Maximum	Minimum	Average
Hs (ft)		1.48	0.03	0.19
DirTp (°)		311	159	172
Tp (sec)		1.89	1.43	1.57

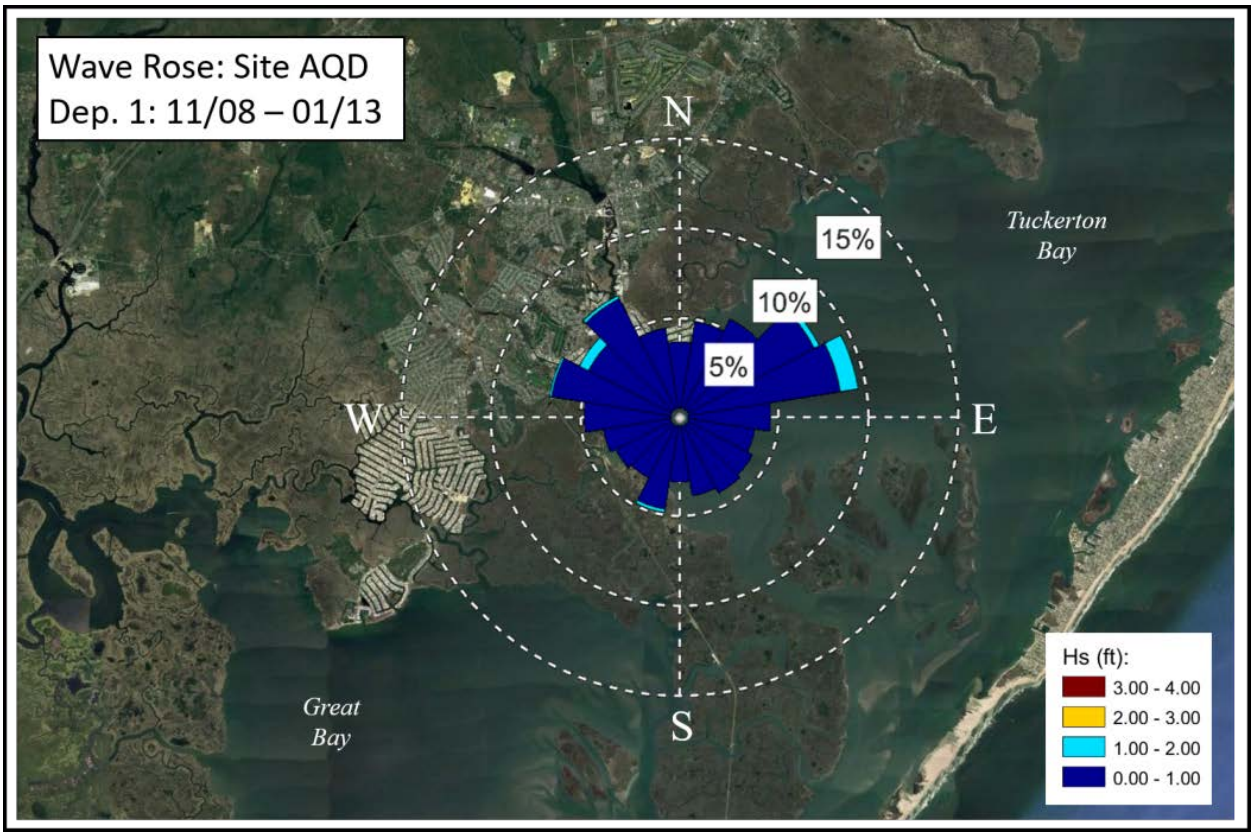


Figure B1. Wave rose plot for deployment 1 showing the percentage of occurrence (concentric circles) and distribution of Hs with DirTp at the AQD site. Wave rose is overlaid on a satellite image of the study area with the center of the rose falling on the AQD site location in order to show wave height and direction in terms of the geography of the area. Satellite image courtesy of 2017 TerraMetrics.

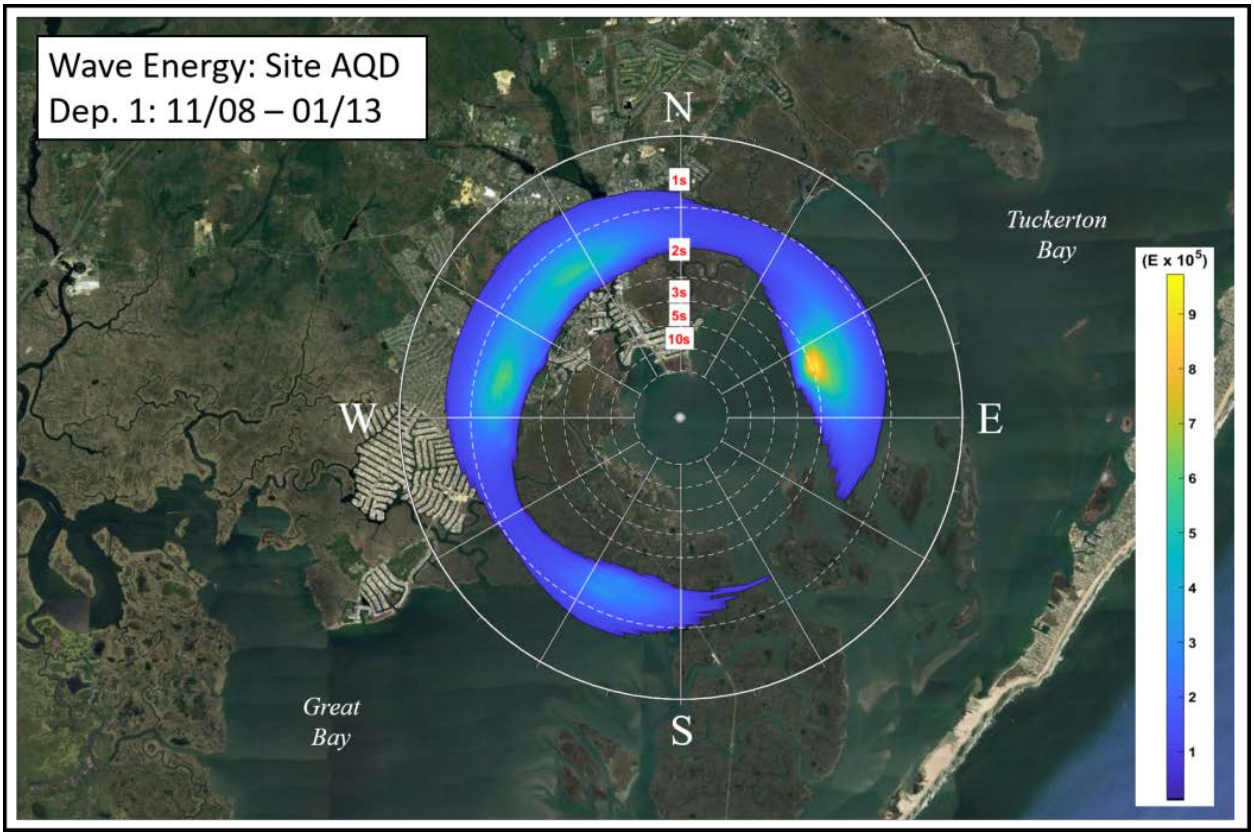


Figure B2. Average wave energy spectrum plot for deployment 1 showing the concentration of wave energy in terms of Tp and DirTp at the AQD site. Energy is represented by the color bar ($E = m^2/(Hz°)$). Wave energy is overlaid on a satellite image of the area with the center of the plot falling on the AQD site location in order to show wave energy in terms of the geography of the area. Satellite image courtesy of 2017 TerraMetrics.

The average Hs was 0.10 ft, the average WDir was 241° (southwest), and the average Ts was 2.47 s at the DW site in Great Bay. The minimum Hs was 0.003 ft with an associated WDir of 234° (southwest) and a negligible Ts, and the maximum Hs was 1.17 ft with an associated WDir of 269° (west) and a Ts of 2.50 s (see Table B2 for a tabular format of the statistical wave parameters). The wave rose plot of deployment 1 shows that wave heights were typically between 0.00-0.50 ft and distributed somewhat evenly around the west direction with a slightly larger tendency to the southwest. Wave directions with the largest percentage of occurrence were from the west direction and the largest wave heights came from the west direction as well (Figure B3). This shows that waves from the west directions are of the main and only concern along the southwest side of the roadway because the only waves measured at this site were from the directional window of 180° to 360°.

Table B2. Statistical wave parameters from deployment 1 for the DW site.

DW - Wave Parameters (Dep. 1)				
		Maximum	Minimum	Average
Hs (ft)		1.17	0.003	0.10
WDir (°)		269	234	241
Ts (sec)		2.58	NaN	2.47

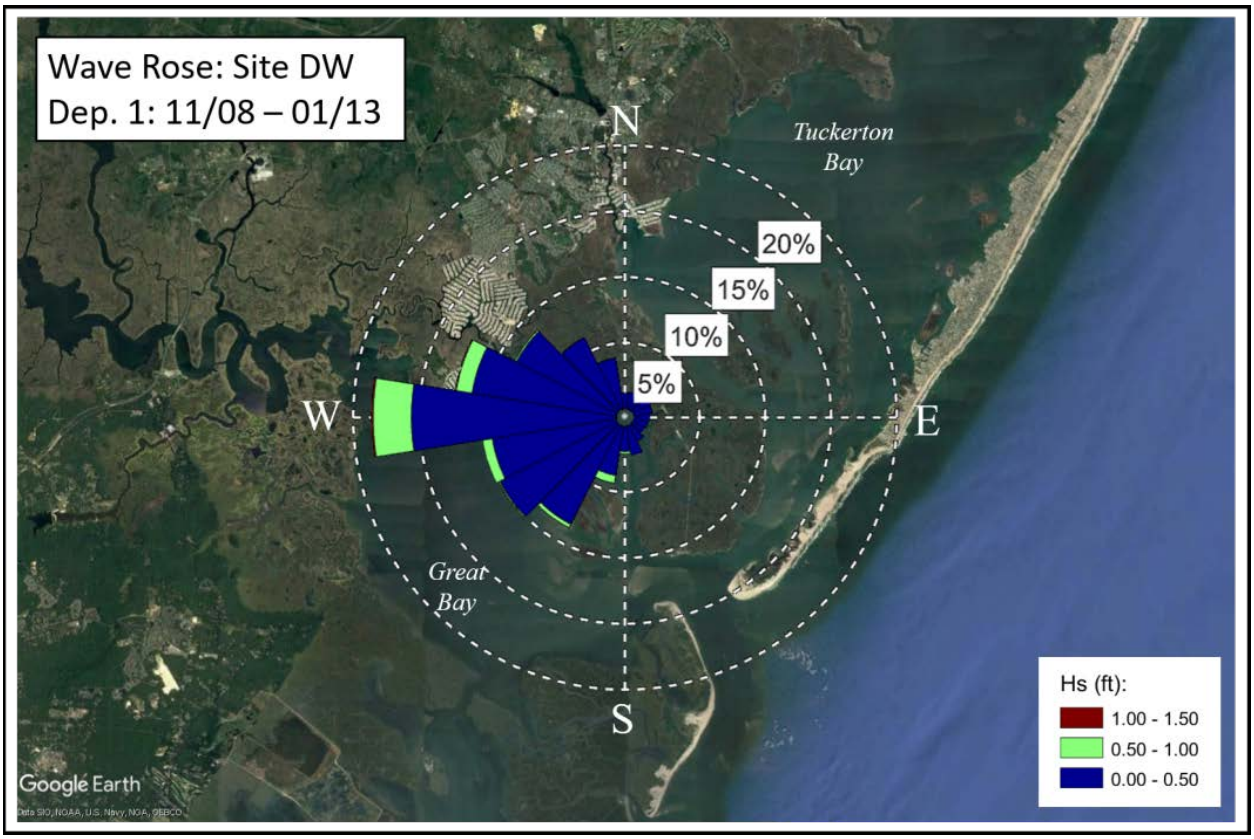


Figure B3. Wave rose plot for deployment 1 showing the percentage of occurrence (concentric circles) and distribution of Hs with WDir at the DW site. Wave rose is overlaid on a satellite image of the study area with the center of the rose falling on the DW site location in order to show wave height and direction in terms of the geography of the area. Satellite image courtesy of 2017 TerraMetrics.

On average, larger wave heights were measured in Tuckerton Bay as compared to Great Bay. This difference in wave heights may be related to the difference in possible fetch associated with each bay. The longest possible fetch in Tuckerton Bay is about 9.00 mi, which is much longer than the longest possible fetch in Great Bay of about 4.50 mi (see Figure B4). The classification of wave heights as small, short period, and locally generated wind waves in the study area is due to the fact that the maximum recorded Hs and Tp (and/or Ts) did not peak above 1.50 ft and 3.00 sec, respectively. In comparison, ocean waves in the nearby Atlantic Ocean can reach maximum Hs values of 8.33 ft with an associated Tp of 6.38 s (Coastal Research Center, 2017). In addition, waves of such short periods indicate local generation because wind must blow over a large area in order to generate waves with a

longer period. This comparison of oceanic waves and the mechanism of wave generation shows that the baseline wave parameters at the study site can be defined as small, short period, and locally generated waves. Lastly, it must also be noted that both sides of the roadway are effected by waves from different directions, with the northeast side being the only side to experience waves from the northeast direction.

Figure B4. Aerial satellite image of the study area showing the difference in fetch length between Tuckerton Bay (Tuckerton Bay Fetch) and Great Bay (Great Bay Fetch). Satellite image courtesy of 2017 TerraMetrics.

Two different types of small-scale storm events were identified and compared from measured data in the first deployment. A storm event was defined as a period of time in which wave heights were greater than or equal to a value of two standard deviations above the deployment average wave height. This specific criterion was selected in order to only isolate the most extreme events during the deployment. In addition, the beginning and end of the storm was selected as the times where the measured Hs intersected with the average Hs value. The two different types of storm events, as isolated by this criteria, were northeast (NE) and west (W) wind storm events. Two of each of these events were

isolated (S1 and S2 in Figures B5-B6). All of these events are considered small-scale storm events because wind speeds barely peak above 25 mph (Figure B5). Comparing measured Hs at both sites during the NE events showed that there was a significant difference between the two sites, with little to no wave activity measured at the DW site (Figure B6 and Table B4). The storm average (averaged over the duration of the storm only) Hs at the AQD site was well above the deployment average Hs for both storms (0.73 ft for S1 and 0.82 ft for S2) and the storm maximum (maximum value during the storm) approached the deployment maximum for both storms (1.31 ft S1 and 1.34 ft for S2) (Table B3). Measured Hs for the W events showed relative similarity in Hs at both sites (Tables B3-B4).

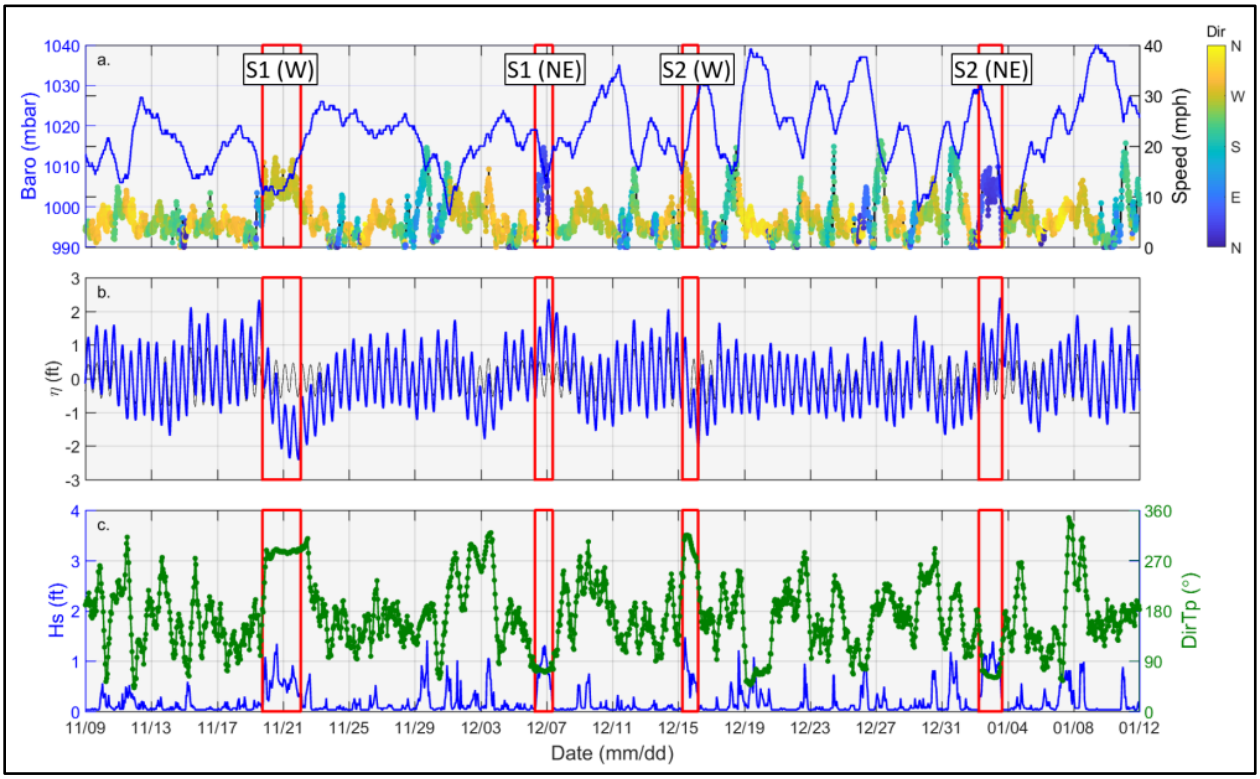


Figure B5. Measured time series of barometric pressure, wind speed, and wind direction (a.), measured (blue line) and predicted (black line) water surface elevations (b.), and Hs and DirTp (c.) for the AQD site from deployment 1. Storm events are indicated with red boxes.

