Coastal Monitoring Program

NC 12 Transportation Management Plan

TIP Project B-2500

2019 UPDATE REPORT

FINAL REPORT

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Executive Summary: 2019 Update Report

Implemented by the N.C. Department of Transportation (NCDOT) in 2011, the primary purpose of the Coastal Monitoring Program is to assess highway vulnerability between Oregon Inlet and Rodanthe and is a condition of the 2010 Record of Decision (ROD) for the NC 12- Replacement of the Herbert C. Bonner Bridge. The program is conducted in conjunction with the U.S. Fish and Wildlife Service, providing data to aid in habitat management decisions within the Pea Island National Wildlife Refuge. This report presents detailed monitoring data for the 2019 study year. Conditions throughout the year are compared to conditions in the prior year (2018) and baseline conditions (2010).

This executive summary provides a brief overview of the report results.

Highway Vulnerability

The primary indicators of highway vulnerability considered are: 1) distance from ocean to estuarine shoreline (island width), 2) dune crest elevation less than 10 feet above the NC 12 centerline, and 3) ocean shoreline within 230 feet of the edge of pavement. Though single indicators were found at multiple study transects, four primary locations of concern based on multiple indicators were identified:

- the Canal Zone just north of the freshwater ponds (primarily dunes and 230-foot buffer, some transects with island width and 230-foot-buffer);
- near the Pea Island Visitors Center between the northernmost and middle ponds (dunes, 230-foot buffer);
- the area just south of the Pea Island Breach (island width, dunes); and
- the S-Curves in northern Rodanthe (island width, dunes, 230-foot buffer).

These four areas have previously been identified as areas of concern, with the Pea Island Breach and S-Curves locations showing consistent vulnerability throughout the study timeframe. The Pea Island Visitors Center, which has suffered from erosion of the beach and dunes, was first identified in 2017.

Morphological Indicators

The status of other morphological indicators included in the monitoring program as of 2019 are as follows:

- **Dune crest (maximum elevation at each study transect):** Elevations were highly variable during 2019 with especially large changes in the Canal Zone and northern pond to the Pea Island Visitors Center. Changes in elevation can be attributed to wind and water transport (decreases) and human intervention/earth moving operations (increases).
- **Dune toe position and elevation:** On average, the October 2019 dune toe position was similar to that determined in 2018. The average dune toe elevation was 9.45 ft, slightly higher than the average in 2018 of 9.4 ft.
- **Beach width:** The beach width as of October 2019 was narrower on average across the study area than that observed in November 2018 (130 ft vs. 175 ft). Most of the area within the Rodanthe beach nourishment project has receded to near pre-project conditions.
- **Erosion resistance volume (volume of beach above mean high water from edge of pavement to ocean shoreline):** The trend for the study area was slight volume decrease since 2018 with an average decrease across the study area of approximately 6 cy/ft since November 2018 (for

reference, a dump truck can hold 10 cy). The northern portion of the area nourished in 2014 was in a condition similar to that in November 2018, with some additional losses just north of Rodanthe. As of October 2019, the average volume in this area was about 8.6 cy/ft greater than pre-project conditions as of April 2014. Overall, since the baseline report (2010), the erosion resistance volume shows a net decrease over the entire study area of 1.4 M cy as of October 2019, despite the addition of 1.3 M cy during the beach nourishment project in 2014.

Vegetation and Land Cover/Habitat

- **Habitat Mapping:** Color Infrared (CIR) images were used to create habitat maps for Pea Island in 2019. Habitat classification maps indicate that dominant habitat classes on Pea Island are marshes, managed wetlands, shrub, bare sand dune, and beach. The largest changes observed in 2019 were from shrub to marsh and from beach to water. The shrub to marsh changes are attributed to management activities (controlled burns), and the beach to water changes are attributed to erosion along the study area shoreline.

Erosion Rate and Shoreline Predictions

A summary of the erosion rate and shoreline prediction analyses is provided.

- **Erosion rate:** Long-term erosion rate trends remain similar to those reported in previous years:
    - Accretion is observed in the first 0.8 miles (Transects 170-200 approximately), with relatively low (<+/- 2 feet/year) rates of erosion and accretion south to mile 3.
    - Erosion with rates ranging between 5 and 10 feet/year is observed from miles 3 to 7.
    - A stable to slightly accreting area exists along miles 8 and 9, where the highly vegetated dune field is in place.
    - Higher rates of erosion on the order of 11-12 feet/year are observed from miles 10 south into Rodanthe.
    - Lower rates of erosion exist near the Rodanthe pier.
- **Current/5-Year Vulnerability:** Currently, a sections in the Canal Zone, a section adjacent to the north pond and Pea Island Visitors Center area, a narrow region just south of the wide dune field area, and the Rodanthe/S-Curves section had shorelines observed within the 230-foot buffer. Two sections spanning the currently vulnerable area in the narrow section north of Rodanthe as well as sections north and south of the currently vulnerable S-Curves section were predicted to be vulnerable within 5 years. These sections are illustrated in Figures 29 to 34.
- **2030 Predicted Shoreline:** By 2030, the high-erosion shoreline position reaches the 230-foot critical buffer in multiple locations, including the Canal Zone, near the Visitors Center along the center of the freshwater ponds, immediately north and south of the Interim Bridge at the Pea Island Breach, and in northern Rodanthe. These sections are illustrated in Figures 35 through 40.
- **2060 Predicted Shoreline:** The 2060 high-erosion and average shorelines reach the critical buffer along a stretch of NC 12 in the Canal Zone south of Oregon Inlet. Near the Visitors Center and adjacent to the Pea Island Breach, even the low-erosion 2060 shoreline moves landward of NC 12 in some areas. Just south of the ponds, the low-erosion 2060 shoreline is within the critical buffer area, and the average-erosion shoreline approaches the road. South of that section, all predicted shorelines lie east of the buffer for approximately three miles until a narrow section north of Rodanthe where the high erosion predicted shoreline transitions to a

position landward of NC 12, with the average predicted shoreline near the road. All predicted shorelines are landward of the road from that area south to the northernmost portion of Rodanthe. The 2060 shorelines are illustrated in Figures 42 through 47.

Breaches

The locations of the Pea Island and Rodanthe breaches (formed in 2011) continue to be monitored, with results as indicated:

- **Pea Island Breach:** The Pea Island Breach was closed for all of 2019, with the most landward shoreline position measured in December 2019. The most seaward shoreline position was observed in May.
- **Rodanthe Breach:** The most landward positions were observed in April, October, and December 2019. There are fewer fluctuations in the shoreline position in this area due to ongoing maintenance of the dunes and roadway clearing. The May 2019 and December 2018 shorelines were the most seaward shoreline positions observed.

Storms

- The three most severe events to impact the study area in 2019 were Hurricane Dorian (September 6-7, 2019), Tropical Storm Melissa (October 8-12, 2019), and a November nor'easter (November 16-19, 2019).
- The Traveler Information Management System data for 2019 indicated that those three events led to hazardous roadway conditions including overwash, sand and water on the road, and wind-blown sand. An additional event September 20-21, 2019 also caused ocean overwash and hazardous conditions during 2019, but did not lead to closure.

USACE Dredging

- Data for both 2018 and 2019 are included in this report as information was not available at the time of the 2018 report.
- In both 2018 and 2019, dredging operations consisted of small volume (<62,000 cy) projects conducted using either a small hopper dredge (Currituck or Murden) or a sidecaster (Merritt). These projects are not expected to significantly affect the shoreline along the study area.

Maintenance Expenses

- Maintenance expenses in 2019 totaled approximately $1.3 million with most of the expenses related to sand removal.
- The October Storm (Tropical Storm Melissa), Hurricane Dorian, and the November 16-20 coastal storm had particular line item expenses delineated with the most expensive being Tropical Storm Melissa with $116,829 in sand removal costs.

Terminal Groin Monitoring

The long-term terminal groin monitoring methodology was changed in 2017 to include a new protocol for determining the historical and project erosion rates. The historical rate is now determined as a linear regression of shoreline positions between October 1968 and October 1988. The project rate is determined as a linear regression of shoreline positions between August 1992 and December 2019. These new rates are used with the same methodology as previous reports to determine the one mile and three mile volume changes.

- **Terminal Groin Monitoring:** As of December 15, 2019, the project erosion rates are much less than the historical rates in the first three miles of the study area, and the project erosion rate does not exceed the historical rate at any point in the first six miles south of the Oregon Inlet terminal groin. The one and three mile volume calculations are well below that which would be expected using the historical rate. In summary, the construction of the groin does not appear to have caused an adverse impact to the shoreline over the six-mile study area.

Physical and Biological Monitoring

NCDOT provided physical and biological survey results which are summarized as follows:

- **Seabeach Amaranth:** No seabeach amaranth plants were observed during surveys in 2019.
- **Physical and Biological Condition of the Beach Sand:** Sand sampling was conducted quarterly (generally in January, April, July, and October) along 64 transects beginning 0.1 miles south of the terminal groin and continuing south every 0.2 miles to the southern terminus of the PINWR. Benthic organisms, grain size, slope and compaction, and heavy mineral content were analyzed.
    - The 2019 data were analyzed with a cubic function rather than a linear function. This function indicates an inverse relationship between grain size and species abundance.
    - Generally, grain size distributions across the study area were as expected with seasonal and long-term variations. The data also indicate that major storms have an influence over benthic numbers, but these numbers recover over time.
    - Beginning in 2018, the Canal Zone, New Inlet/Pea Island Breach, and Rodanthe S-Curves areas were analyzed separately to see if these areas were exhibiting any changes that may have been masked by the overall island analysis. When these areas were analyzed separately, the data indicated seasonal and long-term variation similar to that of the overall analysis. However, the relationship between grain size and abundance is different at each spot. There is a strong inverse relationship at the New Inlet area, a weaker inverse relationship in the Canal Zone and a direct relationship at the S-Curves. The inlet area had an average grain size between 0.8 and 1.0 mm with the average grain size in the other two spots less than 0.8 mm.
- **Submerged Aquatic Vegetation (SAV) – Rodanthe Bridge Project Area:** SAV monitoring began in May 2019 and was repeated in spring and fall through fall 2019. Monitoring was performed using field-based sampling as well as delineation from aerial imagery. Field surveys included Braun-Blanquet quadrat surveys and line intercept surveys. SAV cover was similar in May and September 2018, with substantial decrease in May 2019; SAV coverage showed recovery to near 2018 levels by November 2019.

- **Submerged Aquatic Vegetation (SAV) – Bonner/Basnight Bridge Seagrass Mitigation Site**: During visits to the site, scientists have consistently observed that the Bonner Bridge Seagrass Mitigation Site was composed of patchy seagrass habitat consisting of multiple species including Z. marina, H. wrightii, and R. maritima. Very fine sand (visual observation) sediments has consistently been the dominant substrate type observed.
    - In the relocated seagrass site, as of May 2019, seagrasses were present within both planting areas but no discernable cover was found in the easternmost planting block and cover in the western block was 15.8%.
    - Epibiota colonization was also monitored. As of May 2019 a clear trend of increasing colonization continues with high levels of colonization among all elevations of the wavebreak structure.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

In December 2010, the Federal Highway Administration (FHWA) issued a Record of Decision (ROD) for TIP Project B-2500, which includes the replacement of the Bonner Bridge and a long-term solution for NC 12 between Oregon Inlet and Rodanthe. The Selected Alternative for Project B-2500 is the Parallel Bridge Corridor with NC 12 Transportation Management Plan (NC 12 TMP). As explained in the ROD, a component of the NC 12 TMP is a detailed coastal monitoring program that is designed to assist the agencies in deciding when the planning efforts for future phases of the Project B-2500 should begin. The coastal monitoring program includes detailed annual monitoring reports that summarize data collected by the N.C. Department of Transportation (NCDOT) and other agencies.

The study area for the coastal monitoring program includes both the study area of the existing terminal groin monitoring program (developed in conjunction with the U.S. Fish and Wildlife Service [USFWS], per the permit issued in June 1989) and the TIP Project B-2500 study area. The coastal monitoring program study area begins just over five miles north of the Oregon Inlet Marina and extends approximately 13 miles south of Oregon Inlet to the community of Rodanthe. The highway vulnerability analyses focus on the section of NC 12 between Transect 170 (Old Coast Guard Station, mile 0) and Transect 632 in the northern part of Rodanthe (mile 13.1). The study area includes the entire width of Hatteras Island between the ocean and estuarine (soundside) shorelines.

In August 2012, a new easement (permit) for the terminal groin monitoring was signed. The results of the terminal groin monitoring required as a condition of the 2012 easement are included in the annual coastal monitoring report. Any updates or changes in the terminal groin analysis methodology have been developed in consultation with the U.S. Fish and Wildlife Service (USFWS) and are described in this report.

The present report describes the data collection and analysis completed to update the conditions during the calendar year 2019. Conditions throughout the year are compared to the conditions reported in the 2018 Update Report, herein referred to as the 2018 report. General comparison of current erosion rates and composite vulnerability to baseline conditions (established in the Baseline Report, conditions as of January 14, 2011) are also presented. The erosion rates for the area have been updated with new shoreline position data through December 15, 2019. In addition, all assessments performed under the new terminal groin easement have been updated through December 15, 2019.

The reports generated in conjunction with the NC 12 TMP coastal monitoring program are intended to meet the requirements for both TIP Project B-2500 and the easement issued in 2012 for the retention of the Oregon Inlet terminal groin.

2. DATA COLLECTION AND METHODOLOGY

The key parameters used for monitoring of the extended Oregon Inlet study area are:

- Ocean shoreline location;
- Estuarine shoreline location;
- Distance from ocean to estuarine shoreline;

- Island elevation;
- Dune crest location and elevation;
- Beach volume above mean high water, between eastern edge of pavement and ocean shoreline;
- Dune vegetation coverage;
- Land cover/habitat mapping (first presented in the 2017 update); and
- Erosion rate and road vulnerability.

The data used for this update is detailed in Table 1. Figure 1 shows the extent of the coastal monitoring program transects, and Table 2 lists the location of the transects corresponding to various landmarks along the study area. Transects 0 to 381 were the original transects established for purposes of monitoring the Oregon Inlet terminal groin. Transects are spaced 150 ft apart.

In August 2011, NCDOT implemented a new orthophotography flight schedule (in agreement with the USFWS), replacing the former terminal groin flight schedule (six times annually) with a new schedule that includes flights of the entire B-2500 study area four times annually (February, April, August, and October). The new photography is obtained at a flight altitude of 4500 ft Above Mean Ground Level (AMGL) and ground controlled in order to achieve +/- 0.5 ft accuracy (pers. comm. Rob Allen, NCDOT July 15, 2013). NCDOT generates topographic data from these lower elevation orthophotos. In June and December, NCDOT continues to fly the entirety of Hatteras and Ocracoke Islands, including the B-2500 study area, at 7500 ft AMGL but does not generate topographic data from these photos. Orthophotos from all six flight dates are used for shoreline delineation (oceanfront and soundside) and are used in the analysis of shoreline change. Parameters requiring elevation data (dune crest elevation, for example) are evaluated only at the February, April, August and October dates. Since 2013, color infrared (CIR) photography has been provided once per year (generally in April) to assist with identification of vegetation density and habitat classification.

Table 1. Orthophotos and topographic data used for 2019 monitoring update.

Date of Orthophotography	Topographic Data Available	Data Source	Notes
2/5/2019	Yes	NCDOT	
4/10/2019	Yes	NCDOT	CIR photographic data also provided
5/30/2019	No	NCDOT	Flight took place at the end of May rather than June due to scheduling constraints
8/29/2019	Yes	NCDOT	
10/1/2019	Yes	NCDOT	
12/15/2019	No	NCDOT	

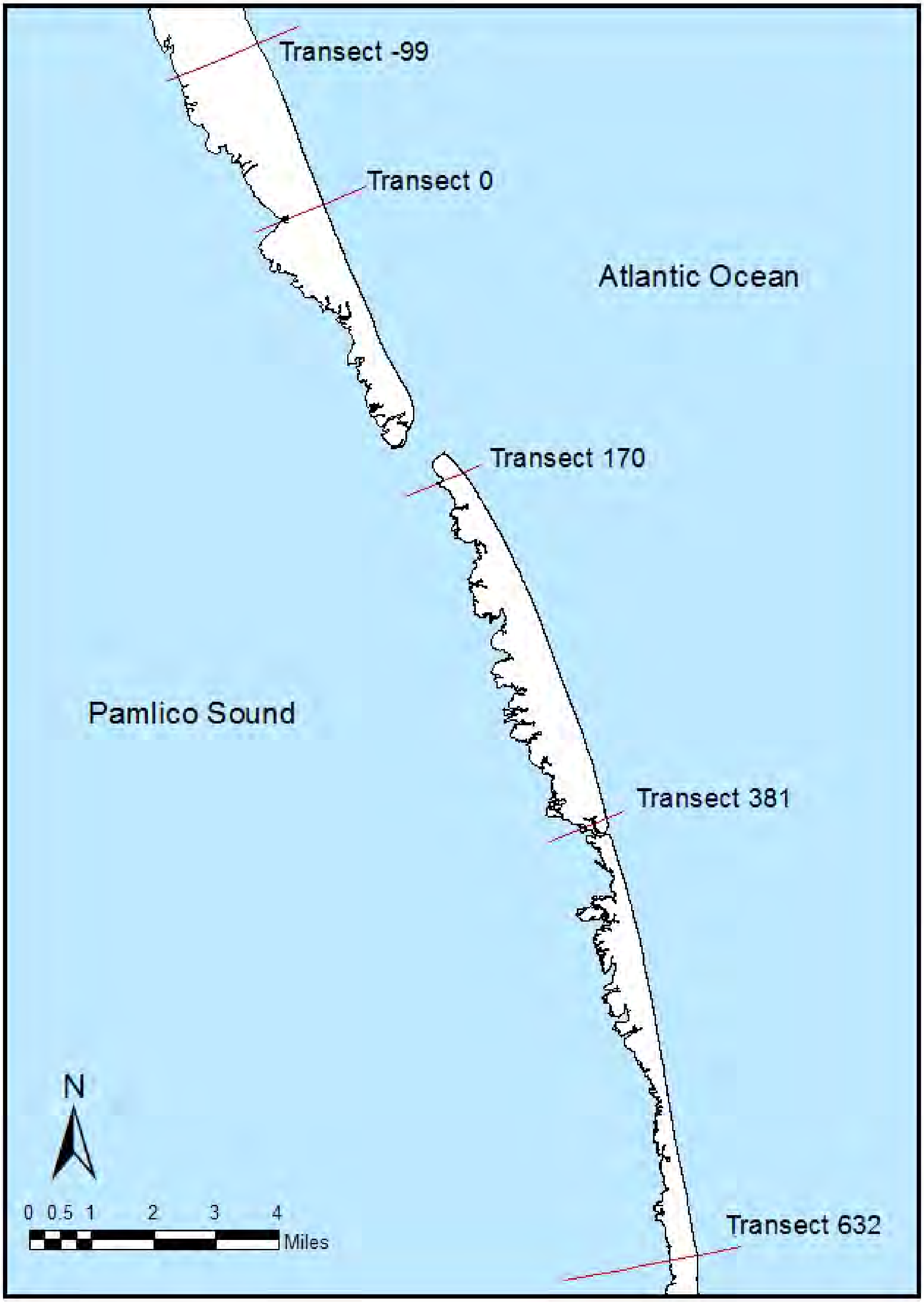

Figure 1. Coastal monitoring program with study area transect extents.

Table 2. Study area landmarks and corresponding transect numbers.

Transect Number	Miles from Transect 170	Location Description
-67	-6.7	Northernmost transect of study area (Bodie Island)
-35	-5.8	South Old Oregon Inlet Road
89	-2.3	Oregon Inlet Marina
150	-0.5	Bonner Bridge Navigation Zone - Midpoint
156	-0.4	Tip of Terminal Groin
170	0	Old Coast Guard Station
254	2.4	Northernmost Dike of Ponds
307	3.9	Pea Island National Wildlife Refuge Visitor Center
378	5.9	Southernmost Dike of Ponds
399	6.5	Oceanside Refuge parking lot
410	6.8	Soundside Refuge parking lot
578	11.6	Southernmost boundary of Refuge
604	12.3	Rodanthe Ferry Terminal
632	13.1	Southernmost transect of study area (Rodanthe Pier)

As detailed in the following sections, additional data on NCDOT roadway maintenance activities, other projects in the study area, and data from other federal and state agencies were also used in this analysis. Physical and biological monitoring has been conducted by NCDOT. Appendix A of this report includes seabeach amaranth monitoring; submerged aquatic vegetation (SAV) monitoring at the Bonner/Basnight bridge area and Rodanthe bridge area; and monitoring of the conditions of the beach sand.

The methodology used to analyze the data collected is described in the following sections. Detailed monitoring of the barrier island morphology is being undertaken along with examination and exploration of indicators of current and future vulnerability of the road.

Ocean and Estuarine Shorelines

The ocean shoreline was digitized for each of the six full study area orthophoto dates (Table 1). The shoreline is represented as the visible wet-dry line for sandy beaches (primarily on the ocean side), and the limit of the marsh vegetation is used to represent the estuarine shoreline (where the estuarine shoreline is sandy, the wet-dry line is used). Estuarine shorelines were updated for each date using the previous estuarine shorelines as a starting point. The estuarine shoreline has not been observed to change significantly over the two-month intervals between photo dates, with the exception of the areas closest to the Pea Island Breach and just south of the new Basnight (Oregon Inlet) Bridge. Because of the limited extent of changes in the estuarine shoreline, it is determined for each date using the following methodology:

- The previous shoreline (2 months prior) is displayed on the current orthophoto. (For example, the December estuarine shoreline is generally displayed on the February orthophoto.)

- Visual inspection of the digitized shoreline relative to the photo identifiable shoreline is made at a scale of 1:1200, and the digitized shoreline is corrected to the most recent orthophoto as required.

The methodology for determining the ocean shoreline is as follows:

- The ocean shoreline is digitized directly from the orthophoto for each date (without comparison with previous shorelines). It is identified as the visible wet-dry line (location where a noticeable darker line of saturated sand is observed). The wet-dry line (also known as the high water line) is used because it has a smaller horizontal displacement than the swash terminus, thus it is more suitable for long-term shoreline change analysis (Dolan et al. 1980).
- Visual inspection of the image at a scale of 1:1200 is made and the wet-dry line is manually digitized and reviewed.

The distance from the ocean shoreline to the estuarine shoreline was evaluated at each transect for the February 5, April 10, May 30, August 29, October 1, and December 15, 2019 orthophotography. Exclusively interior channels and ponds were not considered to be a part of the estuarine shoreline for this analysis. In some cases, the island extended past the first intersection with the estuarine shoreline. In these cases, the distance to the first intersection was used.

As described in the 2011 report, the original study methodology included identifying the smallest 10% of the distances from ocean to estuarine shoreline (in the baseline report); this methodology has changed to an assessment of the locations where that distance was smaller than 1000 ft (in all subsequent reports). Island width is considered to be a vulnerability indicator for island breaching, and 1000 ft was selected based on the island widths at the locations of breaches caused by Hurricane Irene in August 2011. In the present report a width of 1000 ft is used to assess breaching vulnerability.

Island Elevation and Dune Morphology

Photogrammetrically derived digital terrain models from the February 5, April 10, August 29 and October 1, 2019 flights were used to evaluate island elevation and dune morphology. The digital terrain models include spot elevations, breaklines, and contours provided by NCDOT. These are imported into ArcGIS for further analysis. Island elevation values were extracted across each transect for each date at each transect using GIS tools.

<u>Dune Crest/Maximum Elevation between NC 12 and Ocean Shoreline</u>

A profile-based assessment of the maximum elevation between the eastern edge of pavement of NC 12 and the ocean shoreline was performed. The maximum elevation is then used to evaluate the potential vulnerability to wave action and overwash. The maximum elevation between the edge of pavement and shoreline is compared with the road elevation at each transect. Where the maximum elevation is less than 10 ft above the road, there is considered to be an increase in vulnerability.

Dune Toe Position and Elevation

In addition to the evaluation of maximum elevation between the road and the shoreline, identification of the dune toe position and elevation was conducted for the last topographic data set available for the 2019 study year, associated with the October 1, 2019 photography.

To identify the dune toe, a partially automated algorithm was used. For initial dune toe identification, a straight line between the maximum profile elevation and the shoreline was drawn, and the maximum difference between this line and the profile elevation was identified as the toe (see Figure 2). However, in some cases the automatically extracted toe was either not suitable, or no significant dune was present on the profile. This led to the development of an inspection method where the user views the profile at each transect, and can either accept or replace the estimated dune toe, or identify a profile as having no visible dune feature. For profiles identified as "no dune," the dune toe elevation and position were not reported.

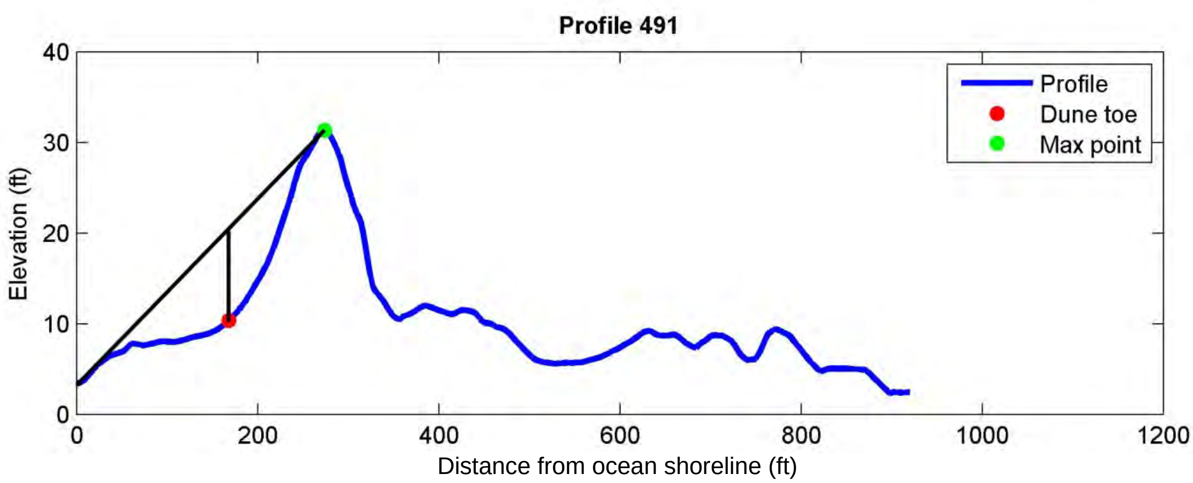

Figure 2. Schematic of dune toe identification methodology. Ocean shoreline is at horizontal position zero.

Beach Width

Dune toe identification also allows for assessment of the beach width. For this study, beach width is defined as the distance from the dune toe to the ocean shoreline. Beach width is important because for wide beaches under typical daily conditions, the dune system is unaffected by wave action and can build due to accumulation of wind-blown sand. Under continual erosion, the beach narrows and steepens, allowing more frequent impact of waves on the dune face and transitioning to an eroding dune system.

In this study, beach widths less than 100 ft are considered to contribute to vulnerability of adjacent dune fields and therefore to the highway vulnerability. Where beaches are less than 100 ft wide, elevated water levels and high waves during typical nor'easter storms can impact the dunes, reducing dune volume and height. If these conditions exist in areas where the total distance from edge of pavement to shoreline is greater than 230 ft, the narrow beach width and loss of the dune make the road increasingly vulnerable to direct wave impact and/or flooding during storm events.

Beach Volume above MHW from Edge of Pavement to Shoreline

The digital terrain models from the February 5, April 10, August 29, and October 1, 2019 flights were also employed to compute the volume of beach material between the NC 12 edge of pavement (EOP) and the ocean shoreline located at the mean high water (MHW) elevation at each transect. Mean high water was determined at the center of the study area using the VDATUM tool developed by NOAA (NOAA 2012). The MHW elevation was estimated at 1.14 ft NAVD 88. The elevations along each transect were extracted from the edge of pavement seaward using GIS tools. These elevations were then imported into the USACE's BMAP (Beach Morphology Analysis Package) program. Volume above the 1.14 ft contour was computed in BMAP and is reported as cubic yards per ft alongshore (schematic shown in Figure 3). Computed volumes were compared with previously reported values. It is noted that the Edge of Pavement (EOP) reference line for the beach volume was adjusted to account for roadway location changes as detailed in Appendix B. These changes affected reported beach volumes at Transect 376-404 adjacent to the interim bridge at the Pea Island Breach and Transects 513 to 526 adjacent to the northern end of the under-construction Rodanthe bridge.

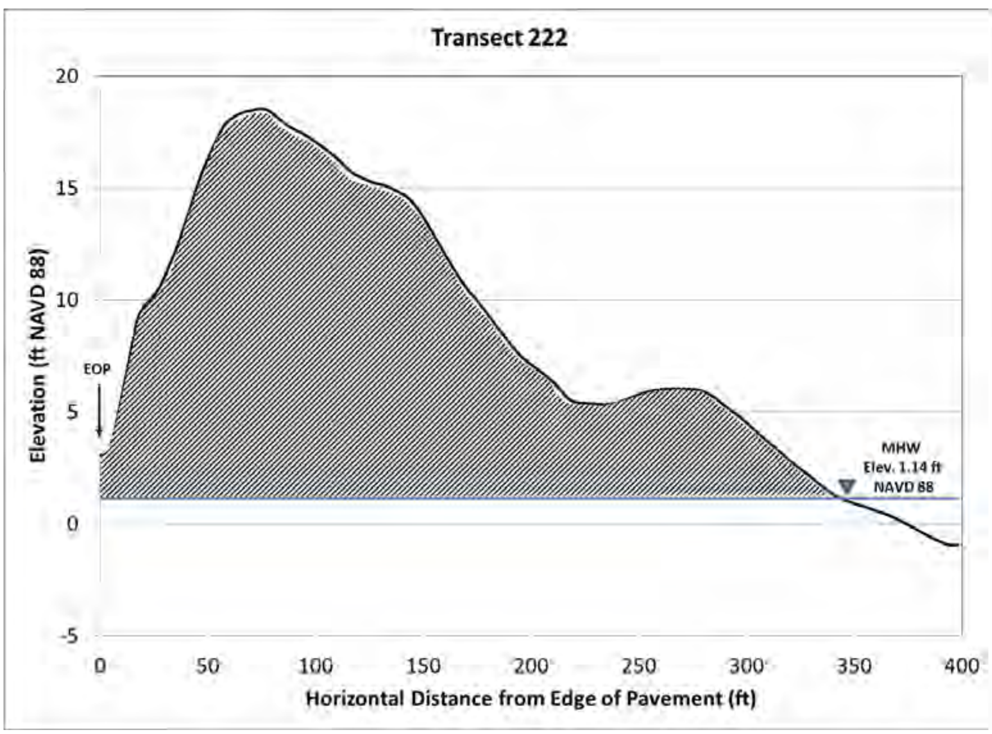

Figure 3. Schematic of unit volume computation. The cross sectional area between the horizontal position of the mean high water (MHW) contour and the edge of pavement (EOP) is calculated as shown, and then converted to unit volume in cubic yards per ft assuming a 1 ft wide profile.

Land Cover/Habitat Mapping

As part of the requirements of the 2012 easement, work has been ongoing to map and model habitat changes within the Pea Island National Wildlife Refuge (PINWR). Initial efforts were undertaken in collaboration with representatives of the PINWR to create land cover maps for the years 1998 and 2015, based on available color infrared (CIR) photography and were described in the 2017 report. In 2018, this effort was expanded and maps were created for each of the years, 2012 to 2018, as described in Appendix B of the 2018 report. *The land cover/habitat mapping replaces the vegetation analysis described in reports prior to 2018, as agreed by representatives of USFWS and NCDOT.* The present report continues the methods initially described in Appendix B of the 2018 report to map the land cover/habitat for the April 10, 2019 color infrared imagery. These methods are described below.

The CIR image was resampled to a 2 ft (0.6 m) resolution. This value was chosen to speed up computational times in ArcGIS, while maintaining enough resolution to differentiate all habitat classes. The resampled image was clipped using the polygon formed by the south end of the PINWR and the estuarine and oceanfront shorelines.

Thirteen habitat classes were identified as the main habitats that could be classified from the CIR imagery. These classes were selected in collaboration with personnel from the U.S. Fish and Wildlife Service (USFWS) and are based on the habitat types listed on the PINWR website <http://www.fws.gov/refuge/pea_island/wildlife_and_habitat/habitat_types.html>. The 13 classes are listed with their descriptions in Table 3.

Habitat classification was completed in ArcGIS using interactive supervised classification based on training polygons digitized over spatially varying locations that represent each habitat class. This method allows for a fast cell-by-cell raster classification based on classes defined by the user. Habitat classes such as *Bare Sand, Estuarine Pond, Salt Flat, Shrub*, *Marsh,* and *Water* are automatically classified using this method.

Seaward of the NC 12 Highway, classification is partially based on the supervised classification and morphological features digitized as polygons. The *Beach* is the region within the oceanfront shoreline and the dune toe. For habitat classification purposes, the horizontal extent of the dunes is defined based on elevation data and transects separated every 150 ft. The dune field is the polygon defined by the dune toe line, the dune heel line and the southern end of the refuge. The location of the dune heel is the defined by the 5 ft contour or the eastern edge of pavement, whichever is seaward (Figure 4). The 5 ft contour was chosen as the landward edge of the dune because it partially matches the edge of NC 12 highway in the northern portion of the island, and because it provides an objective metric for comparison between different dates. The location of the dune toe depends on the dune crest and the shoreline position at each transect. The dune toe is extracted based on the maximum vertical distance between the beach profile and the line traced between the dune crest and the shoreline (Figure 4).

Table 3. Definition of Habitat Classes

Value	Class	Description
1	Bare Sand (BS)	Bare sand excluding the foredune and beach areas. Bare sand includes overwash fans and unvegetated portions of the island covered with dry sand.
2	Estuarine Pond (EP)	Enclosed bodies of water within the island with minimum or no connection with estuarine water. This class does not include the three large manmade managed water ponds of the refuge.
3	Salt Flat (SF)	Estuarine areas subjected to irregular flooding by salt water. This class occurs in shallow depressions where evaporation of the high salinity ocean water concentrates salt. Sparse cover and low diversity characterize its plant density and species composition.
4	Shrub (S)	Shrubs occur in a wide range of conditions from excessively to poorly drained soils in areas protected from salt spray and flooding by salt water. These conditions may occur on stabilized sand ridges, in dune swales, and on sand flats.
5	Marsh (M)	Includes salt and emerging marshes. Salt Marsh occurs on the margins of estuarine channels and on the landward side of barrier island systems in areas under tidal influence. The brackish marsh occurs along the margins of sounds and estuaries in areas not subjected to regular flooding by salt water. Brackish marsh is subjected to irregular flooding mostly from wind tides.
6	Vegetated Dune (VD)	Vegetated dune occurs in the landward side of the dune. This habitat is exposed to salt spray and abrasive wind-blown sand.
7	Bare Sand Dune (BSD)	Un-vegetated portion of dunes limited on the ocean front by the dune toe and landward by the 5 ft (1.524 m) NAVD88 elevation contour or the eastern edge of pavement, whichever is seaward.
8	Water (W)	Estuarine and ocean water.
9	Groin (G)	Terminal groin as visible from aerial imagery.
10	Infrastructure (I)	Paved roads, parking lots, construction sites, and buildings.
11	Maritime Brush (MB)	Growing vegetation in overwash terraces behind dunes and below the 5 ft (1.524 m) NAVD88 elevation contour in areas subject to inundation by the ocean or partial burial due to wind-blown sand.
12	Managed Wetlands (MW)	Manmade impoundments with borrow canals around the perimeter that may include open water, moist soil, exposed sand/mud flats, and emergent vegetation with varying amounts and management regimes. Pea Island National Wildlife Refuge has three impoundments: 390-acre North Pond, 192-acre New Field Pond, and 208-acre South Pond.
13	Beach (B)	Bare sand between the dune toe and the wet-dry shoreline.

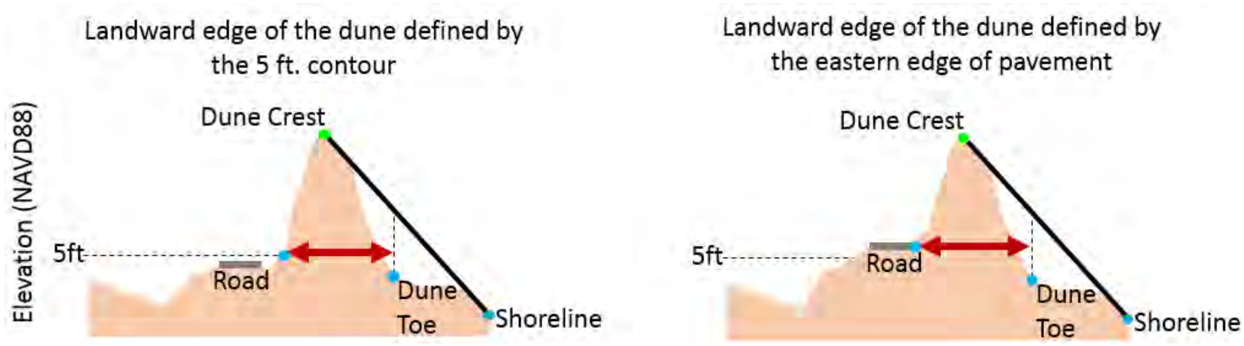

Figure 4. Definition of the horizontal extent of a dune (red arrow) on a cross-shore transect and visualization of the dune toe extraction method.

The dune is classified as *Bare Sand Dune* and *Vegetated Dune* depending on whether it is vegetated or not. Vegetated areas between the landward edge of the dune and NC 12 Highway are classified as *Maritime Brush*, excluding Shrubs. Other areas classified as Maritime Brush were digitized over the portion of overwash fans that have growing vegetation. Other classes that were digitized include the *Infrastructure*, *Groin,* and *Managed Wetlands*.

Once the automated and digitized classifications are completed, visual inspection of the resulting habitat maps is performed at 1:3,000 scale that allows correction of noise and any mis-classifications that may have resulted from the automated process.

Erosion Rate Update

The project included an update of study area erosion rates following the methodology of Overton and Fisher (2005). To update the erosion rates, additional ocean shoreline position data were established using the aerial orthophotography for the 2019 dates, and added to the database of shoreline positions established in the 2010 Baseline Report (Overton 2012) and updated in subsequent reports. The erosion or accretion rates were then calculated by performing a linear regression on the shoreline position data. It is noted that for the transects surrounding the Pea Island Breach (Transects 386, 387, 388, 389, and 390), shoreline positions while the breach was active have been removed from the database, as described in the 2015 Report. Since the 2016 update, post-closure shorelines for those transects have been included in the database, and computation of erosion rates for these transects has resumed.

Critical Buffer and Vulnerability: Present and Future

The vulnerability of the NC 12 roadway at the conclusion of 2019 was assessed using the December 15, 2019 orthophotography. Vulnerable locations were identified using the 230-foot critical buffer established in previous studies[1]. Where the distance from the edge of pavement to the ocean shoreline was less than or equal to 230 ft, the area was considered to be vulnerable. In previous reports, the four

[1] This criterion originated with the first highway vulnerability study completed in 1991 (Stone, Overton and Fisher 1991). That work proposed a critical buffer distance of 230 ft from the edge of pavement to the active shoreline, interpreted as mean high water (MHW), to be used to indicate when a coastal highway became vulnerable to repetitive overwash and sand deposits resulting in excessive maintenance costs. This conclusion was based on the review of NCDOT maintenance records for NC 12.

transects within the original Pea Island Breach (and the associated temporary bridge) were excluded from the vulnerability analysis. NCDOT completed construction of a 0.5-mile interim structure spanning the breach area in late 2017. Because the new structure is not intended as a long-term solution for the maintenance of NC 12, this analysis will continue to assess the distance between the edge of pavement (bridge) and the ocean shoreline within the interim bridge area.

Areas where the shoreline would be expected to recede to the buffer zone within 5 years (based on the updated shoreline position data) were also highlighted. This was done by predicting the expected position of the shoreline in 5 years and highlighting areas where it encroached on the 230-foot critical buffer. The newly computed erosion rate (the linear regression of the cumulative set of shoreline positions) was used to project the shoreline position 5 years into the future and in 10-year intervals from 2030 to 2060. By computing the predicted position in this way, bias toward under-predicting or over-predicting erosion based on the current position is avoided, and all historic positions in the database are incorporated.

To provide an estimate of the range of potential shoreline positions, the concept of prediction interval was used to determine the uncertainty surrounding the expected shoreline positions for the 2030, 2040, 2050, and 2060 predictions. A prediction interval is an estimate of a range in which future observations will fall, with a certain probability, given what has already been observed. The landward-most shoreline position in the 95% confidence interval range is considered a proxy for the potential "high-erosion" shoreline position, while the seaward-most position provides an estimate of the "low-erosion" case. This band of expected positions was compared with the 230-foot critical buffer to assess the potential future vulnerability of NC 12.

Storm Events

The USACE Field Research Facility (FRF), located in Duck, NC (approximately 35 miles north of the study area) maintains a publicly available database of storm events. The FRF storm criterion is defined as a maximum wave height of greater than 2 m (6.6 ft) for a sustained duration greater than 8 hours. (Note: The wave height measured at the FRF, Hmo, is an energy-based statistic equal to four times the standard deviation of the sea surface elevations.) Storm events for 2019 were extracted from this database. In addition, the peak water level during each storm and the maximum difference between the NOAA predicted and observed water levels during the storm were compiled for the water level gage at the FRF.

Recently the data from the Traveler Information Management System for Dare County were made available to the CMP researchers. These data were also compiled to provide information on storm-related closures of NC 12 during 2019.

NCDOT Maintenance

Information on the road maintenance conducted within the study area was provided by NCDOT, including location, type of maintenance, and cost.

Barrier Island Breaches

Hurricane Irene impacted the study area on August 27, 2011. High winds, waves, and elevated water levels on the sound side combined to cause substantial changes to the morphology of the area. In two locations, the barrier island was breached: just south of the freshwater ponds and at the north end of the community of Rodanthe. These breaches are referred to as the Pea Island Breach and the Rodanthe Breach, respectively. The Rodanthe Breach closed shortly after Hurricane Irene in 2011; however, that area was also breached during Hurricane Sandy in 2012 as described in the 2012 report. The Pea Island Breach had essentially closed by May 2013, nonetheless, later orthophotos have revealed occasional flooding at the area. The evolution of these regions were again monitored in 2019.

3. RESULTS

Distance from Ocean to Estuarine Shoreline

Table 4 shows the location of the transects where the distance from the ocean to estuarine shoreline was 1000 ft or less in at least one photography set in 2019. Overall, the locations where island widths are less than 1000 ft correspond to areas that have been identified in previous reports.

Transects 238 to 246 are located just south of the Canal Zone hot spot, adjacent to an interior channel north of the freshwater ponds which has a direct outlet to the sound. As noted in previous reports, this area can fluctuate in width but remains near the 1000 ft that is considered to be increasingly vulnerable to soundside storm surge.

Transects 408 to 426 are located at an area south of the Pea Island Breach that has remained narrow throughout the monitoring period.

Transects 535 to 576 are located just north of Rodanthe in a location that is persistently narrow, and where a beach nourishment project was completed from late July to early September 2014 (the project overview is provided in the 2014 report). The beach nourishment project increased island widths in the area temporarily, but most have returned to pre-project conditions and are less than 1000 ft wide. This area will be bypassed by the Rodanthe Bridge, currently under construction.

To illustrate the conditions of the full study area shoreline at the conclusion of the 2019 study year, the island width as of December 15, 2019 is shown in Figure 5. This figure illustrates the distance from the ocean to estuarine shoreline at each individual transect for this date; transects with island widths less than 1000 ft are highlighted in red. Figure 6 through Figure 11 present the locations of the island width transects on the aerial photography.

Table 4. Transects with distance from ocean to estuarine shoreline less than 1000 ft at least once in 2019. Distances less than 1000 ft are highlighted in gray.

Transect	Location	9-Feb-18	18-Apr-18	11-Jul-18	17-Aug-18	7-Nov-18	18-Dec-18
238	Between Old Coast Guard Station and Freshwater Ponds	1027	1029	1066	1013	**994**	**930**
239		1023	1032	1066	1001	1013	**950**
243		1015	1040	1048	**999**	1002	**972**
244		**982**	**997**	1016	**984**	**997**	**935**
245		**959**	**975**	1010	**975**	**987**	**917**
246		**939**	**959**	**985**	**944**	**967**	**897**
408	Between Refuge Parking Lots	**732**	**762**	**787**	**735**	**737**	**693**
409		**691**	**726**	**751**	**705**	**696**	**644**
410		**649**	**683**	**710**	**668**	**655**	**588**
411		**721**	**779**	**787**	**751**	**748**	**654**
412		**729**	**746**	**767**	**720**	**724**	**626**
413		**663**	**687**	**714**	**663**	**656**	**598**
414		**653**	**683**	**705**	**666**	**649**	**618**
415		**819**	**855**	**869**	**818**	**817**	**810**
416		**934**	**963**	**984**	**942**	**935**	**926**
421		1018	1029	1057	1017	**999**	**964**
422		**933**	**943**	**969**	**925**	**938**	**875**
423		**951**	**959**	1002	**943**	**956**	**894**
424		1022	1046	1082	1028	1032	**963**
426		1072	1076	1116	1057	1045	**996**
535	Southern PINWR/ Rodanthe S-Curves	**966**	**952**	**992**	**960**	**955**	**934**
537		**869**	**886**	**900**	**875**	**860**	**841**
540		**684**	**669**	**696**	**687**	**665**	**646**
541		**960**	**935**	**959**	**967**	**954**	**938**
542		**918**	**862**	**900**	**905**	**900**	**884**
543		**652**	**612**	**626**	**636**	**627**	**621**
544		1071	**963**	**992**	**976**	**959**	**959**
546		**691**	**653**	**720**	**670**	**649**	**643**
547		1042	1009	1059	1017	**992**	**987**
548		**775**	**777**	**798**	**781**	**747**	**731**
549		**889**	**915**	**920**	**895**	**896**	**862**
575		**838**	**826**	**858**	**837**	**828**	**831**
576		**765**	**735**	**786**	**761**	**747**	**746**

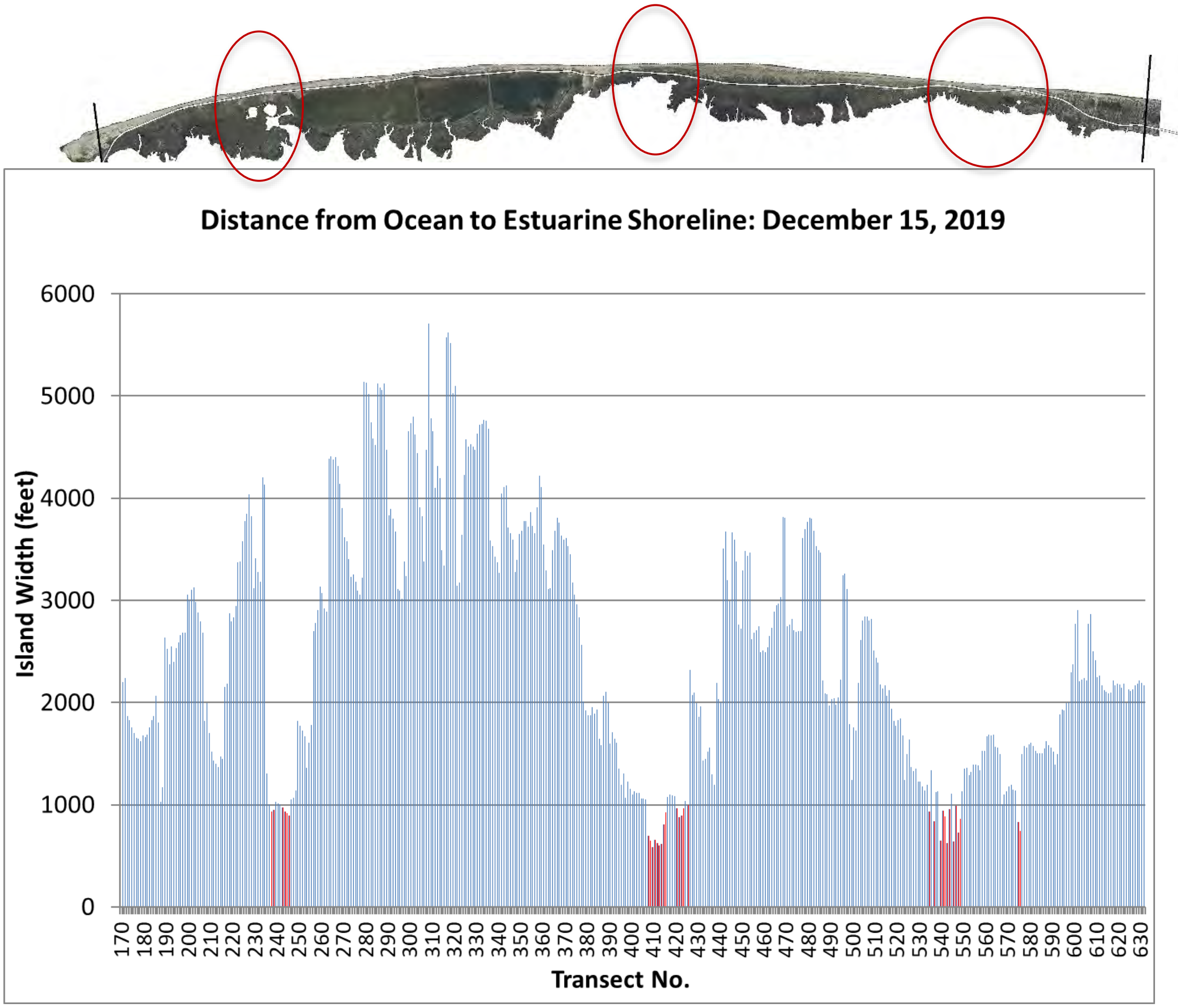

Figure 5. Summary of distance from ocean to estuarine shoreline measurements along the study area as of December 15, 2019. Red indicates distances less than 1000 ft. Transect 170 is located approximately 0.4 miles south of the tip of the terminal groin.

Figure 6

(View 1 of 6)

Pea Island - Distance from Ocean to Estuarine Shoreline

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 10, 2020

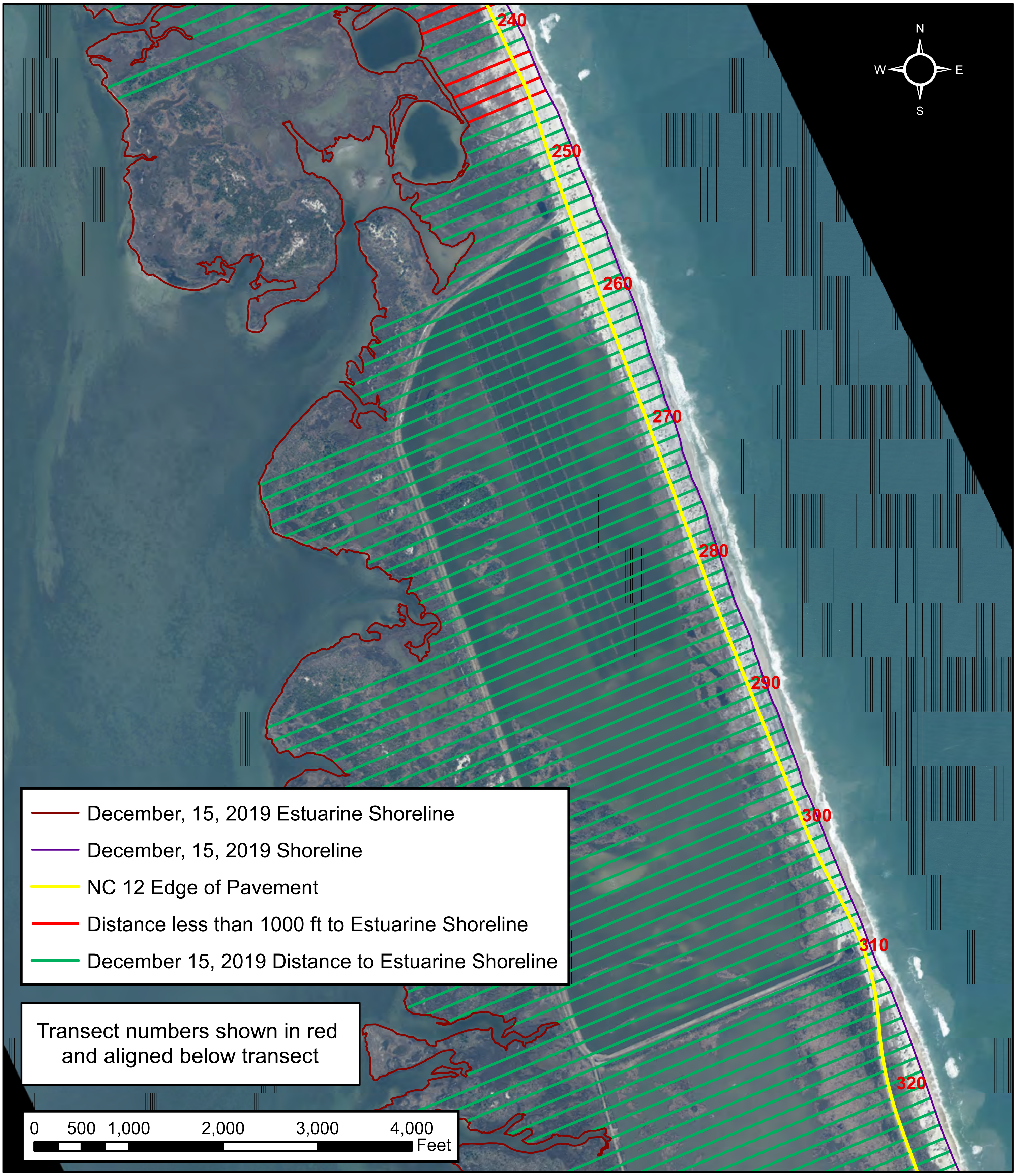

Figure 7

(View 2 of 6)

Pea Island - Distance from Ocean to Estuarine Shoreline

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 10, 2020

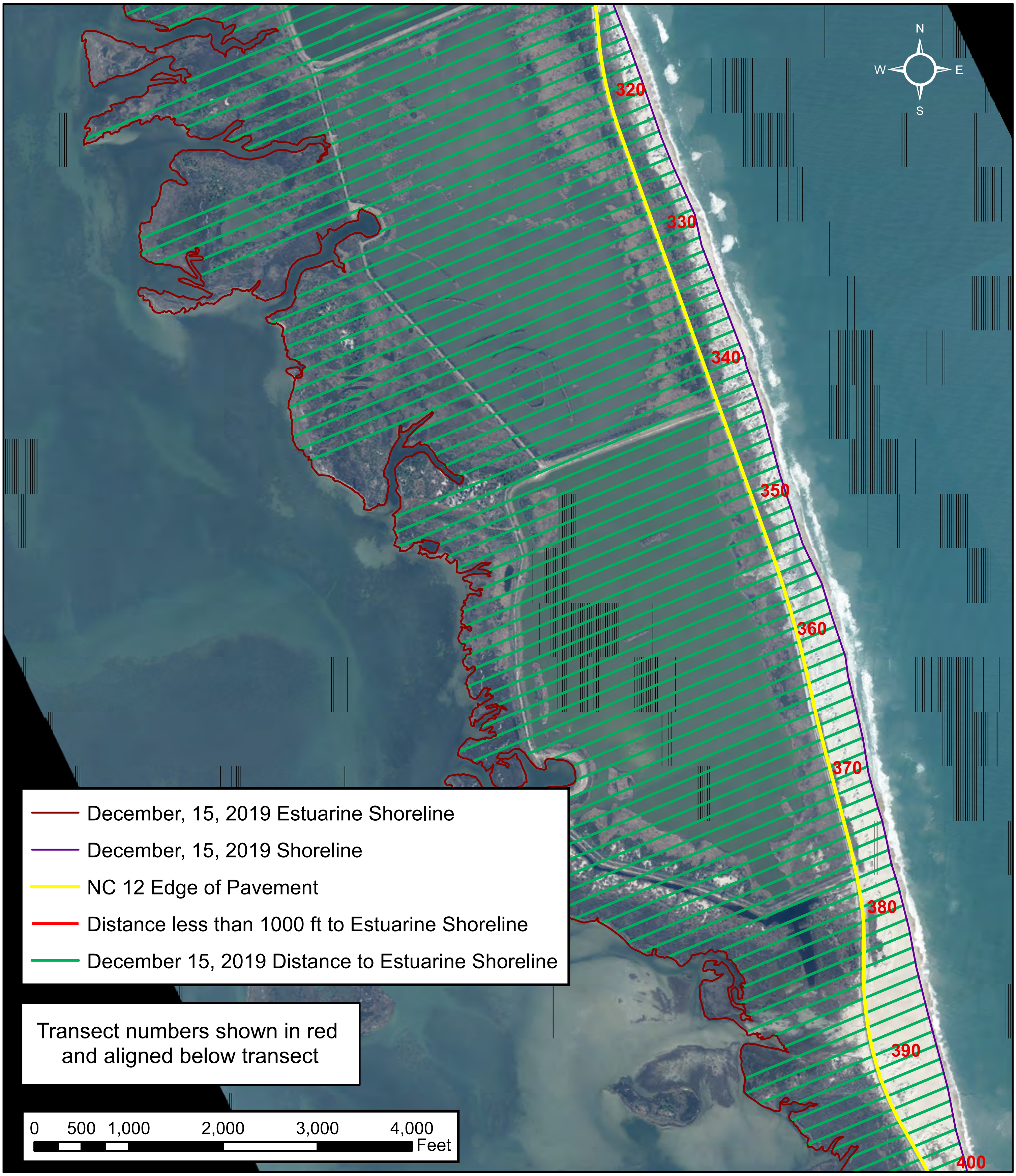

Figure 8

(View 3 of 6)

Pea Island - Distance from Ocean to Estuarine Shoreline

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 10, 2020

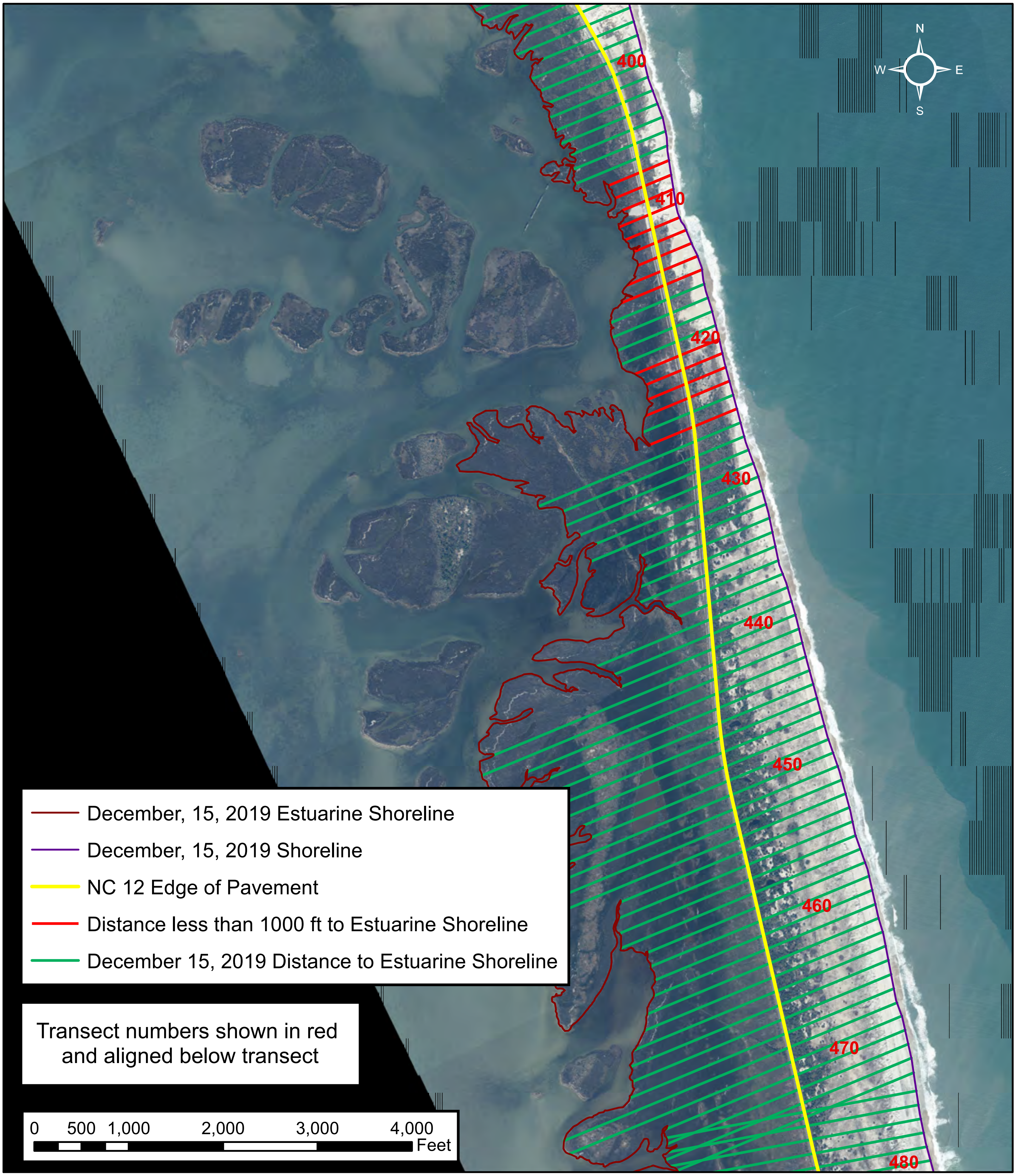

Figure 9

(View 4 of 6)

Pea Island - Distance from Ocean to Estuarine Shoreline

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 10, 2020

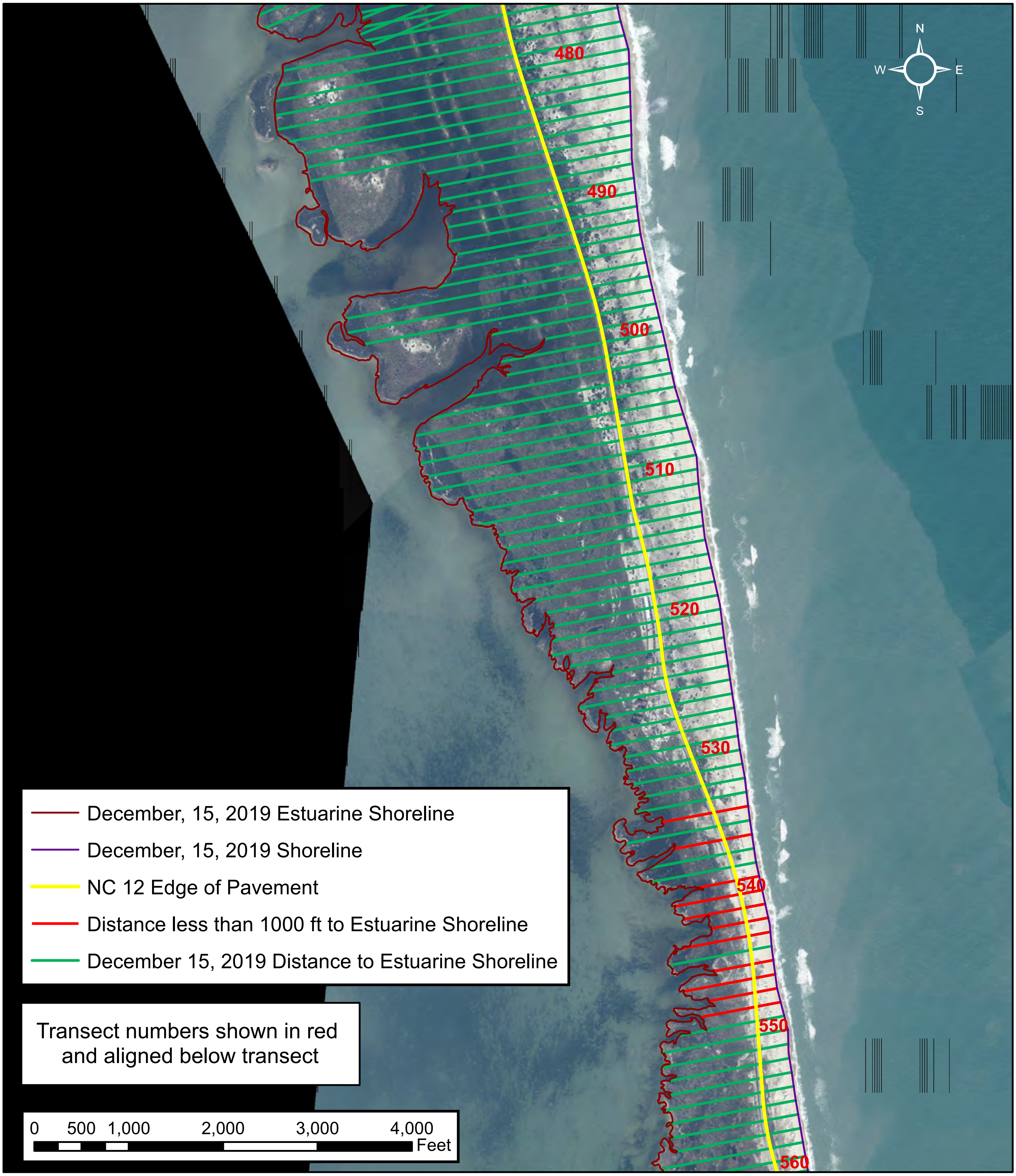

Figure 10

(View 5 of 6)

Pea Island - Distance from Ocean to Estuarine Shoreline

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 10, 2020

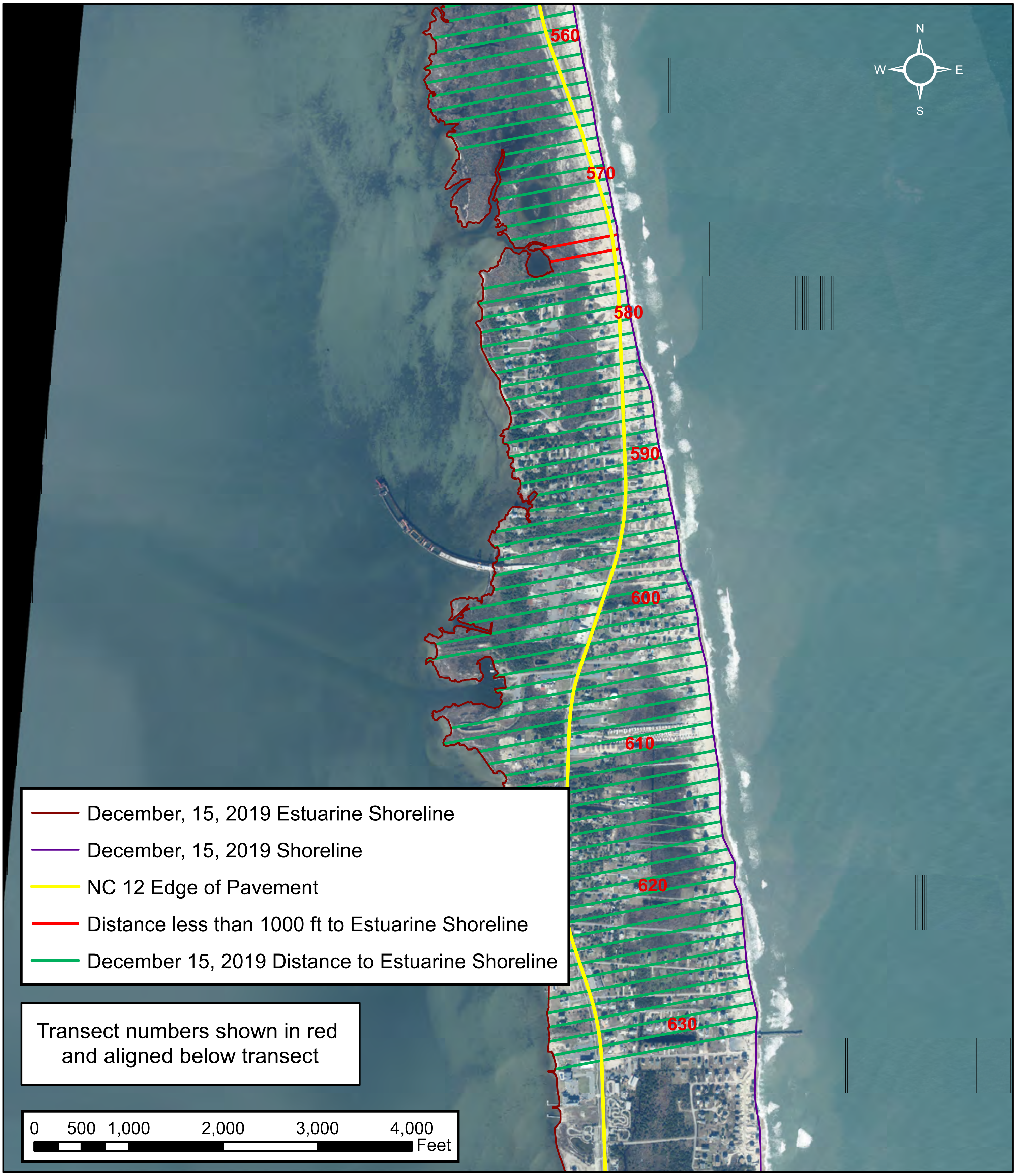

Figure 11

(View 6 of 6)

Pea Island - Distance from Ocean to Estuarine Shoreline

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 10, 2020

Island Elevation and Dune Morphology

Dune Crest/Maximum Elevation between NC 12 and Ocean Shoreline

The maximum elevation between the NC 12 EOP and the ocean shoreline was determined at each transect for the 2019 digital terrain models (February 5, April 10, August 29, and October 1, 2019); for the purpose of this analysis, the maximum elevation is identified as the dune crest. Changes in the maximum elevation from date to date are shown in this section to illustrate the variability. Negative change means the elevation of the later date was lower than that of the earlier date (decrease in maximum elevation); positive change means that the maximum elevation increased between the two dates. Figure 12 illustrates the changes from February 5 to April 10, 2019. The average change in maximum elevation over the entire study area during this time frame was approximately 1.1 ft (computed using the absolute value of the difference). The largest change was an increase of just under 8 ft at Transect 198 near mile 0.8. The largest decrease was just over 12 ft at Transect 186 near mile 0.45. The large number of changes in this time frame can be attributed to impacts of nor'easters in March and subsequent rebuilding which primarily affected the Canal Zone.

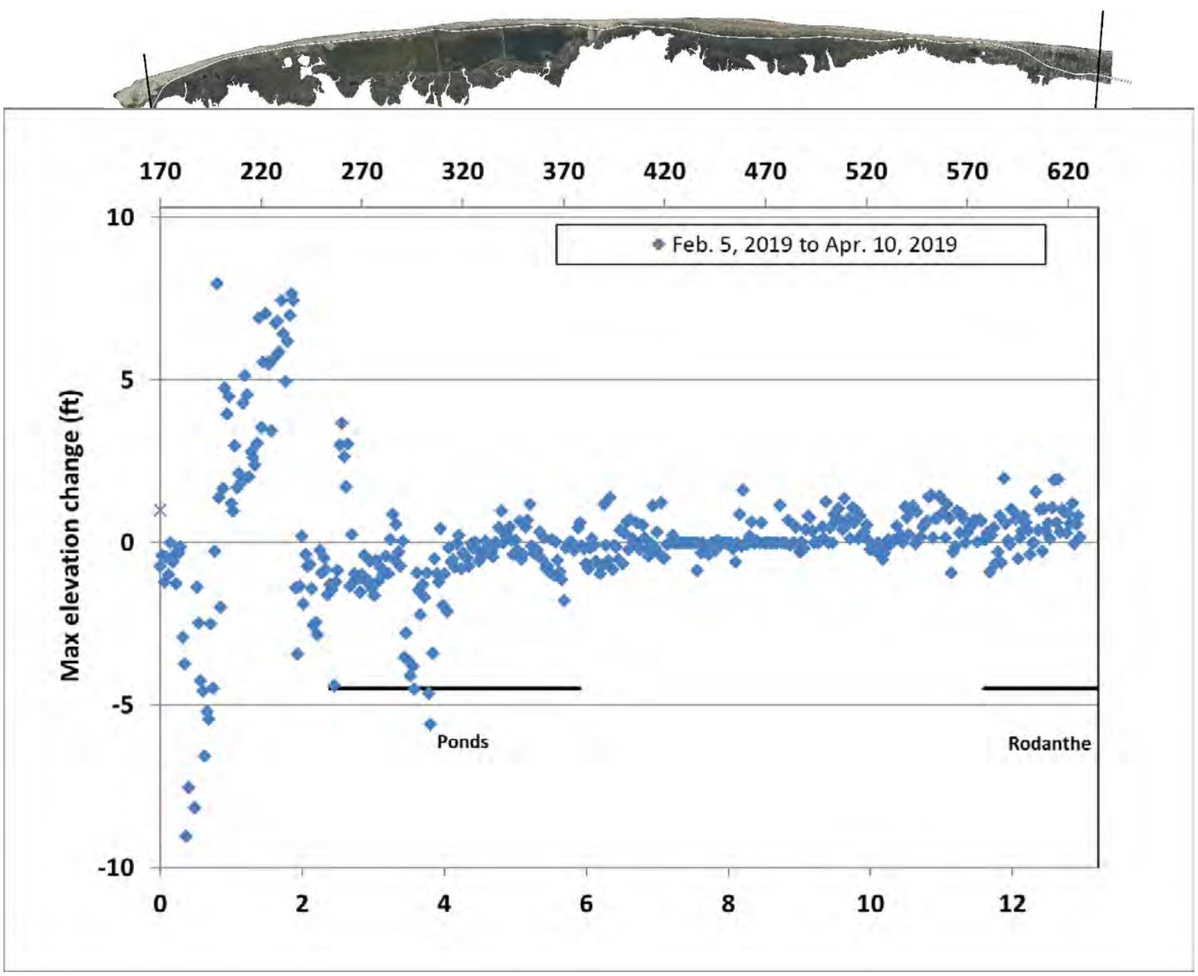

Figure 12. Maximum elevation change from February 5, 2019 to April 10, 2019 at each transect, displayed from north to south along the study area. Note that transects are spaced 150 ft apart.

Changes occurring between April 10 and August 29 are shown in Figure 13. The average change was 1.2 ft. The largest increase was approximately 1.6 ft near mile 0.26 (Transect 179), and the largest decrease just under 11 ft near mile 1.4 (Transect 220). The largest changes during this time period were decreases within the highly active Canal Zone and are attributed primarily to wind transport, because no severe storms were reported during this time period.

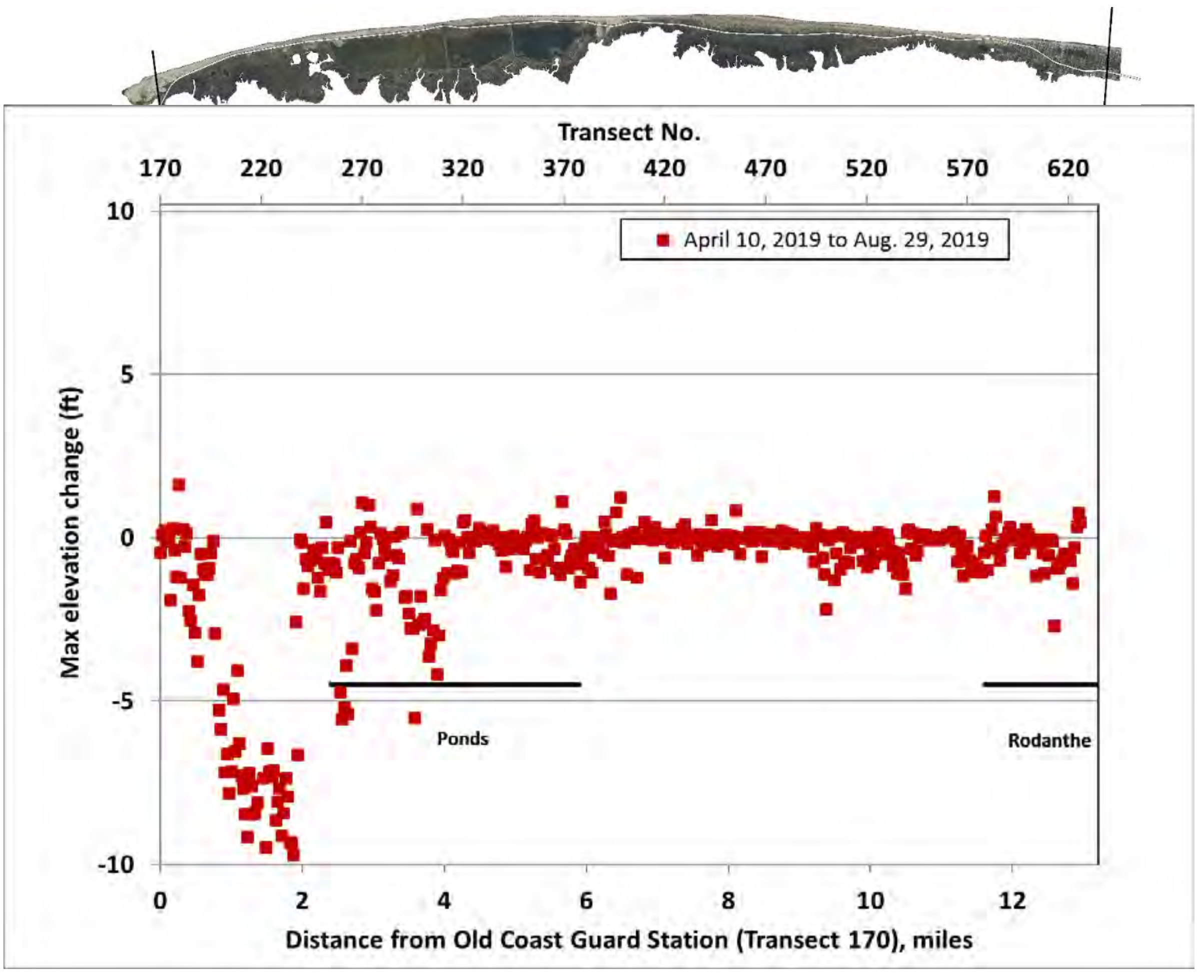

Figure 13. Maximum elevation change from April 10, 2019 to August 29, 2019 at each transect, displayed from north to south along the study area. Note that transects are spaced 150 ft apart.

Changes in maximum elevation from August 29 to October 1, 2019 are shown in Figure 14. Average change during this time period was 0.8 ft. The largest increase was 6 ft at Transect 218 (approximately mile 1.4), and the largest decrease was 6.4 ft at approximately mile 7.1 (Transect 420). The combination of wind-blown and water-borne transport and human intervention on the degraded dune field on Pea Island contributes to the high degree of variability observed over the study year, which for 2019 was primarily observed in the Canal Zone where high rates of sand transport and earth moving operations are frequent.