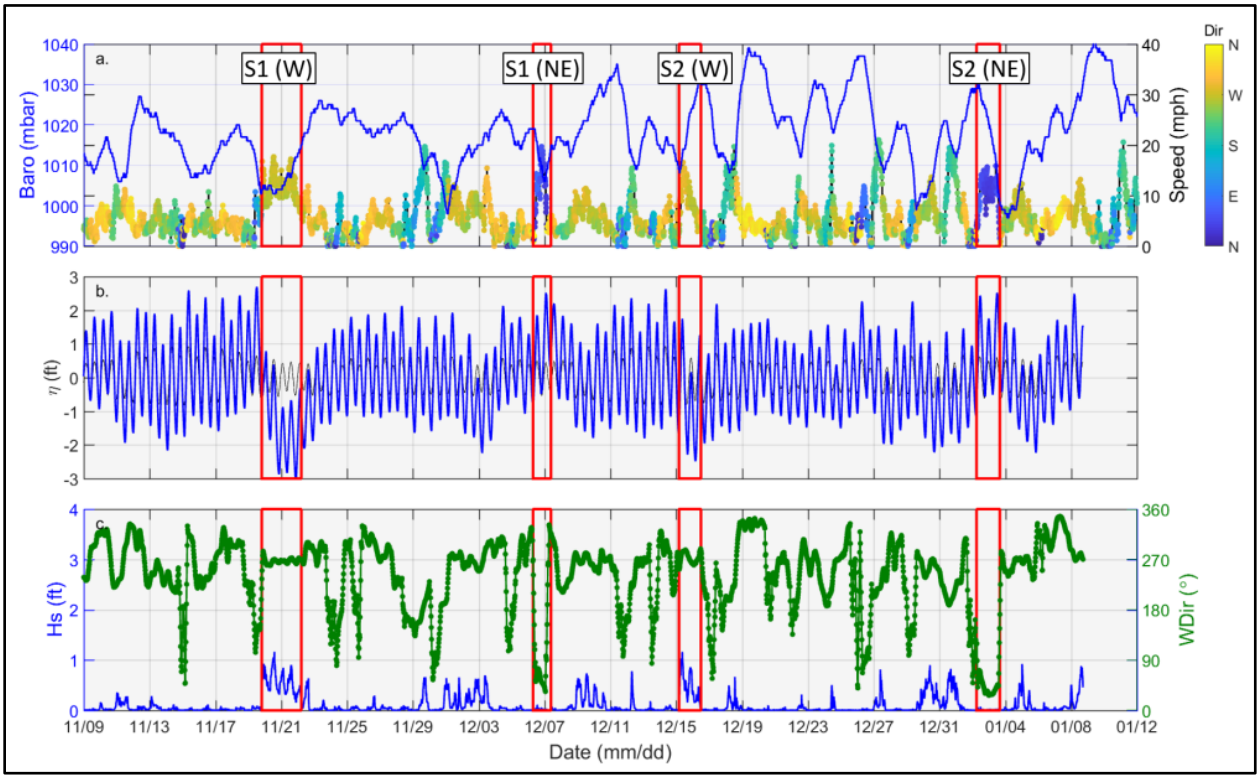


Figure B6. Measured time series of barometric pressure, wind speed, and wind direction (a.), measured (blue line) and predicted (black line) water surface elevations (b.), and Hs and WDir (c.) for the DW site from deployment 1. Storm events are indicated with red boxes.

The comparison of water surface elevations for both storm events, and at both sites, was also of interest and displayed some important differences. Measured water surface elevations were observed to drop below the predicted water surface elevations at both sites during both W events (Figures B5-B6). This suggests that W storm events do not pose a problem and are not the cause of roadway flooding along Great Bay Blvd because tidal elevations dropped below the normal, predicted elevations. This is most likely an effect of the west wind blowing water out of the bay. In contrast to the W storm events, measured water surface elevations were observed to increase above the predicted water surface elevations at both sites during NE storm events, with a more profound increase observed at the AQD site (Figures B5-B6). Since the small-scale NE storm events were the only events that produced elevated water levels, it suggests that NE storm events may be the causes of roadway flooding. In addition, the NE events were the only events to produce elevated water in conjunction with elevated wave heights and only at the AQD site in Tuckerton Bay. This further suggests that NE storm events are of most concern, with the NE facing side of the marsh peninsula being most affected by the events.

Table B3. Date range, maximum wave parameters (storm average parameters shown in parenthesis), and duration of the small scale storm events from deployment 1 for the AQD site. Maximum and average DirTp and Tp are the values associated with the displayed maximum and average Hs.

AQD - Storm Wave Parameters (Dep. 1)						
	Date Range		Hs [ft]	DirTp [°]	Tp [s]	Dur [hr]
S1 (W)	11/19/16 - 11/22/16		1.35 (0.59)	295 (281)	2.07 (1.69)	56
S1 (NE)	12/6/16 - 12/7/16		1.31 (0.73)	69 (74)	2.38 (2.12)	26
S2 (W)	12/15/16 - 12/16/16		1.48 (0.71)	311 (298)	1.89 (1.65)	23
S2 (NE)	1/02/17 - 1/03/17		1.34 (0.82)	63 (74)	2.40 (2.10)	34

Table B4. Date range, maximum wave parameters (storm average parameters shown in parenthesis), and duration of the small scale storm events from deployment 1 for the DW site. Maximum and average WDir and Ts are the values associated with the displayed maximum and average Hs.

DW - Storm Wave Parameters (Dep. 1)						
	Date Range		Hs [ft]	WDir [°]	Ts [s]	Dur [hr]
S1 (W)	11/19/16 - 11/22/16		1.17 (0.55)	269 (267)	2.58 (2.56)	58
S1 (NE)	12/6/16 - 12/7/16		0.11 (0.02)	66 (124)	3.4 (5.49)	26
S2 (W)	12/15/16 - 12/16/16		1.17 (0.46)	289 (273)	2.82 (2.41)	32
S2 (NE)	1/02/17 - 1/03/17		0.07 (0.02)	59 (43)	3.52 (5.10)	34

Six flooding events were isolated at the water level sites during the first deployment (Figures B7-B8). None of the events, however, resulted in roadway flooding due to the baseline conditions and small-scale storm events. All of the events do coincide with elevated or slightly elevated tidal elevations, which are either associated with NE storm events or increases in the tidal range due to spring tides. Comparing the water levels at the sites along each transect shows that higher water levels were observed at the ST as compared to the NT. This shows that the road does not experience flooding during baseline conditions with small-scale storm events. The marsh platform is all that is flooded, with flooding levels being higher at the ST.

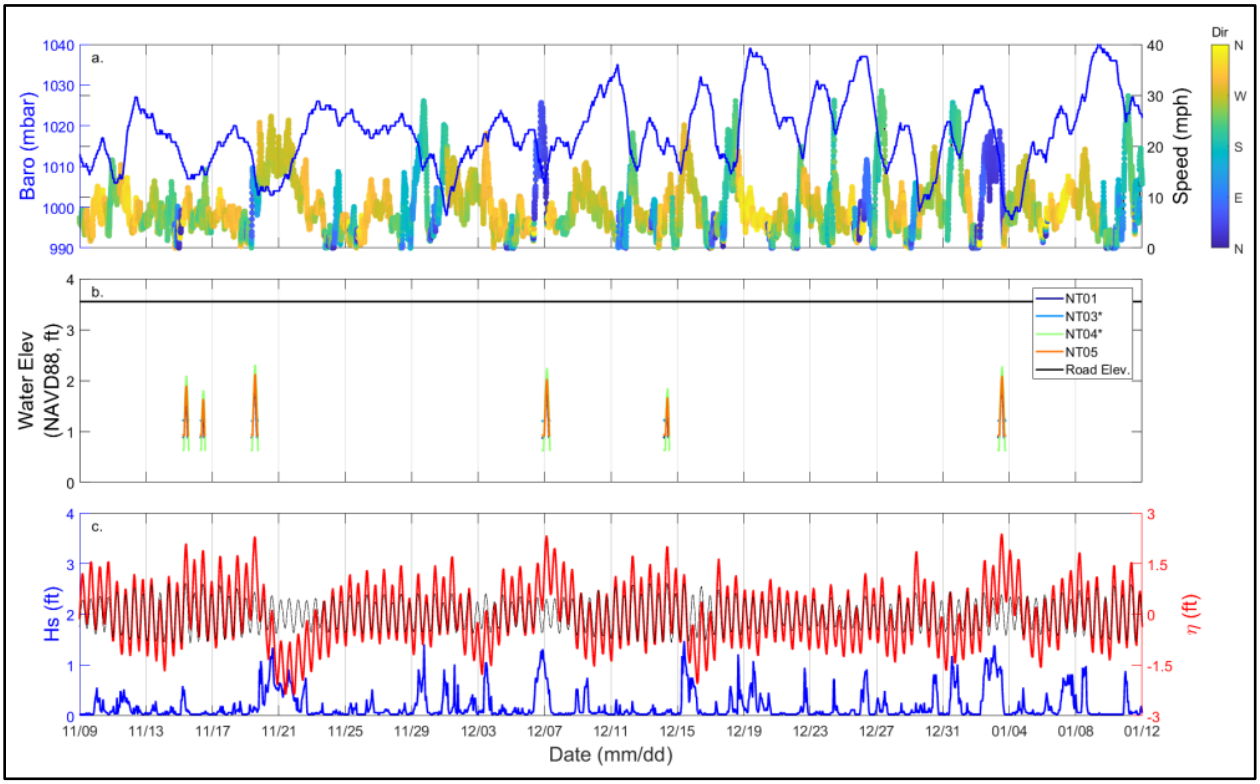


Figure B7. Barometric pressure, wind speed, and wind direction (a.), flooding events from the NT (b.), and Hs, measured water surface elevation (red line), and predicted water surface elevation (black line) from the AQD site (c.) during deployment 1. Each water level site is indicated in the legend in the middle pane (site numbers increase from the northeast to the southwest), sites with an asterisk represent roadway adjacent sites (NT03* and NT04*), and the roadway elevation where the transect intersects the road is represented with the bold black line.

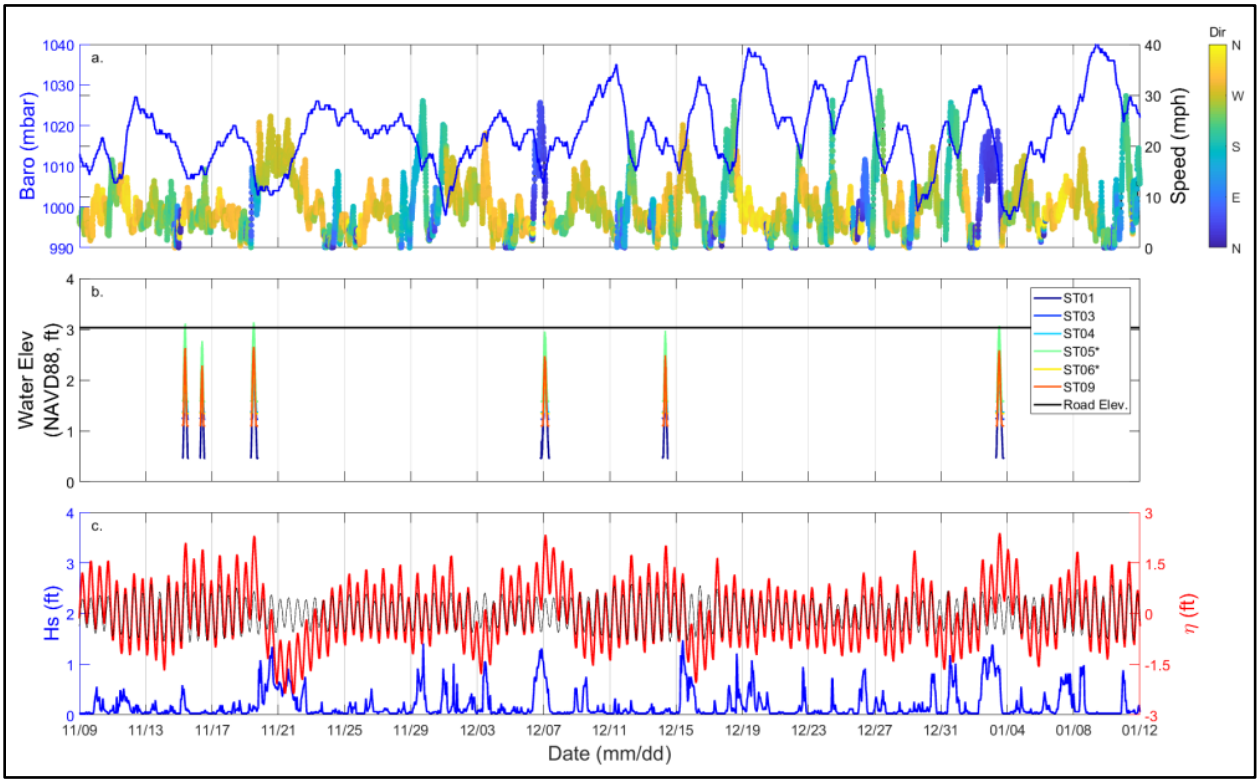


Figure B8. Barometric pressure, wind speed, and wind direction (a.), flooding events from the ST (b.), and Hs, measured water surface elevation (red line), and predicted water surface elevation (black line) from the AQD site (c.) during deployment 1. Each water level site is indicated in the legend in the middle pane (site numbers increase from the northeast to the southwest), sites with an asterisk represent roadway adjacent sites (ST05* and ST06*), and the roadway elevation where the transect intersects the road is represented with the bold black line.

In order to calculate an average marsh edge erosion rate during baseline conditions, the Digital Shoreline Analysis System (DSAS) was used to perform a linear regression analysis on various historical aerial images of the area. Four different marsh edge shoreline locations along the Great Bay Blvd peninsula were selected to perform the analysis on (Figure B9). The change in shoreline position was analyzed from four different aerial images from 1977, 1995, 2007, and 2015. Average erosion rates were calculated for each shoreline location, and then these four rates were averaged together to produce a single average erosion rate for the area of 0.80 ft/year (0.002 ft/day). This would suggest about 30.00 ft of marsh has eroded over the 38 year period that was analyzed. This rate is taken as the average baseline erosion rate for this study in order to quantify average conditions and to have something to compare to for parameters associated with a significant northeast storm. This rate may seem artificially high for a background rate, but it does appear reasonable after looking at the historical shorelines.