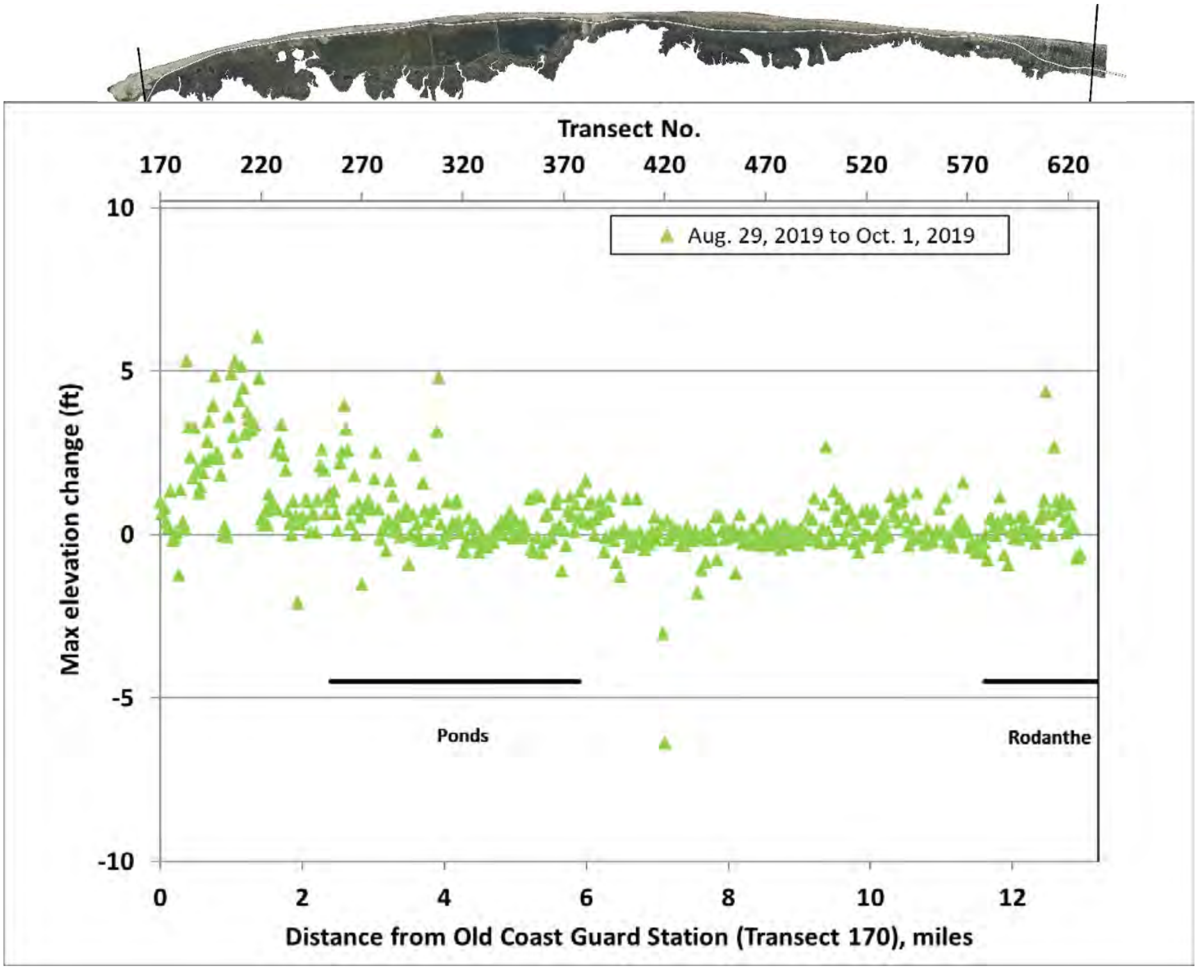

Figure 14. Maximum elevation change from August 29, 2019 to October 1, 2019at each transect, displayed from north to south along the study area. Note that transects are spaced 150 ft apart.

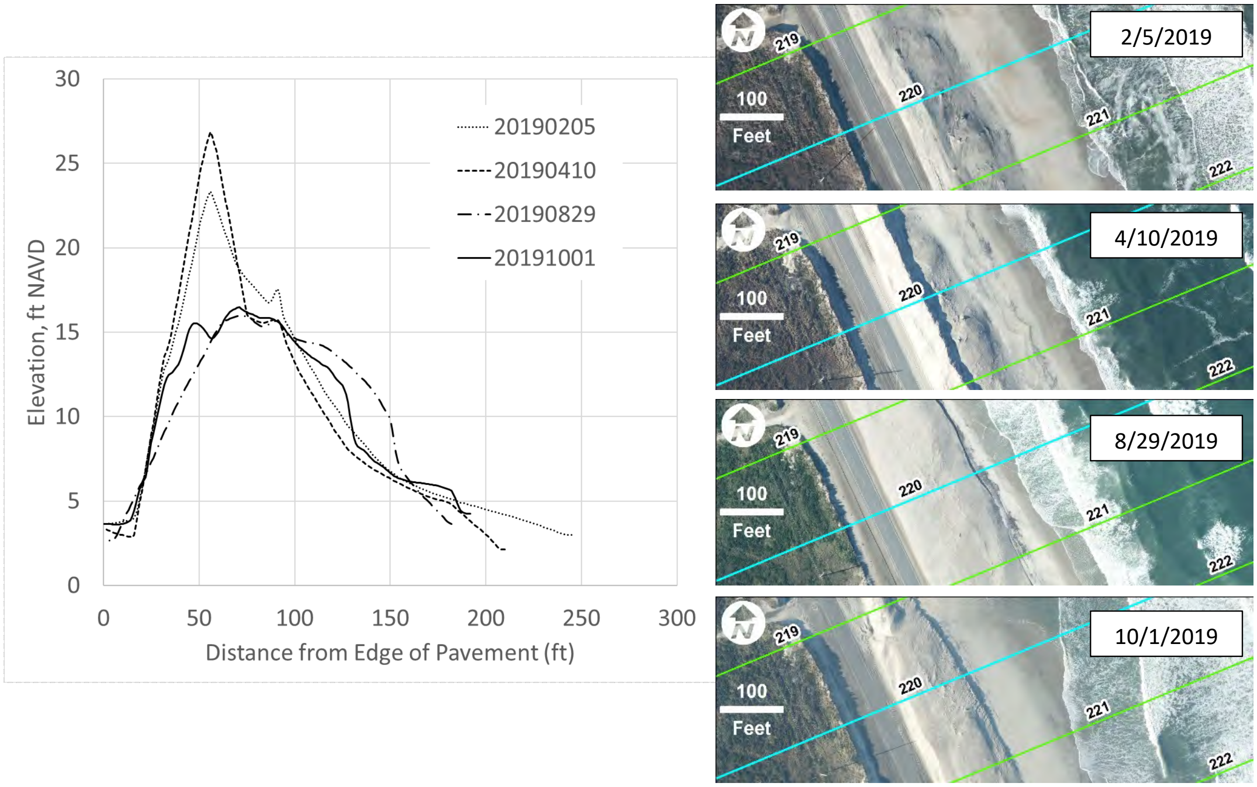

Figure 15. Left, typical Canal Zone Profile at Transect 220, where an increase was shown from February to April, due to dune rebuilding following two nor'easters in March, followed by a decrease of over 10 ft from April to August primarily due to wind effects, since no severe storms were reported during this time period. The maximum elevation increased slightly from August to October. This variability is typical of the Canal Zone, which is very active with frequent wind transport as well as wave/water impacts and frequent earth moving operations. Right panel shows aerial imagery for each of the four dates.

To assess the state of the dunes at the final topographic data collection date of the 2019 study year, the dune crest heights (or simply the maximum elevation along the profile east of the road where no distinct dune was present) along the study area as of October 1, 2019 were plotted (see Figure 16). General trends remain the same as those observed in previous reports. The lowest dunes along the study area are found in three sections: along the Canal Zone and northern side of the freshwater ponds region, adjacent to the Pea Island Breach, and at the south end of the Pea Island National Wildlife Refuge into Rodanthe.

Peak profile elevations (referenced to NAVD 88) ranged from a minimum of approximately 9.2 ft at Transect 386 adjacent to the Pea Island Breach to a maximum of 42.8 ft at Transect 482 in a wide dune field about 3 miles north of Rodanthe. As shown in Figure 16, there is a high degree of variability in the maximum elevation at each transect, due to the non-uniform degradation and buildup of the dune system. A 0.5-mile running average is also plotted to illustrate the overall alongshore trend. In the northern six miles of the study area, the average elevation of the dunes ranges from approximately 15 to 25 ft. Just south of the ponds the dunes were removed by the Pea Island Breach and are gradually recovering. From miles 7 to 10, most dunes were greater than 20 ft in elevation; moving south from this area toward Rodanthe, the dune field is substantially degraded. In many parts of this stretch a narrow artificial dune was previously constructed over sandbags; these dunes were augmented by a beach nourishment project in August-September 2014, although the area has since returned to pre-project or further eroded conditions. As described in the methodology section, the maximum elevation was compared to the elevation of the road at each transect. The trends are similar to those described in previous reports.

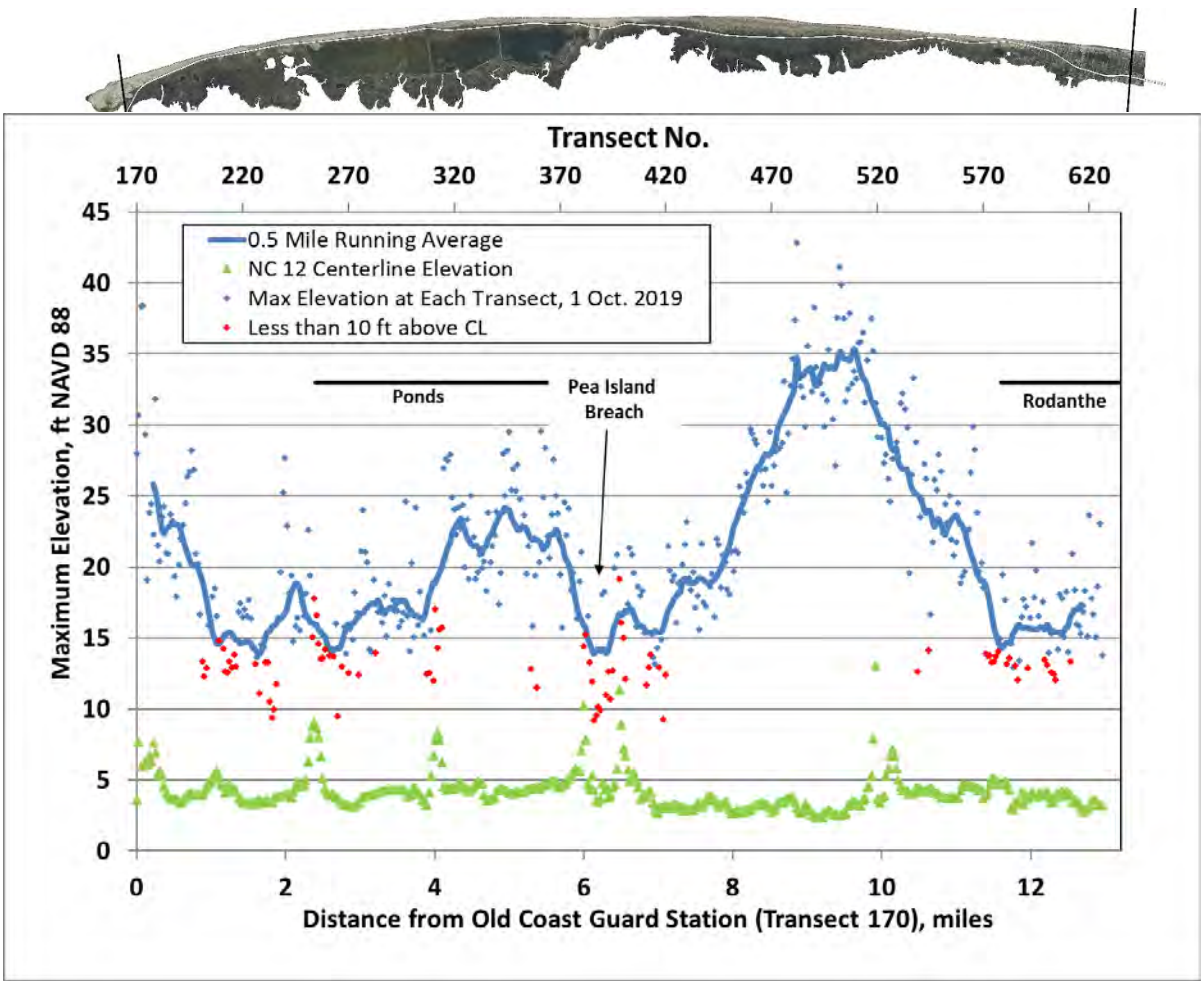

Figure 16. Maximum elevation at each transect, displayed from north to south along the study area for the October 1, 2019 topographic data set. Blue points are > 10 ft above the CL elevation, red points are <= 10 ft above the CL elevation. Note that transects are spaced 150 ft apart. To assist in visualizing the alongshore spatial variation in dune crest height, a 0.5 mile running average of the height is also shown (blue line). Elevations at the centerline of NC 12 are plotted in green for comparison.

Dune Toe Position and Elevation

Dune toe position and elevation for the October 1, 2019 topographic data were evaluated. Figure 17 shows the horizontal dune toe position relative to the NC 12 edge of pavement as well as the shoreline and maximum dune elevation position as of October 1, 2019. The position of the shoreline and maximum elevation as of November 7, 2018 are presented as well, for reference. The position of the dune toe is similar to that in 2019, as were the general patterns across the study area. Dunes along miles 1 through 4 and south of mile 11 have been reconstructed multiple times. It is noted that NCDOT is restricted in where and how high the dunes could be constructed due to the location of the current NC 12 highway easement within the PINWR. NCDOT was required to stay within its existing easement unless otherwise authorized. This is why the dunes in these areas are so close to the roadway.

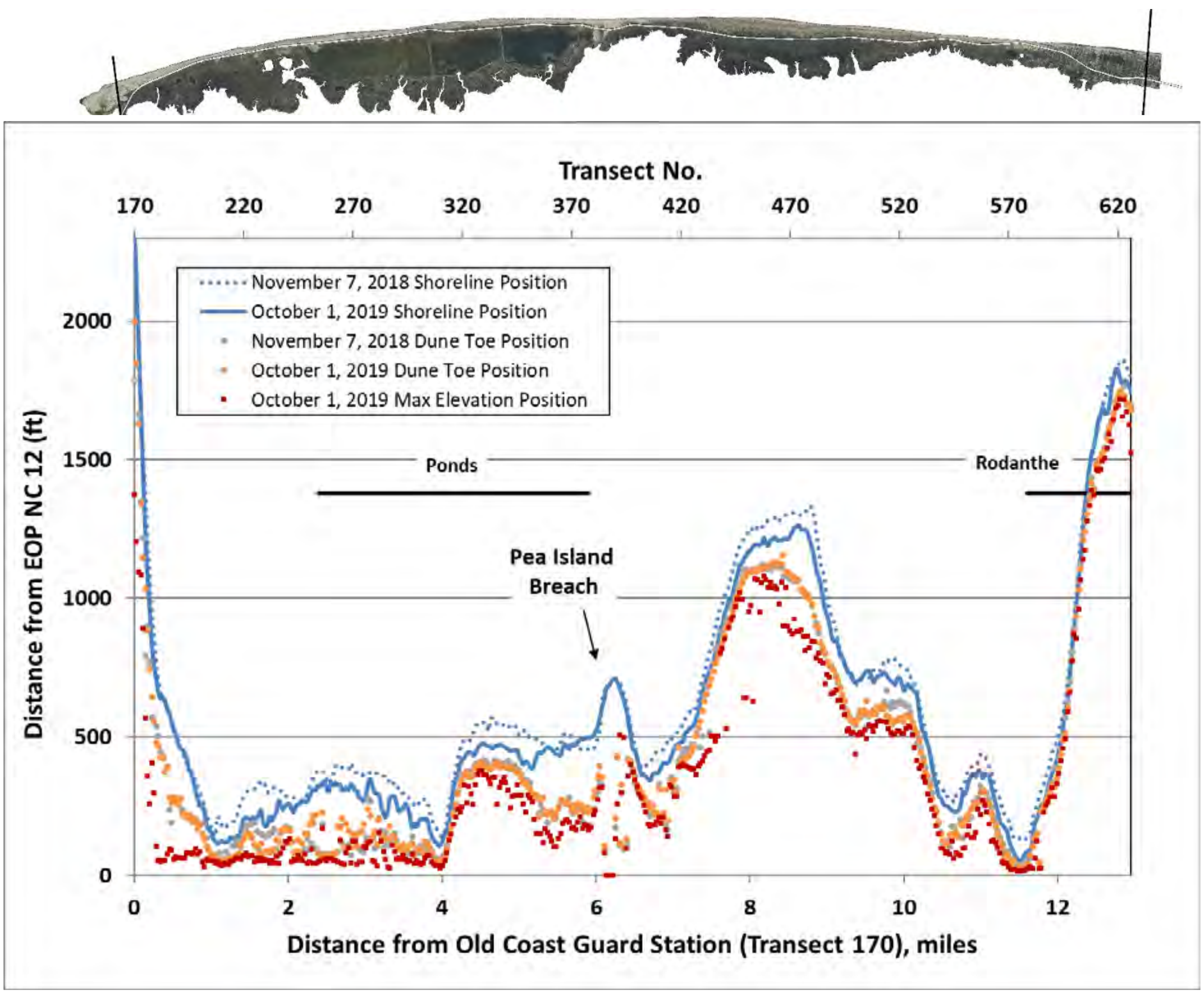

Figure 17. Dune toe, shoreline, and maximum elevation positions as of October 1, 2019, measured as distance from the NC 12 edge of pavement, compared with dune toe and shoreline positions as of November 7, 2018.

Figure 18 shows the elevation of the dune toe as of October 1, 2019, with the NC 12 centerline elevation for comparison as well as the dune toe elevation as of November 7, 2018. The average toe elevation along the study area was 9.45 ft NAVD, similar to the average elevation of 9.4 ft NAVD as of November 7, 2018.

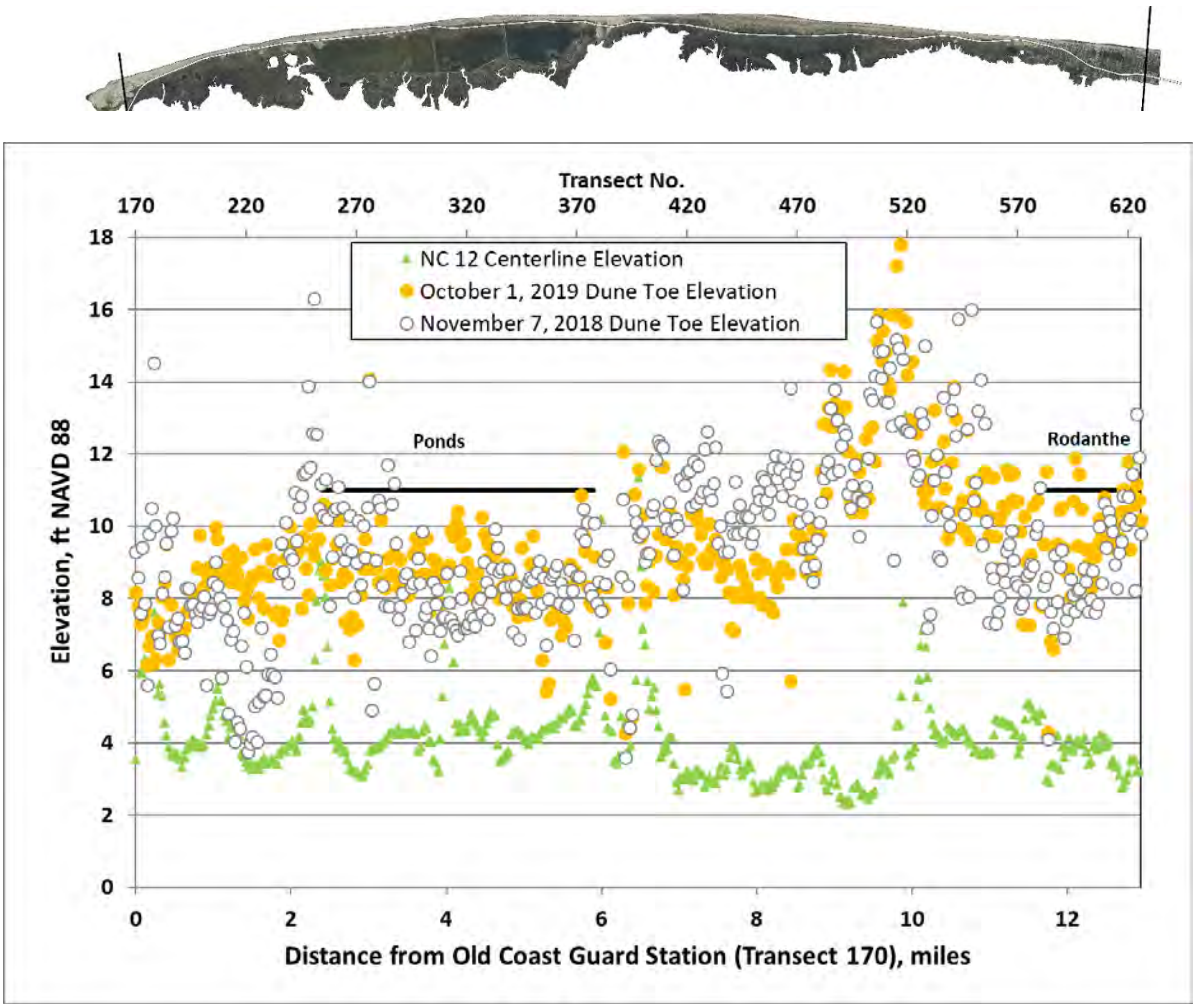

Figure 18. Dune toe elevation as of October 1, 2019, compared with elevation of the NC 12 centerline and dune toe elevations as of November 7, 2018.

Beach Width

Beach width, determined as the distance between the dune toe and ocean shoreline, as of October 1, 2019 is shown in Figure 19, with the beach width as of November 7, 2018 for comparison purposes. As discussed in the methodology section, a beach width of less than 100 ft is considered to increase vulnerability of the dune field to wave impact. In areas where dunes are already degraded, narrow beaches increase the likelihood of further dune erosion and/or overwash. Average beach width across the study area as of October 2019 was 130 ft, whereas in November 2018 the average beach width was 175 ft. The pattern of beach widths as of October 2019 was similar to that from the 2018 report, although the beach widths from November 7, 2018 are generally larger.

At this point in time, five years after placement, the beach width in the area of the Rodanthe beach nourishment project is narrower than pre-project conditions. This was expected as the project was designed to mitigate erosion for three years (see the 2014 Report for further details on the project).

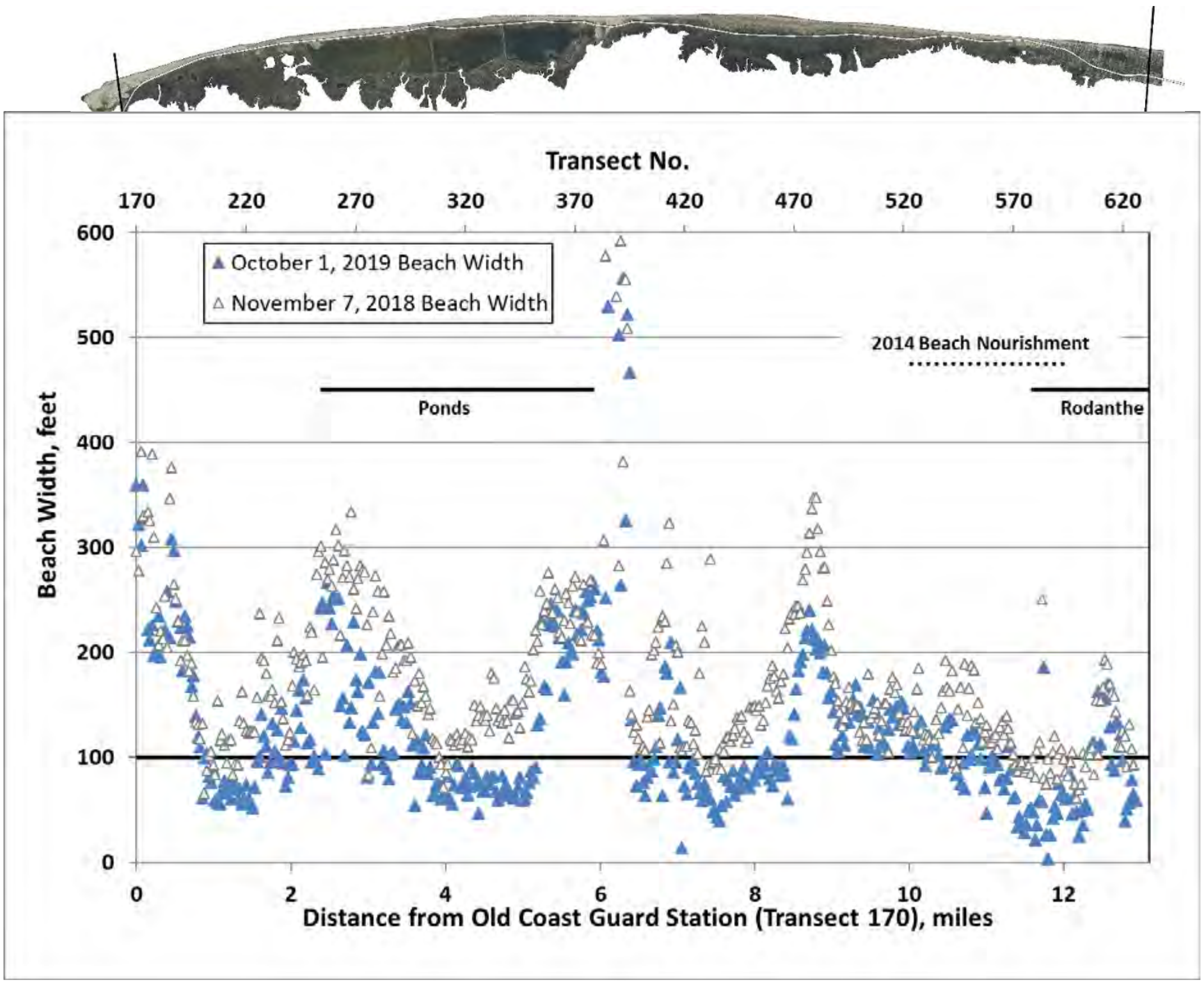

Figure 19. Beach width as of October 1, 2019 (blue), compared with beach width on November 7, 2018 (gray).

Beach Volume above MHW from EOP to Shoreline

The changes in beach volumes above MHW from November 7, 2018 to October 1, 2019 are presented in Figure 20. The volume per unit distance alongshore from the NC 12 EOP to the MHW elevation was computed at each transect. The numbers reflect both dune size and the distance from the road to the shoreline. Also included on the figure is the comparison between October 18, 2017 and November 7,

2018. When the two change rates are compared, it is noted that in several places (e.g. near Mile 6 and Mile 8) a gain from 2017 to 2018 is mirrored by a loss from 2018 to 2019. The beach volume data inherently reflect variability due to storm impacts and recovery. The beach volume change trends from 2018 to 2019 show more overall losses than the prior time period. This same trend is visible in Figure 22, which shows the cumulative change in beach volume. As detailed in Appendix B, there was a change in the edge of pavement reference line for the volume computations in 2019; some of the volume changes are attributed to this reference change. From transects 376 to 404, the EOP shifted west, causing an average increase of 3.2 cy/ft in that area, and from transects 513 to 526, the EOP shifted east, causing an average decrease of 4.6 cy/ft at those transects.

The trend for the study area overall was volume increase from November 2018 with an average loss across the study area of approximately 6 cy/ft (for reference, a dump truck can hold approximately 10 cy). This may be due to the topographic data reflecting the effects of Hurricane Dorian in September 2019.

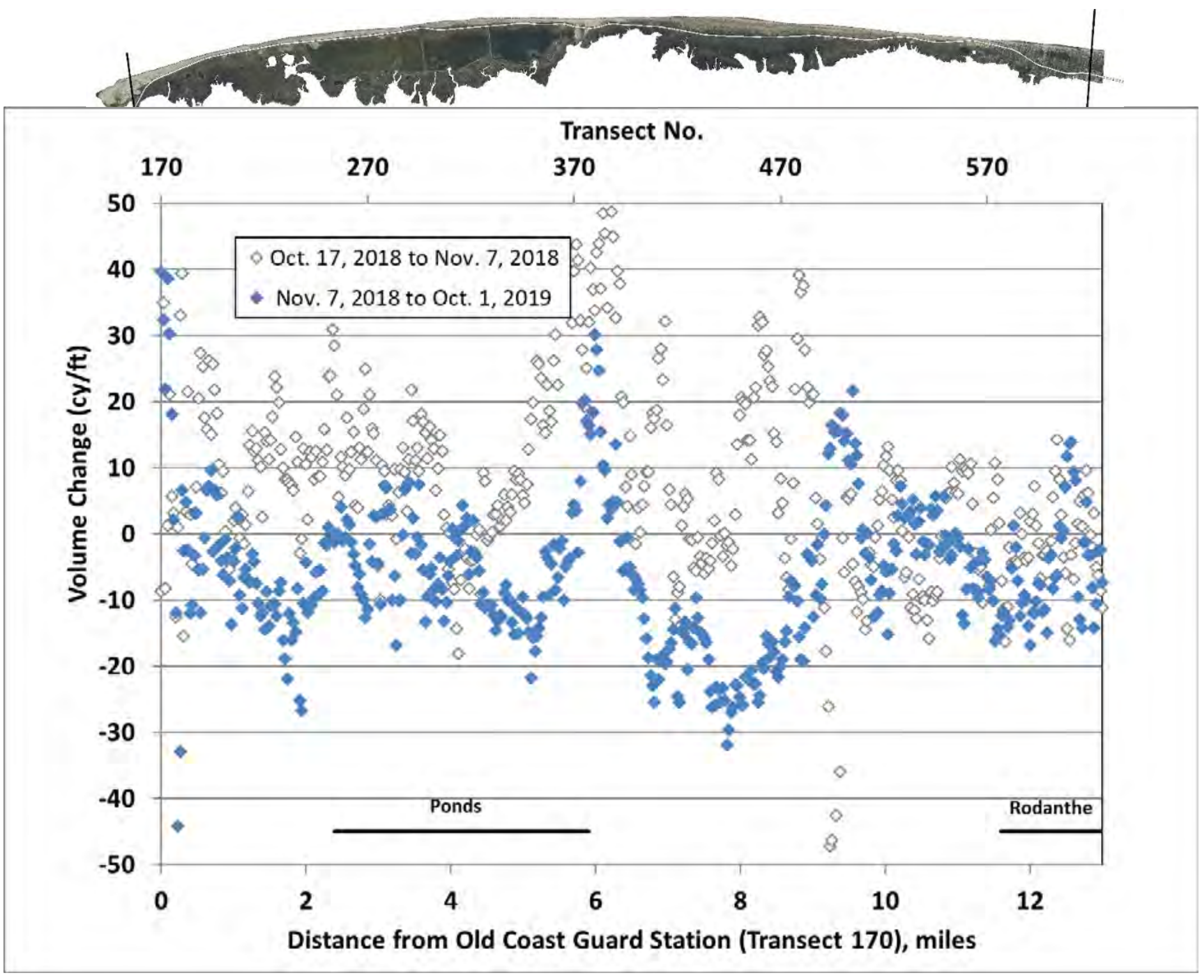

Figure 20. Changes in volume from November 2018 to October 2019, measured from the NC 12 EOP to the shoreline above the MHW elevation (displayed from north to south along the study area). Changes from October 2017 to November 2018 are also shown for reference.

The alongshore profile volumes observed in the region of the beach nourishment project (southern PINWR/ northern Rodanthe) from pre-project, post-project, at the end of 2018, and for dates during 2019 are shown in Figure 21. Volume changes between pre-project and post-project (April 2, 2014 and October 9, 2014) were on the order of 20-35 cy/ft increases in the sub-aerial volume alongshore for the main part of the project. From October 9, 2014 to February 4, 2015 there were some initial losses on the order of 10 cy/ft, after which the volumes remained relatively stable until October 2015 when volumes returned to near pre-project levels; this volume loss was thought to be due to the weather conditions immediately prior to the October 2015 data collection. By April 10, 2016, the area had recovered an average of 17 cy/ft with profile volumes similar to August 2015. From April to August 2016 average profile volume had decreased by about 8 cy/ft. In October 2016, the volumes had again decreased to values similar to those in October 2015, likely due to effects of Hurricane Matthew. By February 2017, the area had recovered an average of 9 cy/ft, and by April had accumulated another 4 cy/ft on average. The volumes in the area of the beach nourishment project remained relatively stable in 2018. As of November 2018, about 14 cy/ft on average remained in the study area as compared to the April 2014 pre-project conditions. The northern area of the nourishment remained relatively stable in 2019, with additional losses observed just north of Rodanthe near Mile 11.5-12. As of October 2019, about 8.6 cy/ft on average remained in the study area as compared to the April 2014 pre-project conditions.

To compare volumetric conditions across the entire study area since the inception of the coastal monitoring program, a comparison of total sub-aerial volume change between the edge of pavement and the shoreline is shown in Figure 22. Dates of sand placement (2013 dredge material disposal near Oregon Inlet and the 2014 beach nourishment project) and significant storms are also indicated. The total volume was calculated by multiplying each of the profile volumes by 150 ft (the distance between the profiles) and summing the total across transects 170 to 626. Significant events affecting the volumes are highlighted by vertical red lines (Hurricane Irene, Hurricane Sandy, the October 2015 "Joaquin-easter" event, Hurricane Matthew in October 2016, Hurricanes Jose and Maria in September 2017, Winter Storm Riley and Hurricane Florence in 2018, and Hurricane Dorian in 2019). As of October 2019 there was an estimated approximately 1.4 million cubic yards less volume between the road and the shoreline than there was under baseline conditions (January 2011). Note that the net volume change over the entire study area due to the shift in EOP was an increase of 4,195 cy.

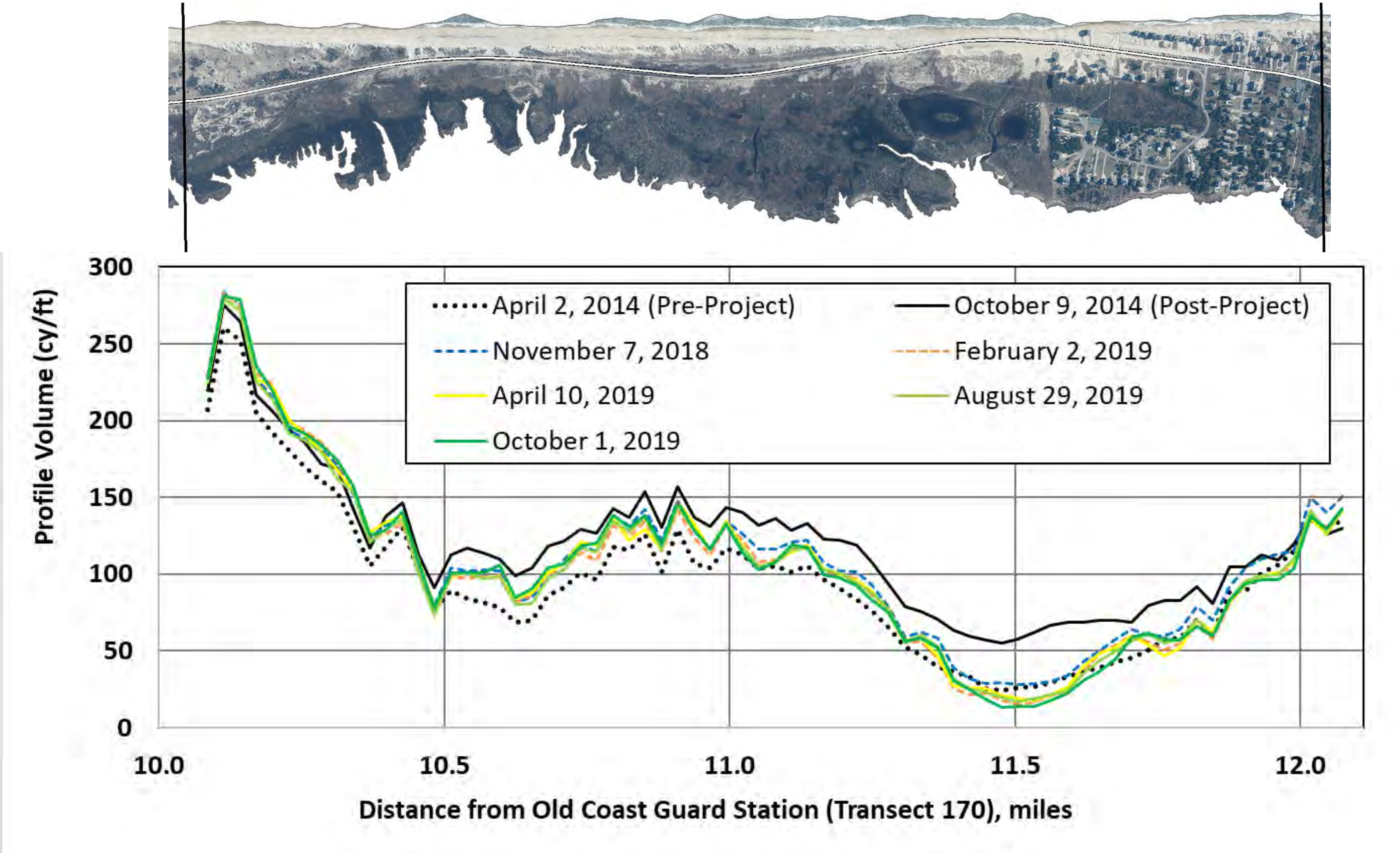

Figure 21. Profile volume from edge of pavement to shoreline, above the MHW elevation, by transect in region of the beach nourishment project.

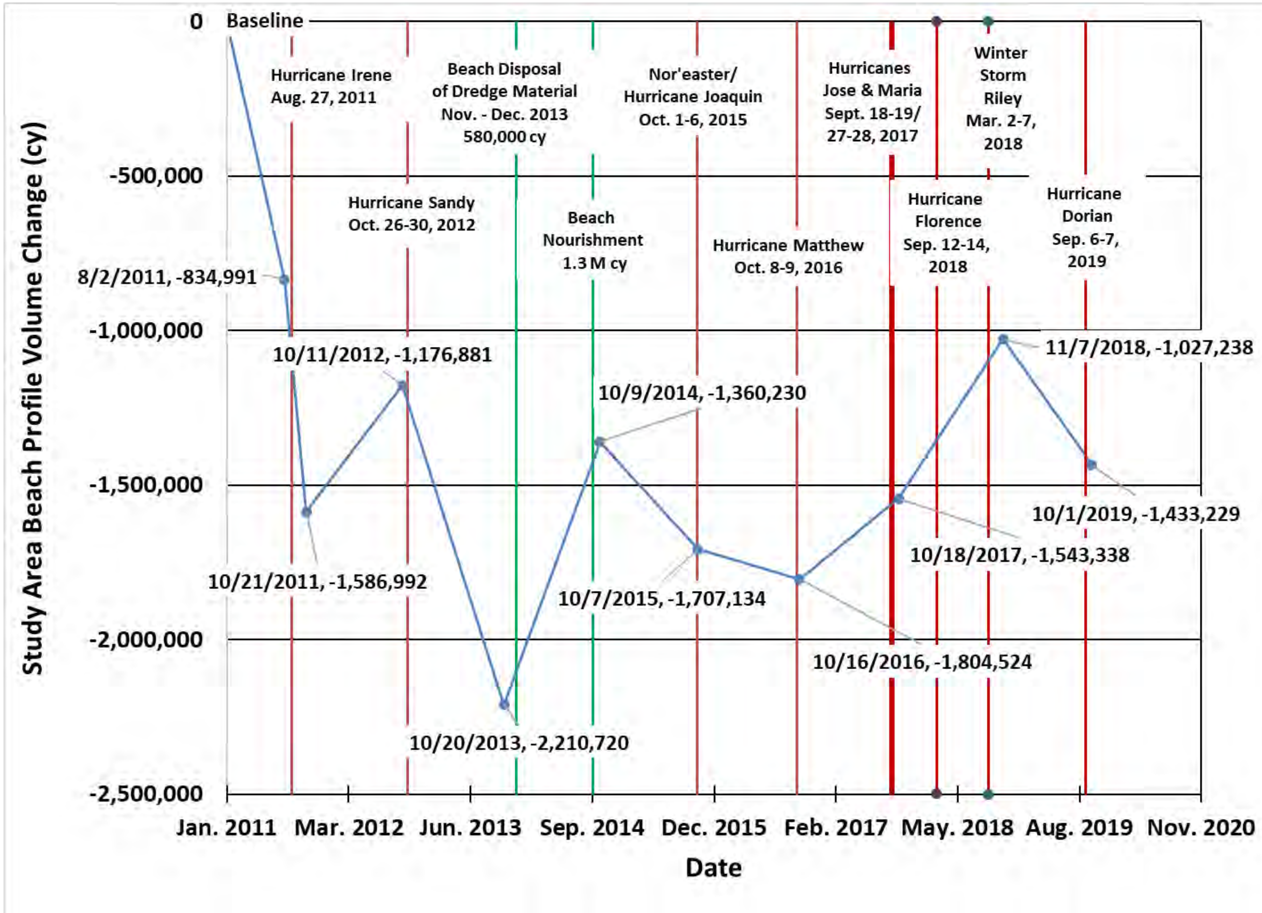

Figure 22. Total beach volume change (EOP to shoreline) across the study area, with respect to baseline conditions.

To assess conditions as of the last available topographic data of 2019, the computed volumes for October 1, 2019 are presented in Figure 23 with the running average of dune height included for comparison. The minimum measured value was approximately 13 cy/ft at Transect 574 at mile 11.5 north of Rodanthe. The average volume from the edge of pavement to the shoreline in October 2019 was approximately 165 cy/ft (in 2018 it was 171 cy/ft). Low values along the Canal Zone and freshwater ponds sections reflect the smaller dunes as well as the proximity of the road to the shoreline. From miles 7 to 10 the larger volumes correspond with higher dunes and the position of NC 12, which is set back further from the shoreline. In general, the spatial variation in profile volumes are similar to those observed in previous reports.

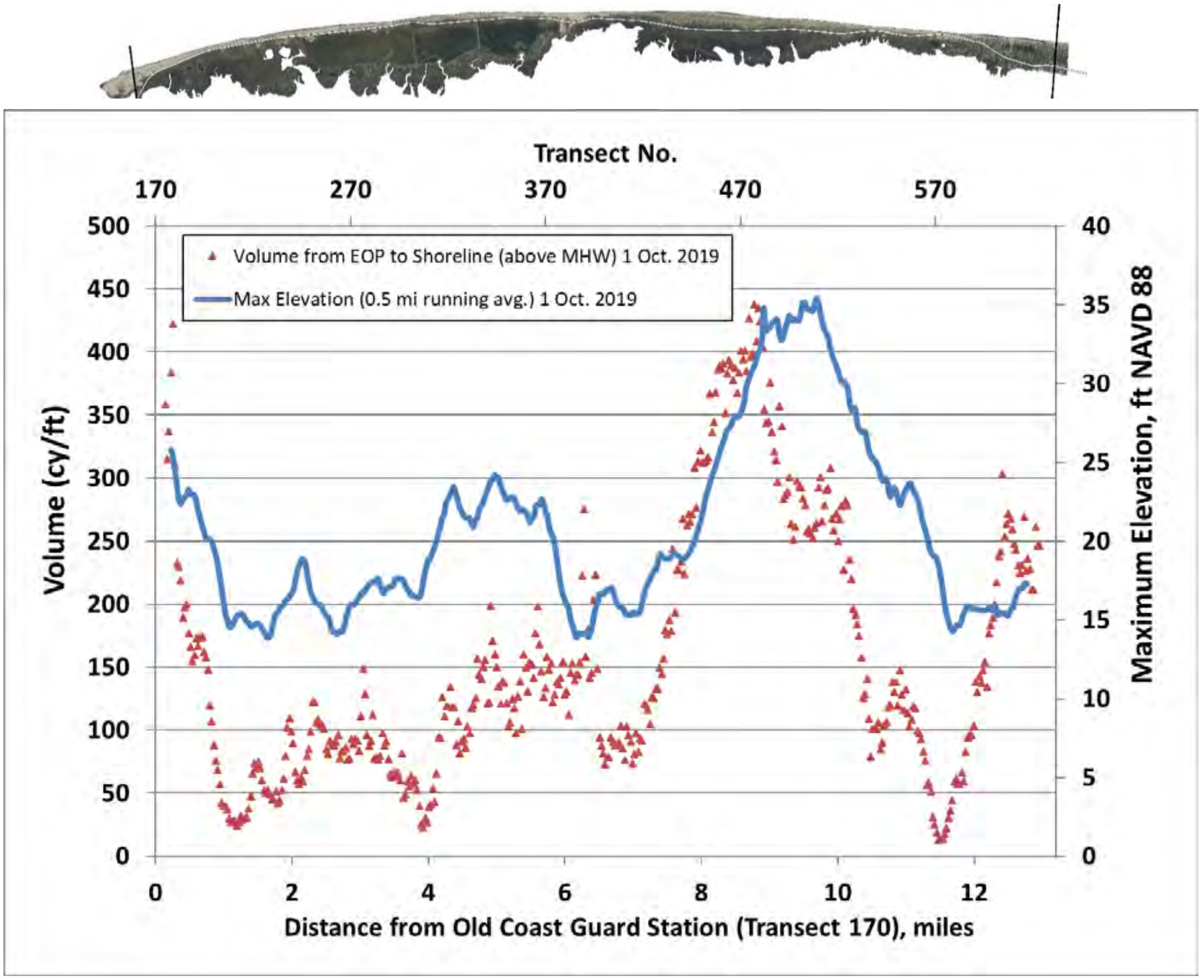

Figure 23. Computed volume as of October 1, 2019, from the NC 12 edge of pavement (EOP) to the shoreline above the MHW elevation displayed from north to south along the study area. The volume follows a trend similar to the running average of the maximum dune crest height, also shown.

Land Cover/Habitat Mapping

Results of the land cover/habitat mapping efforts are presented in this section. Table 5 and Figure 24 show the total areas in acres each year from 2012 to 2019. Overall, marsh is the dominant habitat in PINWR, followed by managed wetlands, shrub, bare sand dune and beach. The variation of total area is, for the most part, a consequence of variation in ocean shoreline positions. Figure 25 shows the mapping for 2018 and 2019.

Table 5. Area (acres) for each habitat class from 2012 to 2019.

Class	2012	2013	2014	2015	2016	2017	2018	2019
Bare Sand	154.45	211.82	175.85	181.25	129.87	108.18	140.17	106.49
Estuarine Pond	65.29	70.02	61.73	82.95	77.44	67.77	77.54	81.77
Salt Flat	168.72	232.80	177.13	163.11	169.72	216.41	140.41	91.45
Shrub	533.98	361.57	403.95	388.09	579.14	620.84	403.76	308.19
Marsh	1932.24	2142.99	2123.44	2173.46	1992.38	1979.52	2162.93	2300.13
Vegetated Dune	167.43	103.96	141.16	121.25	129.86	136.16	122.29	158.16
Bare Sand Dune	282.83	316.74	275.31	309.09	286.65	280.58	275.84	243.67
Infrastructure	42.99	42.81	42.82	51.36	49.96	56.27	46.81	51.35
Maritime Brush	139.55	97.07	116.71	123.90	129.41	126.95	102.44	122.49
Managed Wetland	792.18	784.64	783.51	781.28	779.66	778.91	781.52	781.23
Beach	266.68	285.02	240.50	280.79	267.41	292.78	286.36	249.01
Groin	4.57	4.57	4.42	4.38	4.18	4.22	4.41	4.28
Total	4550.90	4654.01	4546.51	4660.93	4595.69	4668.60	4544.50	4498.21

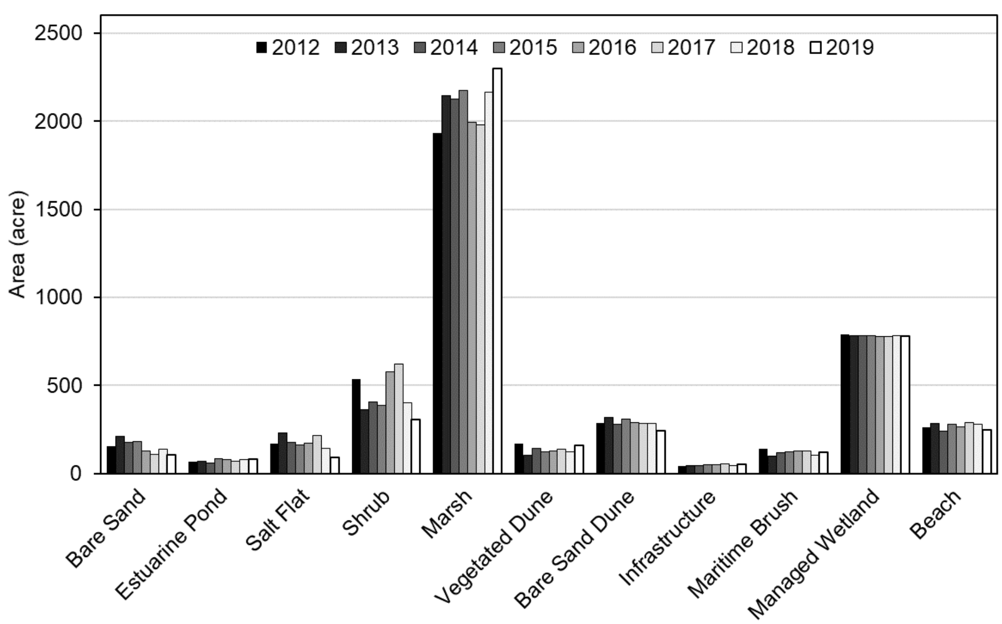

Figure 24. Area for each habitat class from 2012 until 2019

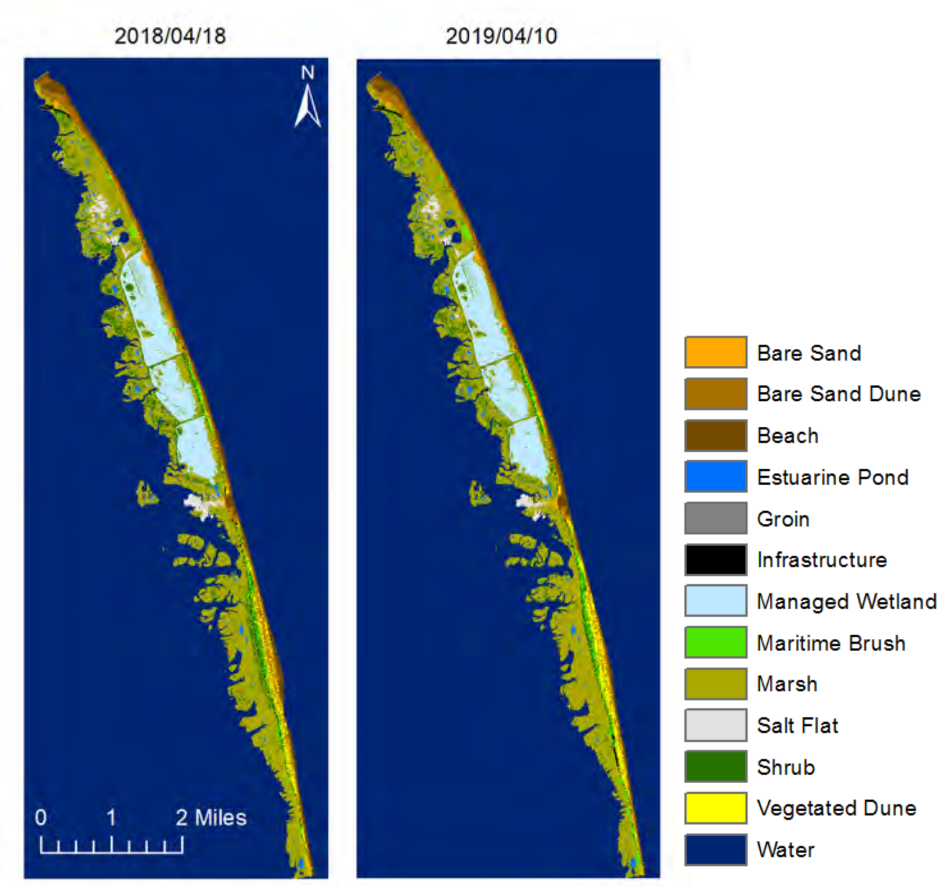

Figure 25. Habitat maps for 2018 and 2019

Evolution of habitat classes is highly variable and dependent on physical, biological, and management factors. Figure 26 shows linear trends for each habitat class. It should be noted that most habitats do not display a linear behavior, however, these trends provide a general idea of whether a given habitat class tends to increase or decrease over time. All classes with the exception of estuarine pond and infrastructure experienced significant changes between 2012 and 2013; this is a consequence of the effects of Hurricane Sandy on the island. Other abrupt changes in bare sand, salt flat, shrub, marsh, and maritime brush occurred between 2017 and 2018. The potential cause for the latter changes are three storms that impacted the Outer Banks in that period, including Hurricane Jose and Maria in mid and late September 2017 and Winter Storm Riley in March 2018, just a few weeks before the CIR image was taken. Between 2018 and 2019, an increase in marsh was observed in contracts to a decrease in shrub. This is attributed to controlled burn management activities in areas with high shrub density. The beach area also decreased significantly between 2018 and 2019.

The panel in the bottom left corner of Figure 26 shows the total area of the island computed as the sum of all classes different from water. The annual variability in this plot is caused by the variability on the ocean shoreline position, which shifts depending on short-term storm impacts (erosion) and recovery (accretion) as well as on the water level when the images were taken. The data indicates that in the past eight years the area of the island has varied between approximately 4,500 to 4,700 acres. However, such variation follows a cyclical pattern that does not confirm gain or loss of the island's horizontal area. The total horizontal area of dunes (vegetated + bare sand dune) has been decreasing over time from 450 acres to 400 acres.

The observed behavior of each habitat class from 2012 to 2019 is described below:

- Bare Sand: Overall decreasing trend, significant increase after major ocean-side storms.
- Estuarine Pond: Highly variable. The number of enclosed bodies of water and their spatial extent depends on the water levels, rainfall, and the water table when the images were taken. Linear trend indicates a slight increase over time.
- Salt Flat: Also highly variable and dependent on water levels. Linear trend indicates a slight decrease over time.
- Shrub and Marsh: These two classes display an inverse behavior and linear trends for marsh indicates slight increase, shrub stable to slight decrease.
- Dune: Bare sand dune has a decreasing trends. Vegetated dune has a stable linear trend but fluctuations are observed. As expected, both classes show a strong sensitivity to ocean-side storms.
- Groin: Changes in groin area are a result of sand deposition over the structure and varying water levels. Overall, groin area visible in the photography has remained within 4.1 and 4.6 acres.
- Infrastructure: Increase from 2012 until 2017 due to the construction of the Basnight Bridge in the north and other NC 12 improvements near Pea Island Breach. Although the linear trend indicates increase in infrastructure over time, the data point in 2018 reflects less construction areas on the island due to completion of two bridge projects. Continued work on the Rodanthe bridge has slightly increased infrastructure in 2019.
- Maritime Brush: Depicts vegetation growth in overwash fans and the landward side of the dunes. Significant decrease after ocean-side storms.
- Managed Wetlands: Slight decreasing trend. From 2012 to 2019 lost approximately 10 acres, most of that area was lost to overwash fans from Hurricane Sandy that reached the ponds.
- Beach: Highly variable and dependent on storm activity and water levels. 2019 data shows a decrease in beach area and the linear trend is relatively flat.

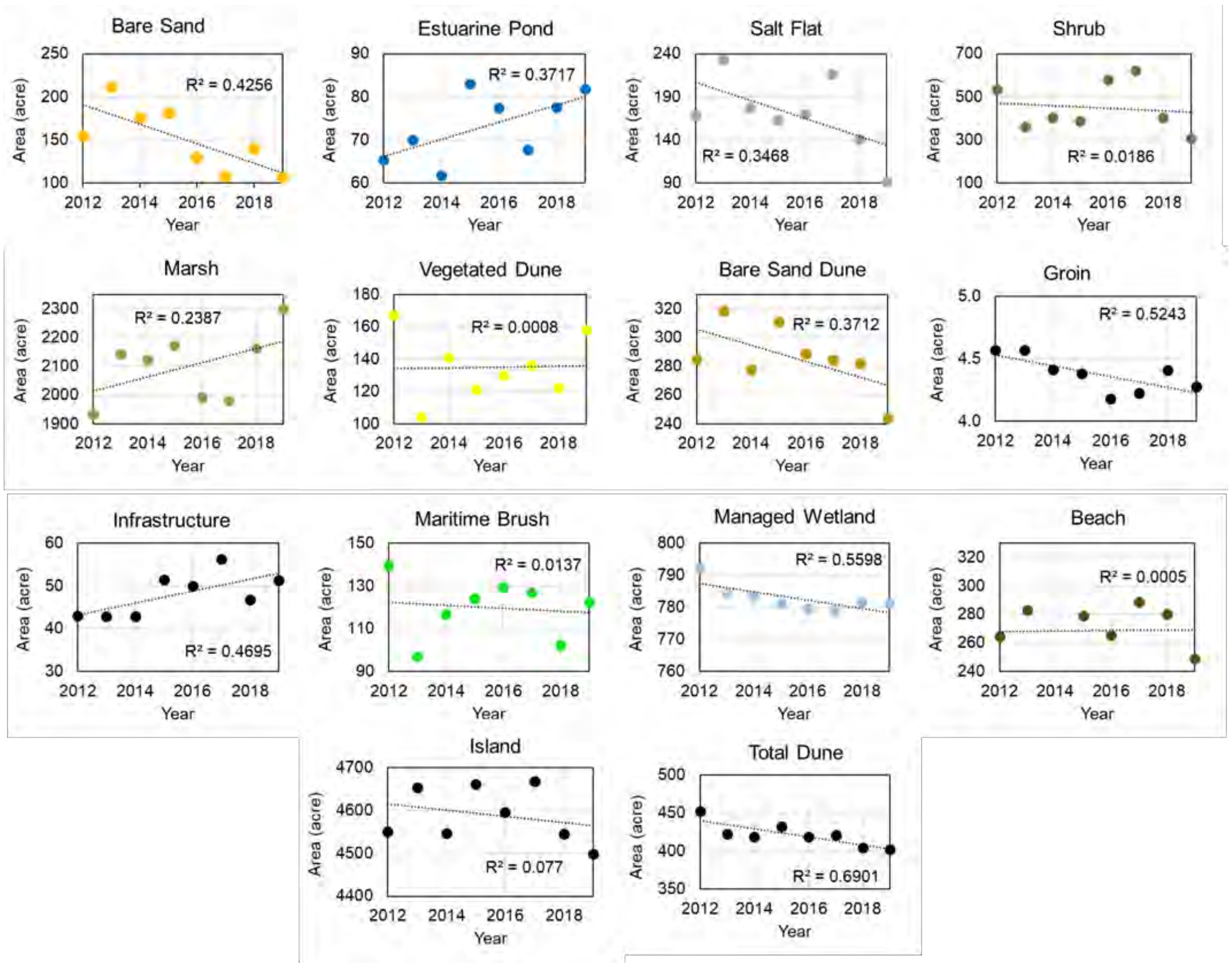

Figure 26. Linear trends for each habitat class.

A change matrix was created to identify changes from one habitat class to another from 2018 to 2019 (Figure 27). (Details of changes between prior years are found in Appendix B of the 2018 report). Green cells in the diagonal of the matrix indicates the stable areas that remained within the same habitat. Warm colors indicate different levels of change with the most significant habitat changes (> 50 acres) in red cells.

		2019												
		Bare Sand	Estuarine Pond	Salt Flat	Shrub	Marsh	Vegetated Dune	Bare Sand Dune	Water	Groin	Infrastructure	Maritime Brush	Managed Wetlands	Beach
2018	Bare Sand	85.91	0.14	0.75	0.59	26.78	0.15	2.19	0.87	0.05	1.32	21.00	0.11	0.30
	Estuarine Pond	0.11	70.94	0.63	0.01	5.28	0.00	0.00	0.32	0.00	0.00	0.06	0.00	0.19
	Salt Flat	3.44	6.45	82.34	0.03	37.38	0.00	0.00	8.47	0.00	0.00	0.01	2.28	0.00
	Shrub	0.89	0.03	0.02	225.07	159.25	5.27	0.21	0.08	0.00	0.54	12.29	0.10	0.00
	Marsh	9.02	3.89	3.13	75.28	2060.97	0.01	0.01	6.59	0.00	0.39	0.61	2.25	0.74
	Vegetated Dune	0.38	0.00	0.00	1.30	0.00	105.36	13.73	0.00	0.00	0.31	1.10	0.00	0.11
	Bare Sand Dune	1.95	0.00	0.00	0.38	0.01	46.43	212.32	0.15	0.00	0.15	0.23	0.00	20.53
	Water	0.12	0.18	2.37	0.07	4.80	0.00	0.00	27397.53	0.06	0.00	0.00	0.00	24.68
	Groin	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	4.14	0.00	0.00	0.00	0.01
	Infrastructure	1.13	0.00	0.00	0.02	0.21	0.01	0.02	0.05	0.00	45.28	0.09	0.00	0.00
	Maritime Brush	3.23	0.11	0.00	5.34	2.32	0.77	0.21	0.00	0.00	3.35	87.10	0.00	0.00
	Managed Wetlands	0.07	0.02	2.21	0.05	2.68	0.00	0.00	0.00	0.00	0.00	0.00	776.48	0.00
	Beach	0.23	0.01	0.00	0.05	0.43	0.15	14.98	61.75	0.03	0.00	0.00	0.00	202.45

No change in class	Area (Acre)	< 0.1	0.1 - 1	1 - 10	10 - 50	> 50

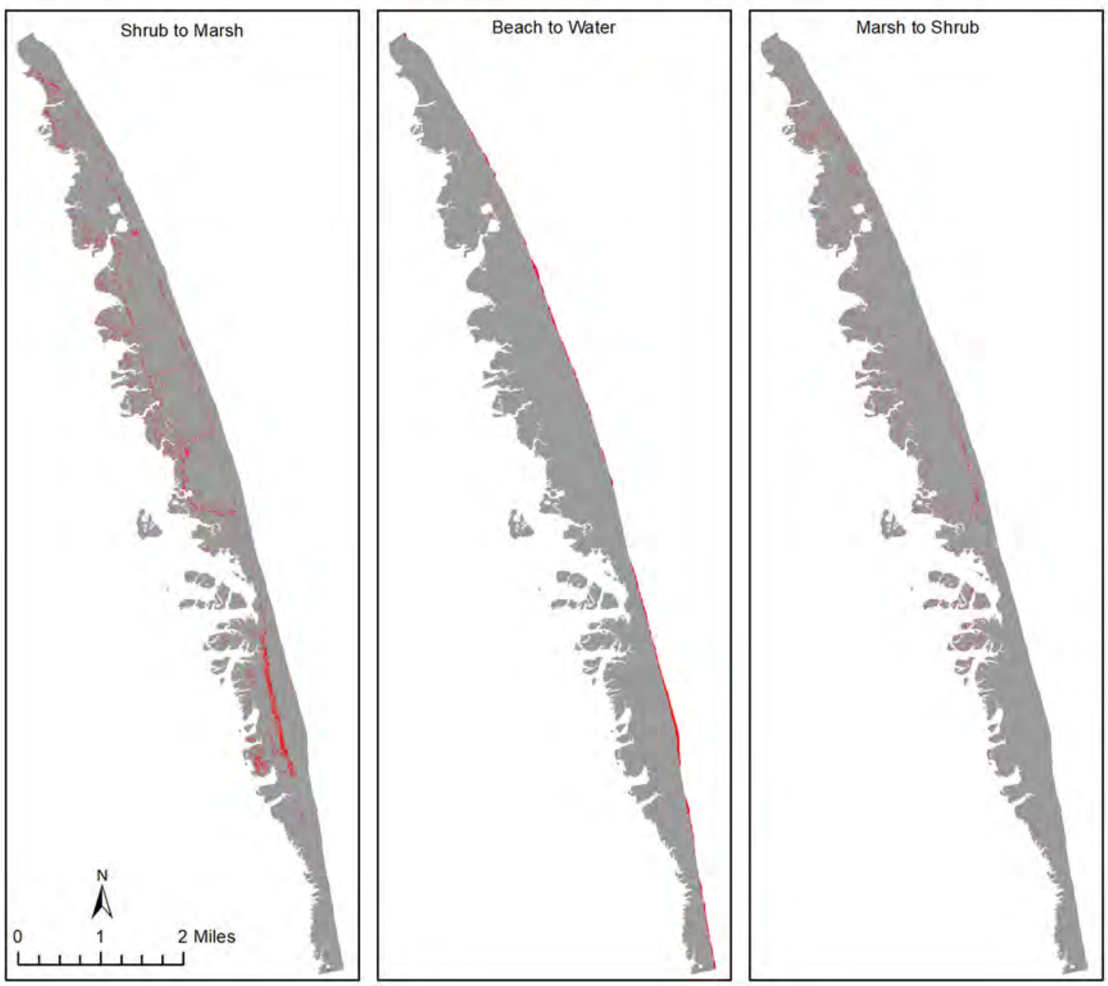

Figure 27. Habitat changes from 2018 to 2019. Top: Change matrix. Bottom: Spatial distributions of the three larger habitat changes enclosed in bold rectangles in the change matrix are shown in red.

The largest changes were from shrub to marsh and from beach to water. The shrub to marsh changes are attributed to management activities (controlled burns), and the beach to water changes are attributed to erosion along the study area shoreline as shown.

Erosion Rate Update

With the recent shoreline position data from 2019 added, the linear regression long-term shoreline change rates for the study area changed very little from the 2018 update conditions, as shown in Figure 28. Note that in this figure, "positive" shoreline change rates indicate erosion. Since the Baseline Report (conditions as of January 2011), similar rates of accretion have been present over the first mile with relatively low erosion (less than 2 ft/year) or slight accretion observed from miles 1 to 3. Over the remainder of the study area, trends have remained similar since the Baseline Report, with an average slight decrease in the rates of erosion in most areas.

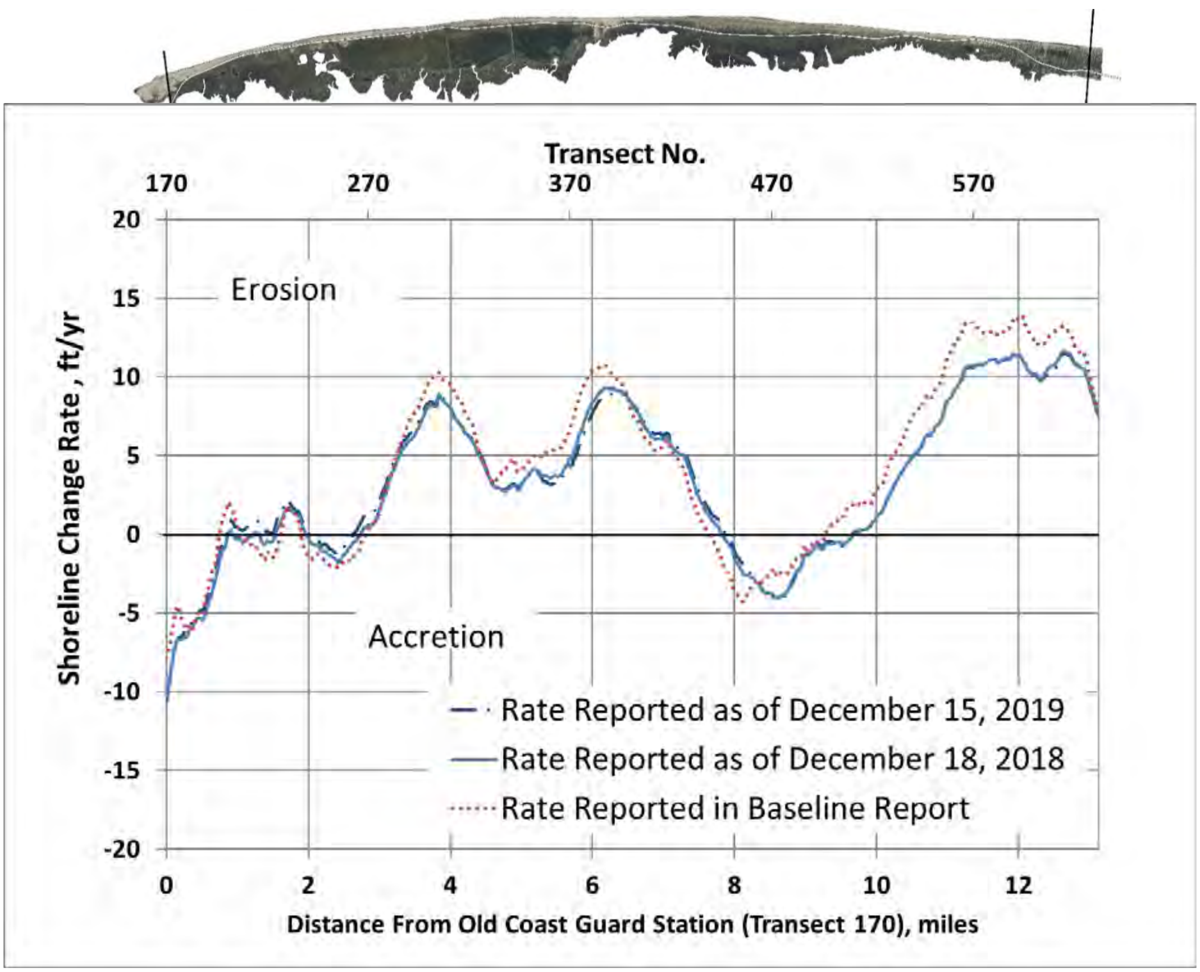

Figure 28. Updated erosion rates through December 15, 2019, compared with 2018 update conditions (as of December 18, 2018) and baseline report conditions.

Critical Buffer and Vulnerability: Present and Future

Baseline and 5-Year Vulnerability

Figure 29 to Figure 34 illustrate the location of the 230-foot buffer offset from the NC 12 edge of pavement at the conclusion of the 2019 study year (photography dated December 15, 2019). The lengths of NC 12 where the shoreline falls within this buffer or would be expected to fall within the buffer within 5 years, using the linear regression predicted average position, are highlighted on these maps. The average predicted position is used for the 5-year forecast to provide an indication of the areas most likely to be immediately impacted. It is noted that if the 5-year forecast from the present report (2023) is compared to 2020 forecast maps from early reports, vulnerable areas are substantially longer in the prior 2020 forecast maps than those shown on the current (2019) and 5-year (2024) vulnerability maps. This is due to the inclusion of the prediction interval bands (i.e., the “worst-case” high-erosion shoreline position) on the previous 2020 maps. This essentially shows the uncertainty associated with the shoreline prediction, which makes the potentially vulnerable section larger.

Areas of current and 5-year vulnerability as determined by the 230-foot buffer include a section along the Canal Zone, a section in the middle of the freshwater ponds stretch near the PINWR visitors center, a narrow region just south of the wide dune field area, and along the shoreline segment in the north part of Rodanthe. The lengths of the vulnerable sections shown on the maps are presented in Table 6.

The section termed A in Table 6 and Figure 29 was identified as vulnerable in the 2018 report, although the length of the vulnerable area has increased since that report, and two previously vulnerable sections have merged. Section B identified in Table 6 and Figure 30 are located along the section of NC 12 near the parking access at the juncture of the northernmost and middle ponds (these sections correspond approximately to the sections identified as C and D in the 2018 report). Sections C, D, and E in Table 6 and Figure 33 correspond approximately to section E in the 2018 report. Sections F, G, and H in Table 6 and Figure 34 correspond with sections F, G, and H in the 2018 report. The total length of the 5-year and current vulnerable sections of NC 12 at the end of the 2019 study year is 17,425 ft, compared to 13,731 ft in 2018. Most of the change was due to the increase in the vulnerable areas within the Canal Zone and expansion of the areas north of Rodanthe.

Table 6. Current and 5-year vulnerable sections of NC 12

Map Location (refer to Figure 29-Figure 34)	Designation in 2018 Report	Vulnerability Timeframe	Length (ft)	Approximate Transect Span	Location Description
A	A, B	Current	7,214	200-248	Canal Zone
B	C,D	Current	5,393	280-316	Adjacent to PINWR Visitors Center (Freshwater Ponds)
C	E	5-year	630	540-544	Narrow area north of Rodanthe
D	E	Current	419	545-547	
E	E	5-Year	136	547-548	
F	F	5-Year	253	562-565	Just north of refuge boundary into Rodanthe (S-Curves)
G	G	Current	3,089	565-585	
H	H	5-year	290	585-587	
TOTAL Current			16,116		
TOTAL 5-Year			1,310		
OVERALL TOTAL			17,425		

Figure 29

(View 1 of 6)

Current and 5-Year NC 12 Vulnerability

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 16, 2020

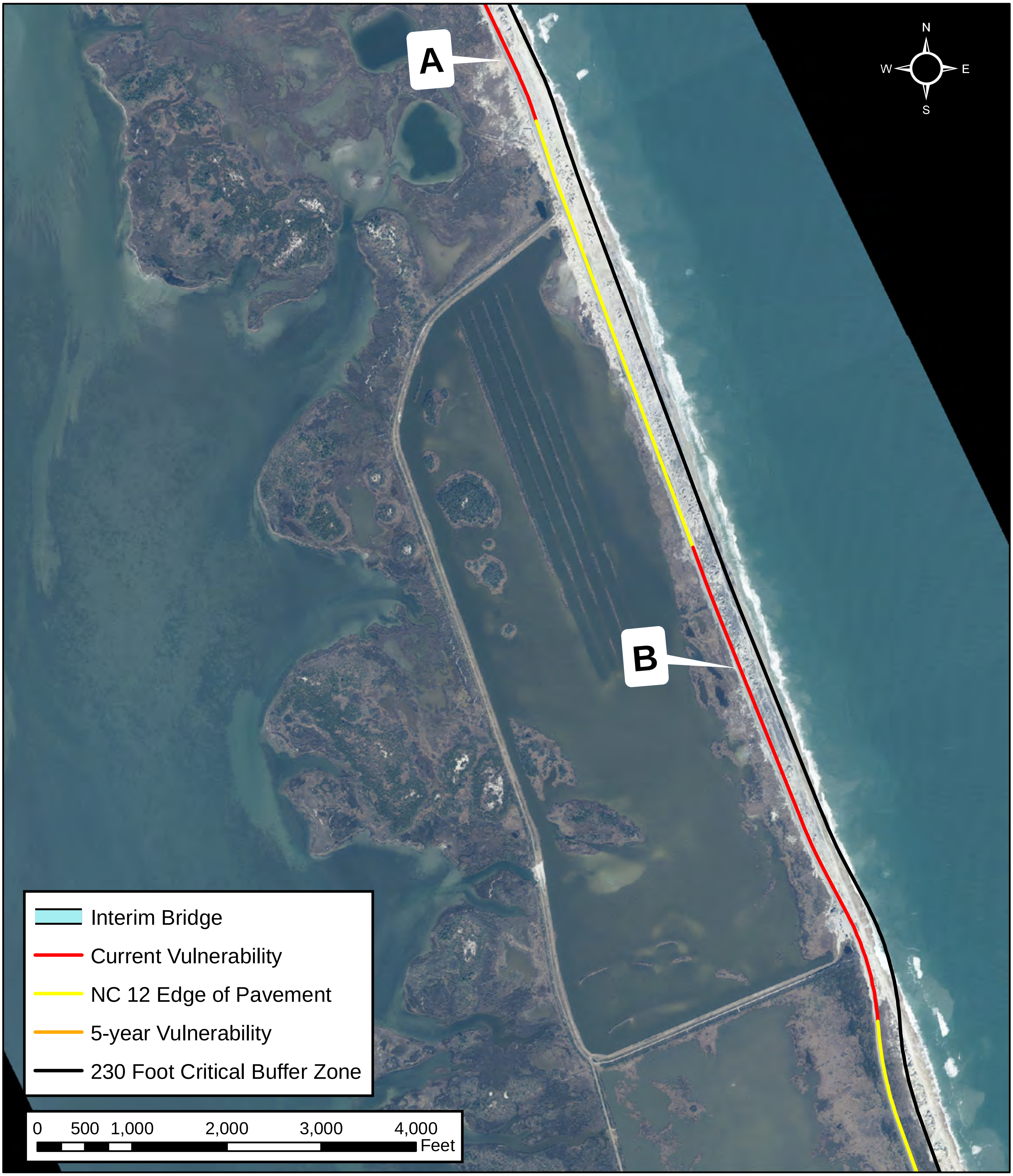

Figure 30

(View 2 of 6)

Current and 5-Year NC 12 Vulnerability

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 16, 2020

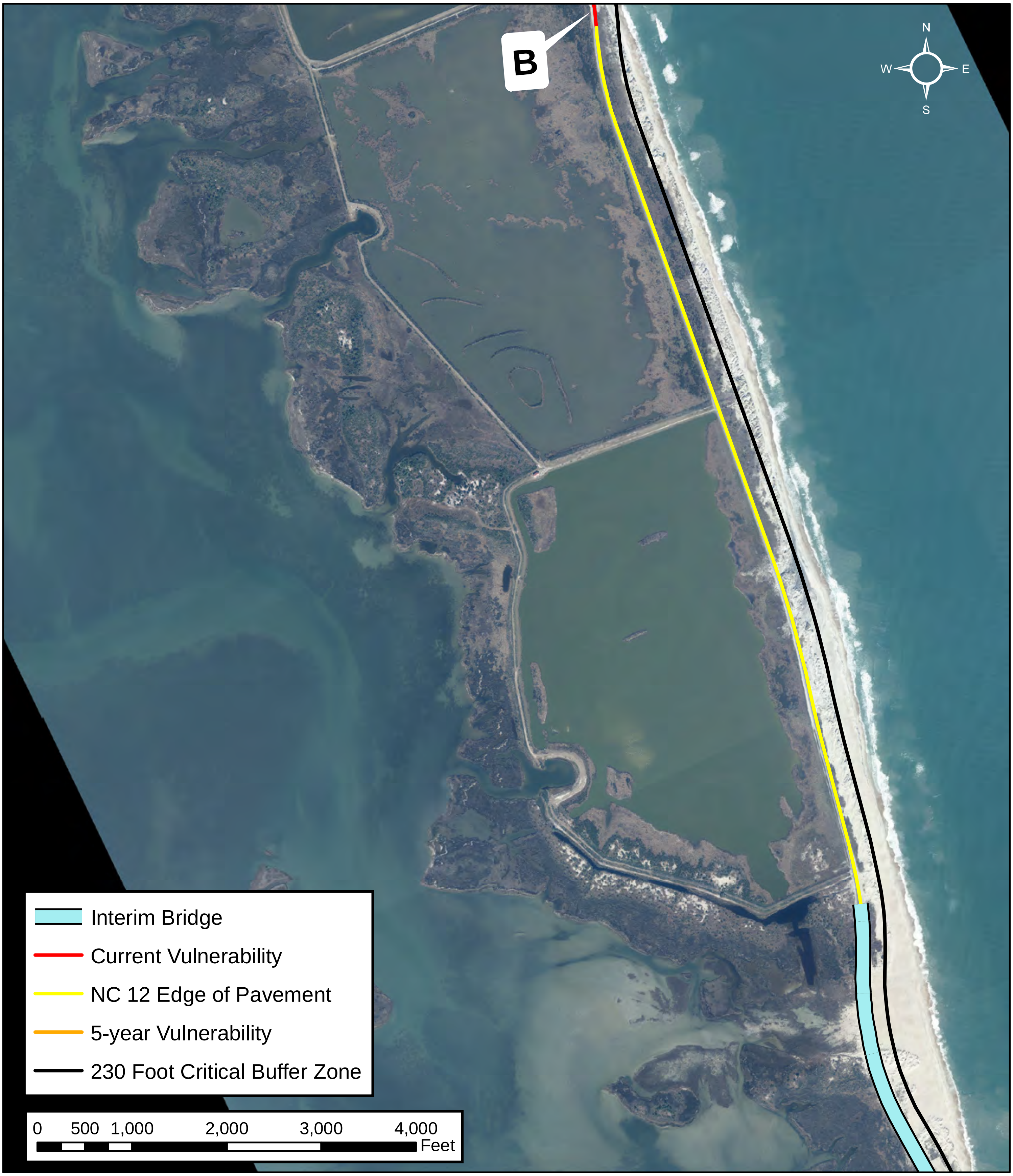

Figure 31

(View 3 of 6)

Current and 5-Year NC 12 Vulnerability

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 16, 2020

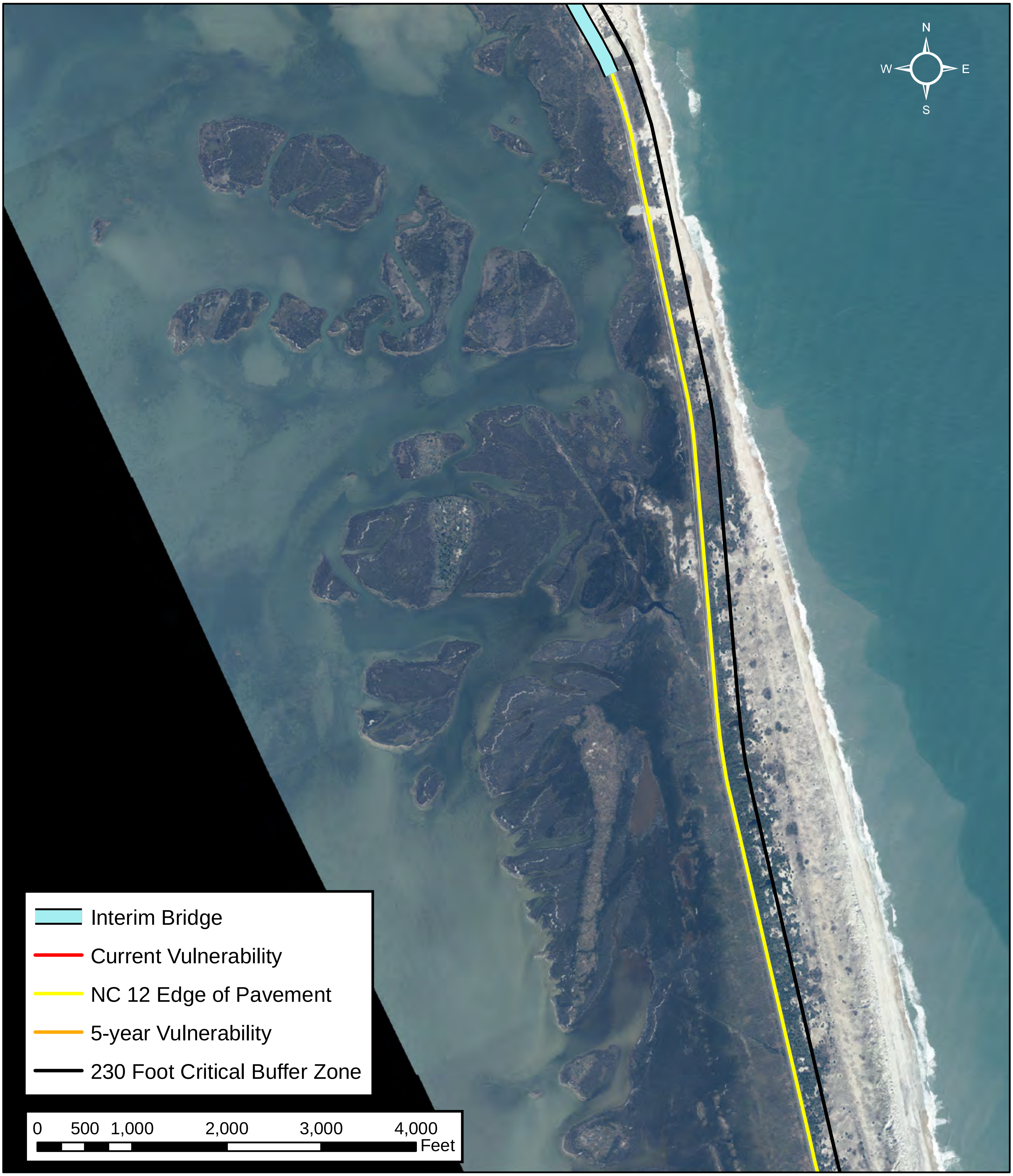

Figure 32

(View 4 of 6)

Current and 5-Year NC 12 Vulnerability

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 16, 2020

Figure 33

(View 5 of 6)

Current and 5-Year NC 12 Vulnerability

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 16, 2020

Figure 34

(View 6 of 6)

Current and 5-Year NC 12 Vulnerability

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 16, 2020

Predicted Shoreline Positions: 2030 and 2060

Figure 35 through Figure 40 show the prediction of the expected average shoreline position in 2030 (referred to as "Predicted 2030 Shoreline" in the figures) based on the linear regression of shoreline position including data through December 2019. For these predictions, a band showing the potential high-erosion and low-erosion position of the shoreline is also presented, determined using the 95% confidence prediction intervals for the position data (this band is referred to as "95% Prediction Interval Range" in the figures). Red highlights the areas along NC 12 where, at a minimum, the high-erosion shoreline (the western edge of the band) encroaches on the 230 ft critical buffer. These areas are considered to be potentially vulnerable roadway. The length and approximate transect span of these locations is summarized in Table 7.