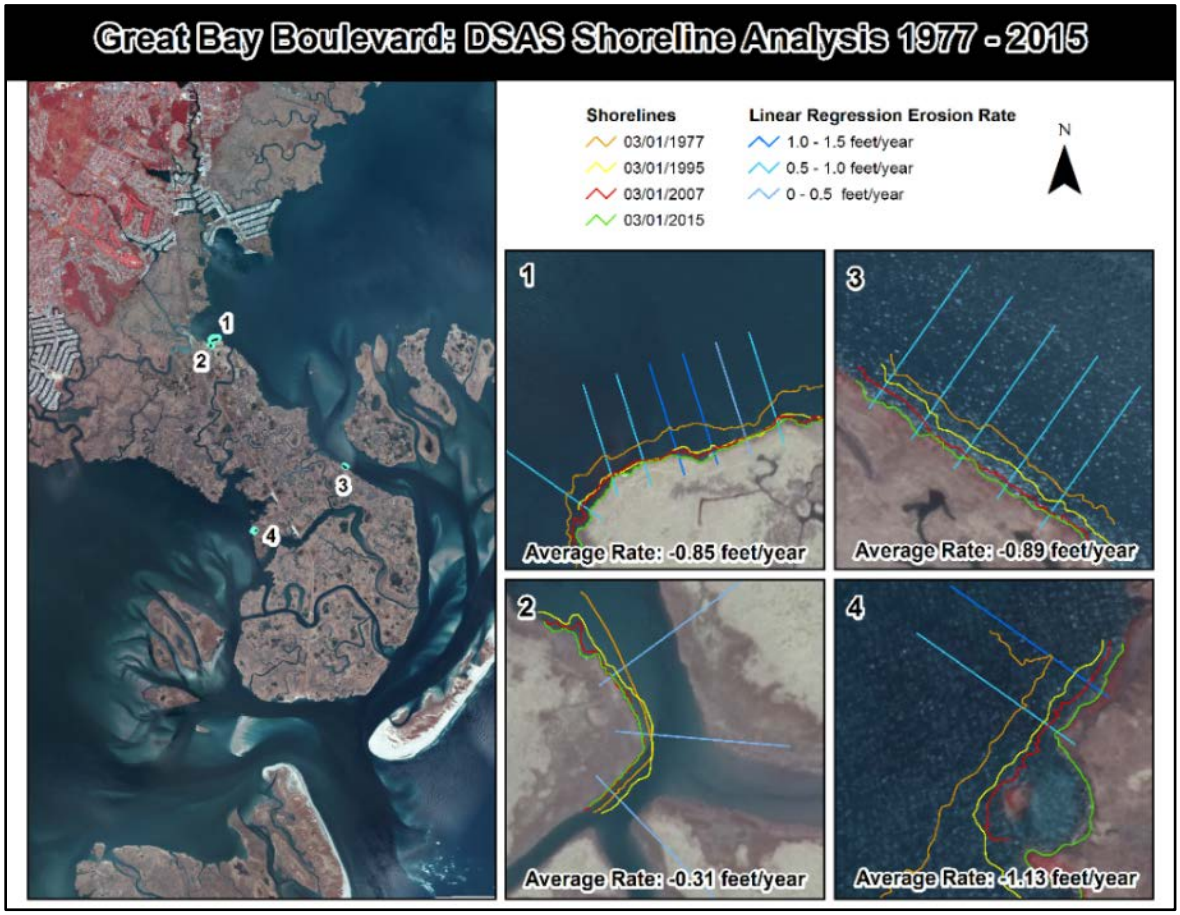


Figure B9. Digital Shoreline Analysis System (DSAS) results for the historical shoreline change analysis performed on the Tuckerton Peninsula. The four sites that were used to perform the linear regression analysis are displayed in this figure as 1-4 with each site being located at the northeast and southwest ends of the two transects (NT and ST). The historical shoreline positions that were used to calculate the average marsh edge erosion are also displayed as various colors (indicated in the figure legend).

Deployment 2 Results

Since results from the first deployment showed that the NE side of the peninsula was of the most interest during NE storm events, with lower water surface elevations and little to no wave activity being observed on the SW side, the AQD site in Tuckerton Bay was of the main focus during the second deployment. Hydrodynamic data was measured at the AQD site during a significant northeast storm that occurred from January 22-24, 2017. The time period of the storm was isolated in the same manner as before by selecting the beginning and end of the storm based on where the measured Hs intersected the deployment average Hs value.

The storm duration was 43 hrs, with average sustained winds of about 20.00 mph from the east-northeast direction (66°), maximum sustained winds of 36.46 mph from the northeast (43°), an average barometric pressure of 1000 mbar, and a minimum barometric pressure of 991 mbar. Both the average and minimum barometric pressures were significantly lower than the average barometric pressure of 1019 mbar from the first deployment, signifying that this was indeed a significant northeast storm event. The

average Hs during the storm was 1.73 ft, the average DirTp was 71.82° (east-northeast), and the average Tp was 2.92 s. The minimum Hs was 0.30 ft with an associated DirTp of 49.46° (northeast) and Tp of 1.99 s and the maximum Hs was 3.12 ft with an associated DirTp of 78.13° (east-northeast) and Tp of 3.71 s (see Table B5 for a tabular format of the statistical wave parameters). The wave rose plot for the northeast storm shows the large waves peaking above 3.00 ft in a narrow directional band from the east-northeast, as generated by the strong east-northeast wind. Small waves between 0.00-1.00 ft were also measured and represent conditions just before and after the storm peaked (Figure B10). The wave energy spectrum plot also shows that the energy was concentrated in a narrow directional band (east-northeast) and focused within the wave period bands of 3.00-5.00 s (Figure B11), which is several bands higher than the background conditions in deployment 1. This shows that the waves during the northeast storm event were highly focused out of the east-northeast direction, larger, and more powerful than what was measured during the background conditions in deployment 1. The relatively large difference in wave heights during this storm, in comparison to the average Hs during the first deployment (0.19 ft), is most likely a results of the strong east-northeast winds blowing over the entire distance of the bay. Winds from this direction are able to blow over the entire expanse of the bay and take advantage of the entire fetch associated with this direction (Figure B4) and can then generate large waves. Due to the orientation of the largest fetch in this bay, storms with winds from the northeast or east-northeast are most likely responsible for generating the largest waves at the measurement site.

Table B5. Statistical wave parameters from the northeast storm during deployment 2 for AQD site.

AQD - Wave Parameters (Dep. 2)						
			Maximum	Minimum	Average	
NE Storm	Hs (ft)		3.12	0.3	1.73	
	DirTp (°)		78.13	49.46	71.82	
	Tp (sec)		3.71	1.99	2.92	
	Dur (hrs)					43

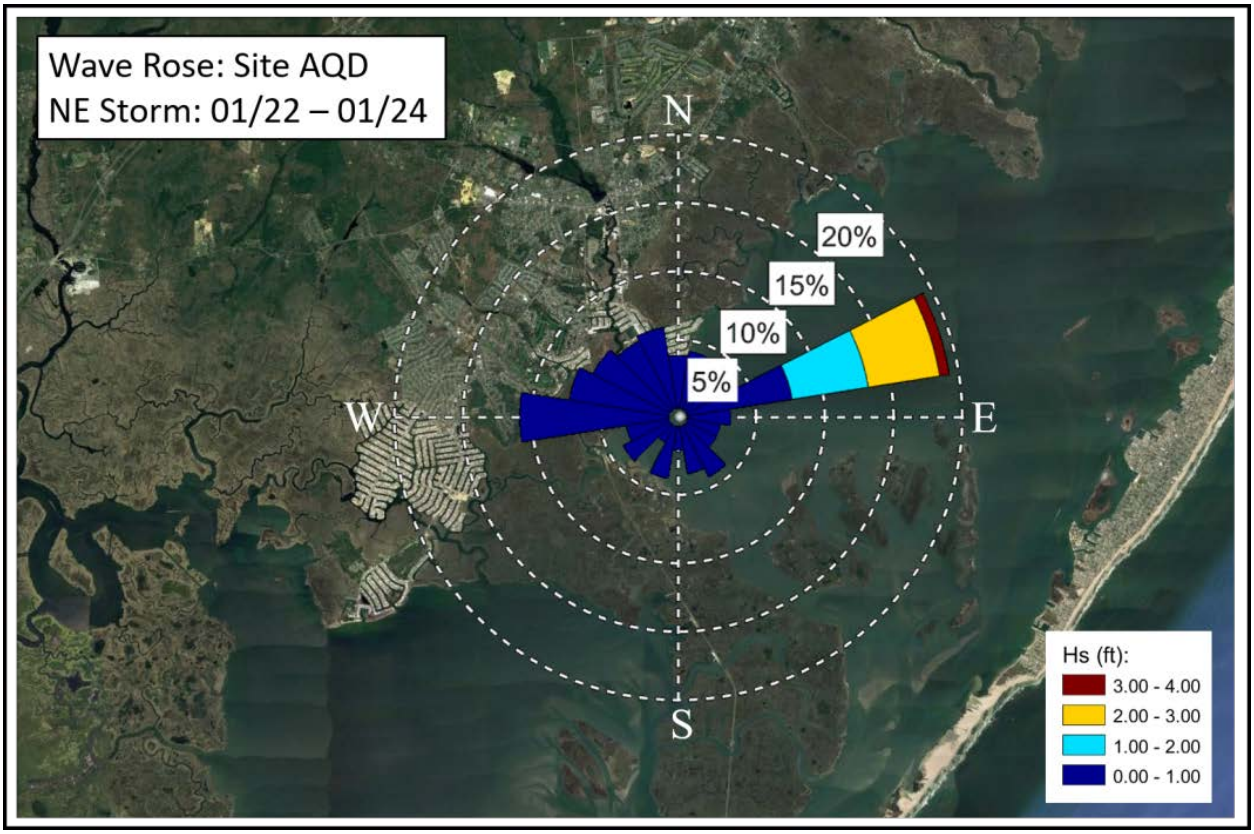


Figure B10. Wave rose plot for the NE storm (deployment 2) showing the percentage of occurrence (concentric circles) and distribution of Hs with DirTp at the AQD site. Wave rose is overlaid on a satellite image of the study area with the center of the rose falling on the AQD site location in order to show wave height and direction in terms of the geography of the area. Satellite image courtesy of 2017 TerraMetrics.

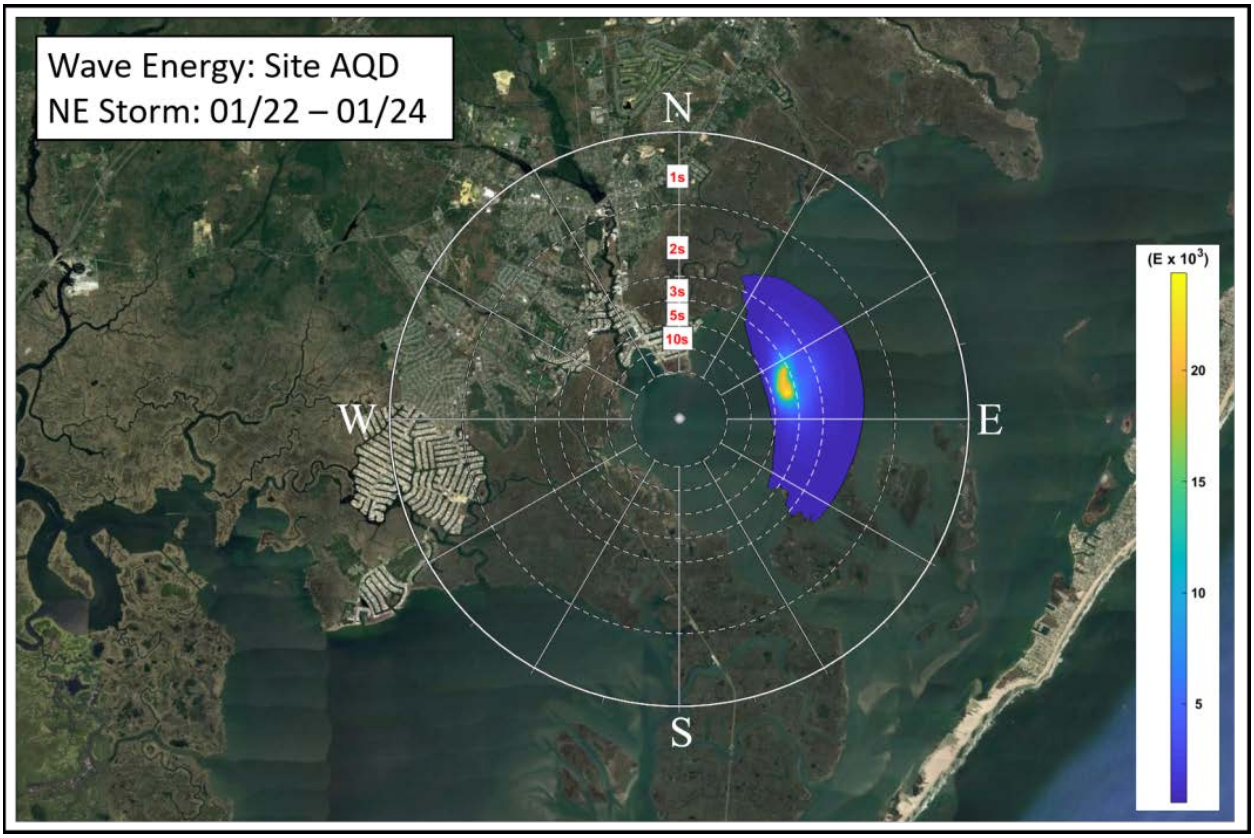


Figure B11. Average wave energy spectrum plot for the NE storm (deployment 2) showing the concentration of wave energy in terms of Tp and DirTp at the AQD site. Energy is represented by the color bar (E = m^2/(Hz°)). Wave energy is overlaid on a satellite image of the area with the center of the plot falling on the AQD site location in order to show wave energy in terms of the geography of the area. Satellite image courtesy of 2017 TerraMetrics.

Analysis of the water surface elevations at the AQD site during the storm shows that the tidal elevations peaked at almost 4.00 ft above the predicted tide (Figure B12). Water surface elevations were almost 4.00 ft above predicted for two tidal cycles and over 2.00 ft above predicted for three tidal cycles. These peak levels represent significant deviations from the predicted (or typical) tidal elevations and were responsible for significant flooding of the marsh platform and the road, which will be displayed and quantified in this section. The large increases in water surface elevations appear to be attributed to two factors: the wind and the barometric pressure. The initial jump in elevations appeared to follow the jump in wind speed and the peak in wind speed matched the peak in water levels. The wind was also blowing from the east-northeast direction during the period when the water levels rose to the first peak. Wind from this direction acted to blow water into the bay, essentially piling the water up, and causing water levels to increase. The secondary peak in water levels, which occurred on January 24th, peaked when the wind speed diminished to around 10 mph and changed direction to the northwest (Figure B12). Wind from this direction and at this speed should not cause tidal elevations to increase. In contrast, wind from this direction should cause water surface elevations to decrease because wind from this direction acts to blow water out of the bay. At the time of this secondary peak, however, barometric pressure reached its lowest value during the measurement period. The drop in barometric pressure coinciding with the secondary peak in water levels showed that barometric pressure also acted to increase the water surface elevation. The wind most likely caused the water to pile up in the bays

initially and elevate the water surface elevations, while the low barometric pressure acted to keep the water levels elevated even when the wind switched direction and decreased in speed.

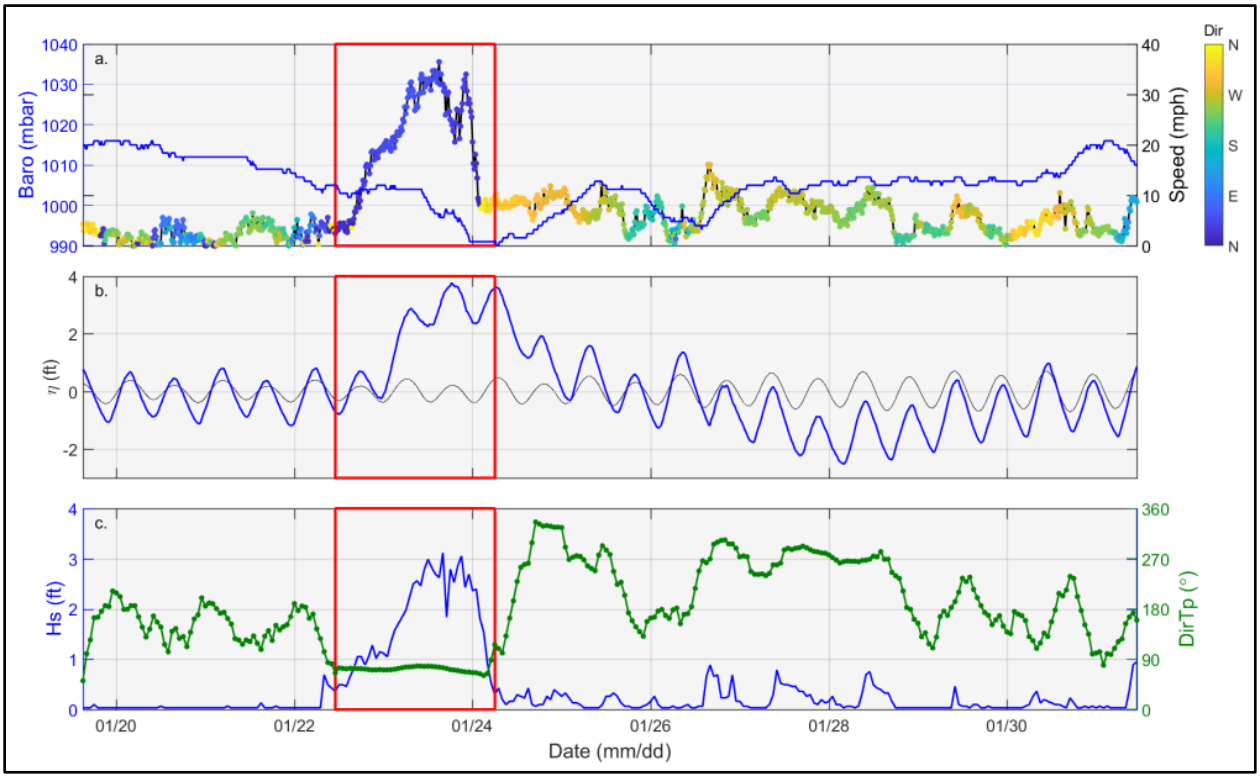


Figure B12. Measured time series of barometric pressure, wind speed, and wind direction (a.), measured (blue line) and predicted (black line) water surface elevations (b.), and Hs and DirTp (c.) for the AQD site from deployment 2. The NE storm event (according to the previously defined criteria) is indicated with red boxes.