By 2030, the high-erosion shoreline position reaches the 230-foot critical buffer throughout the Canal Zone near Oregon Inlet (Figure 35), north of the freshwater ponds. [It is noted that this area is already showing vulnerability in the current year; this is because the short-term recession of the shoreline has been greater than the long-term rate used for the prediction. It is too soon to know whether the trend may reverse as part of the bar attachment cycle, however, the current vulnerability makes this an area of immediate concern.] The average 2030 shoreline position (represented by the mid-point of the band) reaches the buffer near the center of the freshwater ponds, while the high-erosion shoreline approaches the road (Figure 36). Figure 37 shows the 2030 high-erosion shoreline encroaching on the buffer along the southernmost freshwater pond and adjacent to the Pea Island Breach, and along a small section south of the breach. The 2030 high-erosion shoreline is well within the critical buffer zone and encroaches onto the road along the section of NC 12 north of Rodanthe and into the northern section of Rodanthe, as shown in Figure 39 and Figure 40.

The potentially vulnerable sections in the 2030 prediction were similar overall to those in previous reports, with small differences from the 2018 report. Sections A, B, and E were slightly longer than the corresponding sections in the 2018 report. Section D from the present report was a small area (210 ft) which was not predicted to be vulnerable as of the 2018 report. The total length of potentially vulnerable roadway with the 2030 forecast is 27,410 ft, compared with 27,310 ft in 2018.

Table 7. 2030 potentially vulnerable sections of NC 12

Map Location (refer to Figure 35-Figure 40)	Designation in 2018 Report	Length (ft)	Approximate Transect Span	Location Description
A	A	8,170	196-250	Canal Zone
B	B	5,827	280-319	North of, Adjacent to, and South of Pea Island Visitors Center (Freshwater Ponds)
C	C	3,761	355-380	Adjacent to South Pond and just north of Pea Island Breach
Interim Bridge	C	506	380-383	Small section at the north side of the Interim Bridge span
D	--	210	403-404	Small section south of the Interim Bridge
E	D	8,936	535-594	Narrow area north of Rodanthe, past refuge boundary into Rodanthe (S-Curves)
TOTAL		27,410		

Figure 35

(View 1 of 6)

Projected 2030 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 18, 2020

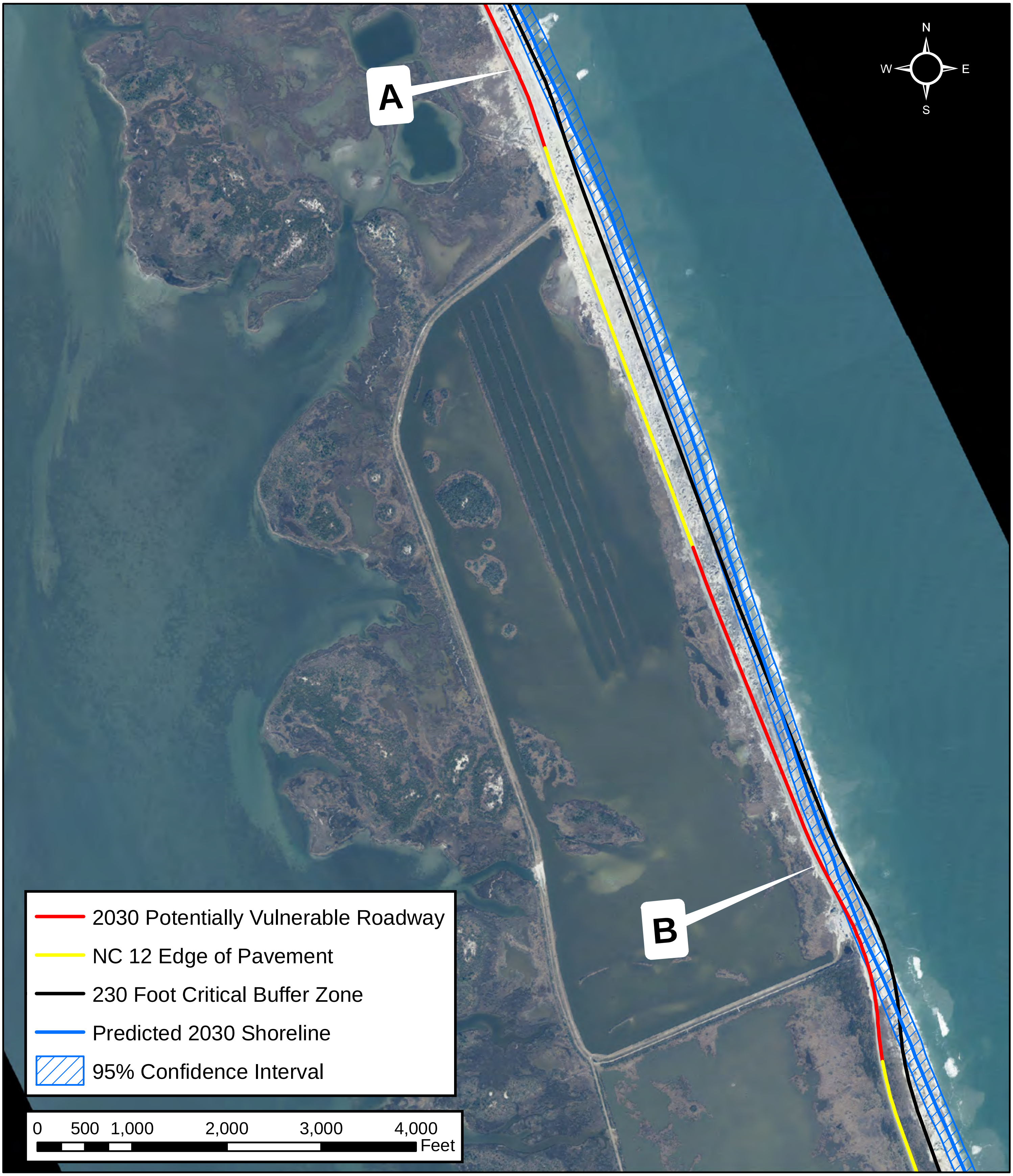

Figure 36

(View 2 of 6)

Projected 2030 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 18, 2020

Figure 37

(View 3 of 6)

Projected 2030 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 18, 2020

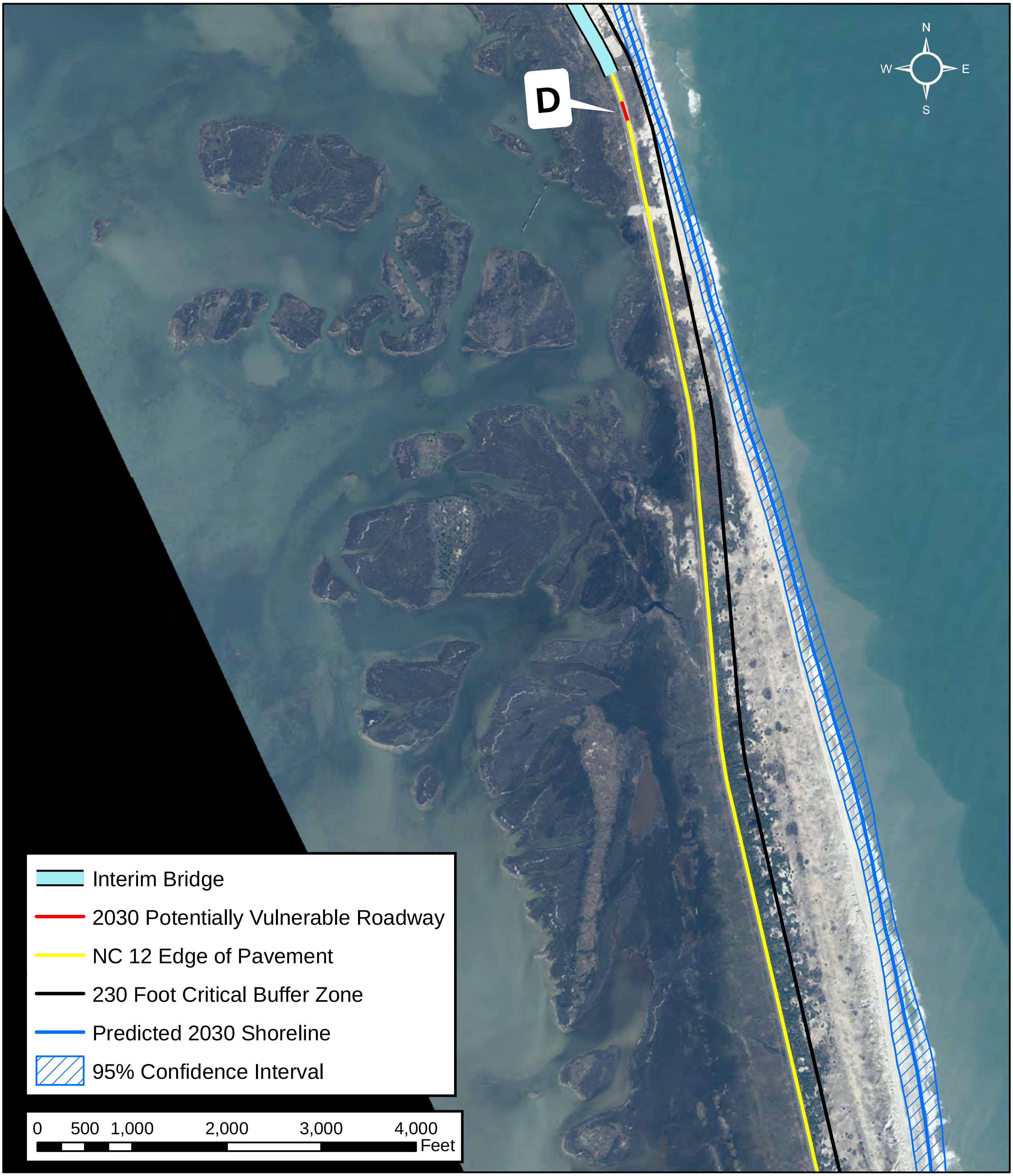

Figure 38

(View 4 of 6)

Projected 2030 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 18, 2020

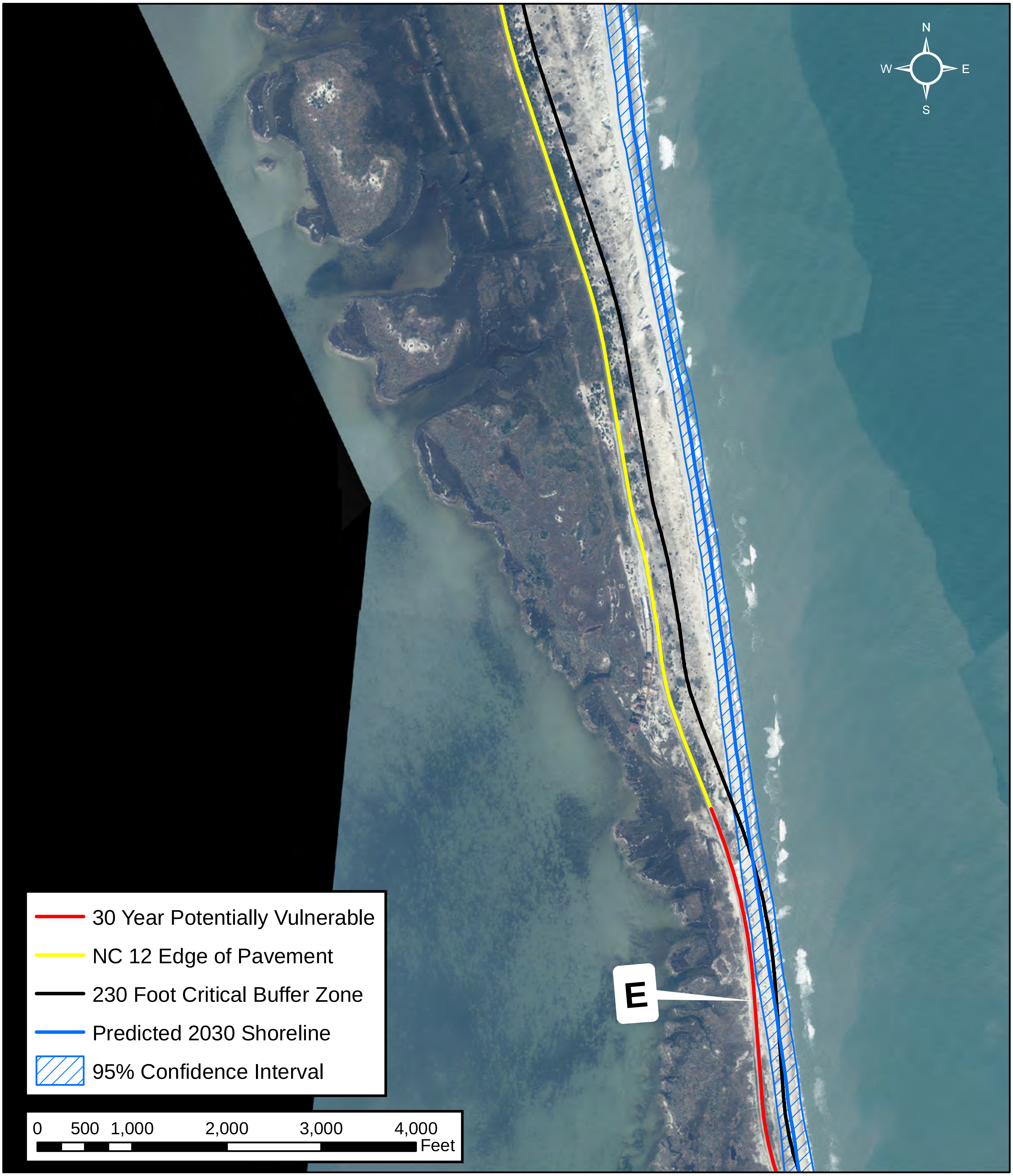

Figure 39

(View 5 of 6)

Projected 2030 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 18, 2020

Figure 40

(View 6 of 6)

Projected 2030 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 18, 2020

The prediction of the expected average shoreline position in 2060 (referred to as “Predicted 2060 Shoreline”), along with a band showing the potential high-erosion and low-erosion shoreline positions (referred to as “95% Prediction Interval Bounds”) is presented in Figure 42 through Figure 47. The length and approximate transect span of the areas where the band encroaches on the 230 ft buffer is summarized in Table 8.

As shown in Figure 42, the 2060 high-erosion shoreline reaches the critical buffer along a stretch of NC 12 just south of Oregon Inlet. This area is currently showing very slight accretion in the long-term rates (see Figure 28); therefore Area A in this figure is slightly smaller than Area A (along the same stretch of roadway) shown in Figure 35. In the shadow of the terminal groin and north of the ebb shoal bar attachment point, the shoreline is essentially stabilized, fluctuating around an average position with cyclic periods of erosion and accretion. This cyclic fluctuating shoreline behavior is a function of the presence of the terminal groin that traps sand, the ebb shoal bar which tends to refract the waves and reverse the direction of alongshore transport (to the north) and the occasionally episodic supply of sand provided by the dredge disposal activities of the USACE. Figure 41 shows the approximate location of the ebb shoal bar, and provides an example of a period of sediment transport to the north such that sand accumulated on the inlet side of the terminal groin. A linear analysis of these kinds of data typically results in a small shoreline change rate (either erosion or accretion) and a large prediction interval reflecting the uncertainty of the trend. In this area at the present time, accretion is indicated by the linear regression analysis. *It is noted that there is a limit to how much accretion will be maintained before the shoreline position oscillates back to an erosion condition*. Future monitoring will determine if the shoreline change rate reverses trend in the future, and subsequent shoreline position predictions will be adjusted accordingly.

Along the freshwater ponds and adjacent to the Pea Island Breach, even the low-erosion 2060 shoreline moves landward of NC 12 in some areas (Figure 43 and Figure 44). Just south of the ponds, the low-erosion 2060 shoreline is within the critical buffer area, and the average-erosion shoreline approaches the road (Figure 45). South of that section, all predicted shorelines lie east of the buffer for approximately three miles until a narrow section north of Rodanthe where the high erosion predicted shoreline transitions to a position landward of NC 12 (Figure 46). All predicted shorelines are landward of the road from that area south to the northernmost portion of Rodanthe (Figure 47).

The total length of potentially vulnerable roadway for the 2060 prediction is 37,763 ft, about 3,000 ft longer than the total length of potentially vulnerable roadway for the 2060 prediction in the 2018 report, 34,726 ft. Note that the length of the Interim Bridge span is included in this estimate, because this bridge is considered a temporary solution to the vulnerability in that area.

Table 8. 2060 potentially vulnerable sections of NC 12

Map Location (refer to Figure 42-Figure 47)	Approximate Corresponding Section in 2030 Maps (Figure 35-Figure 40)	Designation in 2018 Report	Length (ft)	Approximate Transect Span	Location Description
A	A	A	7,982	196-249	Canal Zone
B	B	B	8,182	273-327	North of, Adjacent to, and South of Pea Island Visitors Center (Freshwater Ponds)
C	C	C	5,135	346-380	Adjacent to South Pond to north of Interim Bridge
Interim Bridge	Interim Bridge	C/D	3,238	380-401	Span of Interim Bridge
D	D	D	3,043	401-421	South of Interim Bridge
E	E	E	10,183	532-599	Narrow area north of Rodanthe, past refuge boundary into Rodanthe (S-Curves)
TOTAL			37,763		

Figure 41. Diagram showing approximate location of the ebb shoal bar (visible due to waves breaking over the shallower areas of the bar) and local reversal of sediment transport, leading to sand deposition on the inlet side of the terminal groin.

Figure 42

(View 1 of 6)

Projected 2060 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 20, 2020

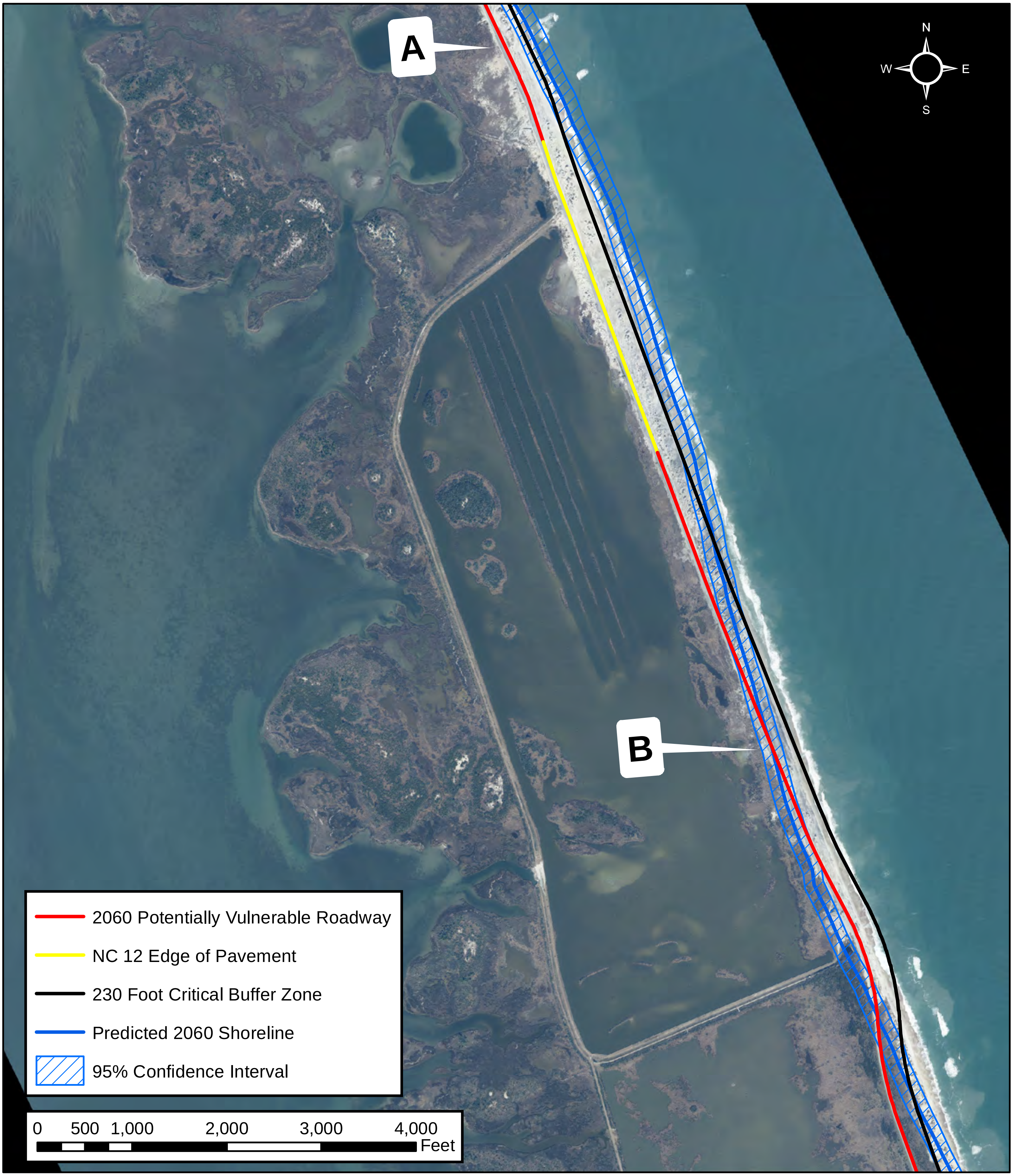

Figure 43

(View 2 of 6)

Projected 2060 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 20, 2020

Figure 44

(View 3 of 6)

Projected 2060 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 20, 2020

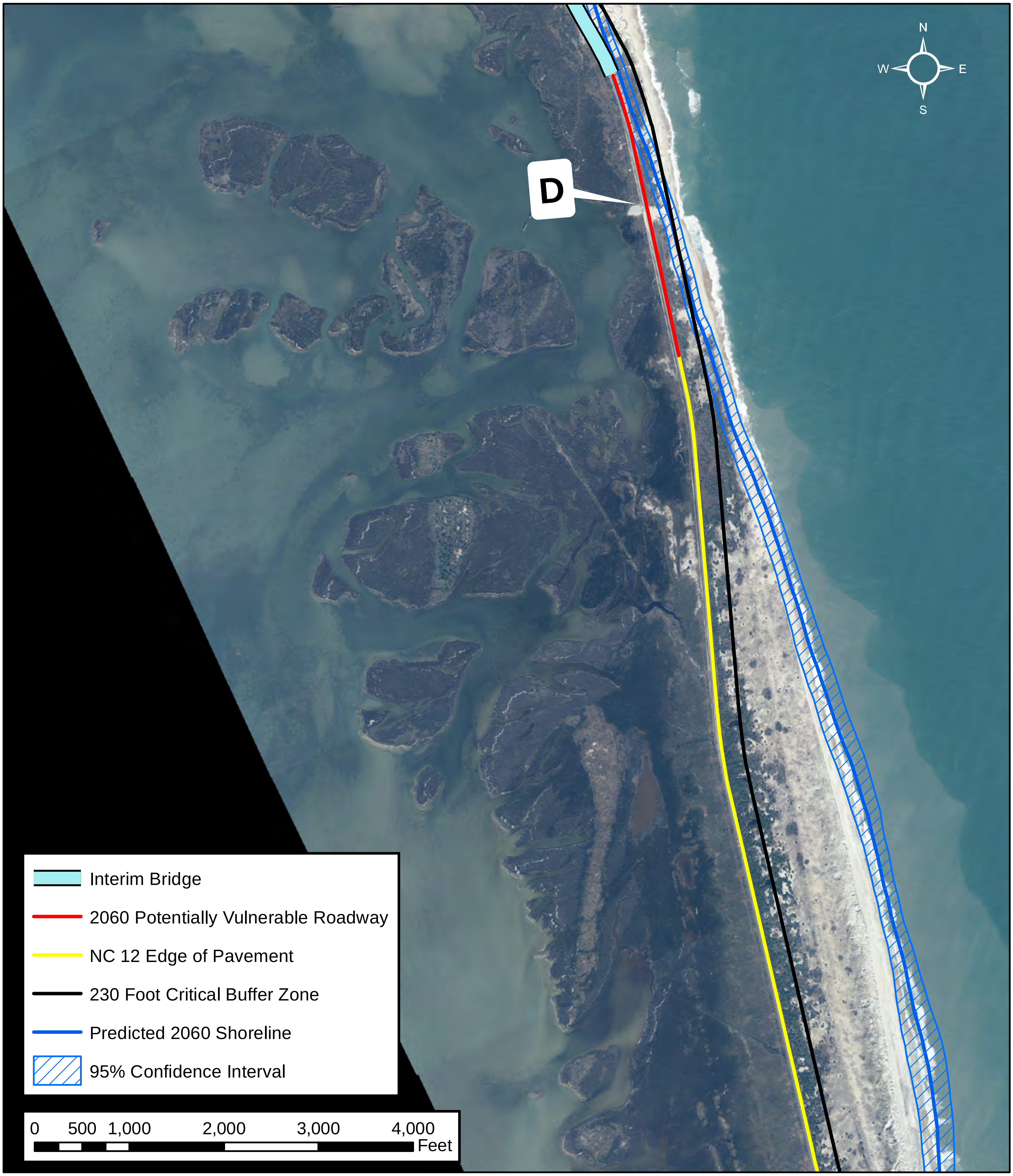

Figure 45

(View 4 of 6)

Projected 2060 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 20, 2020

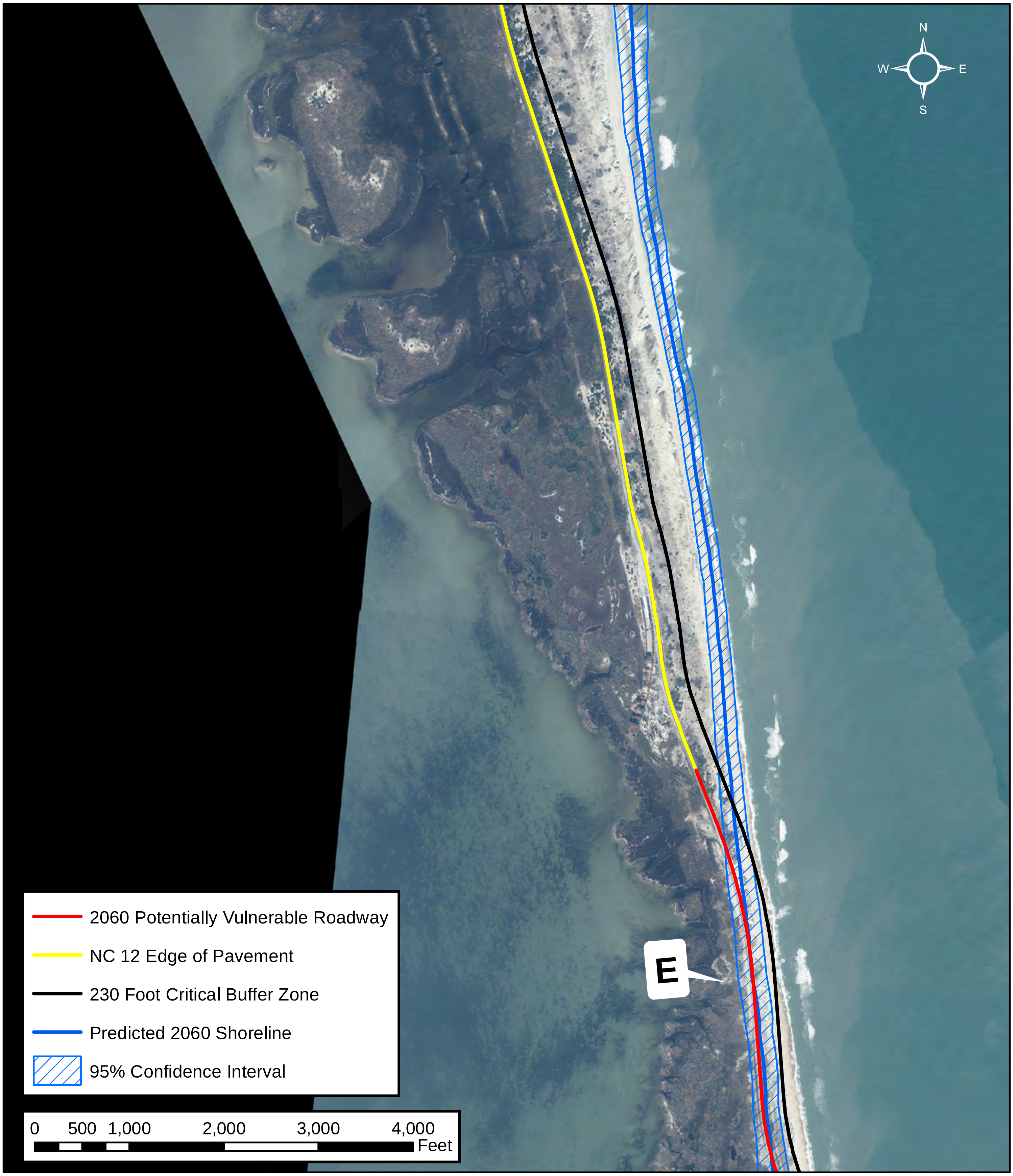

Figure 46

(View 5 of 6)

Projected 2060 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 20, 2020

Figure 47

(View 6 of 6)

Projected 2060 Shoreline with 95% PI

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: March 20, 2020

Storm Events

Table 9 presents the storm events compiled from the USACE Duck Field Research Facility. The maximum water level was the maximum elevation measured over the storm time frame from the hourly data. Maximum storm surge was the maximum of the difference between the observed and predicted water levels. The three most severe events in 2019 were Hurricane Dorian, which impacted the area September 6-7, 2019, Tropical Storm Melissa, with effects felt from October 8 to 12, 2019, and a November coastal storm, occurring from November 16 to 19, 2019. Table 10 shows dates when NC 12 on Pea Island was hazardous or closed according to the NCDOT Traveler Information Management System. The three above referenced events were associated with all of the closures, with one other hazardous incident (overwash) occurring during a storm September 17-20, 2019.

Table 9. Storm events, 2019, as measured at the Duck Field Research Facility 17 m waverider (waves) and pier (water levels) (events had a maximum wave height greater than 6.6 ft for a sustained duration greater than 8 hours.) Date and time shown in EST.

Start Date	End Date	Max Hmo (ft)	Duration (hr)	Max Water Level (ft NAVD)	Max Storm Surge (ft)
1/13/2019 18:00	1/15/2019 8:00	10.1	38.0	0.9	1.3
3/21/2019 7:00	3/22/2019 0:30	8.5	17.5	1.9	2.2
3/26/2019 10:30	3/28/2019 8:00	10.4	45.5	0.5	0.4
4/2/2019 20:00	4/3/2019 5:30	9.8	9.5	1.0	1.3
9/6/2019 3:00	9/7/2019 5:00	14.6*	26.0*	3.6*	3.1*
9/17/2019 22:00	9/20/2019 6:30	9.7	56.5	1.1	0.9
10/8/2019 12:30	10/12/2019 12:30	10.7**	96.0**	2.4**	2.1**
11/8/2019 10:30	11/8/2019 21:00	9.0	10.5	0.3	0.2
11/12/2019 20:00	11/13/2019 17:30	9.0	21.5	0.6	0.4
11/16/2019 4:30	11/19/2019 2:00	15.4⁺	69.5⁺	1.9⁺	2.0⁺
11/29/2019 1:30	11/29/2019 10:30	7.7	9.0	0.9	0.5

*Hurricane Dorian

**Tropical Storm Melissa

⁺November coastal storm

Table 10. Traveler Information Management System NC 12 closure data for 2019, Pea Island

StartTime (EST)	EndTime (EST)	City	Closed or Hazardous	Reason
9/6/2019 21:24*	9/12/2019 22:24*	Nags Head	Hazardous	Sand and Deep standing water on Roadway Basnight Bridge to Hatteras Village travel along NC12 is extremely Hazardous
9/7/2019 8:20*	9/10/2019 7:00*	Near Nags Head	Closed	NC12 From Basnight Bridge to Mirlo is currently closed due to sand and water on roadway clearing efforts are in progress.
9/20/2019 6:52	9/21/2019 12:00	Near Rodanthe	Hazardous	There is ocean overwash across both directions of NC-12 near Blue Sea Drive. Motorists should use caution when traveling through the area.
10/10/2019 8:30**	10/12/2019 8:30**	Rodanthe	Hazardous	Ocean over wash on NC12 in the area of the S-curves prior to Rodanthe, crews are clearing sand from NC12 however motorists should use caution when traveling the entire section of NC 12 from Basnight Bridge to Hatteras Village. Areas of sand and water are on the rodaway.
10/10/2019 18:58**	10/11/2019 4:00**	Near Rodanthe	Closed	The road is closed near Blue Sea Rd due to flooding
10/11/2019 6:00**	10/11/2019 18:00**	In Rodanthe	Closed	The road is closed near Corbina Dr due to overwash.
10/11/2019 6:00**	10/14/2019 18:00**	Near Rodanthe	Closed	The road is closed from the Oregon Inlet to Rodanthe due to overwash.
11/16/2019 17:00+	11/20/2019 15:00+	Nags Head	Closed	NC 12 South of Oregon Inlet Bridge to Rodanthe is closed due to hazardous travel conditions. Current weather conditions wind blown sand, ocean over wash are hampering clearing operations. Conditions are not forecast to improve until midday Monday. NCDOT crews will continue clearing operations when weather conditions improve.

*Hurricane Dorian
**Tropical Storm Melissa
+November coastal storm

USACE Dredge and Disposal Records

The USACE has historically dredged and placed material within the project monitoring area on a near-annual basis as described in the baseline report. However, in recent years dredging and placement events have been sparse. Data are gathered from the USACE Navigation Data Center databases (https://usace.contentdm.oclc.org/digital/collection/p16021coll2/id/2641). At the time of the 2018 report, these data were not available, so this report includes dredging information for both 2018 and 2019 (Table 11). There were no contract dredging activities in Oregon Inlet in either 2018 or 2019. All dredging was conducted with USACE-owned dredges, either sidecasters or small hopper dredges which place dredged material in the nearshore. These are generally smaller volume operations and are not expected to significantly affect the shoreline along the study area. The total volume dredged in FY 2018 was 325,778 cubic yards, and in FY 2019 106,946 cubic yards.

Table 11. USACE Dredging Activities, FY 2018 and 2019.