Two additional flooding events were isolated during the second deployment, with the one of main interest being the event that occurred during the storm (Event 7 in Figures B13-B14). Event 7 was the most extreme flooding event to be measured during this study and dwarfed all other events in terms of event duration and flood elevation. The entire flooding event, with both marsh platform and roadway flooding included, had a duration of about 2.00 days. The roadway flooding was separated into three sub-events (F7.1, F7.2, and F7.3) because the roadway was found to have flooded three separate times during the storm. Roadway flooding was quantified by defining and calculating several parameters. Flood height was defined as the maximum difference in elevation between the roadway elevation and the water level elevation, referenced to NAVD88. Roadway elevation (NT_road and ST_road in Table B6) was defined as the highest elevation on either side of the roadway along each transect line. Flood duration was defined as the amount of time between when the water level increased above and decreased below the road elevation. The flood height and duration was calculated for each sub-event and for each roadway adjacent site (NT03 and NT04 at the NT and ST05 and ST06 at the ST). In order to compare flooding based on transect location, two additional parameters were also defined: average transect elevation and NE side marsh width. Average transect elevation (NT_avg and ST_avg in Table B6) was defined as the average elevation of all sites along each transect and NE side marsh width was defined as the distance along each transect from the road to the marsh edge on the northeast side of the roadway.

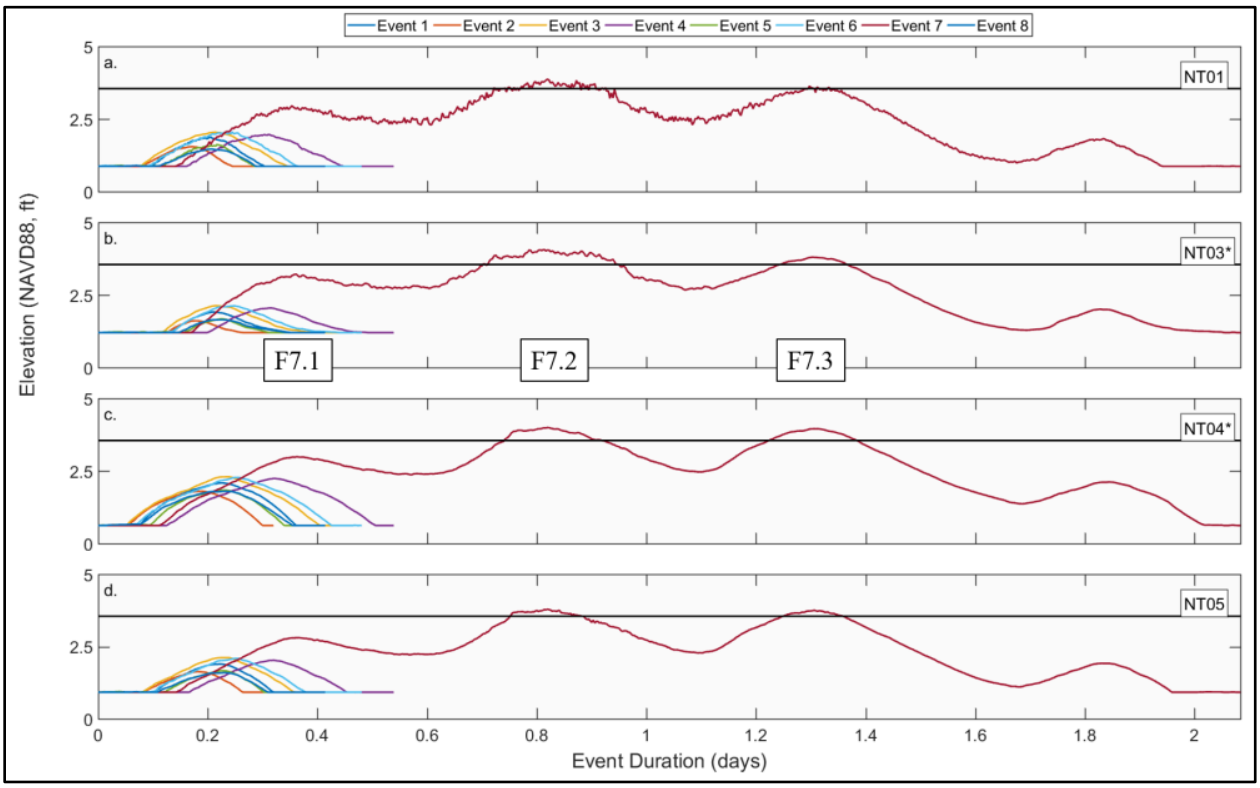


Figure B13. All flooding events measured during the study at the NT (described in the legend as different colors) plotted as the Event Duration versus the flood Elevation, referenced to NAVD88, ft. Each figure pane (a.-d.) represents the individual water level sites and the sites labeled with an asterisk (NT03* and NT04*) represent the roadway adjacent sites. Event 7 (dark red line) represents the measured data from the NE storm, which is separated into the three sub-events F7.1-F7.3. The bold black horizontal line represents the elevation of the roadway where it is intersected by the transect.

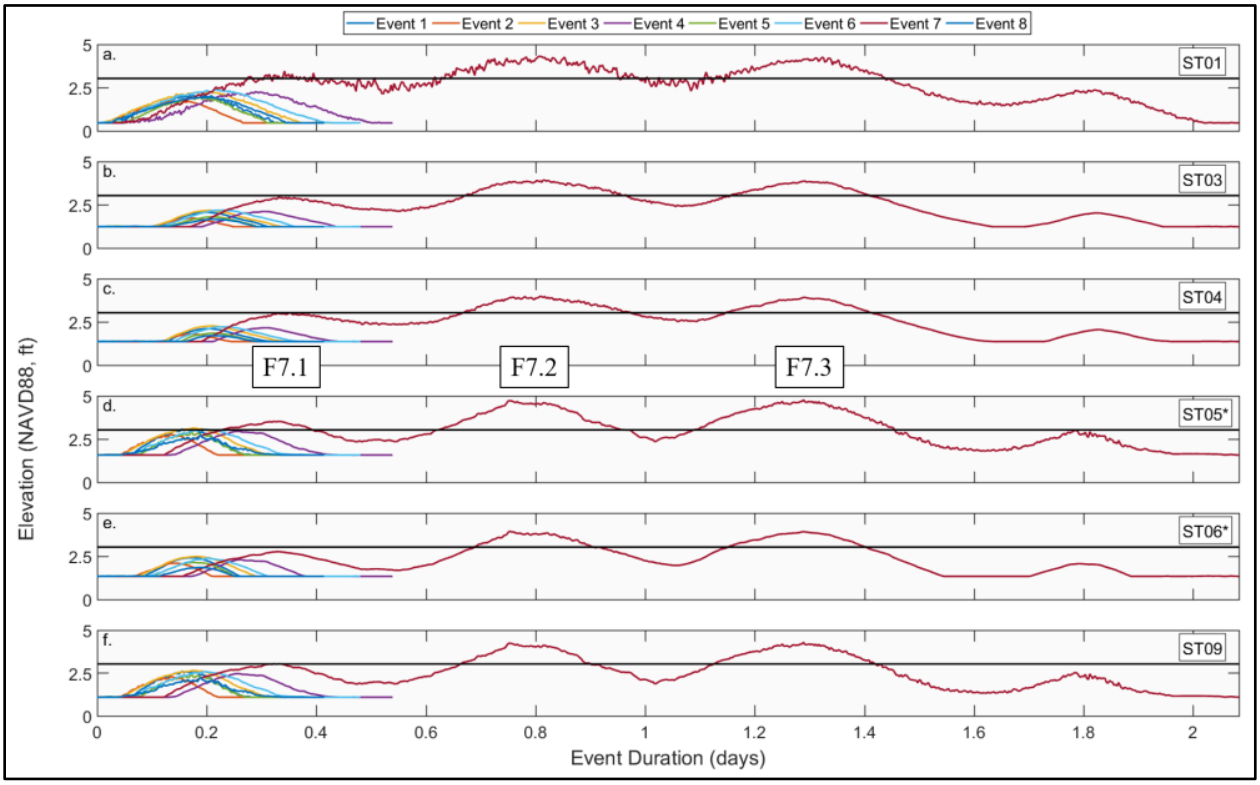


Figure B14. All flooding events measured during the study at the ST (described in the legend as different colors) plotted as the Event Duration versus the flood Elevation, referenced to NAVD88, ft. Each figure pane (a.-f.) represents the individual water level sites and the sites labeled with an asterisk (ST05* and ST06*) represent the roadway adjacent sites. Event 7 (dark red line) represents the measured data from the NE storm, which is separated into the three sub-events F7.1-F7.3. The bold black horizontal line represents the elevation of the roadway where it is intersected by the transect.

Sub-events F7.2 and F7.3 were the most dramatic in terms of roadway flood height and duration, with sub-event F7.1 showing minimal roadway flooding and only at the ST. The roadway was flooded by almost 0.50 ft at the NT (road elevation 3.55 ft NAVD88) and by almost 2.00 ft at the ST (road elevation 3.05 ft NAVD88), both on two occasions and both coinciding with the peaks in flood tide. The individual flood heights ranged from 0.25 ft to 0.51 ft at the NT and from 0.49 ft to 1.73 ft at the ST (Table B6). The individual flood durations ranged from 2.93 hrs to 5.60 hrs at the NT and from 4.00 hrs to 8.80 hrs at the ST (Table B6). In order to further compare the roadway flooding, flood height and flood duration values for each roadway adjacent site and each sub-event that resulted in roadway flooding were averaged to produce a single value for each transect. The average flood height was 0.40 ft for the NT and 1.14 ft for the ST and the average flooding duration was 4.15 hrs for the NT and 6.44 hrs for the ST. Therefore, on average, the ST displayed larger flood heights and longer flood durations during the northeast storm, as compared to the NT. The flood duration parameter is of specific importance because it represents the period of time in which the roadway was essentially impassable.

Table B6. Elevation, flood height, and flood duration for the NT and ST roadway adjacent sites for each sub-event during Event 7. Roadway elevation (NT_road and ST_road) and average transect elevation (NT_avg and ST_avg) are also displayed for comparison purposes.

Elevation & Flood Data (NE Storm - Event 7)							
Site	Elev [NAVD88 ft]	Flood Height [ft]			Flood Dur [hrs]		
		F7.1	F7.2	F7.3	F7.1	F7.2	F7.3
NT03	1.20	-	0.51	0.25	-	5.60	2.93
NT04	0.62	-	0.44	0.40	-	4.27	3.80
NT_road	3.55						
NT_avg	1.28						
ST05	1.58	0.49	1.69	1.73	4.00	8.20	8.80
ST06	1.34	-	0.91	0.88	-	5.20	6.00
ST_road	3.03						
ST_avg	1.55						

The transect comparison of average flood height and flood duration during Event 7 (northeast storm) showed that the measured flooding was worse at the ST, as compared to the NT. A more in-depth analysis of the defined parameters was required in order to determine why flooding appeared to be worse at the ST. The NE side marsh width was much larger at the ST (4000.00 ft) as compared to the NT (1500.00 ft) and the average transect elevation was higher at the ST (1.55 ft) as compared to the NT (1.28 ft). The road elevation, however, was higher at the NT (3.55 ft) as compared to the ST (3.05 ft). This shows that the marsh width and marsh elevation did not act to protect the roadway during the storm because the ST displayed the most extreme roadway flooding, even though it had the highest average transect elevation and largest NE side marsh width. The fact that the roadway elevation was lower at the ST as compared to the NT seems to explain why the flooding was worse at the ST. The marsh did not act to protect the roadway and the flooding seemed to be directly related to the elevation of the road itself. This does not suggest that the marsh cannot act to protect the roadway in other conditions, but it does suggest that the water surface elevations may have been past a critical elevation in which the marsh could have acted to successfully protect the roadway from flooding.

Since the ST is closer to Little Egg Inlet than the NT, one additional parameter was analyzed in order to explain the differences in flood height between both transects. This parameter was the variation in water surface elevations in terms of distance to the inlet. In order to calculate this, the water surface elevations from the AQD site were compared to the USGS tidal gage 01409335 Little Egg Inlet near Tuckerton, NJ (USGS-TB in Figure B15) during the time period of deployment 2. The comparison of water surface elevations at these two sites showed that the tidal range at the USGS-TB site was greater than the AQD site. The peak water levels (water levels at high tide) at the USGS-TB site were higher than those at the AQD site at every tide during deployment 2 (Figure B15). Since the USGS-TB site is closer to Little Egg Inlet than the AQD site, this comparison suggests that water surface elevations (and tidal range) increase with decreasing distance to the inlet. Since water surface elevations displayed an increase moving closer to the inlet, it may also suggest that road flooding in the area may be related to the proximity of the road to the inlet.

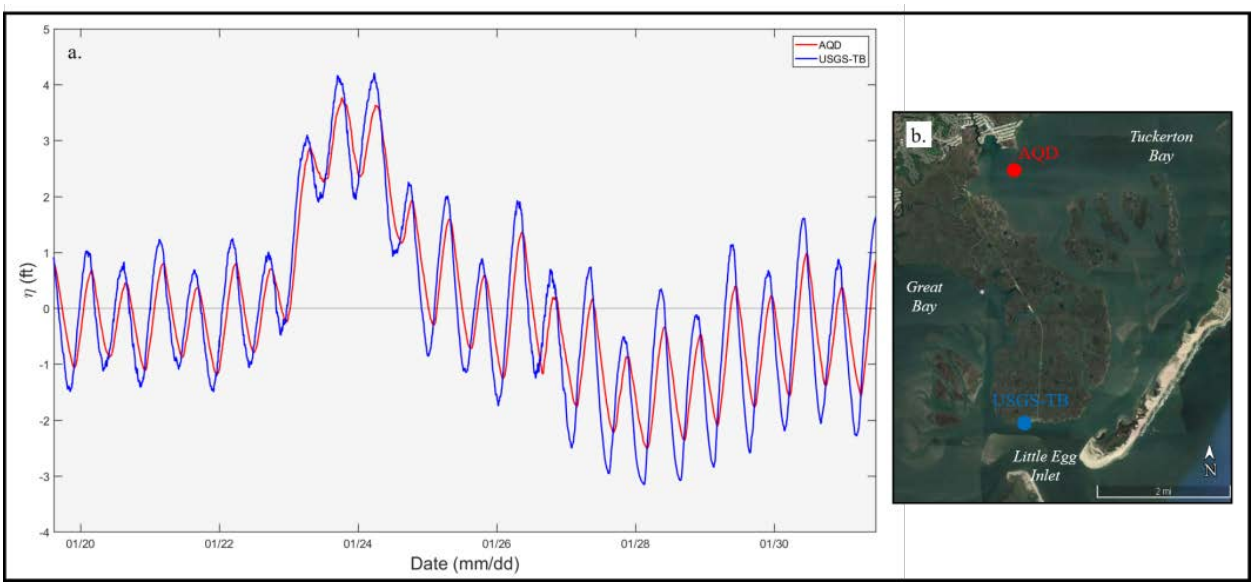


Figure B15. Time series plot of water surface elevations from the AQD site (red line) and the USGS-TB site (blue line) over the duration of deployment 2 (a.) and aerial satellite image of the study site showing the locations of the AQD and USGS-TB sites in relation to Little Egg Inlet (b.). Satellite image courtesy of 2017 TerraMetrics.