Fiscal Year	Job Name	Dredge Name	Dredge Type	Start Date	End Date	Amount Dredged (cy)
2018	OREGON INLET, NC	CURRITUCK	small hopper	10/1/2017	10/12/2017	29,355
2018	OREGON INLET, NC	CURRITUCK	small hopper	10/23/2017	11/1/2017	36,415
2018	OREGON INLET, NC	CURRITUCK	small hopper	11/13/2017	12/7/2017	61,195
2018	OREGON INLET, NC	CURRITUCK	small hopper	12/16/2017	1/11/2018	28,042
2018	OREGON INLET, NC	CURRITUCK	small hopper	1/25/2018	1/26/2018	670
2018	OREGON INLET, NC	CURRITUCK	small hopper	2/5/2018	2/18/2018	22,830
2018	NCDOT/MANTEO	CURRITUCK	small hopper	2/16/2018	2/17/2018	2,255
2018	NCDOT/Manteo	CURRITUCK	small hopper	3/16/2018	3/19/2018	14,495
2018	Oregon Inlet, NC	CURRITUCK	small hopper	3/19/2018	3/20/2018	1,360
2018	ROLLINSON, NC	CURRITUCK	small hopper	3/30/2018	3/31/2018	220
2018	OREGON INLET, NC	CURRITUCK	small hopper	4/1/2018	4/17/2018	17,840
2018	OREGON INLET, NC	CURRITUCK	small hopper	5/9/2018	5/18/2018	23,205
2018	OREGON INLET	CURRITUCK	small hopper	6/22/2018	6/26/2018	7,990
2018	OREGON INLET, NC	CURRITUCK	small hopper	7/1/2018	7/25/2018	52,511
2018	OREGON INLET, NC	CURRITUCK	small hopper	8/17/2018	8/19/2018	9,085
2018	OREGON INLET, NC	CURRITUCK	small hopper	9/5/2018	9/11/2018	8,105
2018	OREGON INLET, NC	MURDEN	small hopper	8/10/2018	8/17/2018	10,205
Total amount dredged, 2018						**325,778**
2019	OREGON INLET, NC	CURRITUCK	small hopper	12/20/2018	12/28/2018	4,695
2019	OREGON INLET, NC	CURRITUCK	small hopper	9/1/2019	9/30/2019	not reported
2019	TRANSITED & ROLLINSON	MERRITT	sidecaster	3/7/2019	3/13/2019	11,208
2019	OREGON INLET, NC	MERRITT	sidecaster	4/18/2019	5/3/2019	30,288
2019	OREGON INLET, NC	MERRITT	sidecaster	5/13/2019	5/26/2019	26,148
2019	OREGON INLET, NC	MERRITT	sidecaster	7/1/2019	7/24/2019	not reported
2019	OREGON INLET, NC	MERRITT	sidecaster	8/11/2019	8/21/2019	not reported
2019	ROLLINSON, NC	MURDEN	small hopper	1/12/2019	1/13/2019	0
2019	OREGON INLET, NC	MURDEN	small hopper	1/16/2019	2/15/2019	16,590
2019	OREGON INLET, NC	MURDEN	small hopper	5/17/2019	5/25/2019	18,017
2019	OREGON INLET, NC	MURDEN	small hopper	6/29/2019	7/21/2019	not reported
Total amount dredged, 2019						**106,946**

NCDOT Maintenance Records

NCDOT provided information on NC 12 roadway maintenance activities in 2019. Table 12 lists the maintenance activities undertaken within the monitoring program study area in the year 2019. This list does not include any work associated with the Herbert C. Bonner Bridge or the Basnight Bridge, nor any work reported on NC 12 outside of the study area. As shown, maintenance expenditures in 2019 were approximately $1.3 million with most of the expenses related to sand removal. The October Storm (Tropical Storm Melissa), Hurricane Dorian, and the November 16-20 coastal storm had particular line item expenses delineated as well.

Table 12. NCDOT Highway 12 Maintenance, 2019 Expenditures.

Task	Description	Labor	Equipment	Fully Operated Rental	Other	Total
Sand Removal Pea Island	October Storm Sand Removal Pea Island	$61,877.98	$33,691.52		$21,259.86	$ 116,829.36
Sand Removal Pea Island	Sand Removal Pea Island	$5,614.40	$120,867.91	$464,456.96	$354,239.33	$ 945,178.60
Hurricane Dorian	Dare - NC 12 CCTV Cameras	$8,137.16	$3,021.40		$12,192.80	$ 23,351.36
Coastal Storm Nov 16, 2019	NC 12 Canal	$27,465.13	$10,963.85	$56,011.64	$20,700.00	$ 115,140.62
Coastal Storm Nov 16, 2019	NC 12 Mirlo Beach	$55,381.02	$32,061.21			$ 87,442.23
					TOTAL	$1,287,942.17

Barrier Island Breaches

In two locations, the barrier island was breached by Hurricane Irene in August 2011: just south of the freshwater ponds (Pea Island Breach) and at the north end of the town of Rodanthe (Rodanthe Breach). The evolution of these breaches during 2019 is shown in Figure 48 and Figure 49. The original breach configurations following Hurricane Irene are shown as dashed lines on the figures. Figure 48 shows Pea Island Breach shorelines digitized from available photography over the December 15, 2019 photograph. Similarly, Figure 49 presents the Rodanthe Breach shorelines digitized, over the December 15, 2019 photography. The Pea Island Breach was closed for all of 2019, with the most landward shoreline position measured in December 2019. The most seaward shoreline position was observed in May.

The majority of the Rodanthe Breach (within the right of way) was filled by NCDOT shortly after its formation in order to repair the roadway, and the area is continuing to be monitored. The most landward positions in this area were observed in April, October, and December 2019. There are fewer fluctuations in the shoreline position in this area due to ongoing maintenance of the dunes and roadway clearing. The May and February 2019 shorelines were the most seaward shoreline positions observed.

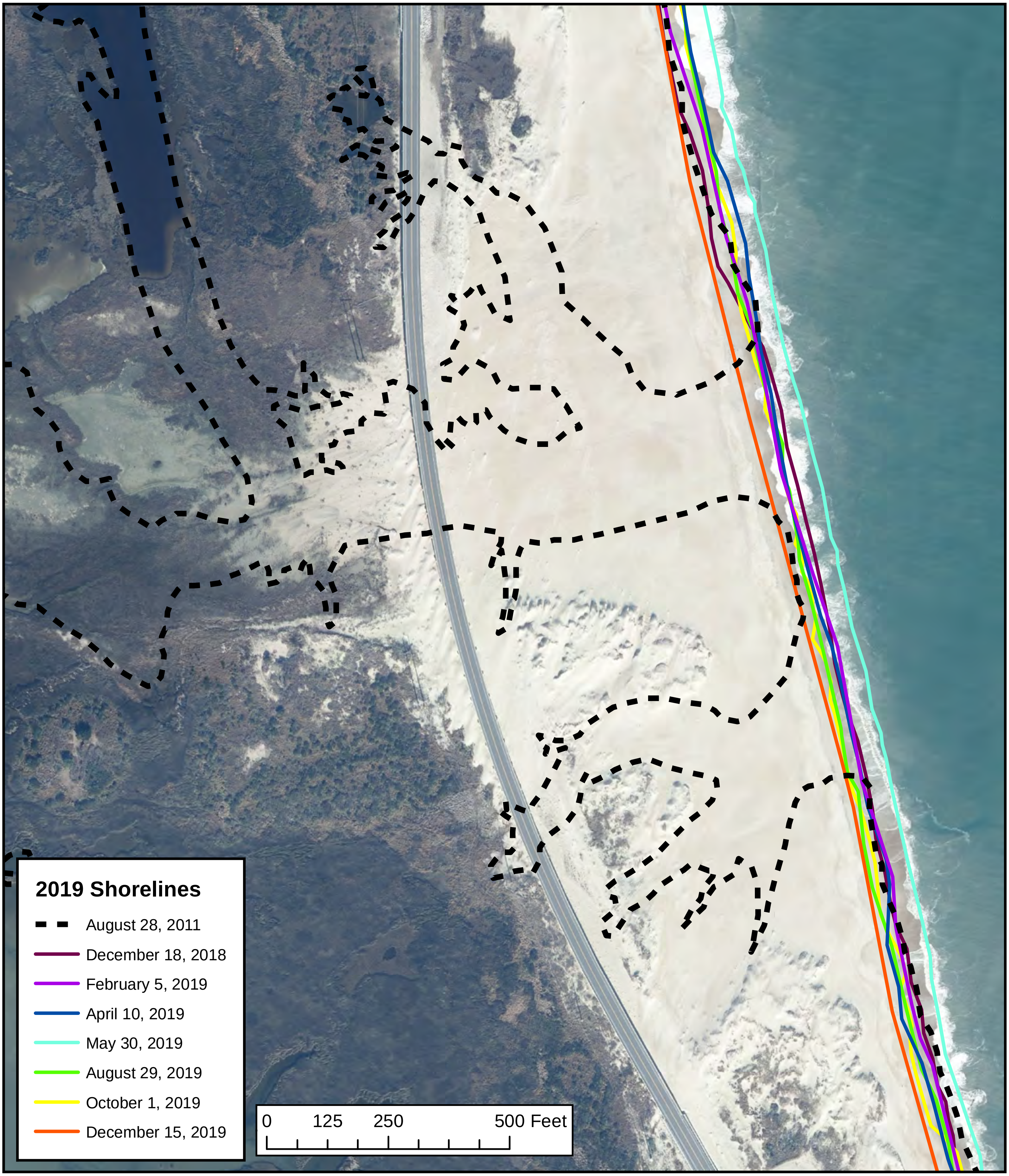

Figure 48

(Image 1 of 1)

Evolution of the Pea Island Breach

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: October 20, 2020

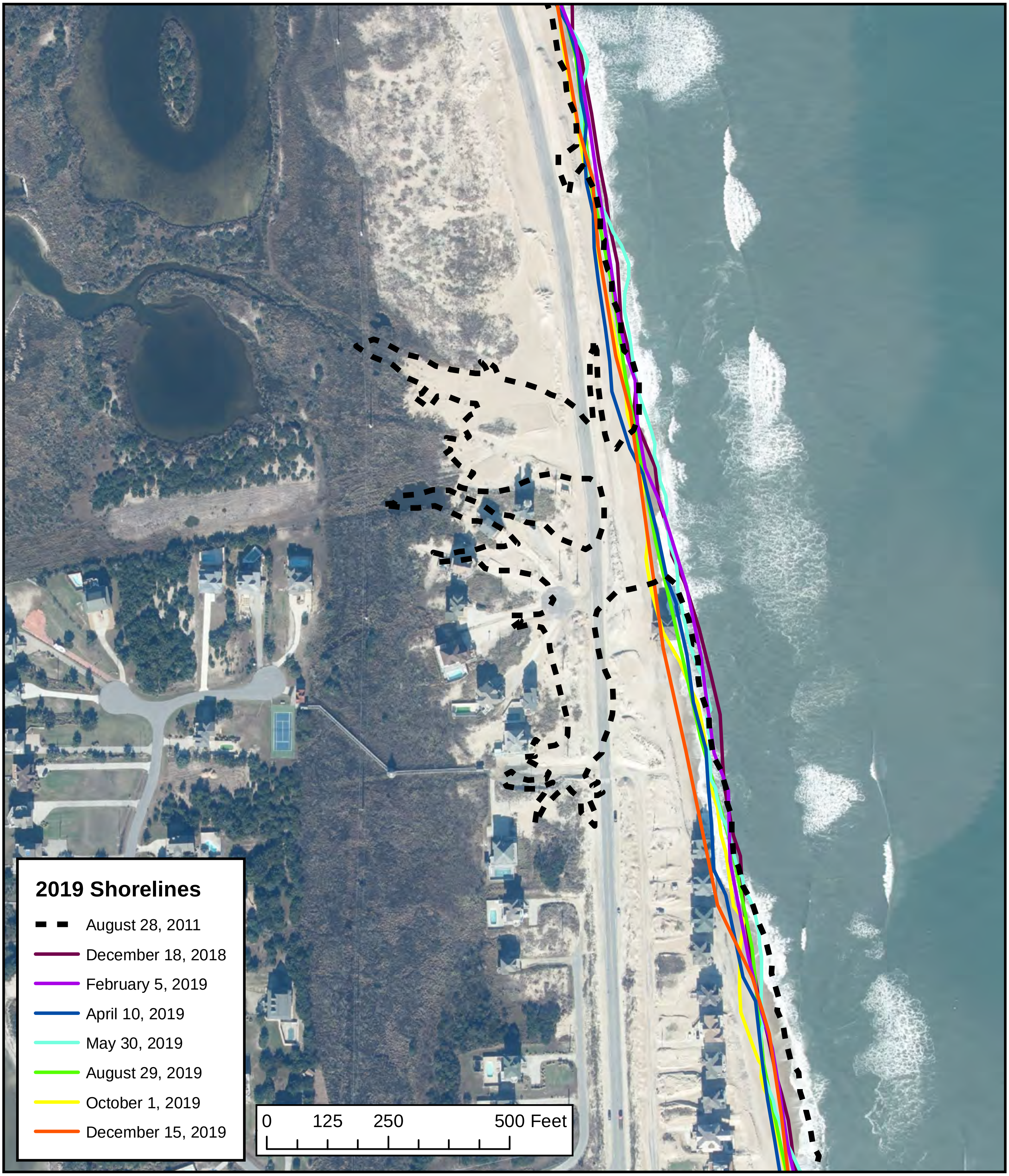

Figure 49

(Image 1 of 1)

Evolution of the Rodanthe Breach

Prepared for the North Carolina Department of Transportation
Horizontal Datum: North Carolina State Plane Feet 1983 FIPS 3200
Orthophoto Date: December 15, 2019; Map Created: October 20, 2020

4. TERMINAL GROIN MONITORING

A subset of the Coastal Monitoring Program is the specific analysis of shoreline data as required by the easement (permit) for the Oregon Inlet Terminal Groin. Two permits have been issued for the groin, one in 1989 and a second in 2012.

In 1989, prior to construction, a monitoring program was proposed and accepted to meet the requirements of the permit. Key elements of the program were: 1) the establishment of a historical shoreline change rate, 2) the determination of a project shoreline change rate every two months and 3) a comparison of the project rate to the historical rate to determine possible adverse impact. If the monitoring program determines that there is an increase in shoreline erosion above the background historical rates, then two thresholds for corrective beach nourishment have been established.

These criteria are, in summary:

1) If the erosion, in volume of sand (1 sq ft = 1 cu yd), exceeds the predicted loss in the amount of 250,000 cu yd in any one mile segment of the Pea Island monitoring area, or

2) If the volume of erosion in any three mile segment of the monitoring area exceeds the predicted loss by 500,000 cu yd, and

3) If either of these losses is confirmed through two consecutive two-month cycles of the monitoring program, then

4) Beach nourishment will be scheduled by NCDOT with the minimum volume equaling that which is necessary to replace the excess erosion at the time of confirmation of need.

A conversion of 1 square ft of beach surface to 1 cubic yd of beach volume is commonly used in coastal engineering design and reflects a vertical distance from the beach berm to a depth of closure of 27 ft.

Under the conditions of the new terminal groin easement signed in August 2012, the historical rate must be reviewed in order to validate or update in light of climate change and related coastal processes. This review has been presented in a separate report to NCDOT (Overton 2014) and discussed at a number of meetings with NCDOT and US Fish and Wildlife Service. On April 6, 2018, a memo was received from the US Fish and Wildlife Service (included in the 2018 report) confirming the new methodology to determine the historical and project rates.

Beginning in this report and going forward, the historical rate is determined as a linear regression rate using shoreline data between October 1968 and October 1988. The project rate is determined as a linear regression rate using shoreline data beginning in August 1992 to present. These rates are used along with the established methodology for determination of adverse impact.

Unlike the previous sections, the terminal groin monitoring focuses on the first six miles of Hatteras Island immediately south of Oregon Inlet (Transects 170 to 381).

Completed per the conditions of the August 2012 USFWS easement, the terminal groin monitoring results are presented in this section.

Historical Analysis

The dates selected for the historical analysis are October 3, 1968 to October 9, 1988, inclusive of intermediate dates presented in Table 13. These dates have been selected following analysis (Overton 2014) and multiple discussions with NCDOT and USFWS representatives. The early date of October 3, 1968 was selected because it was in the 1960s as mentioned in the 2012 easement, and was also 6 years after the 1962 "Ash Wednesday" nor'easter, which had a dramatic impact on the barrier island morphology. The more recent date, October 9, 1988, was chosen because it is the most recent set taken prior to the March 1989 nor'easter, a storm that caused considerable erosion. The use of photography just after this storm had the potential to bias the historical erosion rate analysis to higher values.

Table 13. Shoreline position data used for computation of historical shoreline change rate

Date	Shoreline Position Data Source
10/3/1968	COASTS database
6/4/1974	COASTS database
12/2/1978	CERC-UVA Rectified photos
10/21/1980	COASTS database
9/19/1984	NCDOT Archive
10/1/1986	COASTS database
7/10/1987	CERC- UVA Rectified photos
10/9/1988	NCDOT Archive

Figure 50 shows the annual historical erosion rate based upon linear regression of shoreline position at each transect from October 1968 to October 1988. Transect 170 corresponds to mile zero reported in Figure 50, and Transect 381 corresponds to mile 6 (see Figure 1 for transect locations). In general, the historical erosion rate along this portion of Pea Island was relatively high, with a mean value of about 12.7 ft/yr. The portion of the shoreline within the first mile of the old Coast Guard Station (closest to the inlet) was clearly the area of highest erosion, as one would expect near the inlet. In this area, the erosion rate has a maximum value of 36 ft/yr, and decreases to about 12 ft/yr approximately 1 mile south of the old Coast Guard Station. Rates increase to over 20 ft/year at the northernmost pond (mile 2.6), with lower rates further south.

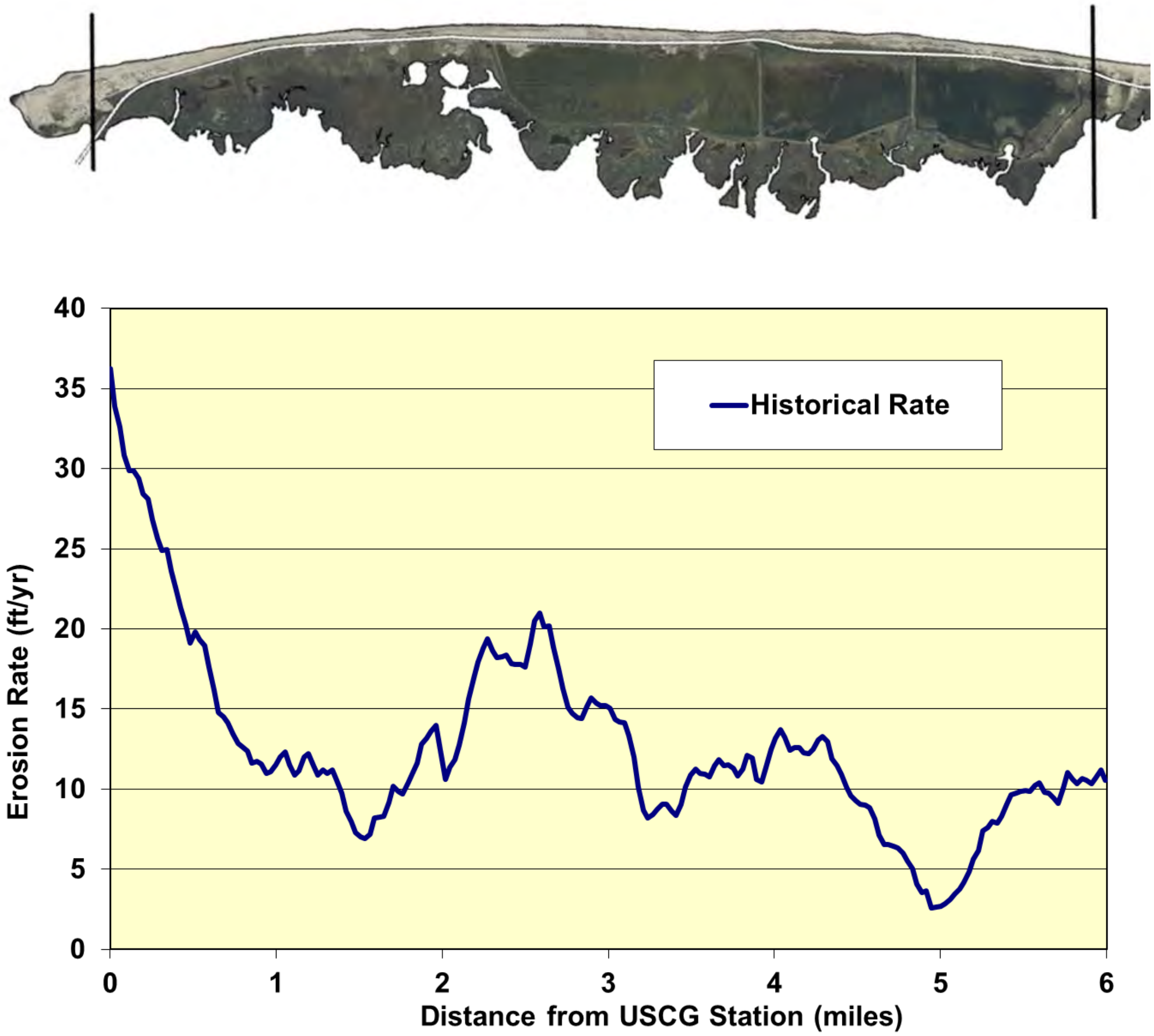

Figure 50. Annual Historical Erosion Rate: October 3, 1968 to October 9, 1988.

Dates of Aerial Photography

Shorelines digitized from the 2019 aerial photography (Table 1) were used along with other historical data in the following analysis.

Shoreline Change Adjacent to the Terminal Groin

An enlargement of the map of the northern end of Pea Island is shown in Figure 51 and Figure 52. Each figure shows the shoreline differences over a six month time span (December 2018 to June 2019 [May 30, 2019 photo], Figure 51, and June 2019 [May 30, 2019 photo] to December 2019, Figure 52). Three shoreline positions are presented in each figure: the two between which differences are noted and the initial position prior to terminal groin construction (October 5, 1989). For the purpose of monitoring the impact of the terminal groin, the study area begins at Transect 170, which cuts through the old US Coast Guard Station. However, approximately 2,000 ft of shoreline lies between the groin and Transect 170. While the change in shoreline in the vicinity of the groin is not included in the standard analysis of shoreline change, it is documented each survey period. Using Transect 170, the terminal groin, the October 5, 1989 shoreline, and the current shoreline as boundaries, it is possible to determine the net change in beach area since construction of the groin. The beach area between the terminal groin and transect 170 was essentially filled in by October 1992. At that time the area was approximately 51 acres. Since then, the beach area has varied, for the most part, between 50 and 70 acres, as seen in Figure 53. As of December 2019, the area between the groin and transect 170 was approximately 51 acres, while the greatest area in 2019 was observed in August and was approximately 64 acres.

Method of Analysis

The method used to determine shoreline change rate has changed from endpoint in previous reports to linear regression, as discussed above and outlined in the USFWS correspondence included in Appendix D. At each transect, the locations of all shoreline positions in the dataset from August 8, 1992 to present are used in a linear regression analysis. The shoreline change rate is the slope of the linear regression line at each transect. This establishes what is referred to as the "project rate," which is then compared to the historical shoreline change rate. This allows for a comparison of the shoreline change observed during the project period (in this case, from August 8, 1992 through the end of calendar year 2019) as compared to the rate of the shoreline change during the period established for historical reference (between October 1968 and October 1988).

In order to determine if there is any significant increase in erosion along the northern end of Pea Island, the one-mile and three-mile criteria have been established, as discussed previously. The one-mile threshold is 250,000 cu yd, while the three-mile threshold is 500,000 cu yd. The one-mile volume is calculated using 35 transects (approximately 5,250 ft), and the value is assigned to the transect at the mid-point of the section. Thus, the first value reported is for transect 187 (170 + 17).

The three-mile volume calculations are made in a manner similar to the one-mile, with 106 transects (15,900 ft, or 3.01 miles) used as the distance. Again, the value used in reporting is assigned to the transect at the mid-point of the section. Therefore the first value is assigned to transect 223 (170+53).

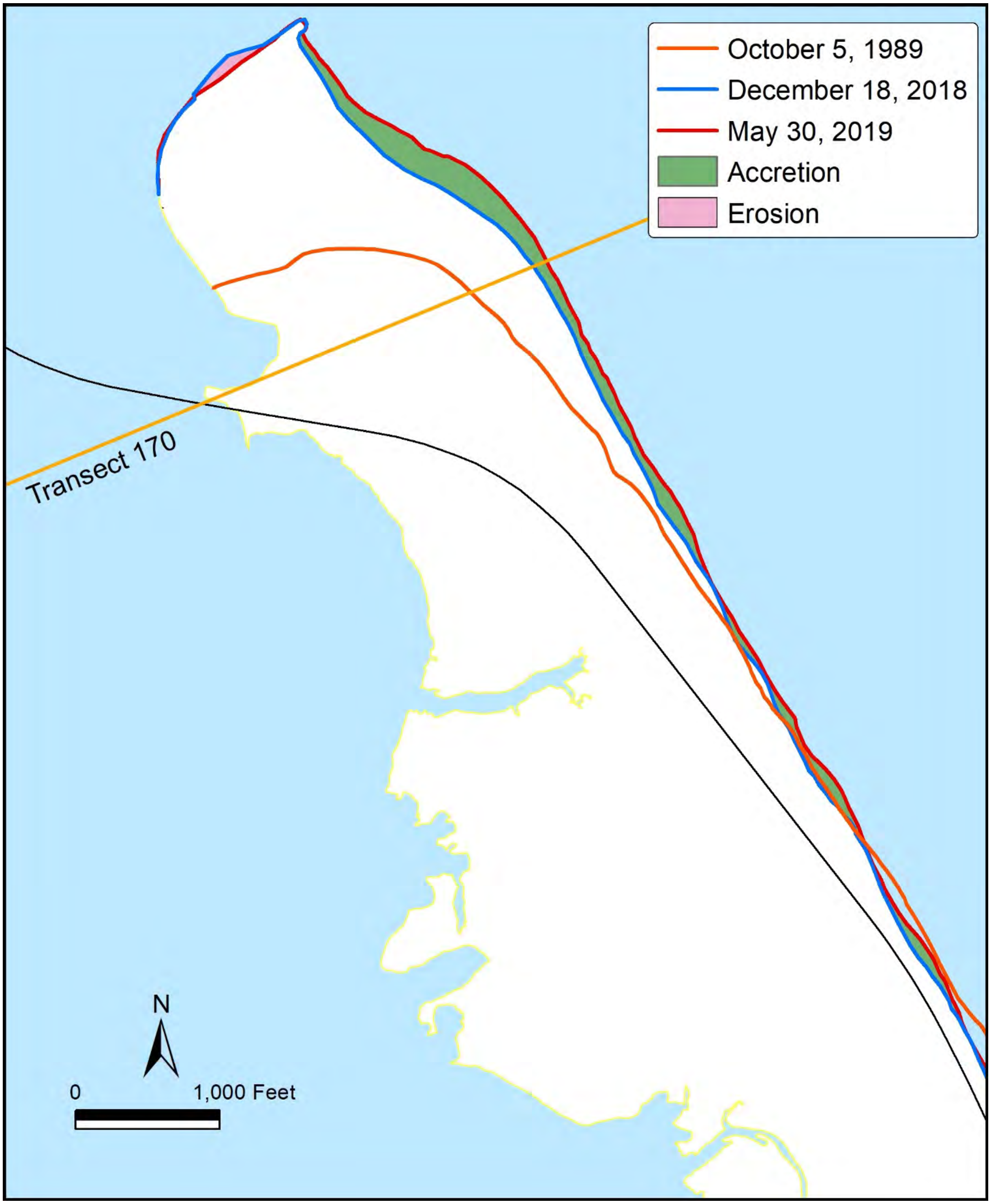

Figure 51. Shoreline Change near the Terminal Groin, December 2018 to May 2019

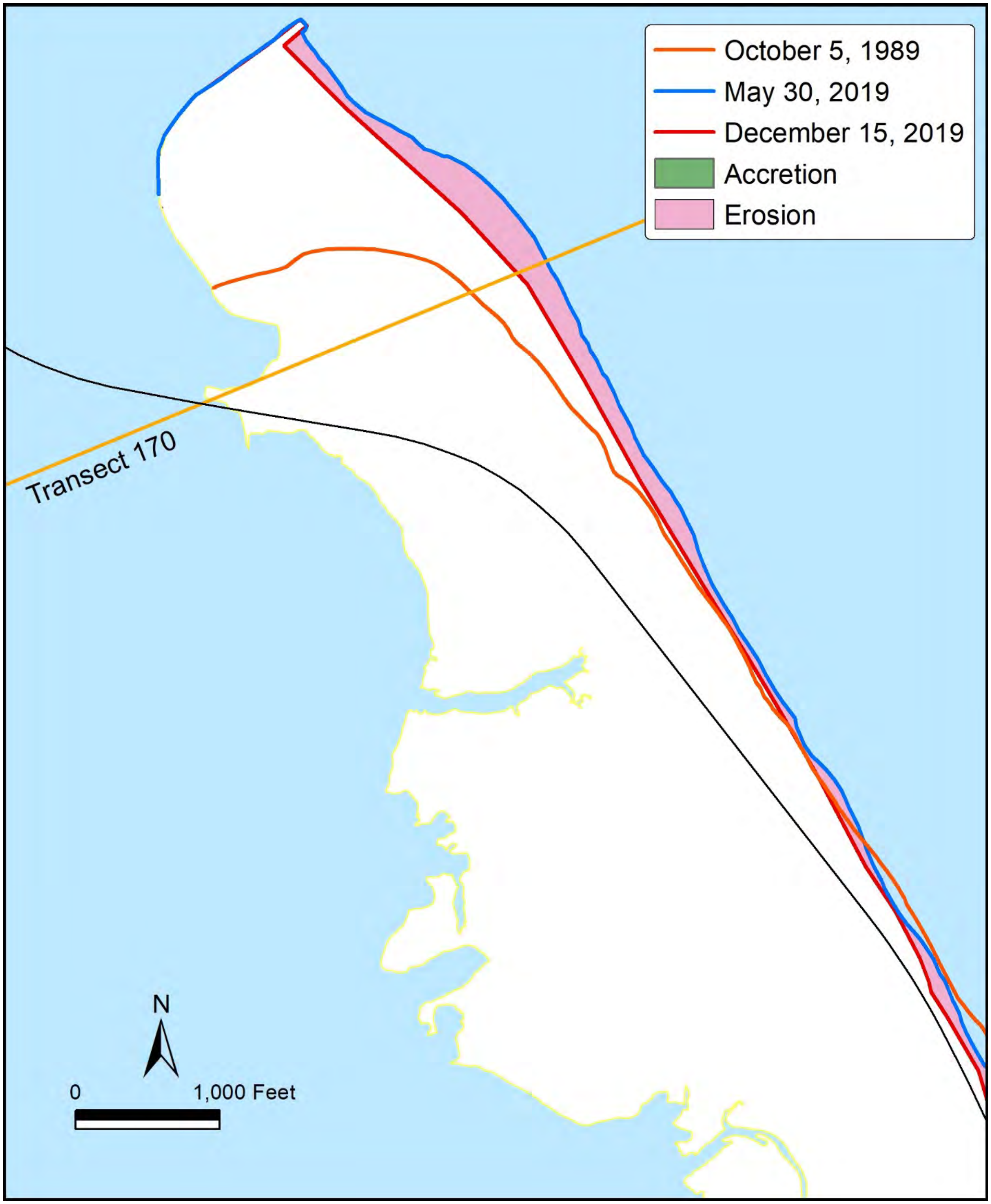

Figure 52. Shoreline Change near the Terminal Groin, May 2019 to December 2019

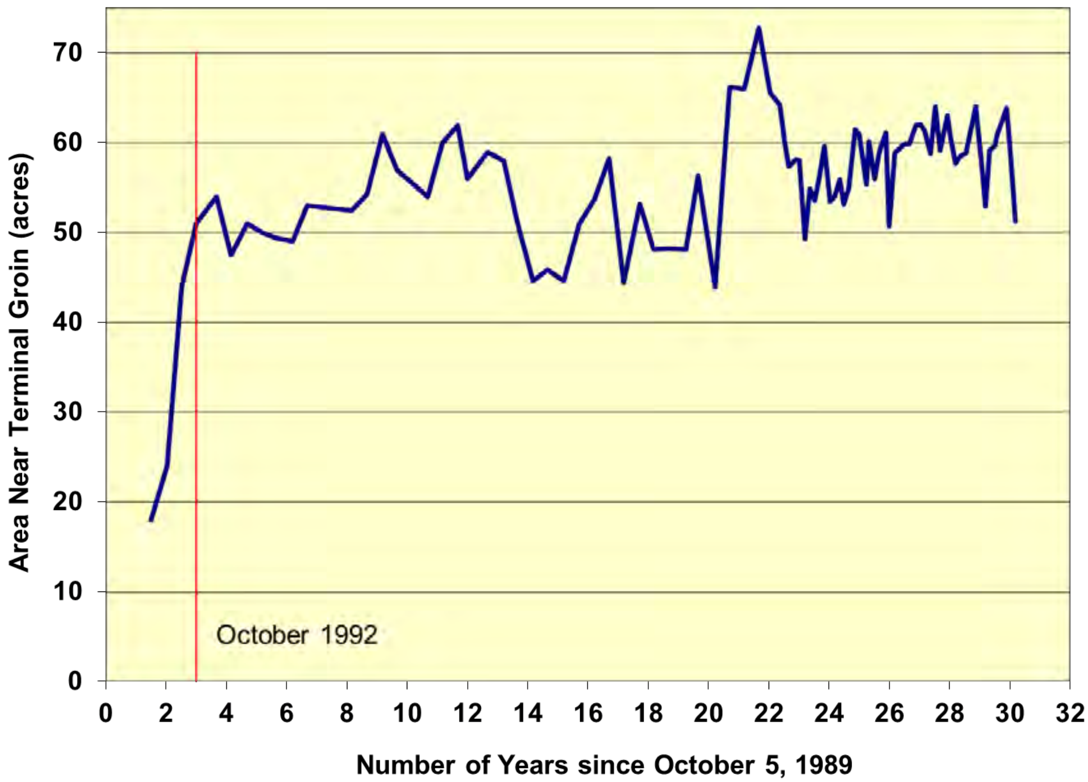

Figure 53. Area of Accretion between Transect 170 and the Terminal Groin

Project Erosion Rate

Using the August 8, 1992 to December 15, 2019 data, the current project erosion rate is computed and compared with the previously reported historical erosion rate in Figure 54. The historical rate can be characterized by trends in three sections: in the first mile, the erosion rate was high with a peak of 36 ft/yr and an average of 21 ft/yr. In the next three miles, the rate was approximately 13 ft/yr; in the last two miles, the average rate was 9 ft/yr. The trends of the current project rate can also be examined according to spatial variation along the project area. Within the first mile of the study area, the project rate and hence, shoreline position, is clearly influenced by the groin and any dredge disposal activity that has taken place. The project rate in this section is, on average, 3.1 ft/yr of accretion. In the next three miles of the study area, the current project rates are also less than the historical rates. The average project rate from mile 1 to 4 is 2.1 ft/yr of erosion. In the last two miles the average erosion rate is 3.1 ft/yr. The lower rates closer to the groin are due to the cyclic fluctuating shoreline caused by the presence of the terminal groin that traps sand, the ebb shoal bar which tends to refract the waves and reverse the direction of alongshore transport (to the north) and the occasional episodic supply of sand provided by the dredge disposal activities of the USACE. The project rate does not exceed the historical rate at any transect in the study area for 2019.

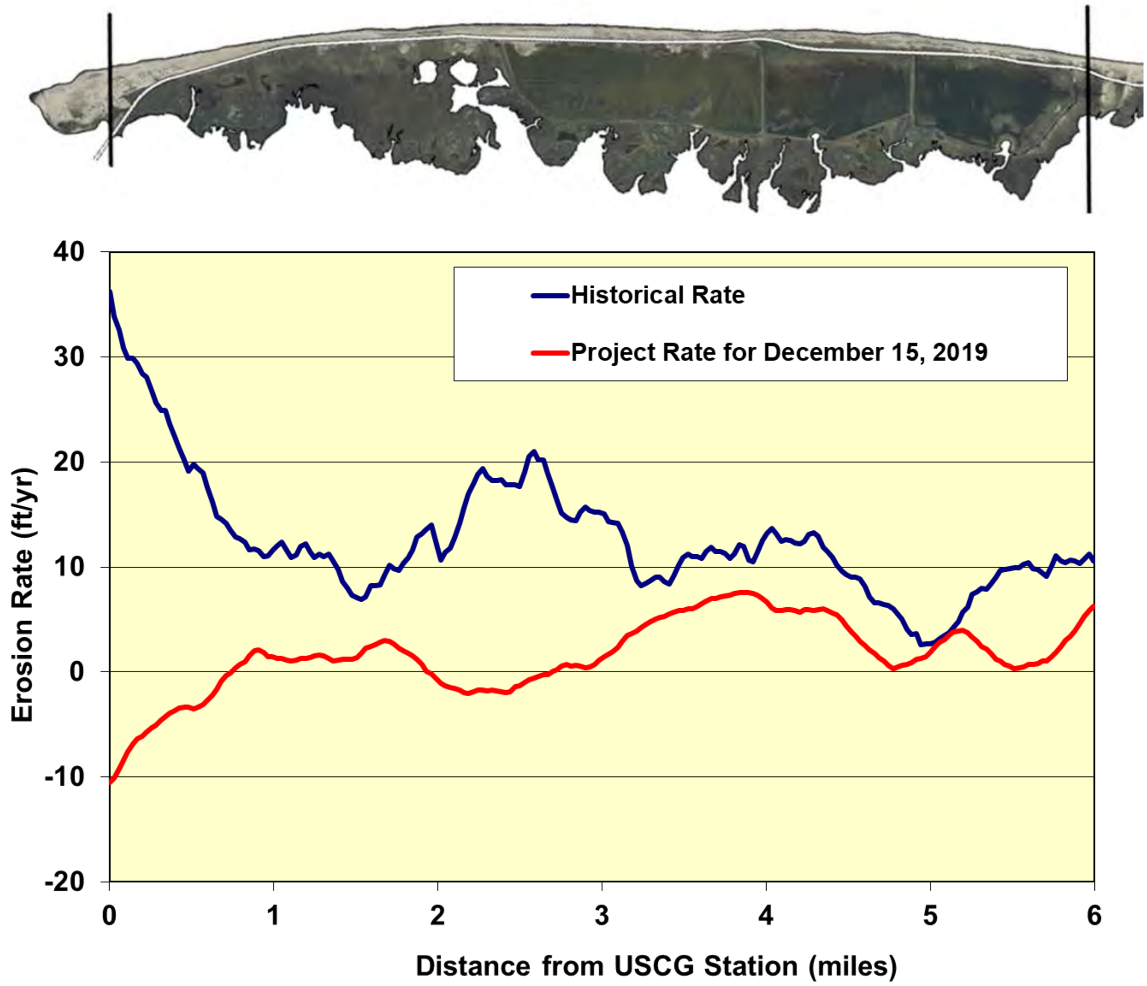

Figure 54. Comparison: Historical Erosion Rate and Project Erosion Rate for December 15, 2019

One-Mile Volume Change Analysis

The one-mile volume analyses for February 2019 through December 2019 are presented in Figure 55. The values are different from those in earlier reports because of the change in methodology for calculating the historical and project rates as of the 2017 report. Additionally, the values are similar from date to date because the linear regression project erosion rate does not change substantially during the year. The volume change everywhere is less than that predicted by the historical rates.

Three-Mile Volume Change Analysis

The three-mile volume analyses for February 2019 through December 2019 are presented in Figure 56. The values are different from those in earlier reports because of the change in methodology for calculating the historical and project rates, and volume change everywhere is less than that predicted by historical rates.