In addition to calculating roadway flooding during the storm only at the locations in which each transect intersected the road, a proximity analysis was performed in order to estimate maximum flooding heights along the entire roadway (Figure B16). This proximity analysis presented the change in flood heights along the roadway and showed how far away severely flooded areas were from minimally flooded areas. This additional analysis allowed for flooding to be quantified in a spatial sense, in addition to the temporal quantification that was done at each measurement site. The maximum flood height during Event 7 was taken from each transect and used to calculate a flood height along the entire distance of the roadway from the southern side of the first bridge out the southern end of the roadway, with the bridge elevations ignored. The maximum flood height from the NT was used to calculate the flood height from the southern side of Big Thorofare (the southern side of the first bridge) down to a location along the roadway halfway between the NT and ST, and the maximum flood height form the ST was used for the remaining portion of the roadway. This was done in order to utilize the data collected at each transect and account for local differences in water levels along the marsh peninsula. This analysis produced a spatial map of maximum roadway flood heights along the entire length of Great Bay Blvd during the measured northeast storm (Figure B16). This map reiterates the difference in flood heights between the NT and ST as previously shown. The flood heights along the roadway in the area in which the roadway is intersected by the ST (represented by the red colors) are noticeably higher than the flood heights in the area in which the roadway is intersected by the NT (represented by the blue colors). The map also shows a noticeable variation in flood height along the roadway. There was an increase in flood heights from the ST south to a location about halfway between Big Sheepshead Creek and Little Sheepshead Creek, but an overall decrease in flood heights (blue colors) along the roadway from just north of Little Sheepshead Creek to the very southern end of the marsh peninsula. Since it was previously shown that water surface elevations increase with decreasing distance to the inlet, the decreasing roadway flooding to the south of Little Sheepshead Creek shows that the roadway elevation increases by an amount great enough to counteract the increase in water levels in this area. This increase in elevation is enough to

diminish roadway flooding in this area but still not enough to completely prevent the roadway from flooding during this event. Therefore, the increase in roadway elevation appears to be the controlling factor in roadway flooding near the southern end of the peninsula, since flood heights were shown to decrease to the south of Little Sheepshead Creek.

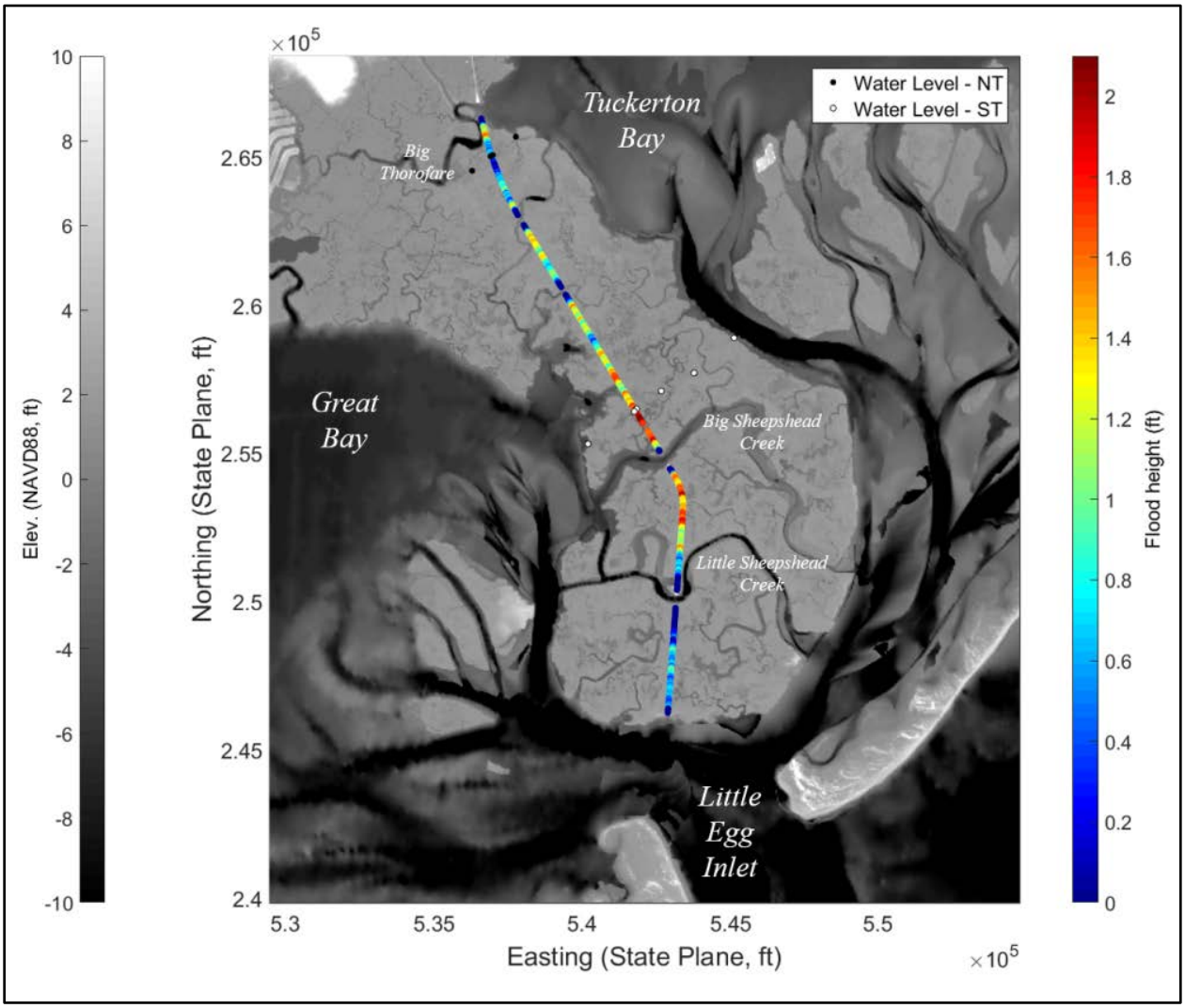


Figure B16. Spatial map of the study area with maximum flood heights during the northeast storm along the entire length of Great Bay Blvd. The spatial reference is NJ State Plane, ft, the vertical datum is NAVD88, ft and represented by the grayscale color bar, and the Flood Height (ft) is represented by a jet (rainbow) color bar.

In addition to analyzing roadway flooding over the entire length of the roadway, the effect that the three boat ramps had on roadway flooding could also be analyzed with the development of the spatial roadway flooding map. It was hypothesized that the boat ramps may be one of the main causes of roadway flooding because they could be acting as entranceways for water to easily flow through and flood the road. The first boat ramp, BR01, is located just north of the NT and provides access to Big Thorofare (Figure B17). The roadway flood height just next to BR01 was about 1.00 ft, and the maximum flood height in the immediate area (about 1.70 ft) was about 40.00 ft to the south of BR01. The close proximity of BR01 to the maximum flood height in the area, suggests that this boat ramp

could be causing some of the roadway flooding problems in the area close to the ramp. The second and third boat ramps, BR02 and BR03, are located to the north and south of the ST, respectively (Figure B18). BR02 provides access to Great Bay, and BR03 provides access to Big Sheepshead Creek. The roadway flood height just next to BR02 is about 1.00 ft, with higher flood heights of about 1.70 ft within 40.00 ft to the north. The roadway flood height just next to BR03 is over 2.00 ft, which is one of the highest flood heights in the immediate area. The close proximity of BR02 to high flood heights in the immediate area suggests that it may be contributing to some of the roadway flooding problems close to the ramp, similar to BR01. The fact that BR03 falls immediately adjacent to one of the maximum flood heights in the immediate area suggests that it appears to be a definite cause of roadway flooding in the area close to the ramp. Therefore, boat ramps BR01 and BR02 may be contributing to flooding problems because high flood heights were present within 40.00 ft of both ramps. Boat ramp BR03, however, does appear to be a direct cause of flooding problems because one of the highest flood heights in the area was located directly adjacent to the ramp.

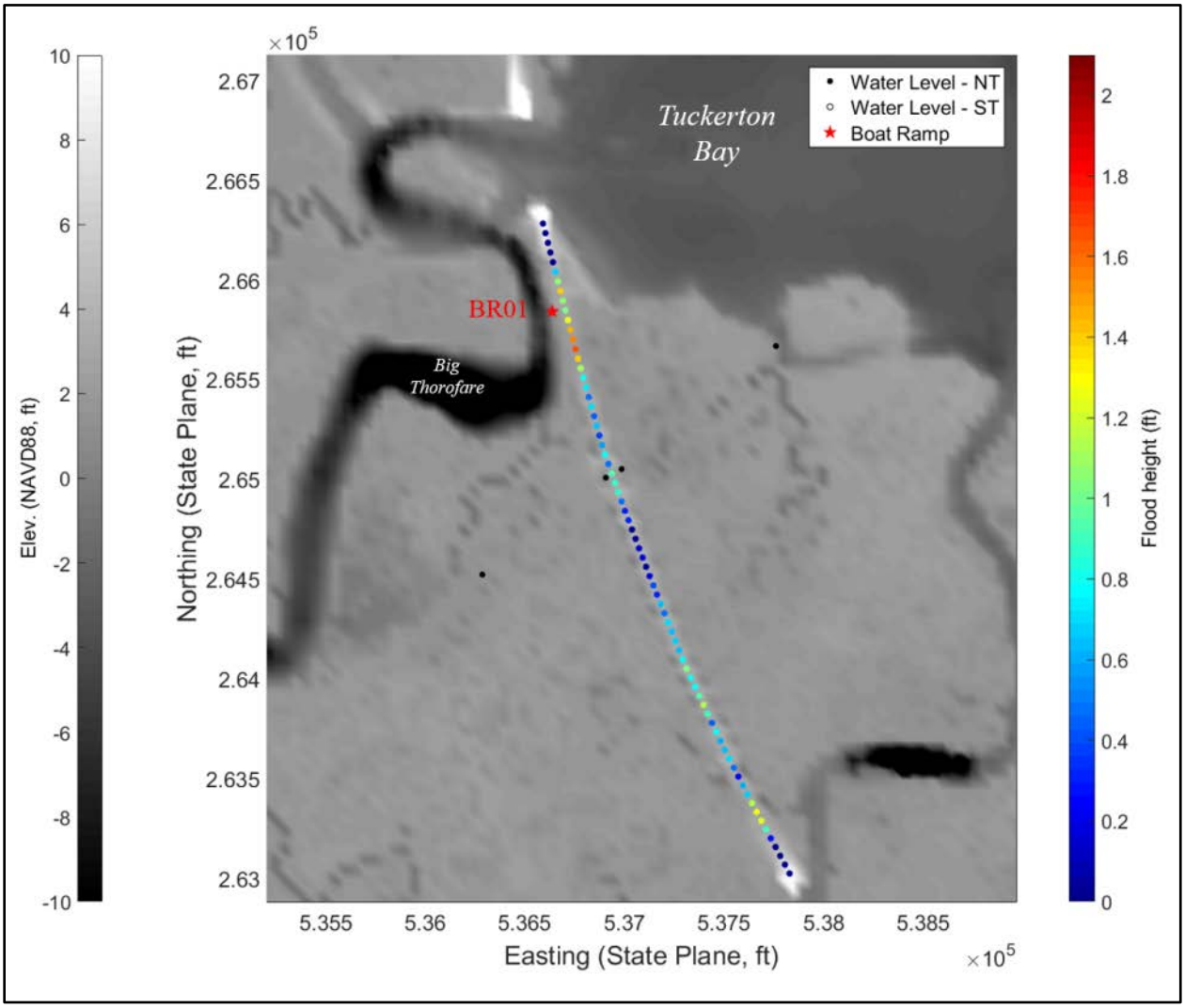


Figure B17. Spatial roadway flooding map of a zoomed in area of the northern portion of Great Bay Blvd showing boat ramp, BR01. Roadway flood height dots are spaced at 10.00 ft intervals. The spatial reference is NJ State Plane, ft, the vertical datum is NAVD88, ft and represented by the grayscale color bar, and the Flood Height (ft) is represented by a jet (rainbow) color bar.

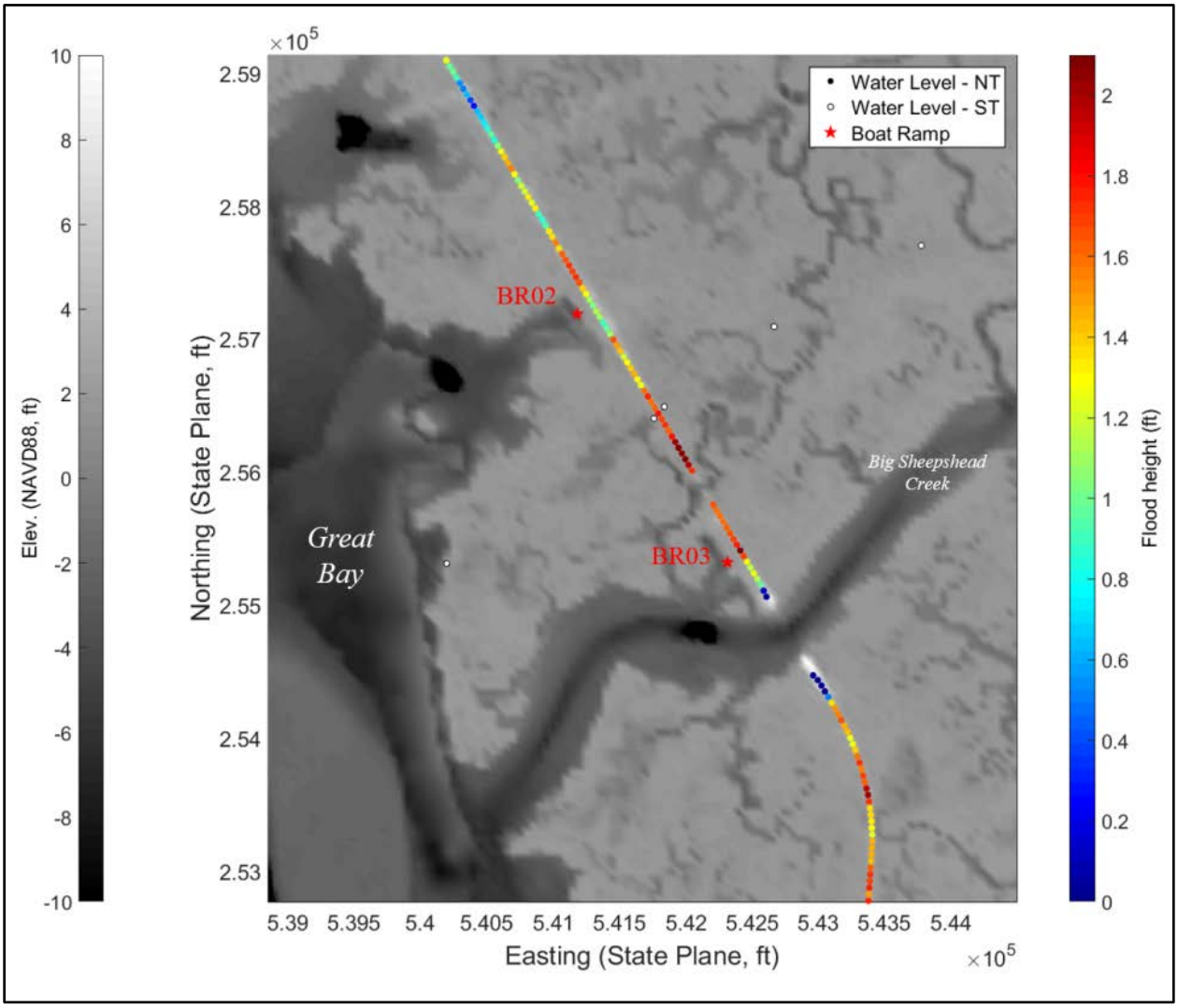


Figure B18. Spatial roadway flooding map of a zoomed in area of the middle portion of Great Bay Blvd showing boat ramps, BR02 and BR03. Roadway flood height dots are spaced at 10.00 ft intervals. The spatial reference is NJ State Plane, ft, the vertical datum is NAVD88, ft and represented by the grayscale color bar, and the Flood Height (ft) is represented by a jet (rainbow) color bar.

In addition to the background marsh edge erosion rate, an average marsh edge erosion rate during the storm was also calculated in order to quantify the erosional effect of the storm. The marsh edge erosion rate during the storm was calculated for the marsh edge on the northeast side of the peninsula because this was the edge that was directly influenced by the larger waves generated during the storm. In order to calculate this event-specific rate, the following equation was taken from Leonardi, Ganju, and Fagherazzi (2015):

$$E_i = a^* \left(\frac{P_i}{P_{avg}}\right) E_{avg}, a^* = 0.67 \qquad \textbf{(B1)}$$

where E_i represents the erosion rate (ft/year) at time i, P_i represents the wave power at time i, P_{avg} represents the average background wave power at the site, and E_{avg} represents the average background

erosion rate. The wave power at time i was calculated from the wave heights during the storm, as measured at the AQD site, using the following equation:

$$P_i = \frac{1}{8}\rho g Hs_i^2 \qquad \textbf{(B2)}$$

where ρ is the density of saltwater, g is the gravitational acceleration, and Hs_i is the significant wave height at time i. Using the background erosion rate of 0.80 ft/year (as calculated prior), the wave power over the duration of the storm, and the wave power averaged over the duration of the first deployment as the average background wave power, the average marsh edge erosion during the storm was calculated to be 18.70 ft/year (0.05 ft/day). This suggests that an average amount of about 1.10 in of marsh edge was eroded during the 43 hr duration of the northeast storm. The erosion rate associated with the northeast storm was about twenty times greater than the background erosion rate for the area. This shows that marsh edge erosion associated with this northeast storm was significant. It also suggests that northeast storms are the main drivers of marsh edge erosion in this area, with the erosion occurring in a periodic manner since these type of storms typically occur only several times per year. It should also be noted that the high rate of erosion during the storm event is only possible to occur in a periodic manner because the rate is so high that if it were to occur consistently, the marsh would be gone. This acts to further reiterate the erosive potential of a northeast storm such as this one, and to show that this type of erosion only occurs in a periodic manner.

APPENDIX C – DELFT3D MODEL DETAILS

Model Setup

The model grid was constructed as a rectilinear grid with grid cell sizes ranging from about 1000.00 m (3280.84 ft) at the eastern offshore boundary down to a minimum cell size of about 10.00 m (32.81 ft) within the vicinity of the study site at Great Bay Blvd (Figure C1). The model grid extends offshore about 19 mi to the location of NDBC Buoy 44091 and to a depth of about 85.00 ft, inland about 7.00 mi, up to Seaside Park, NJ to the north, and to Margate City, NJ to the south (Figure C2). The model grid was constructed over such a large area because hydrodynamic parameters within a small area of interest are directly and indirectly effected by the processes occurring within that immediate area and over larger scales. Ideally a grid would need to cover the entire east coast, if not the entire world, in order to take into account all existing small and large scale processes and produce the most accurate results. This, however, is not physically possible so the grid was constructed to include the most important geographical features that appear to directly affect the study area, such as Barnegat Inlet to the north and Little Egg inlet to the south. It was imperative to include these two inlets in the grid because the study site fell within the back-barrier bay and these two inlets are the main areas of tidal exchange between the back-barrier bays and the Atlantic Ocean. In addition, the grid extends so far offshore because wave data was taken from NDBC Buoy 44091 in order to force the model at the offshore boundary (Figure C2). Since this data was used to force the model at the offshore boundary, the grid needed to extend to about this location so that it was part of the model domain.

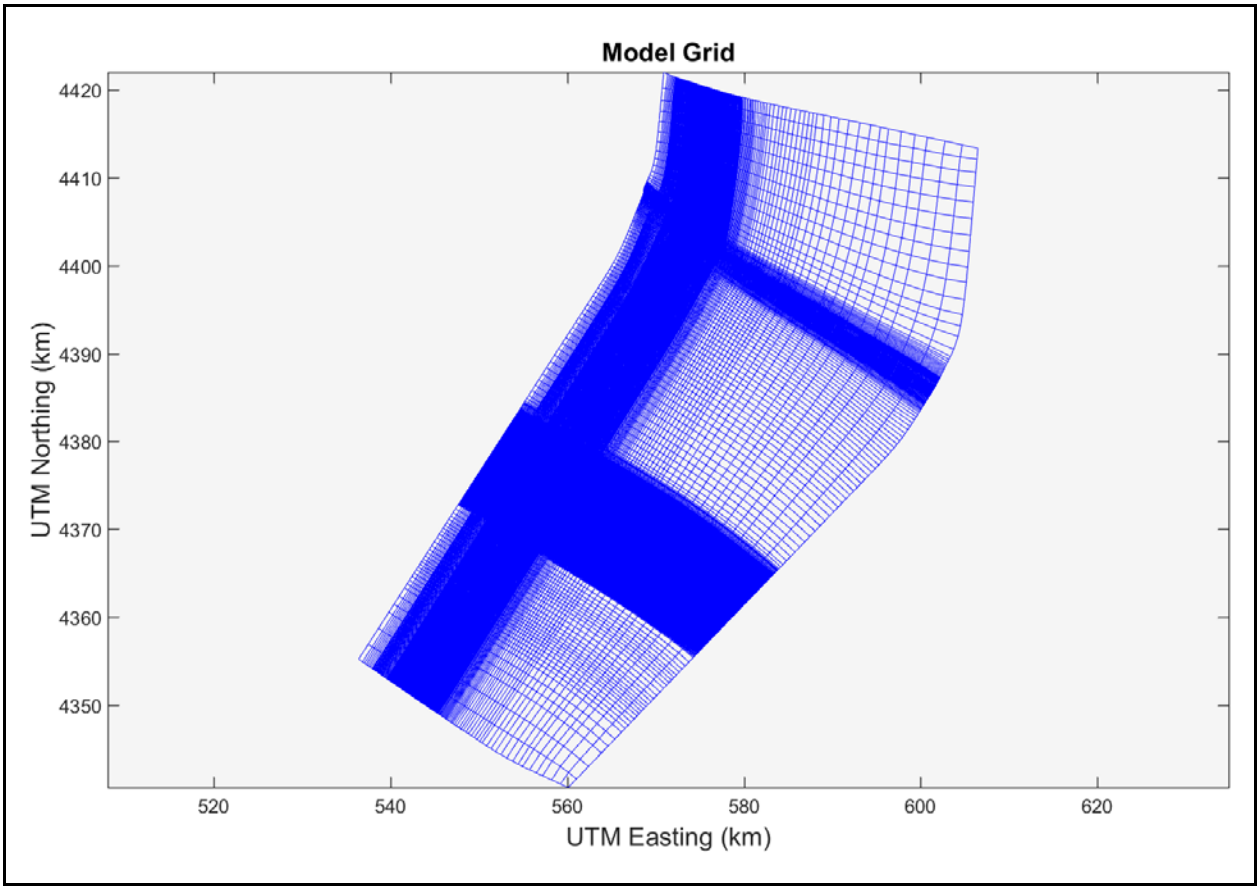


Figure C1. Rectilinear grid used for the modeling in *Delft3D* with grid cell sizes ranging from 1000.00 m (3280.84 ft) at the eastern boundary down to a minimum of about 10.00 m (32.81 ft) within the vicinity of Great Bay Blvd (around 560 km Easting and 4380 km Northing).

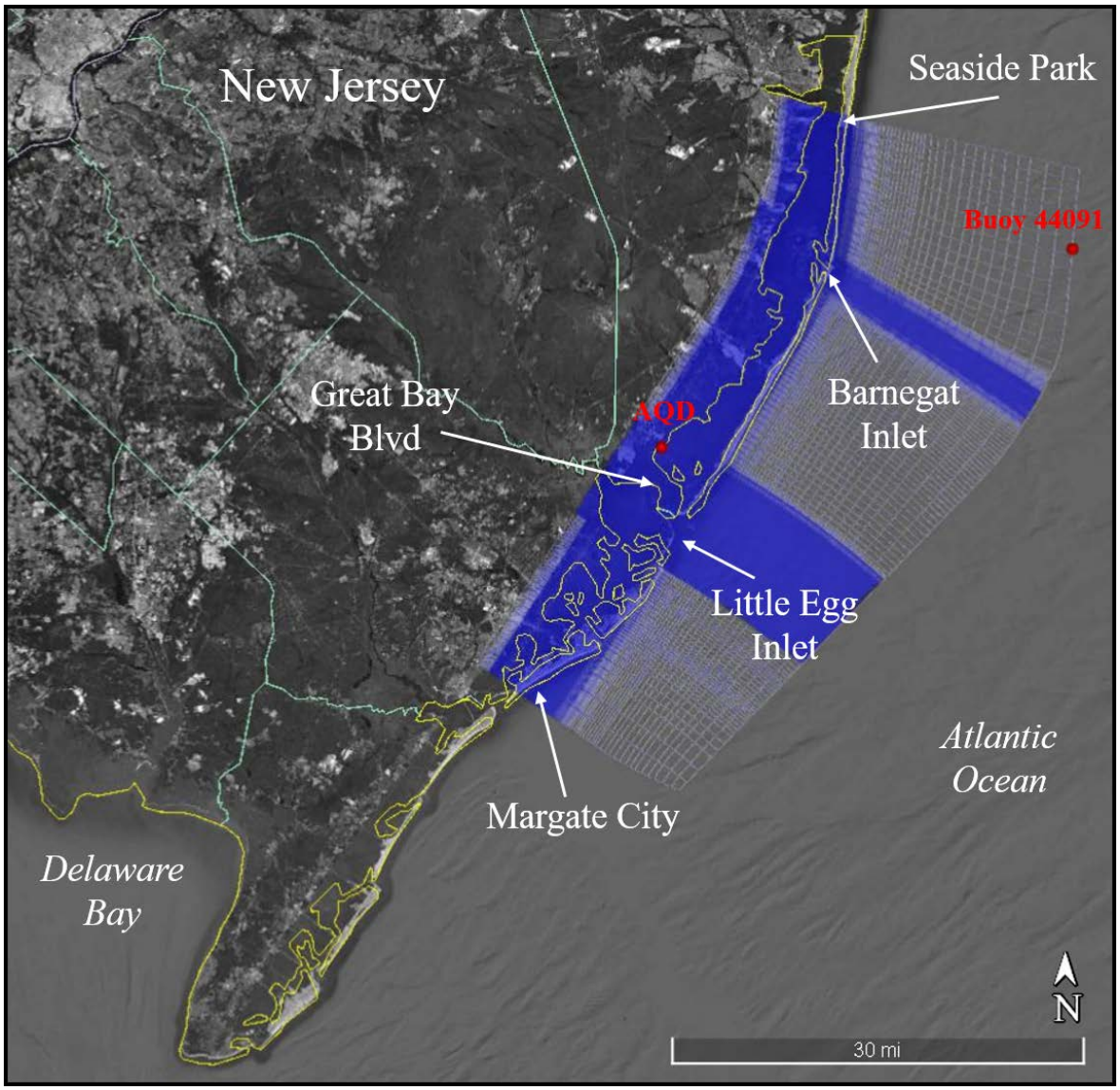


Figure C2. Model grid for *Delft3D* overlaid on a satellite image of New Jersey. The study site (Great Bay Blvd) and all other pertinent locations and features are indicated, as well as the AQD site in which in situ data was measured during the northeast storm and the location of NDBC Buoy 44091. Satellite image courtesy of 2017 TerraMetrics.

In adding to the model grid, topobathymetric data had to be extracted from several digital elevation model (DEM) data sets and interpolated to the constructed rectilinear model grid. Nearshore data was extracted from the CoNED data sets and the far offshore bathymetry was extracted from the U.S. Coastal Relief Model (CRM) Southeast Atlantic 3 arc-second DEM. All of the topobathymetric data was combined and interpolated to the model grid so that it could be used in the model (Figure C3).

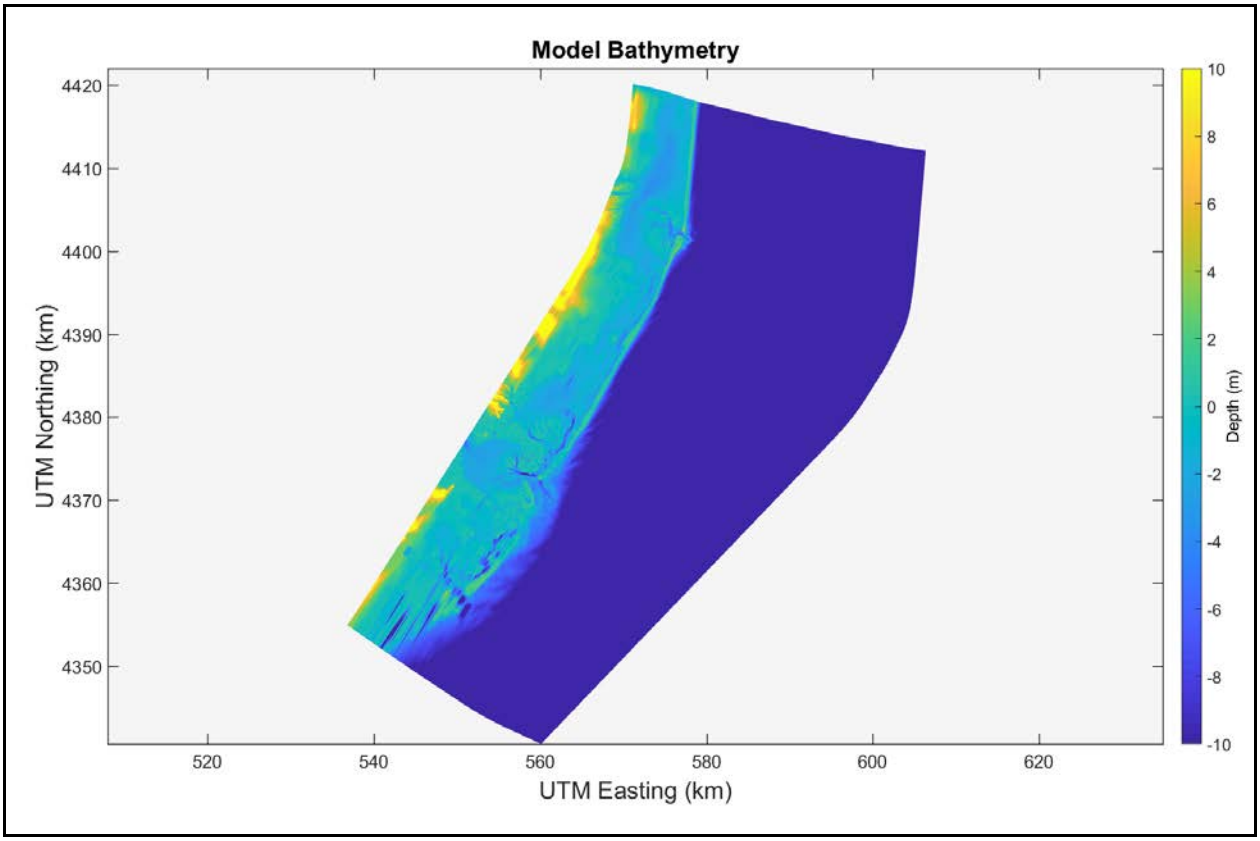


Figure C3. Combined topobathymetric data interpolated onto the model grid. Data is displayed as UTM Northing (km) and UTM Easting (km) and Depth (m) because the model inputs for Delft3D must be metric. Displayed depth values are also restricted to a range of -10.00 – 10.00 m (-32.81 – 32.81 ft) in order to enhance the topobathymetric features along the coastline, but then actual depth values encompass the extremes of the data.

Delft3D was used to model a time period from January 17, 2017 – January 26, 2017. Even though the time period of interest was the northeast storm that began on January 22, 2017, the model must be set to begin computations at least three to five days before the time period that is of main interest because it needs time to reach equilibrium. Providing enough time for the model to reach equilibrium is absolutely necessary to allow computed tidal phases to match up with the measured tidal phases. As previously stated, the model was forced at the offshore boundary with wave data taken from NDBC Buoy 44091 (i.e. Hs, Tp, and DirTp). In addition, the model was also forced along the offshore boundary with predicted tides that were extracted from tidal prediction software from the southeast and northeast corners of the model grid. Lastly, the model was also forced with wind data as extracted from the CDMO Nacote Creek meteorological station in JCNERR, NJ and uniformly applied over the expanse of the model grid.

Model Results

In order to determine the potential impacts of the proposed adaptation options, the model had to be validated against the measured data in order to be sure that the model was able to mimic the conditions observed during the northeast storm event as closely as possible. Then, the proposed plan was to re-run the model with the adaptation options added to the area, and compare the conditions from both

simulations in order to determine the impact of the adaptation options. Validating the model, however, turned out to be much more difficult than anticipated and the model was unable to replicate the observed conditions during the northeast storm within an acceptable margin of error. Tidal water levels were the most important aspect of this study since they were determined to be the root cause of the roadway flooding during the northeast storm event, but tidal water levels as calculated by the model did not match those as measured in the field. In order to deem the model as successfully validated, the water level elevations from the model, as extracted from the AQD site, had to match the measured water levels at the AQD site within about a 0.50 ft margin of error. However, the water level elevations at the AQD site, as extracted from the model, were almost 3.00 ft lower than the measured water level elevations during the northeast storm (Figure C4). The difference in modeled water elevations versus measured water level elevations during the northeast storm was greater than the acceptable (as deemed by the CRC) difference between model and measured data and this large difference resulted in little to no roadway flooding. This, in turn, forced the CRC to deem the model as unsuccessfully validated. Therefore, since the model could not be successfully validated against the measured data, the potential impacts of the proposed adaptation options could not be analyzed. There was no accurate modeled flooding data based on the existing conditions of the area to compare to modeled flooding data that was a result of the added adaptation options in order to determine their effect on roadway flooding.