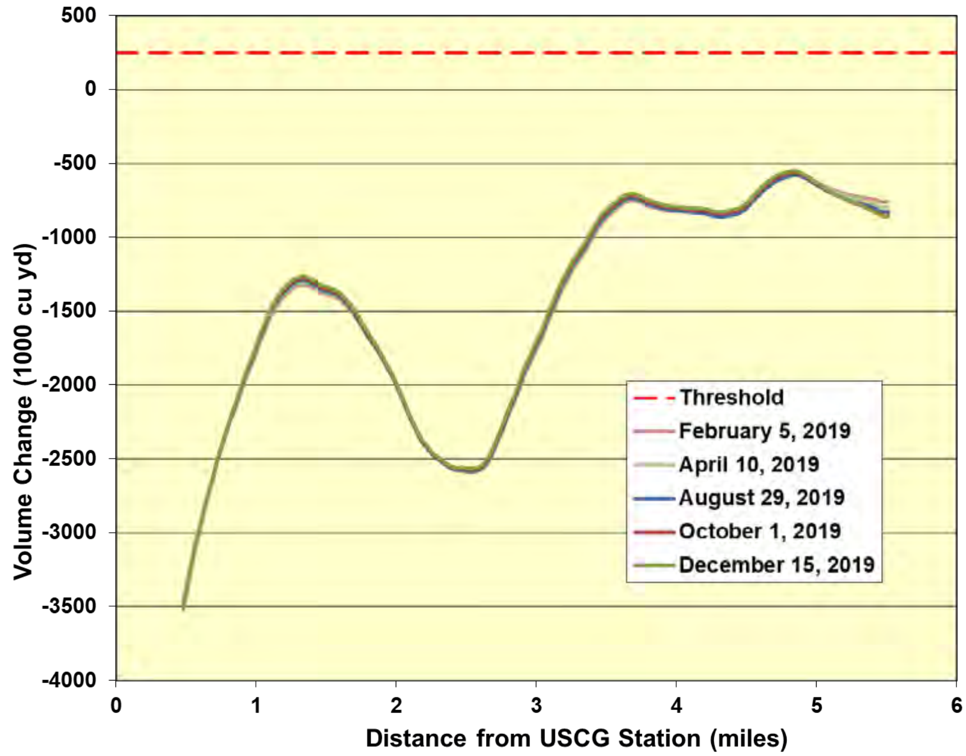

Figure 55. One-Mile Volume Change for 2019.

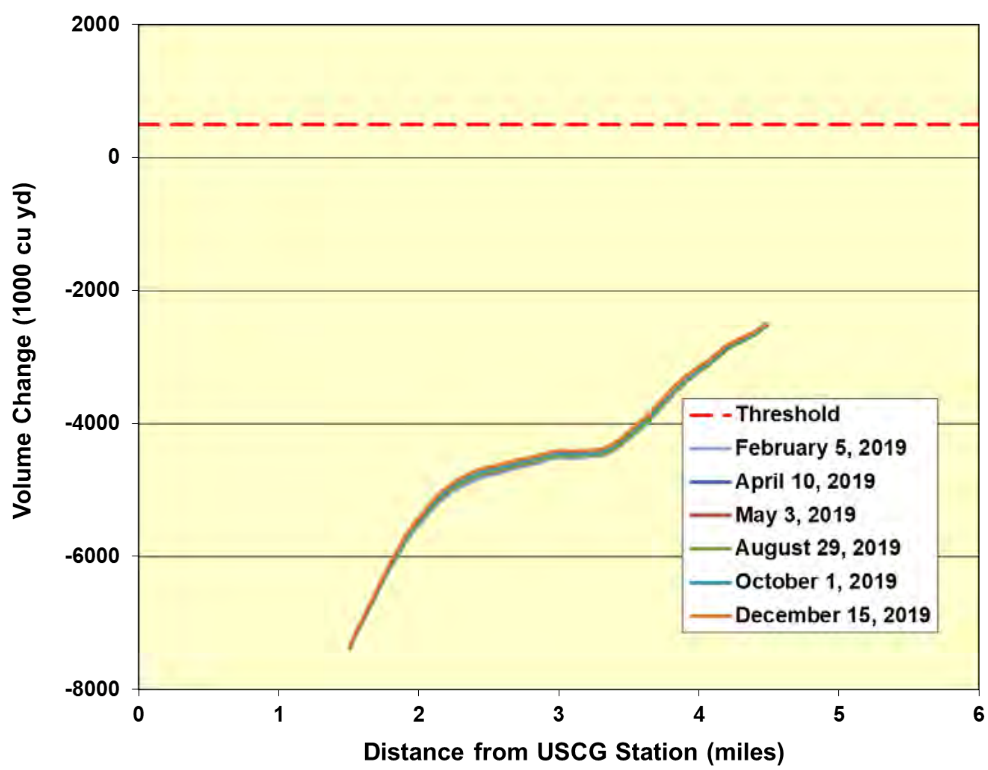

Figure 56. Three-Mile Volume Change for 2019.

Terminal Groin Monitoring Summary and Conclusions

As of December 15, 2019, the project erosion rate does not exceed the historical rate at any point in the first six miles south of the Oregon Inlet terminal groin. The one and three mile volume calculations are well below that which would be expected using the historical erosion rate. In summary, the construction of the groin does not appear to have caused an adverse impact to the shoreline over the six-mile study area.

5. HIGHWAY VULNERABILITY CONCLUSIONS

Figure 57 illustrates the changes in vulnerability throughout 2019, including values for each indicator as well as a composite of the three at each photo date. For the dates when no topographic data were obtained, the dune crest height corresponding to the previous photo date was used.

In order to assess overall vulnerability at each transect during 2019, a composite of three of the primary criteria discussed in this report was created, and it is shown in Figure 58. The summary criteria were: 1) Island width (measured as distance from ocean to estuarine shoreline) less than 1000 ft; 2) Dune crest elevation less than 10 ft above NC 12; and 3) The critical buffer, where the NC 12 edge of pavement was within 230 ft of the present shoreline. In a change from previous reports, and based on feedback from meetings with NC DOT and US FWS, this figure shows the composite vulnerability based on the transect meeting the criterion at any point during the study year (i.e., if one transect met the island width criterion in February and the critical buffer criterion in December, it would be reported as having met two criteria during the study year). This change has led to an overall increase in the reported numbers of vulnerable transects.

In reports between 2011 and 2017, the four transects within the original Pea Island Breach (and the associated temporary bridge) were excluded from the vulnerability analysis. NCDOT completed construction of a 0.5-mile interim structure in late 2017. Because the new structure is not intended as a long-term solution for the maintenance of NC 12, this analysis will continue to assess the distance between the edge of pavement (bridge) and the ocean shoreline within the interim bridge area. All transects are included in the composite vulnerability plots from the 2018 report and moving forward.

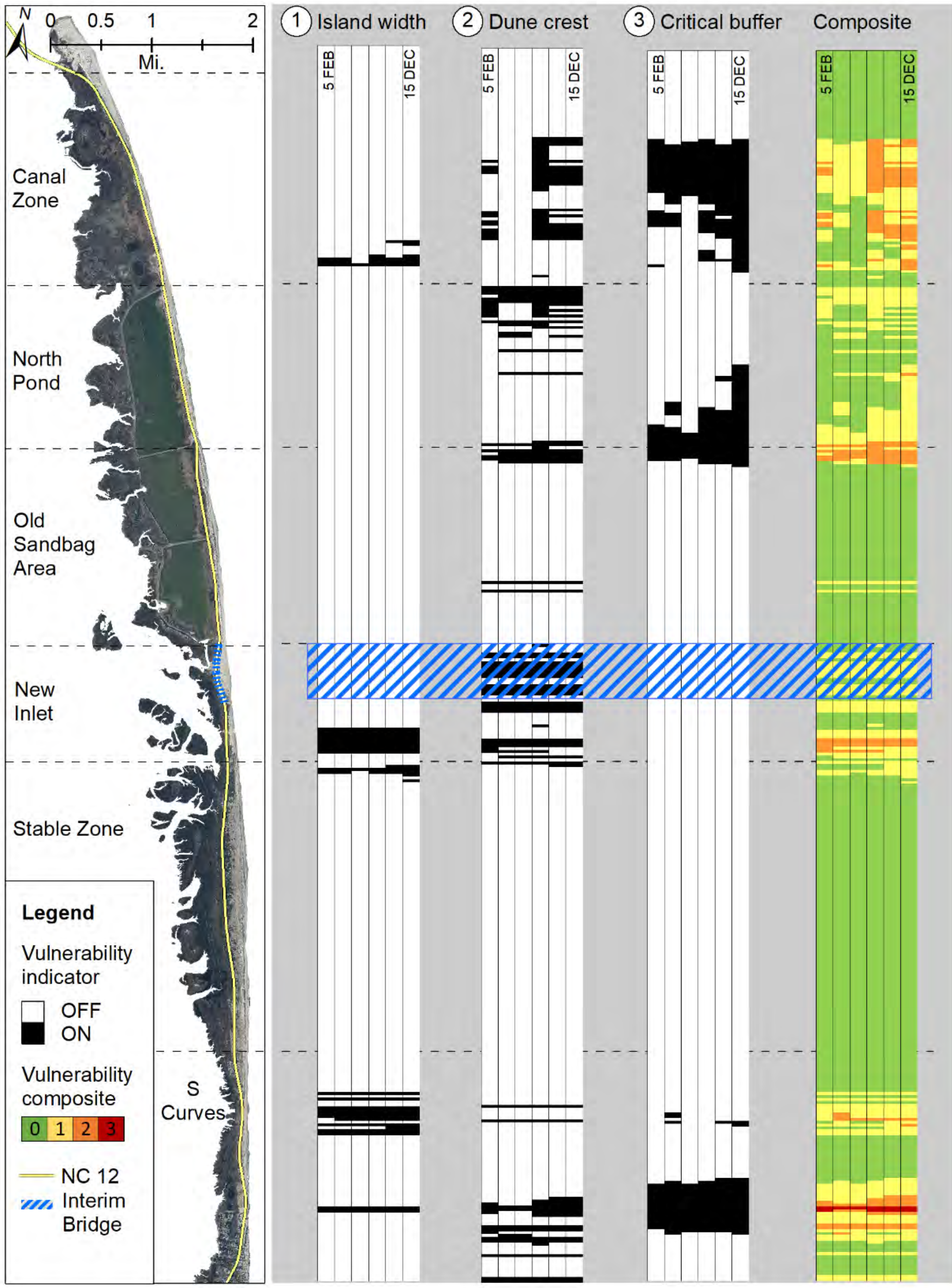

Figure 57. Composite NC 12 vulnerability along the study area at each photo date; note that for the May and December imagery, the dune crest height at the previous date was used because no topographic data were obtained.

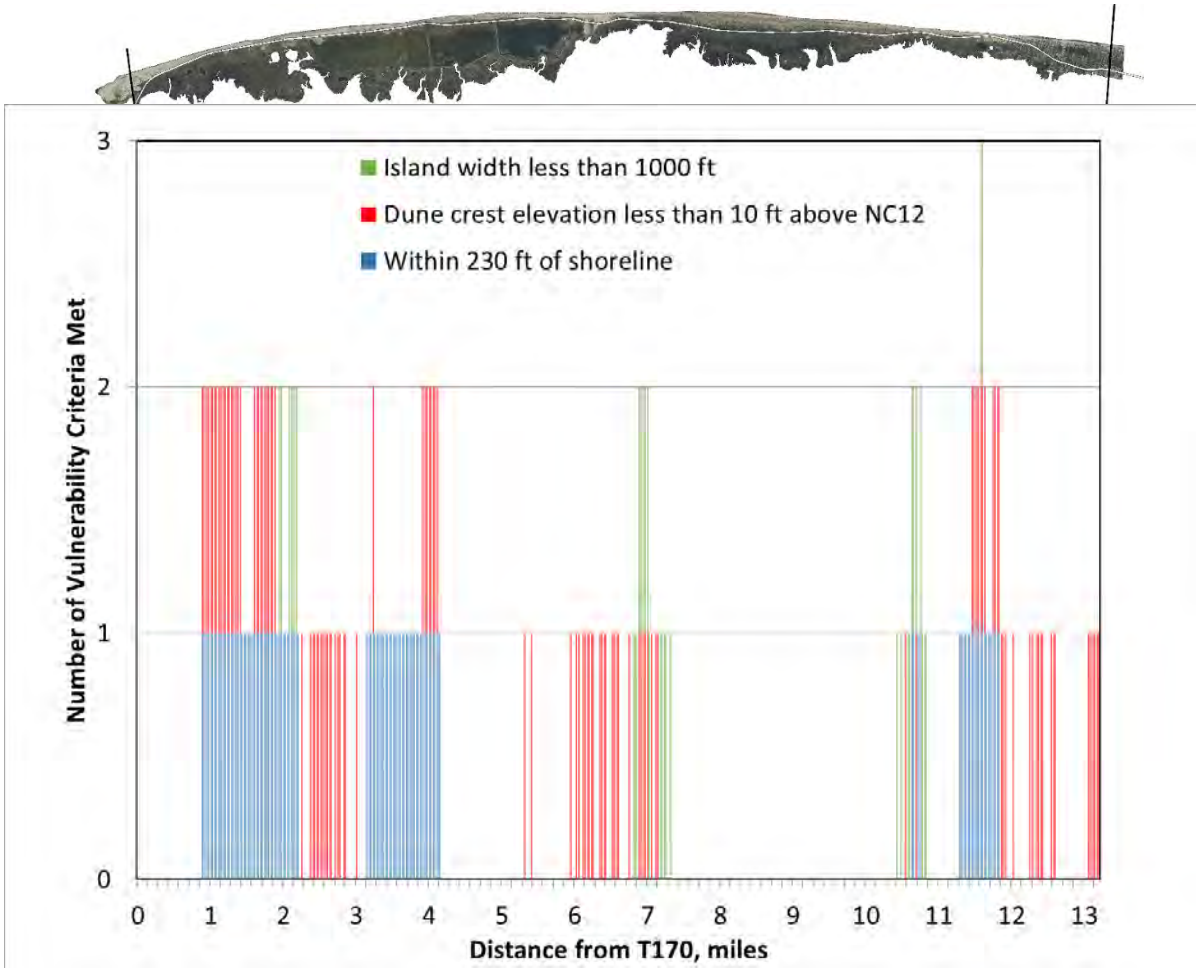

Figure 58. Composite NC 12 vulnerability along the study area, considering criteria met during any of the photo dates in 2019.

As determined by the established 230 ft critical buffer vulnerability criteria, there were 107 transect locations along NC 12 that were vulnerable in 2019, an increase from the number reported at the end of 2018. The transects where the shoreline was located within the 230 ft buffer were Transects 201-247 Transects 280-315, Transects 542-543 and 545-546, and Transects 565 to 584.

There were 33 transects at which the island widths were less than 1000 ft during the 2019 study year: Transects 238-239 and 243-246 in the Canal Zone, Transects 408-416 and 421-424, 426 south of the Pea Island Breach; 11 transects distributed between Transects 535 and 549 (narrow area north of Rodanthe, approximately miles 10.4 - 10.8); and Transects 575 and 576 (approximately mile 11.5 near the southern refuge boundary).

There were 117 transects with dune crest elevations less than 10 ft above the NC 12 centerline elevation at some point in 2019. The transects with dune crest elevations less than 10 ft above the NC 12 elevation are widely distributed over the study area, with the exception of the well-developed dune field in place from approximately miles 7.5 to 10.5 south of the Old Coast Guard Station.

The areas of primary concern (meeting more than one of the criteria) as shown on Figure 58 were located in the Canal Zone, near the Pea Island Visitors Center between the north and center ponds, south of the Pea Island Breach, and in northern Rodanthe.

Figure 59 presents a comparison of the vulnerability from the baseline report to the present (2019) report. These conditions are the conditions at the end of each study year. The transects that have been the most vulnerable throughout the study period are highlighted in red (Transects 244-245 and Transects 575-576).

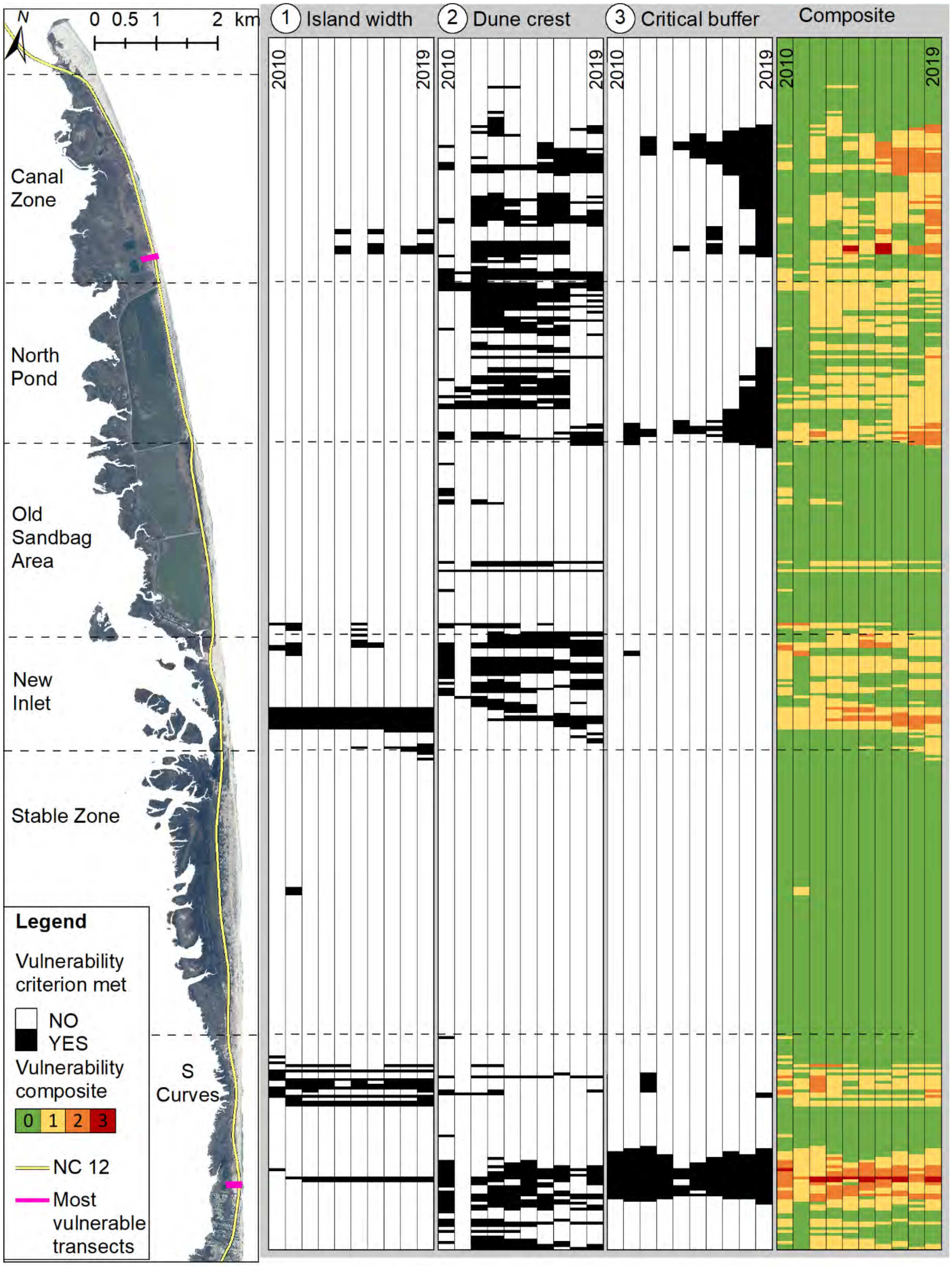

Figure 59. Comparison of vulnerability from the baseline report to the 2019 report. Vulnerabilities reported at the end of each study year.

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APPENDIX A

NCDOT Physical and Biological Monitoring Reports – 2019

August 26, 2019

Memorandum To: John Conforti, REM, Senior Project Manager/Eastern Region
Project Management Unit
Michael Turchy, Environmental Program Supervisor
Environmental Analysis Unit

From: Tyler Stanton, Environmental Program Supervisor
Environmental Analysis Unit

Subject: Seabeach Amaranth Survey (2019) for B-2500 Phase I and Phase IIa, Dare County.

Dear Mr. Conforti,

The proposed projects include 1) the construction/demolition/removal of a bridge to replace the Herbert C. Bonner Bridge at Oregon Inlet and 2) construction/demolition/removal of a bridge to replace the temporary bridge at New Inlet in Dare County, NC.

Seabeach amaranth (*Amaranthus pumilus*) is federally-listed as "Threatened" by the U.S. Fish and Wildlife Service for Dare County. A description for the species follows:

Amaranthus pumilus Seabeach amaranth Plant
Family: Amaranthaceae
Federal Status: Threatened, April 7, 1993 Flowers
Present: June till frost
Survey Window: July – October
NC Distribution: Brunswick, Carteret, Currituck, Dare, Hyde, New Hanover, Onslow, Pender.

Seabeach amaranth is an annual plant that grows on sand dunes in clumps containing 5 to 20 branches and are often greater than a foot in width. The trailing stems are fleshy and reddish-pink or reddish in color. Seabeach amaranth has thick, fleshy leaves that are small, ovate-spatulate, emarginate and rounded. The leaves are usually spinach green in color, cluster towards the end of a stem, and have winged petioles. Both fruits and flowers are relatively inconspicuous and borne along the stem. Seabeach amaranth is endemic to Atlantic Coastal Plain beaches.

Seabeach amaranth occurs on barrier island beaches where its primary habitat consists of overwash flats at accreting ends of islands, lower foredunes, and upper strands of noneroding beaches (landward of the wrack line). In rare situations, this annual is found on sand spits 160 feet or more from the base of the nearest foredune. It occasionally establishes small temporary populations in other habitats, including sound-side beaches, blowouts in foredunes, interdunal areas, and on sand and shell material deposited for beach replenishment or as dredge spoil. The plant's habitat is sparsely vegetated with annual herbs (forbs) and, less commonly, perennial herbs (mostly grasses) and scattered shrubs. It is, however, intolerant of vegetative competition and does not occur on well-vegetated sites. The species usually is found growing on a nearly pure silica sand substrate, occasionally with shell fragments mixed in. Seabeach amaranth appears to require extensive areas of barrier island beaches and inlets that function in a relatively natural and dynamic manner. These characteristics allow it to move around in the landscape, occupying suitable habitat as it becomes available.

In accordance with conservation measures set forth in the U.S. Fish and Wildlife Service (USFWS) Raleigh Field Office's Biological and Conference Opinions of the Bonner Bridge replacement, plant surveys were conducted on August 12, 2019. A survey for habitat as well as species presence within the project limits was conducted.

Surveys were conducted within the project area of Phase I, from north of the Oregon Inlet Marina and Fishing Center Parking lot on the beach side (accessed by ramp #4) to the end of Bodie Island by Cape Hatteras National Seashore biologists, and on Hatteras Island from the Terminal Groin to approximately 2500' south of the Bonner Bridge to the entrance of the service road that leads to the old coast guard station by RK&K staff.

Surveys were also conducted at locations north of Rodanthe; 1.5 miles on either side of the Pea Island inlet (New inlet). Survey team members accessed the project study area locations by Utility Terrain Vehicle (UTV) and conducted surveys on foot. Surveys were concentrated in habitat consisting of overwashed locations and lower foredunes. Additional habitats, including, blowouts in foredunes, and sand/shell material areas placed as a result of NC 12 maintenance were also investigated.

A review of the North Carolina Natural Heritage Program's database (updated 7/08/19) of rare species and unique habitats indicates no seabeach amaranth plants within the project region. However, since it is listed for Dare County, surveys were conducted. No plants were observed during the 2019 surveys.

According to the Cape Hatteras National Seashore, Seabeach Amaranth Surveys 2014 Annual Report, no plants have been found within the seashore since 2005.
https://www.nps.gov/articles/caha_sba2014.htm

Based on these findings, we consider the biological conclusion associated with seabeach amaranth for B-2500 to be "**No Effect**".

STATE OF NORTH CAROLINA
DEPARTMENT OF TRANSPORTATION

ROY COOPER
GOVERNOR

J.ERIC BOYETTE
SECRETARY

04/17/2020

Mr. Tyler Stanton
Biological Surveys Group Project Manager
NCDOT Environmental Analysis Unit
1598 MSC
Raleigh NC, 27699-1598

April 2020

Memorandum To:	Nora McCann, Project Manager, Project Management Unit Michael Turchy, Environmental Program Environmental Analysis Unit
From:	Tyler Stanton, Environmental Supervisor Environmental Analysis Unit
Subject:	2019 Data Summary: Shoreline Monitoring of Physical and Biological Condition of the Beach Sand on Pea Island National Wildlife Refuge, Dare County, NC

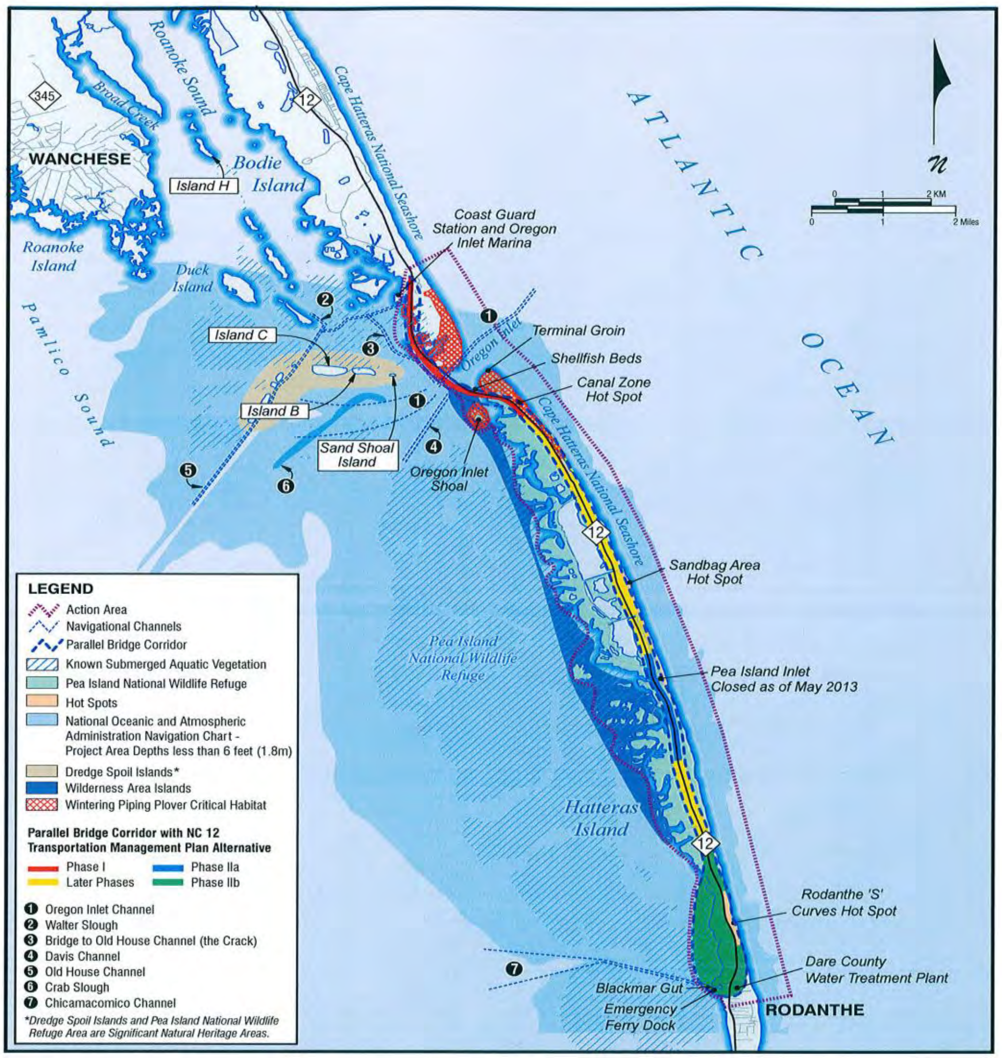
Introduction

This report summarizes and graphically presents the results of eight years (4 quarterly sampling events per year) of monitoring the physical and ecological condition of the beach on Pea Island National Wildlife Refuge (PINWR) from the Terminal Groin to Mirlo Beach.

In 2012, as a condition of the new easement for Retention and Maintenance of the Oregon Inlet Terminal Groin at Pea Island NWR, the North Carolina Department of Transportation Biological Surveys Group, (NCDOT BSG) implemented a monitoring program to provide the US Fish and Wildlife Service (USFWS) with data on the physical and biological attributes of the beach sand on PINWR. This study encompasses the entire length of the Refuge beach, from the Terminal Groin to Rodanthe.

The purpose of this multi-year study is to monitor the environmental effects of the Terminal Groin and any future beach nourishment or other activities on Pea Island National Wildlife Refuge in Dare County, NC.

Sampling was conducted quarterly; usually in January, April, July and October. There are 64 total transects beginning at the terminal groin (TG) and continuing south every 0.2 miles to the southern terminus of PINWR in Mirlo Beach. The first transect is located 0.1 mi south of the TG (numbered TG1), the 2nd 0.3 mi south of the TG (numbered TG2) and the third 0.5 mi south of the TG (numbered TG1, TG2). TG1 through TG 29 continue with odd numbers, so that they coincide with existing PINWR data points, and are located at 0.2 mi intervals, T 30 is located 0.1mi from T29 and subsequent transects are located at 0.2 mi intervals (and numbered in sequence) to the southern boundary of the Refuge.



BIOLOGICAL ASSESSMENT ACTION AREA AND NATURAL RESOURCE-RELATED FEATURES | Figure 1

Meteorological and Other Activities Affecting the PINWR Beach

In August 2011 Hurricane Irene breached NC12 in two locations in the project area – in northern Rodanthe (the "Rodanthe breach") approximately 12 miles south of Oregon Inlet and within the Pea Island National Wildlife Refuge (Refuge) approximately 6 miles south of Oregon Inlet (the new "Pea Island inlet") (see Figure 1). NCDOT repaired the section of NC12 at the Pea Island inlet by installing a temporary bridge across the inlet. This temporary bridge was completed in October 2011. The Rodanthe breach was filled using sand sources from Hatteras Island, and the NC12 roadway was repaired within the existing easement. Since then, this bridge has been replaced by an interim bridge over the Pea Island breach to provide for interim safe and reliable transportation while the long-term solution is re-evaluated and constructed.

Hurricane Sandy, in October 2012, and two subsequent northeasters in November 2012 caused extensive shoaling near the mouth of the Pea Island inlet. Overwash during Hurricane Sandy resulted in more than three miles of dunes being lost or severely damaged between Oregon Inlet and Rodanthe. Repair work on NC12 including rebuilding the sandbag dune at the S-curves occurred between November 2012 and January 2013. As of May 2013, the Pea Island Inlet closed as a result of naturally-occurring coastal processes.

From November to December 2013 sand was bypassed from a dredging operation in Oregon Inlet to the PINWR beach just south of the Terminal Groin. Approximately 581,000 cubic yards of sand were deposited on the Pea Island beach just south of the terminal groin.

From May through October 2014 a beach nourishment project was conducted on the southern 2 miles of PINWR and further onto National Park Service beach property. The sand sampling event occurred 1 week after the completion of the project and Transects 66 thru 73 occur in the nourishment area (Figure 2).

Hurricane Arthur, in July 2014, hit the outer banks, including Pea Island as a Category 2 Hurricane. Hurricane Arthur caused the Inlet, that was originally opened by Hurricane Sandy, to re-open; however, flow in subsequent weeks was reduced to limited sheet flow during high tides and the inlet closed again.

In the winters of 2015 and 2016, heavy Nor'easters hit Pea Island with 30-45 mph winds and gusts in the upper 60+ mph range. The surf was approximately 12+ feet causing flooding and major washouts. Nor'easters are common during the winter, but many are not this intense.

In September 2016, Hurricane Hermine hit as a tropical storm, with heavy rainfall. Directly following in October 2016 Hurricane Mathew brings record rainfall and devastating flooding to the area. Hurricane Mathew brought approximately 9.4 inches of rain and wind speeds reached 74 mph.

On September 18, 2017 Hurricane Jose passed the outer banks as a tropical storm with sustained winds of 85 mph, causing major flooding along PINWR and NC12. Although the strongest winds stayed offshore, with no direct hit to the outer banks, approximately 4 inches of standing water was reported causing closures of NC12 through the PINWR.

On September 26 and 27, 2017 Hurricane Maria downgraded to a tropical storm with sustained winds of 70 mph before hitting the outer banks of NC, including the PINWR. Maria brought high storm surges with flooding which led to the temporary closure of many roads in the area. At the time, because of the predicted damage due to high winds and a water level rise of at least 2-4 ft, an evacuation was recommended in this area.

Winter Storm Riley affected the US East Coast in early March 2018 causing coastal flooding and beach erosion over multiple high tides prompting the closure of NC12 through PINWR during these high tides.

Tropical Strom Chris formed off the coast of North Carolina in early July 2018. This storm caused heavy rain and erosion. High swells from the storm affected multiple areas along the Outer Banks.

Hurricane Florence, on September 14, 2018, brought winds up to 90 mph to the island with ocean overwash and a 13-foot storm surge. This contributed to dune erosion within PINWR. NCDOT closed NC12 between Hatteras Village and the Bonner Bridge noting multiple locations were impassable including areas near PINWR.

Hurricane Michael was downgraded to a tropical storm as it passed through North Carolina on October 11 and 12, 2018. Gusts were observed as high as 74 mph in the northern Outer Banks including PINWR and water levels, from the storm surge, were 2-4 feet above ground level.

On September 6, 2019, Hurricane Dorian made landfall on Ocracoke Island and moved north over Hatteras Island causing severe beach erosion. This storm also resulted in a 7ft. storm surge on the sound.

October 11 and 13, 2019 Sub-Tropical storm Melissa hung offshore during a Harvest Moon tide causing three-four days of high tide overwash of NC12 which buried the S-Curves area under approximately 5 ft of sand.

On November 16 and 17, 2019 heavy winds, up to 45 mph, and rain caused sand overwash and flooding: the storm compromised NC12 near Hatteras causing closures from Marc Basnight Bridge (Oregon Inlet) to Rodanthe.

SAMPLING METHODS

Macrobenthos

The swash zone of a beach is a constantly changing and complex habitat that supports many species of organisms unique to shorelines. Surf clams and mole crabs are two species that stand out as inhabitants of the surf zone. Both animals are extremely fast burrowers, able to rebury themselves almost as fast as they become exposed in shifting sands. The surf clam, also known as the coquina clam (*Donax variabilis*), is a filter feeder that uses its gills to filter microalgae, tiny zooplankton, and small particulates out of seawater. The mole crab (*Emerita talpoida*) is a suspension feeder that feeds by capturing zooplankton with its antennae. Further up the beach, somewhat removed from intense wave action, is where the ghost crab (*Ocypode quadrata*) makes its home by burrowing into the sand. (Dolan, et al. 2004).

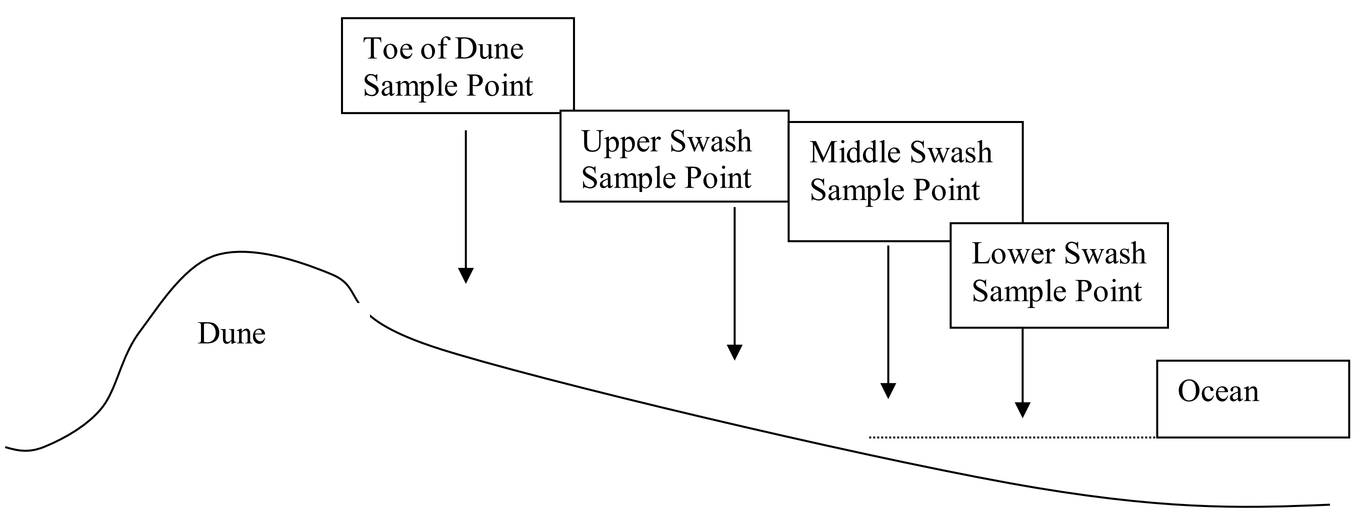
Figure 2. Location of Transects, Pea Island National Wildlife Refuge, Dare County, NC Within the 2014 Beach Nourishment Area.

These organisms serve as excellent indicator species for estimating the overall physical conditions of sandy beaches as well as deviations from the natural state of these beaches. These two taxa (mole crabs and coquina clams) do not flourish when the beach sand is too coarse, too fine, or polluted. Both have adapted to rapid physical changes in the swash-zone in order to maintain their positions in the beach to optimize feeding efficiency. To ensure survival, these intertidal organisms must respond rapidly to the changes that beach nourishment introduces or perish. Any changes to the beach that impact coquina clams and mole crabs have ecological impacts far beyond the swash zone (Dolan, et al. 2004).

Finer sand with a heavier mineral content increases compaction which makes it harder for the clams and mole crabs to burrow in and out of the sand. Decreases in the abundances of these animals, as well as ghost crabs, results in a loss to the base of the food chain on PINWR.

Benthos Field Methods
Three sand samples were taken from each transect at random locations within the swash zone. In addition, a ghost crab burrow count was made in the upper beach area at the foot of the dunes. To conduct these counts a 1-meter diameter hoop was randomly tossed three times in the area between the toe of the dune and the wrack line. The number of crab burrows were counted from each toss and combined. The benthic sand samples were taken using a cylindrical corer with internal diameter of 4” (PVC pipe), inserted 4” into the swash zone. The resulting sample was then filtered through a 1mm mesh sieve to isolate the macrofauna. The mole crab (Emerita spp.) individuals were measured for separation into size classes, enumerated and released. Donax spp., amphipods and worms were enumerated and released. The size classes for Emerita sp. are as follows: Small (1-4mm), Medium (4-8mm), and Large (>8mm). Physical data collected included water temperature, air temperature, wave height, salinity, sand bar distance offshore, and presence and height of erosion scarps on the beach face. Digital photographs were taken at each transect during each sampling occurrence.

SAMPLE TRANSECT



Collecting benthos sample in swash zone

Sand sample in sieve

Counting benthos

Emerita talpoidea

Coquina clams in the swash

Sand Sampling Introduction

Sediments that comprise the beaches and barrier islands of the Outer Banks of NC can be described in three size classes: Coarse, consisting of sands and gravel (0.5mm up to 2mm), medium (0.25mm to 0.5mm) and fine (grain size below 0.25mm) (Dolan et al, 2004). Changes to beach sand size or color (mineral content) can affect its biological and ecological processes. Darker sand will cause an increase in temperature that could affect turtle hatching and changes in sand coarseness will alter the distribution and density of the benthic community and could result in changes to beach slope and scarping if too much fine sand is deposited. The sand used to nourish the beach at the project location must be compatible with regards to grain size and mineralogy to the indigenous sand of Pea Island.

Sand Field Methods

Each of the 64 transects has 4 sample locations for a total of 256 samples. The upper beach sample was collected at the toe of the dune at a depth of 8-12 inches. The upper swash surface sample was collected at the wet line. The lower swash sample was collected half way between the upper and lower swash areas. All swash samples were collected within 6 inches of the surface. Samples and sample locations were identified by the site: Transect (1 through 76) and location (toe of dune=D, upper-swash=C, mid-swash=B, lower-swash=A).