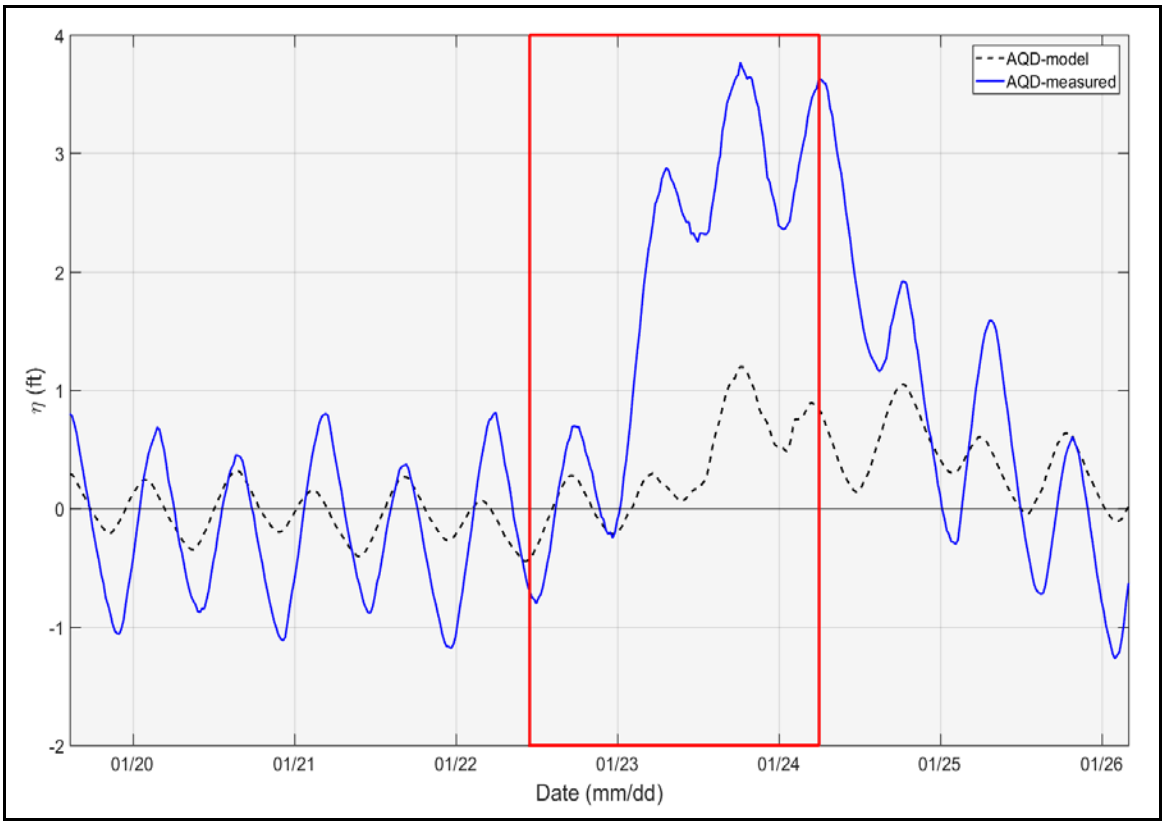


Figure C4. Time series plot of modeled (black dashed line) versus measured (solid blue line) water surface elevations from the AQD site in Tuckerton Bay. Northeast storm (as defined in Appendix B) is indicated with the red box.

The CRC was able to identify two reasons as to why the model could not be successfully validated for this study. The first was due to the fact that the CRC did not budget enough time to calibrate the model

for the northeast storm conditions, as this task ended up being significantly more complicated than initially thought. If additional work were to be done for this study, much more time would need to be allotted for the modeling task and the majority of any additional work would need to be solely focused on modeling. The second was due to the fact that the modeling software, *Delft3D*, is very new to the CRC, but is the only capable modeling program that the CRC has enough knowledge of, that can be used to model a coastal and back bay area such as the Great Bat Blvd marsh peninsula. This area is a very complex system that requires a complex, 2- or 3-D modeling program that is capable of resolving most, if not all, hydrodynamic and meteorological processes in order to model the processes successfully, especially during a northeast coastal storm event. As was discussed in Appendix B, the barometric pressure during the storm was a very important parameter for flooding because the pressure appeared to force water surface elevations to remain almost 4.00 ft above predicted even once the wind and wave heights completely dropped (Figure B12). The fact that the CRC is relatively new to using *Delft3d* and that its members are still working to build up their knowledge of the program meant that the CRC did not know how to add barometric pressure to the forcing conditions of the model. This suggests that the model was not able to mimic the observed water level elevations during the northeast storm, within the appropriated margin of error, because barometric pressure was not included in the model forcing parameters. This fact was a letdown for the study, but it did act to reinforce an important result that was discovered from the measured data. The fact that modeled water levels did not mimic measured water levels, without the addition of barometric pressure to the model, showed that barometric pressure was indeed a very important parameter in causing increased tidal water surface elevations and roadway flooding during this northeast storm. Therefore, even though the unsuccessfully validation of the model did not allow for the CRC to evaluate the effectiveness of the proposed adaptation options, it did shed additional light on the importance of barometric pressure during the northeast storm in causing increased tidal water levels and roadway flooding along Great Bay Blvd.

APPENDIX D – GEOTECHNICAL REPORT

GREAT BAY BOULEVARD

CORE # = HNT 01

NOTE: MEASUREMENTS GIVEN IN FEET

DATE = 11/8/16
TIME = 11:30

PENETRATING DEPTH = 9.5ft
CORE (RECOVERY) = 7.9ft

STRATIGRAPHY NOTES:

Soil Probe Rod: Penetrated 16 feet with no sand contact

NOTE: NOT TO SCALE

GREAT BAY BOULEVARD

CORE # = HNT 03

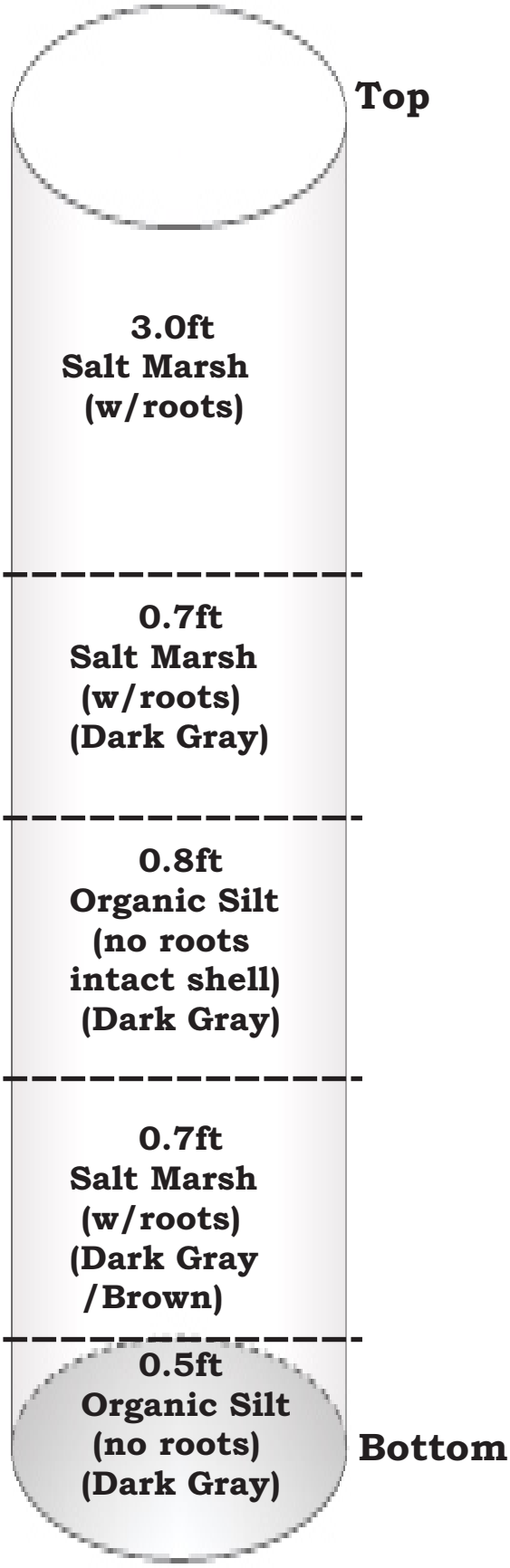
NOTE: MEASUREMENTS GIVEN IN FEET

DATE = 11/10/16
TIME = 14:00

PENETRATING DEPTH = 7.0ft
CORE (RECOVERY) = 5.7ft

STRATIGRAPHY NOTES:

Soil Probe Rod: Penetrated 16 feet with no sand contact



NOTE: NOT TO SCALE

GREAT BAY BOULEVARD

CORE # = HNT 04

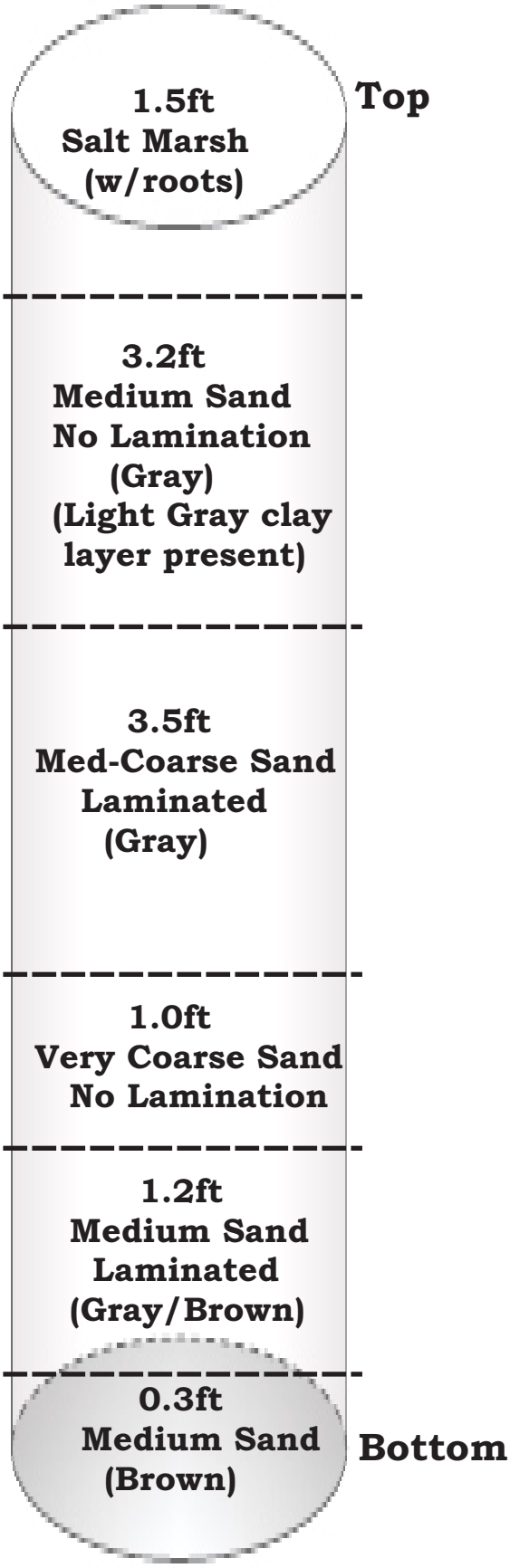
NOTE: MEASUREMENTS GIVEN IN FEET

DATE = 11/10/16
TIME = 14:15

PENETRATING DEPTH = 10.2ft
CORE (RECOVERY) = 10.7ft

STRATIGRAPHY NOTES:

Sand believed to be associated with man-made activities corresponding to road construction.



NOTE: NOT TO SCALE

GREAT BAY BOULEVARD

CORE # = HNT 05.3

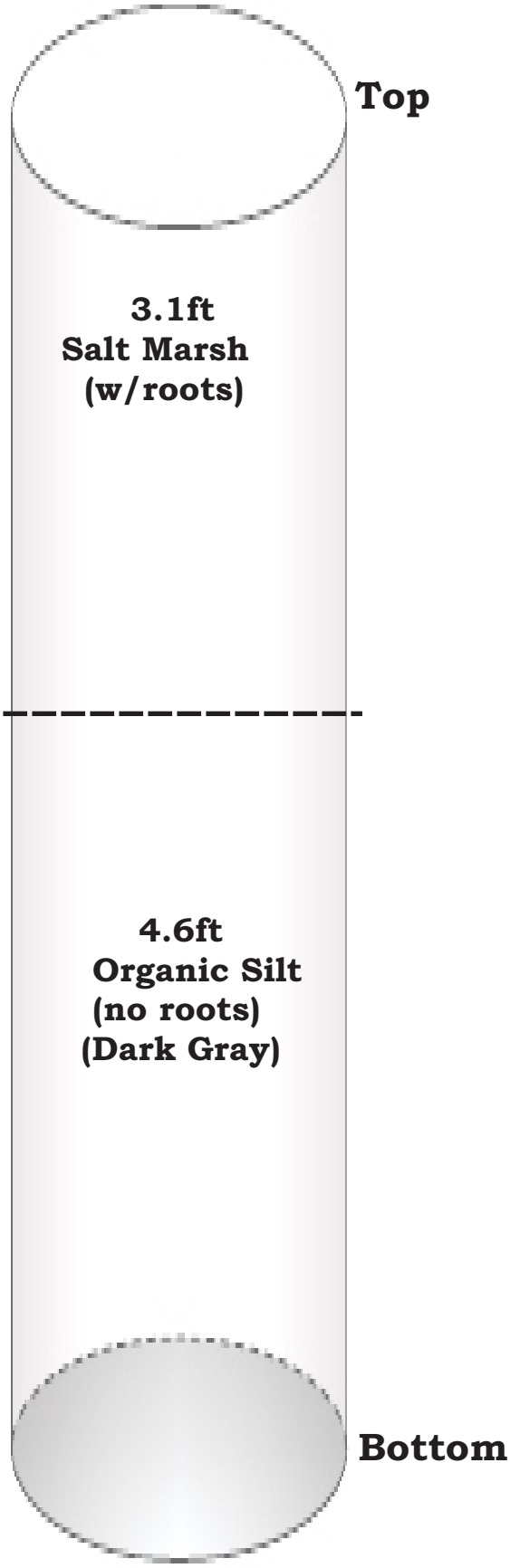
NOTE: MEASUREMENTS GIVEN IN FEET

DATE = 11/10/16
TIME = 15:15

PENETRATING DEPTH = 10.0ft
CORE (RECOVERY) = 7.7ft

STRATIGRAPHY NOTES:

Soil Probe Rod: Penetrated 16 feet with no sand contact



NOTE: NOT TO SCALE

GREAT BAY BOULEVARD

CORE # = HST 01

NOTE: MEASUREMENTS GIVEN IN FEET

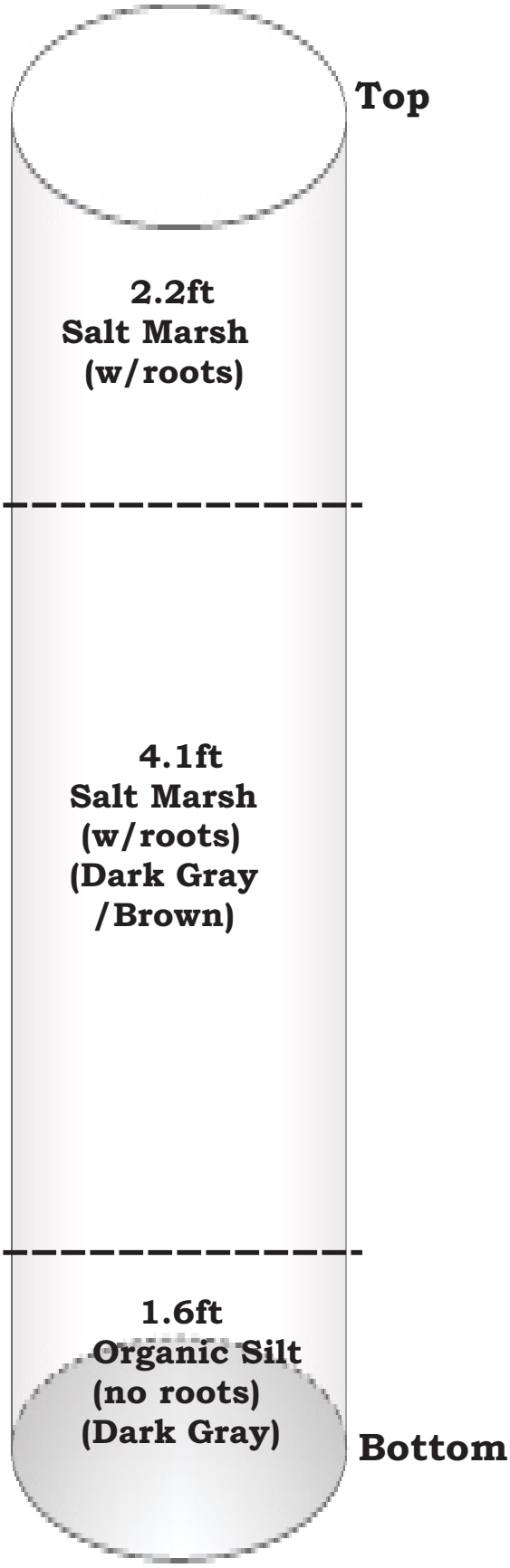
DATE = 11/8/16
TIME = 12:15

PENETRATING DEPTH = 8.4ft
CORE (RECOVERY) = 7.9ft

STRATIGRAPHY NOTES:

Soil Probe Rod: Penetrated 16 feet with no sand contact

****Shell Layer used for C-14 dating located 0.3 feet from bottom of core****



NOTE: NOT TO SCALE

GREAT BAY BOULEVARD

CORE # = HST 02

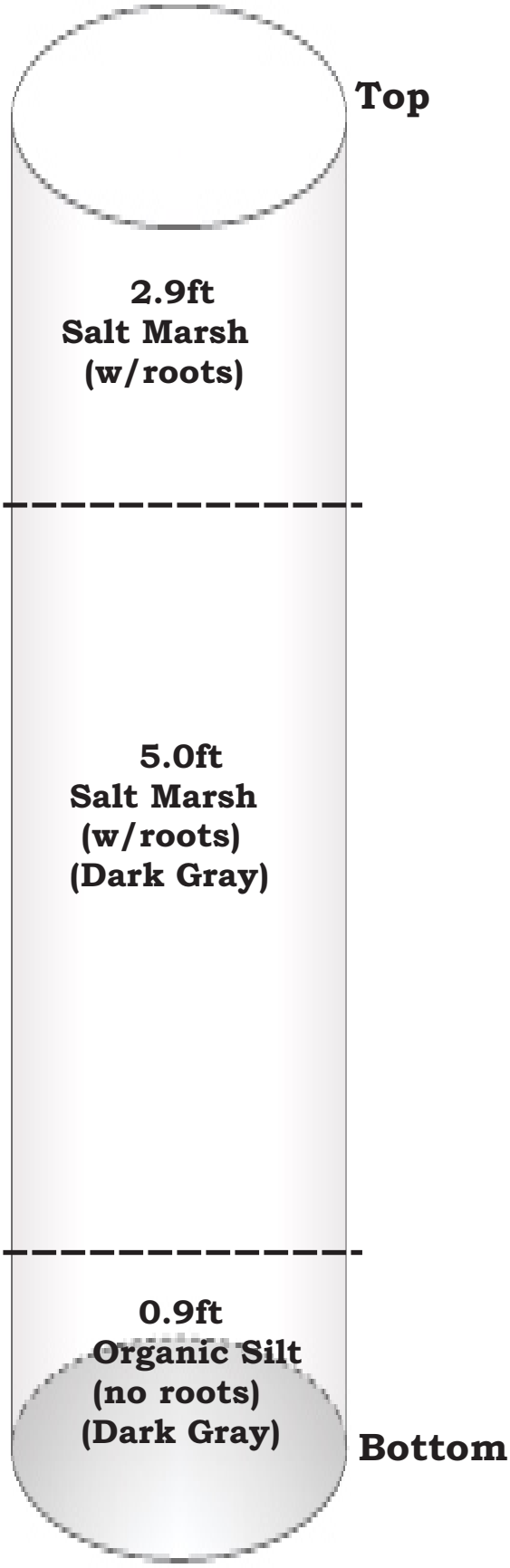
NOTE: MEASUREMENTS GIVEN IN FEET

DATE = 11/10/16
TIME = 12:00

PENETRATING DEPTH = 9.6ft
CORE (RECOVERY) = 8.8ft

STRATIGRAPHY NOTES:

Soil Probe Rod: Penetrated 16 feet with no sand contact



NOTE: NOT TO SCALE

GREAT BAY BOULEVARD

CORE # = HST 03

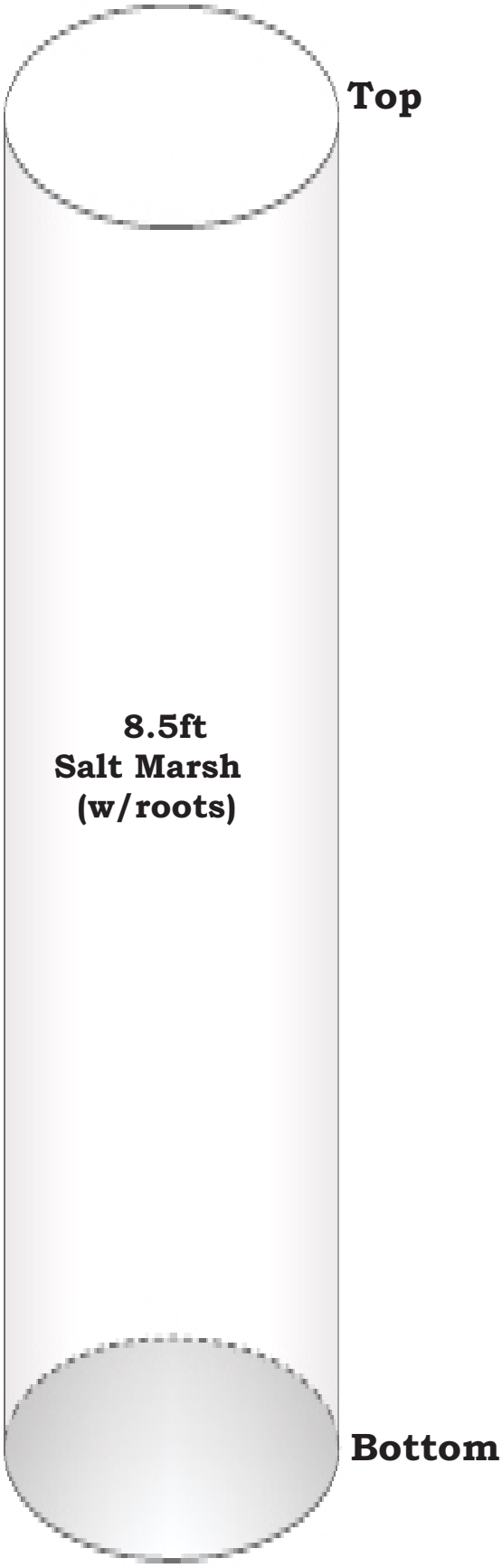
NOTE: MEASUREMENTS GIVEN IN FEET

DATE = 11/10/16
TIME = 10:00

PENETRATING DEPTH = 9.5ft
CORE (RECOVERY) = 8.5ft

STRATIGRAPHY NOTES:

Soil Probe Rod: Penetrated 16 feet with no sand contact



NOTE: NOT TO SCALE

GREAT BAY BOULEVARD

CORE # = HST 04

NOTE: MEASUREMENTS GIVEN IN FEET

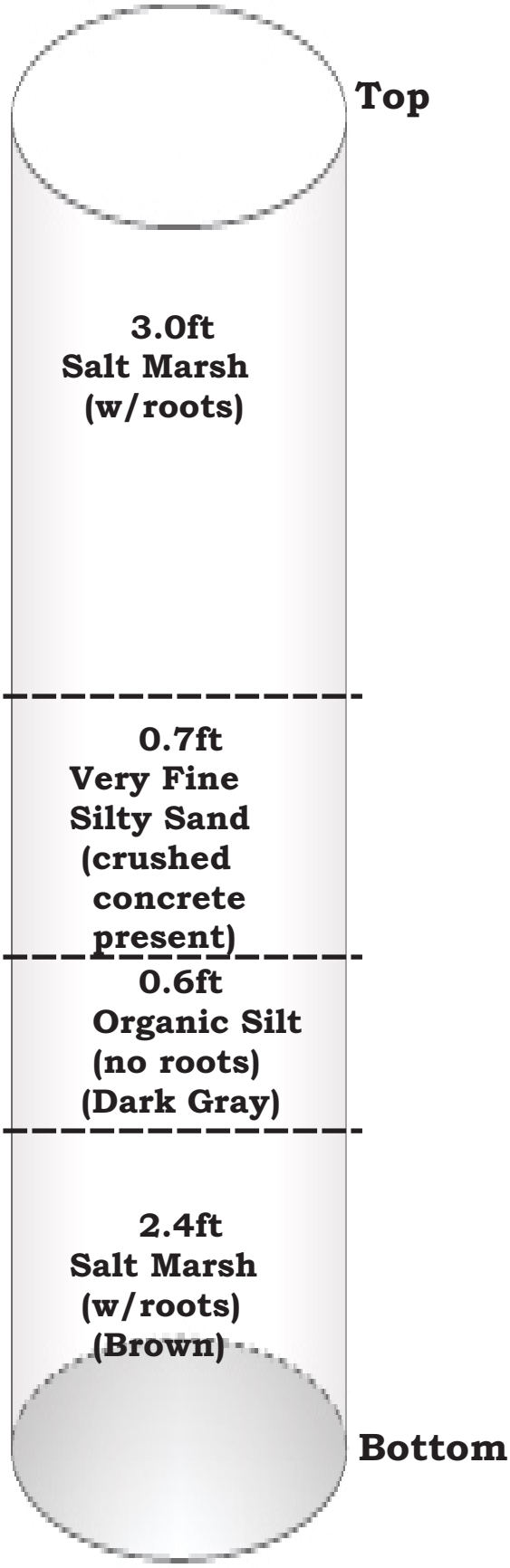
DATE = 11/10/16
TIME = 10:30

PENETRATING DEPTH = 7.8ft
CORE (RECOVERY) = 6.7ft

STRATIGRAPHY NOTES:

Soil Probe Rod: Penetrated 16 feet with no sand contact

Sand believed to be associated with man-made activities corresponding to road construction located approx. 25 feet from Great Bay Blvd 2.5 feet below surface.



NOTE: NOT TO SCALE

GREAT BAY BOULEVARD

CORE # = HST 05

NOTE: MEASUREMENTS GIVEN IN FEET

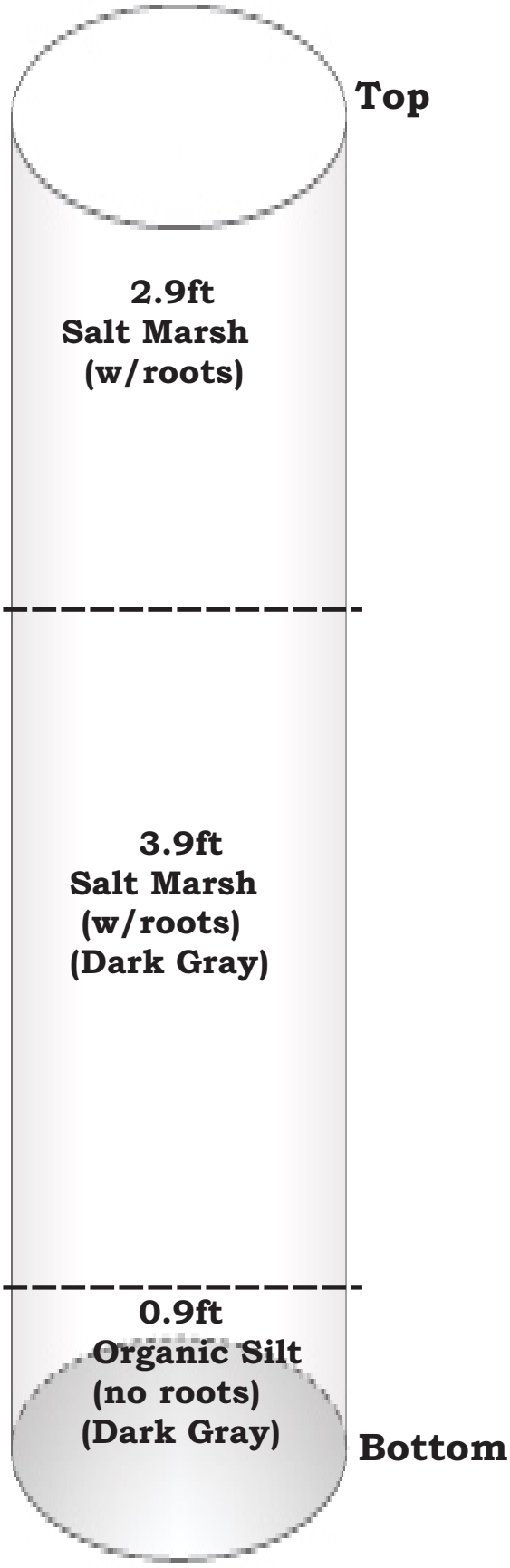
DATE = 11/8/16
TIME = 1:00

PENETRATING DEPTH = 8.7ft
CORE (RECOVERY) = 7.7ft

STRATIGRAPHY NOTES:

Soil Probe Rod: Penetrated 17 feet with no sand contact

****C-14 Dating performed on Marsh sample 2.0ft from bottom of core****



NOTE: NOT TO SCALE

GREAT BAY BOULEVARD

CORE # = HST 06

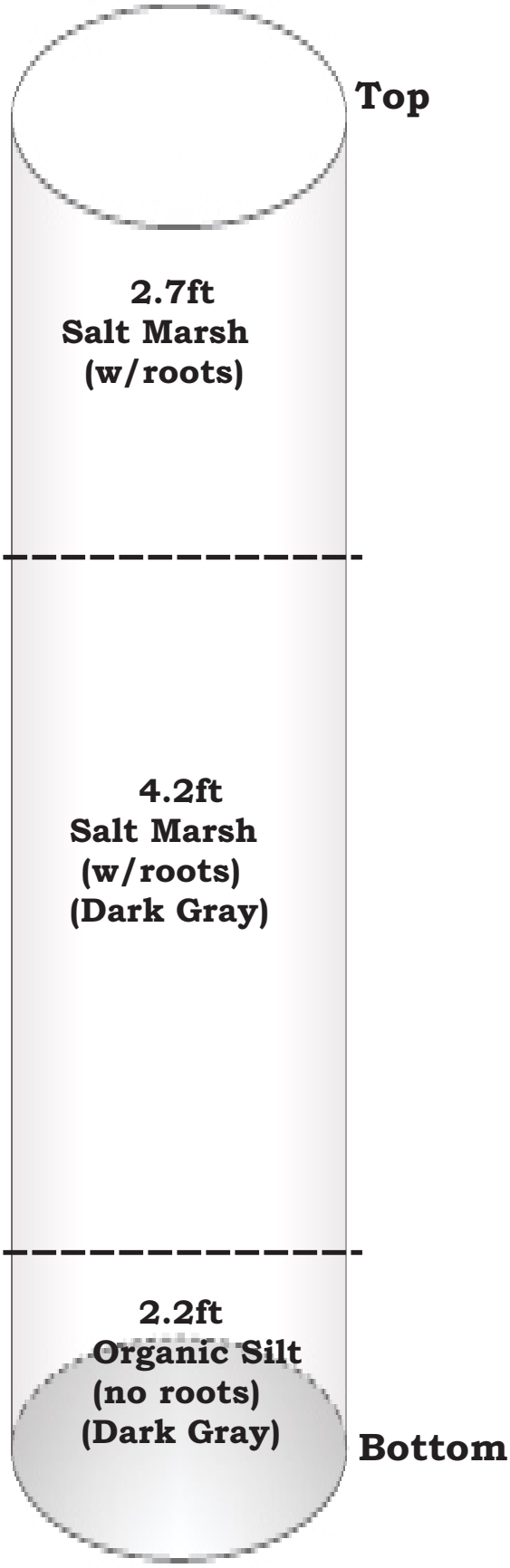
NOTE: MEASUREMENTS GIVEN IN FEET

DATE = 11/10/16
TIME = 12:50

PENETRATING DEPTH = 9.5ft
CORE (RECOVERY) = 9.1ft

STRATIGRAPHY NOTES:

Soil Probe Rod: Penetrated 16 feet with no sand contact



NOTE: NOT TO SCALE