Compaction and the slope of the beach were measured from each transect just above the upper swash zone. Each sand sample was analyzed for grain size and heavy mineral content.

Compaction measurements were collected just above the upper-swash zone from the surface to 12-inches deep with a DICKEY-john® Soil Compaction Tester. Compaction measurements were recorded every three inches. According to United States Army Corp of Engineers personnel, this equipment (DICKEY-john® Soil Compaction Tester) is commonly used for compaction testing in similar studies. There is no ASTM method associated with the soil compaction tester. Slope measurements were made using a Brunton™ compass placed on a 12-inch board. The 12-inch board was oriented perpendicular to the water's edge.

Sand samples consisting of an amount equivalent to about ¼ cup of material were placed in sealable polyethylene bags for lab analysis. Samples were submitted to the NCDOT Materials and Test Unit Soils laboratory for sieve analysis and to the North Carolina Geologic Survey for heavy mineral analysis.

Collecting sand sample for grain size analysis

Laboratory Testing

Grain size analysis

Samples were delivered to the NCDOT Soil Laboratory for sieve analysis in accordance with 1995 Standard Specifications. The following sieve sizes were used for analysis. #4 (4.75mm), #10 (2mm), #18 (1mm), #25 (0.75mm), #35 (0.5mm), #60 (0.25mm), #100 (0.15mm), and #140 (0.106mm). The samples were dried, split evenly and approximately *spacing* 200 grams was weighed for sieve analysis. Samples were washed over the # 200 sieve until the wash water ran clear, transferred to a sample container and placed in an oven to dry at a temperature of 230 degrees Fahrenheit. Dried samples were then poured into the nest of required sieves and shaken for a short period of time. The retained material on each individual sieve was weighed and recorded.

Mean grain size was determined by calculating the mean of the 25th and 75th percentiles of the % of sand passing through each size sieve. The 25th, 75th percentile were determined by graphing the % passing results of each sample per sieve size.

Measuring compaction

Laboratory Testing

Minerals analysis

The samples were analyzed by the North Carolina Geological Survey Lab and the UNC Geology lab. Each of the two hundred and fifty-six (256) samples, per sampling event, was washed over a sieve with 62.5 micron, (4 phi (Ø), openings to remove salt water and any mud. The samples were then placed in a warm oven overnight until dry. The samples were reduced in size, with a sample splitter until a reasonably sized sub sample was obtained. Each sample was transferred into a Pyrex dish, 88 mm in diameter, spread out until a single layer of mineral grains was obtained, and then examined with a binocular microscope at 10x. Nine (9) random views were examined under the binocular microscope for each sample. The number of heavy mineral grains in each of the nine views were counted and recorded. Volumetric estimates were performed on the percent of heavy minerals by comparing the views with standard area percentage diagrams. An average number of heavy minerals for each of the 256 samples was calculated. An average percent of heavy minerals for each of the 256 samples was also calculated. Five (5) samples were chosen at random and re-counted for quality control. The QC analyses were within 10% of the original counts. Two (2) samples, per sampling event, were chosen and the heavy mineral content was identified to individual mineral species. The following minerals were identified: epidote, staurolite, garnet, kyanite, ilmenite, magnetite, zircon, tourmaline, rutile, and pyroxene/amphibole. Pyroxene and amphibole are grouped together due to difficulty in differentiating the separate minerals.

RESULTS AND ANALYSIS

Physical parameters and biological data were entered to an Excel spreadsheet after each sampling event. Tabulated sample results and copies of the raw data were submitted to the Pea Island NWR biologist at the end of the sampling year. An annual report will be submitted in hard copy and electronic format.

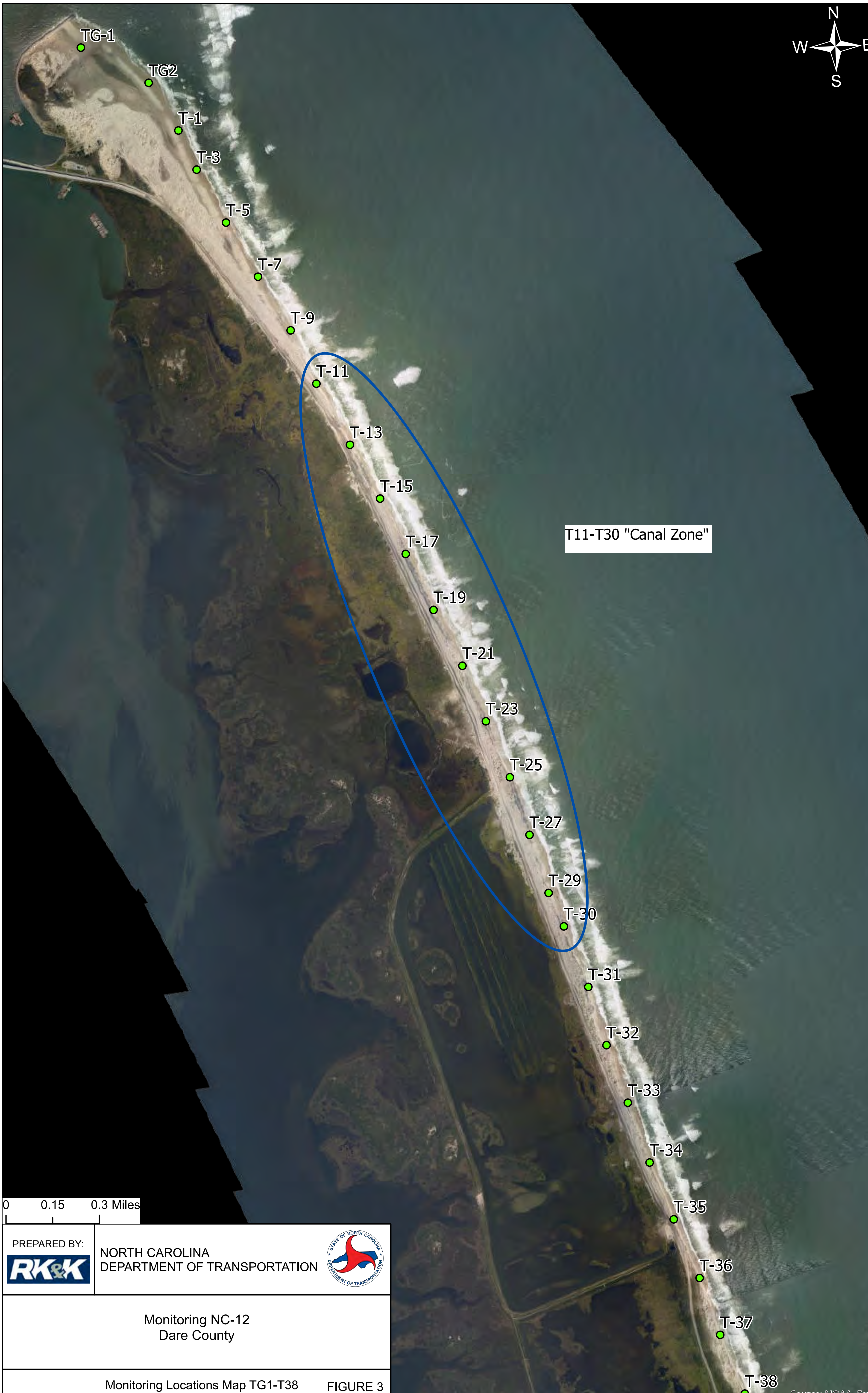
Data will be analyzed according to methods in Dolan, 2004: Analysis of Changes in the Beach Sediment and Beach-face Organisms Associated with Sand Bypassing from the Oregon Inlet to Pea Island, North Carolina, 1990-2002.

The graphs represented at the end of this document summarize the data collected in 2012 through 2019.

Beginning in 2018, three areas identified by the ongoing Coastal Monitoring Program as problem areas: the Canal Zone, the PI Inlet area and the Rodanthe S-Curves (Figures 3-7), were separated out and the data were analyzed to determine if these areas were exhibiting any changes that may have been masked by the overall island analysis. These graphs are presented after the overall analyses.

The 2019 data was analyzed with a cubic function rather than a linear function. This function indicates an inverse relationship between grain size and species abundance. Generally, grain size distributions and species abundance across the study area were as expected with seasonal and long-term variations. The data also indicate that major storms have an influence over benthic numbers, but these numbers recover over time.

When the three “trouble spots” were analyzed separately, the data indicates seasonal and long-term variation in congruence with the overall analysis. Although the relationship between grain size and abundance is different between each “trouble spot.” The data indicates a strong inverse relationship between grain size and abundance in the PI Inlet area, a weaker inverse relationship in the Canal Zone and a direct relationship at the Rodanthe S-Curve. The Inlet area had an average grain size between 0.8 and 1.0 mm from 2012 through 2019, while the average grain size within the other “trouble spots” were less than 0.8 mm. With this data we see a stronger correlation between grain size and species abundance as grain size surpasses 0.8 mm.



PREPARED BY: RK&K

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

Monitoring NC-12
Dare County

Monitoring Locations Map TG1-T38

FIGURE 3

Monitoring NC-12
Dare County

Monitoring Locations Map T38-T74

FIGURE 4

PREPARED BY: RK&K

NORTH CAROLINA
DEPARTMENT OF TRANSPORTATION

Monitoring NC-12
Dare County

T11-T30 "Canal Zone"

FIGURE 5

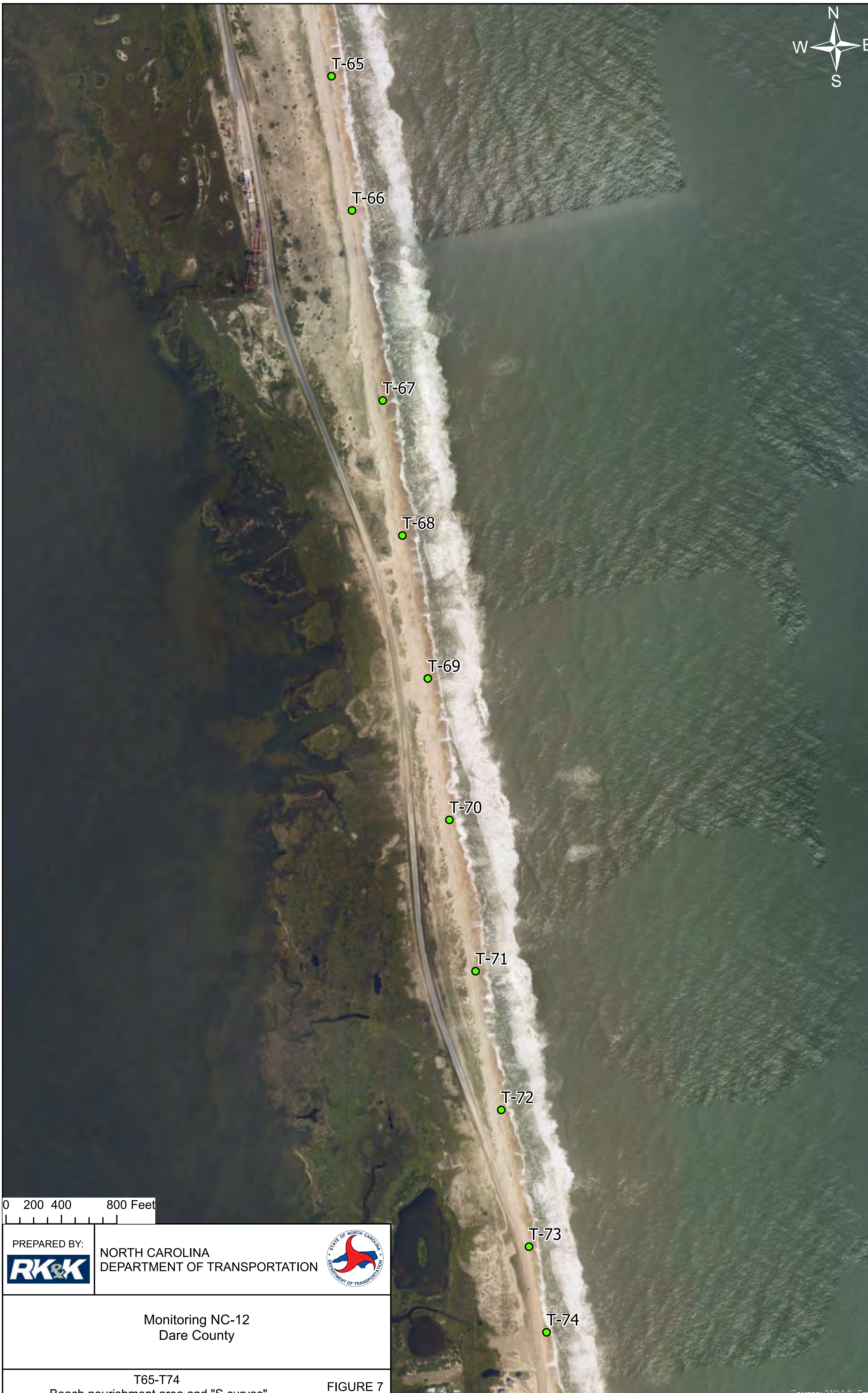
PREPARED BY: RK&K

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

Monitoring NC-12
Dare County

T47-T54 Narrow Area South of PI Inlet Area

FIGURE 6



PREPARED BY:
RK&K

NORTH CAROLINA
DEPARTMENT OF TRANSPORTATION

Monitoring NC-12
Dare County

T65-T74
Beach nourishment area and "S curves"

FIGURE 7

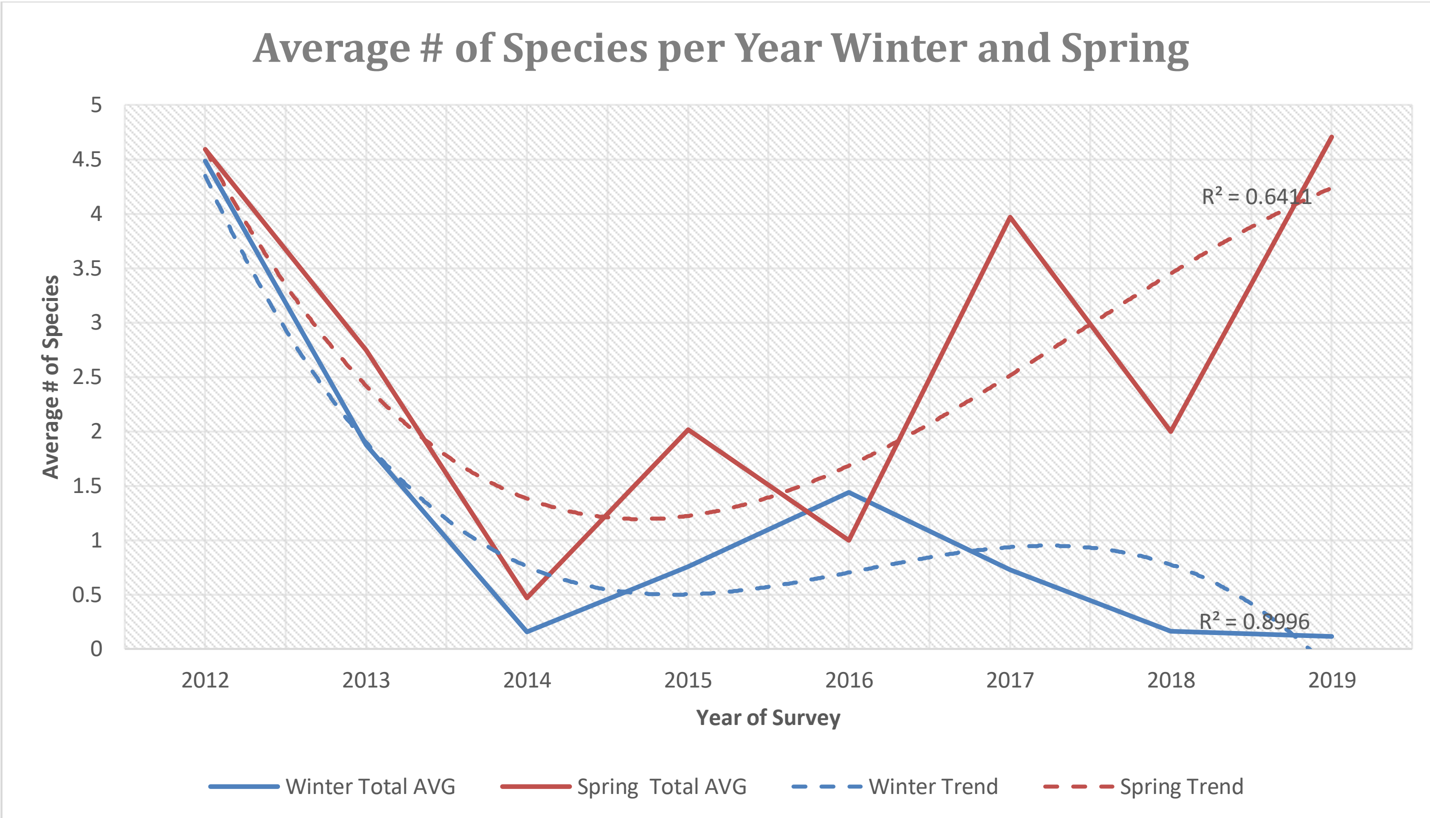


Fig.1 – Average number of species per Season in the Winter and Spring of 2012-2019.

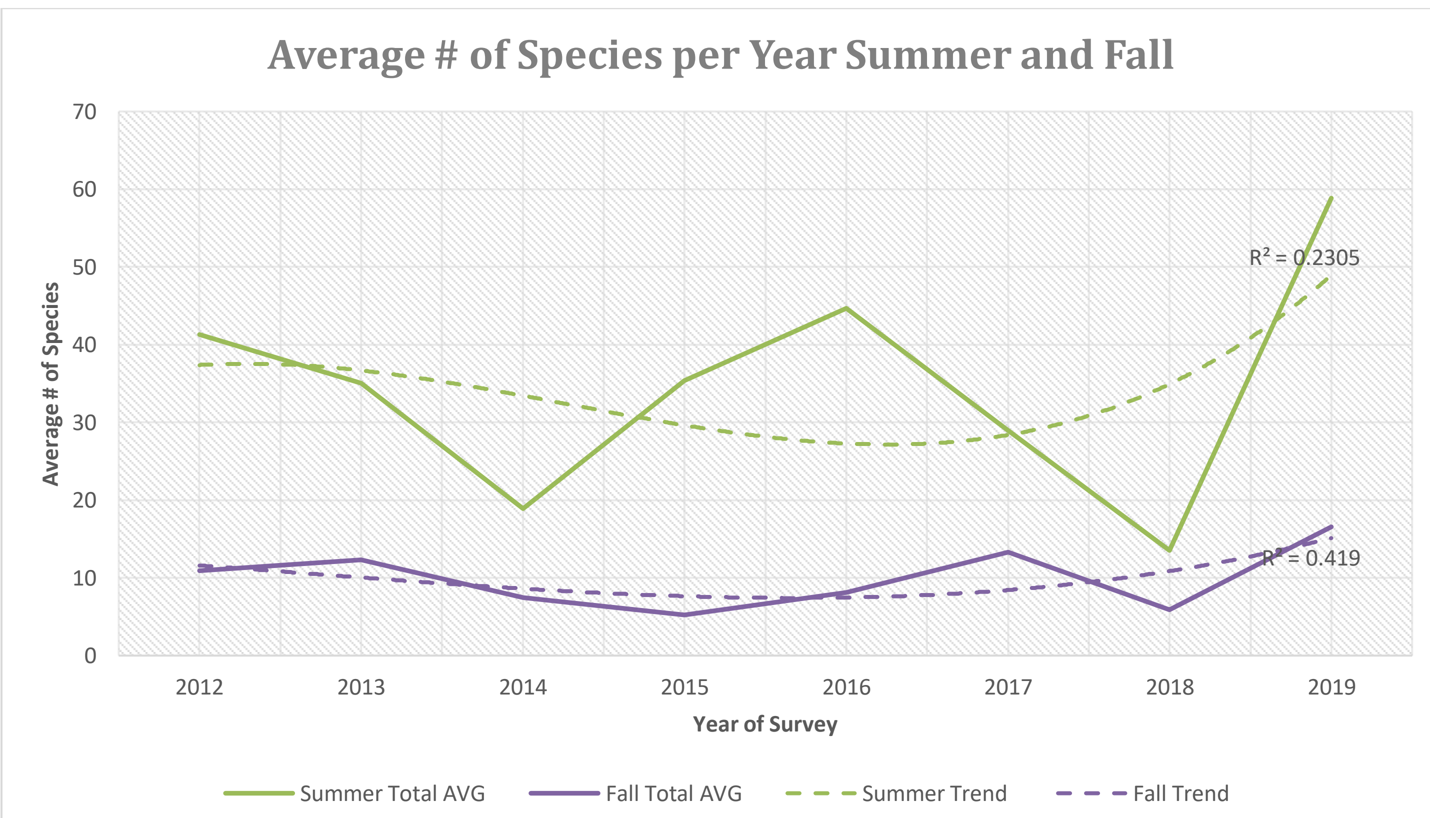


Fig.2 – Average number of species per Season in the Summer and Fall of 2012-2019.

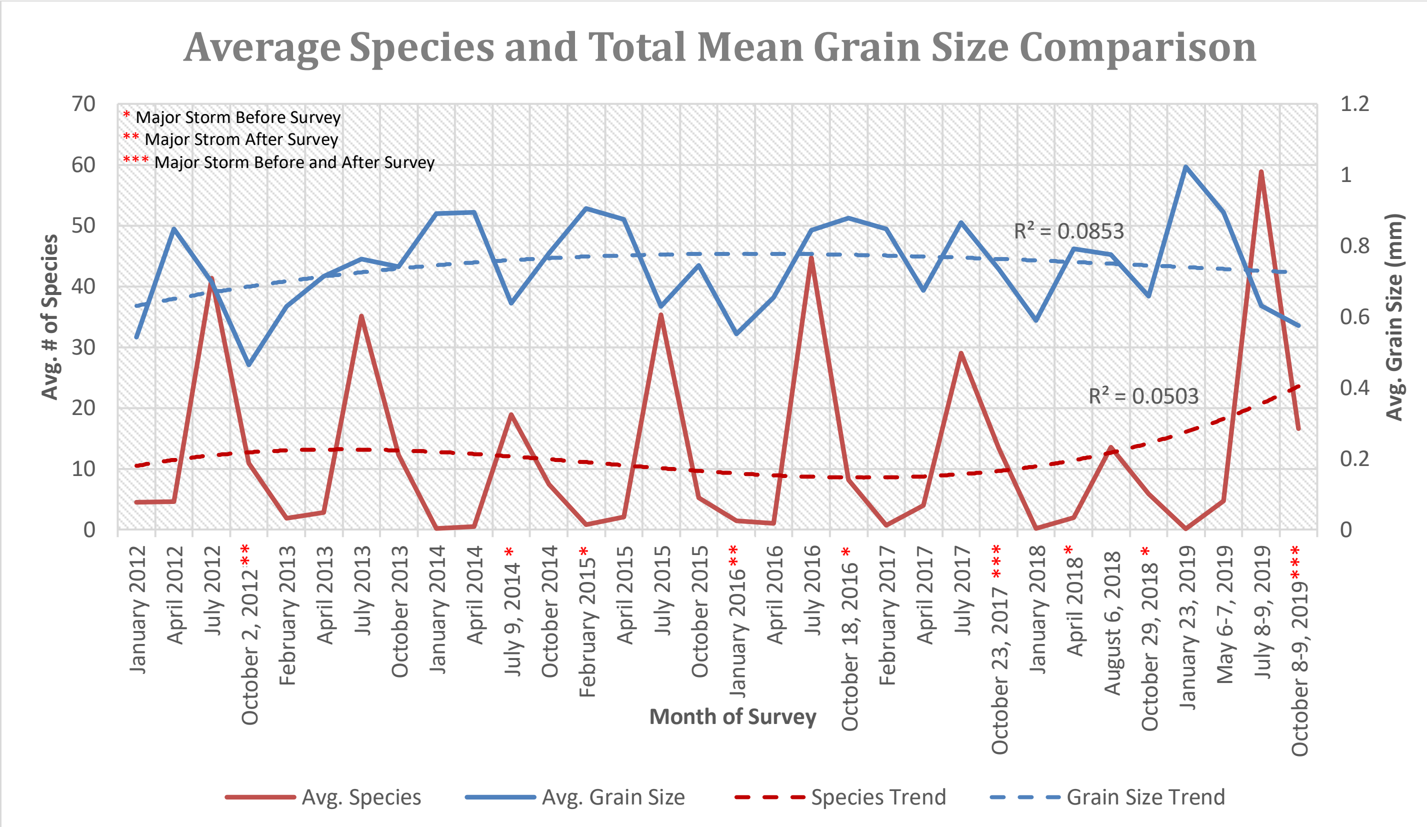


Fig. 3 – Average species and total mean grain size comparison.

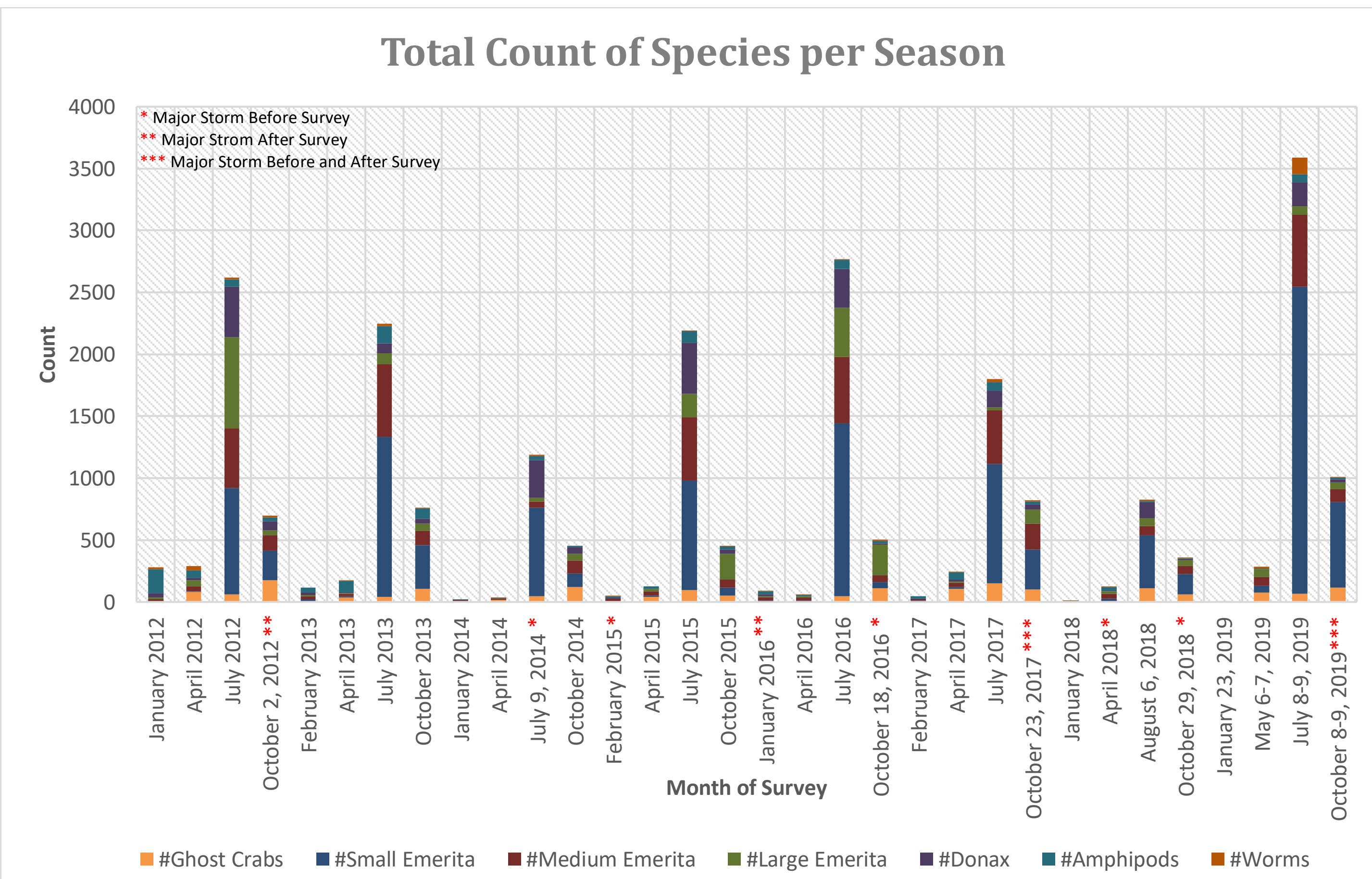


Fig. 4 – Total number of species found during each survey.

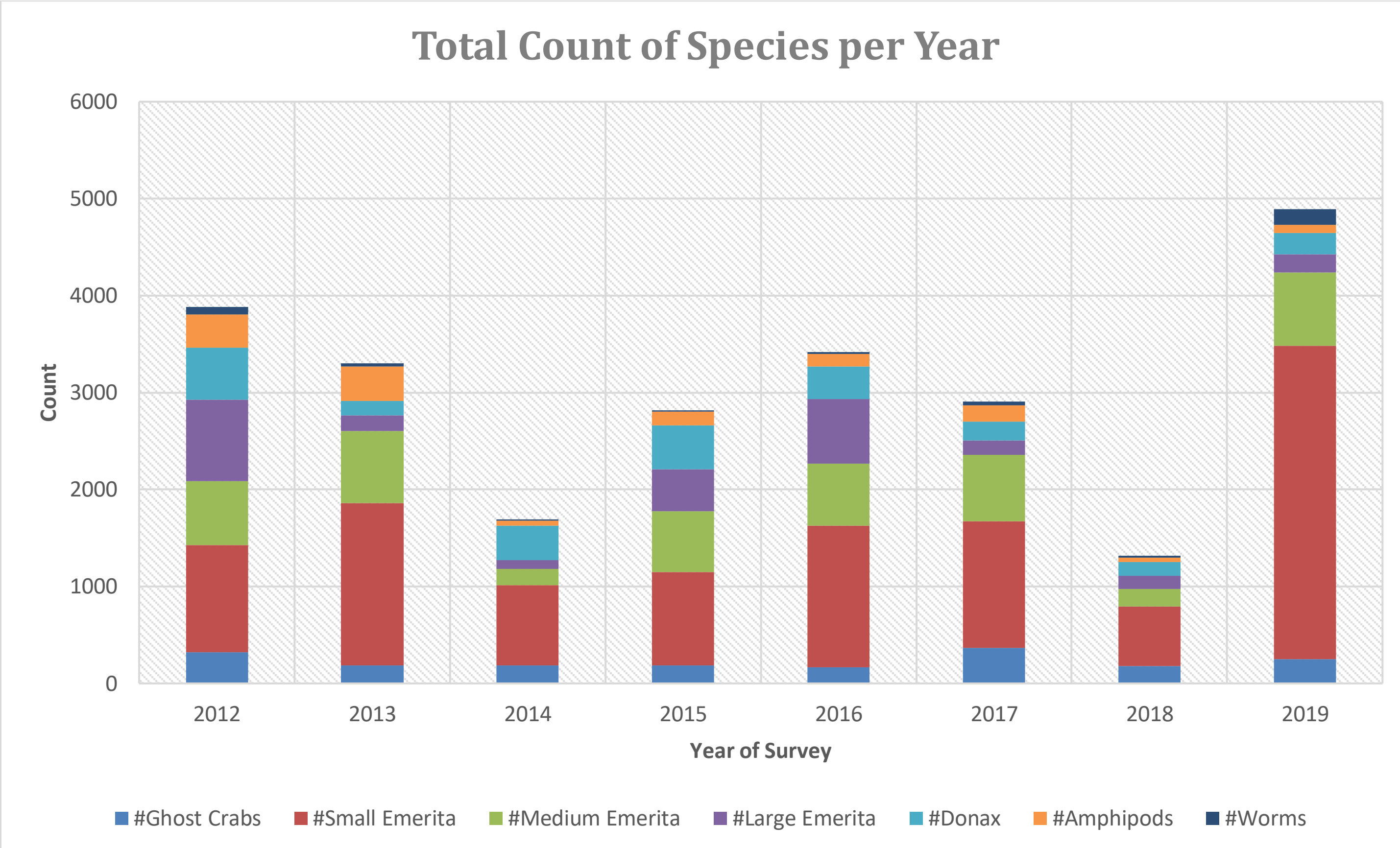


Fig. 5 – Total number of species found per year.

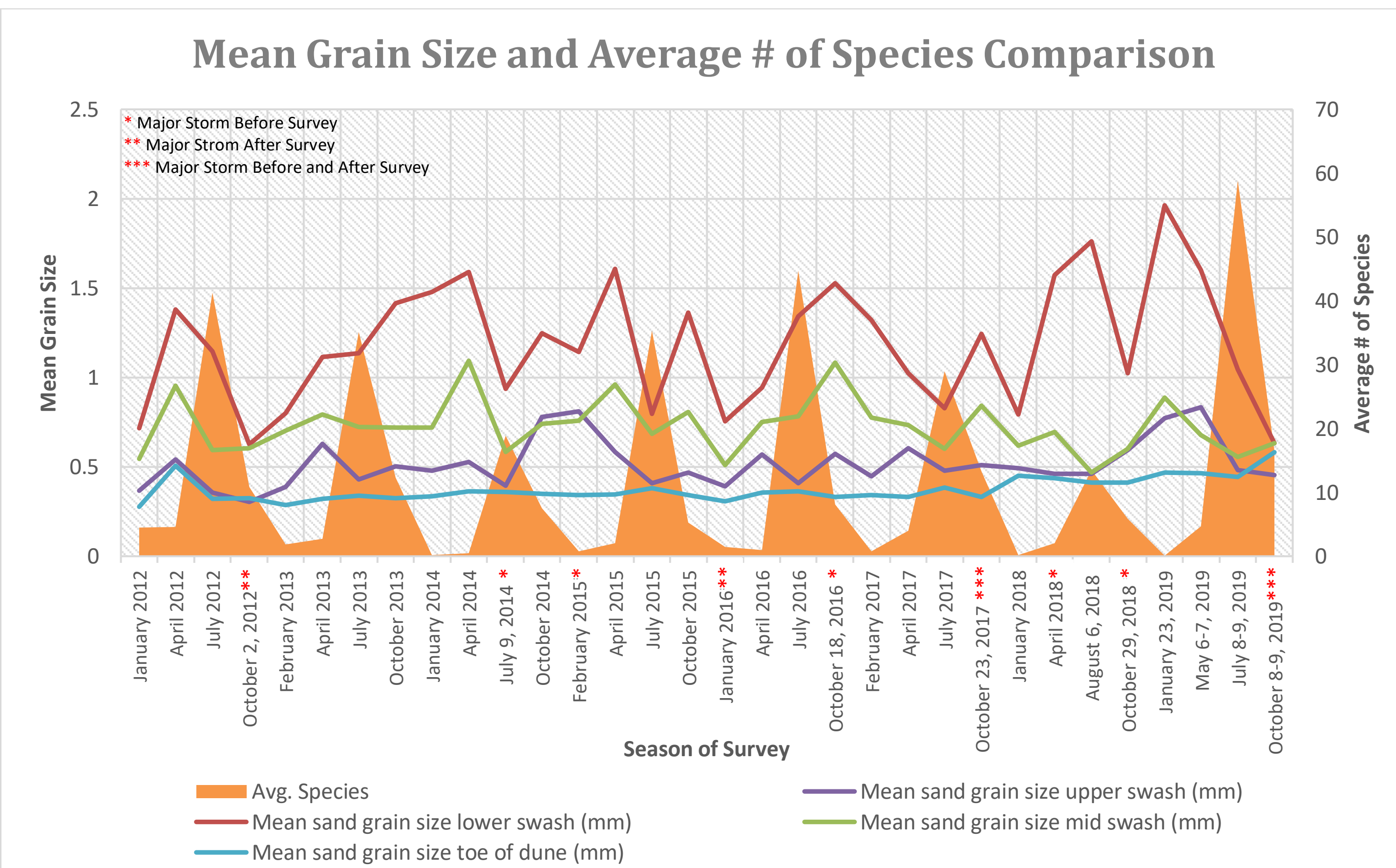


Fig. 6 – The mean grain size compared to the average number of species found per survey.

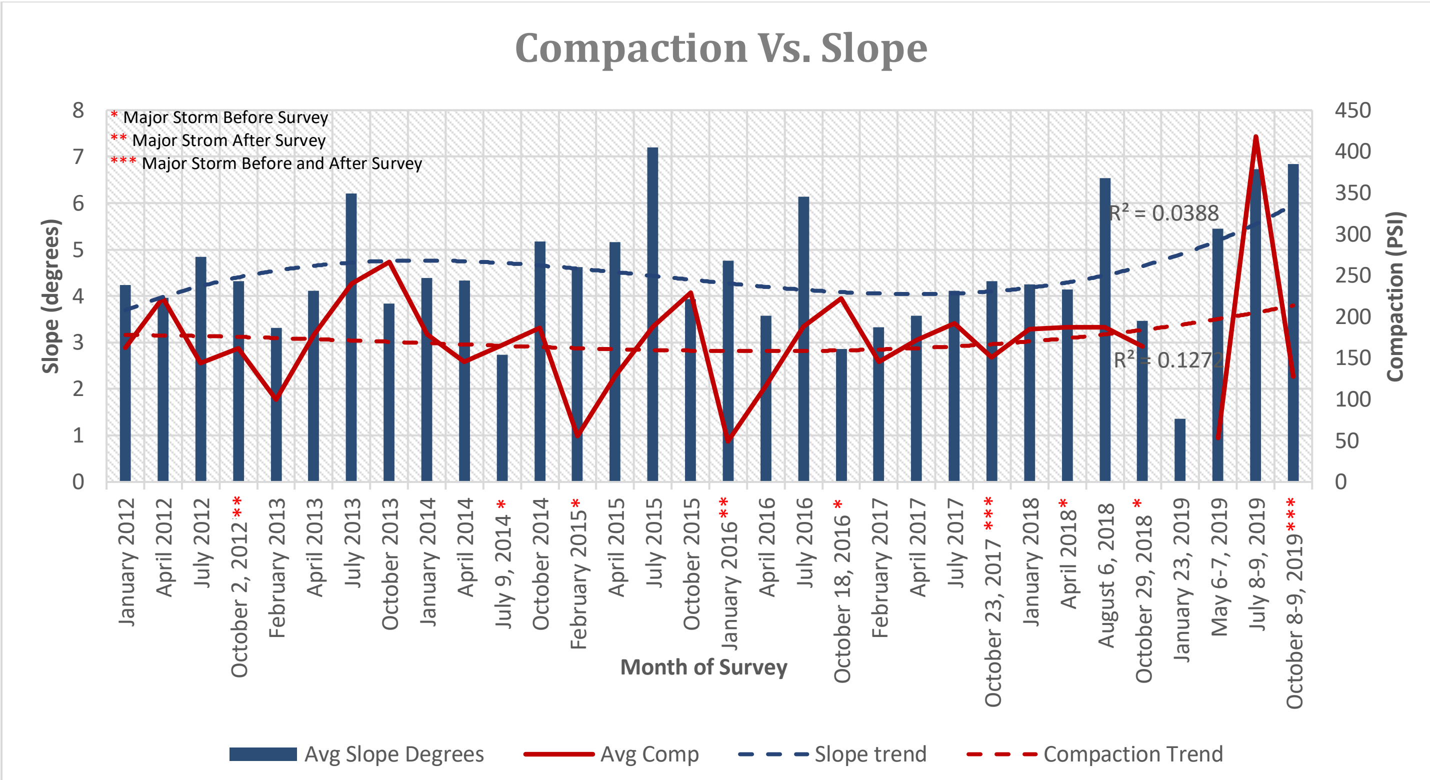


Fig. 7 – The comparison between compaction and slope.

Note: January 2019 compaction data not available.

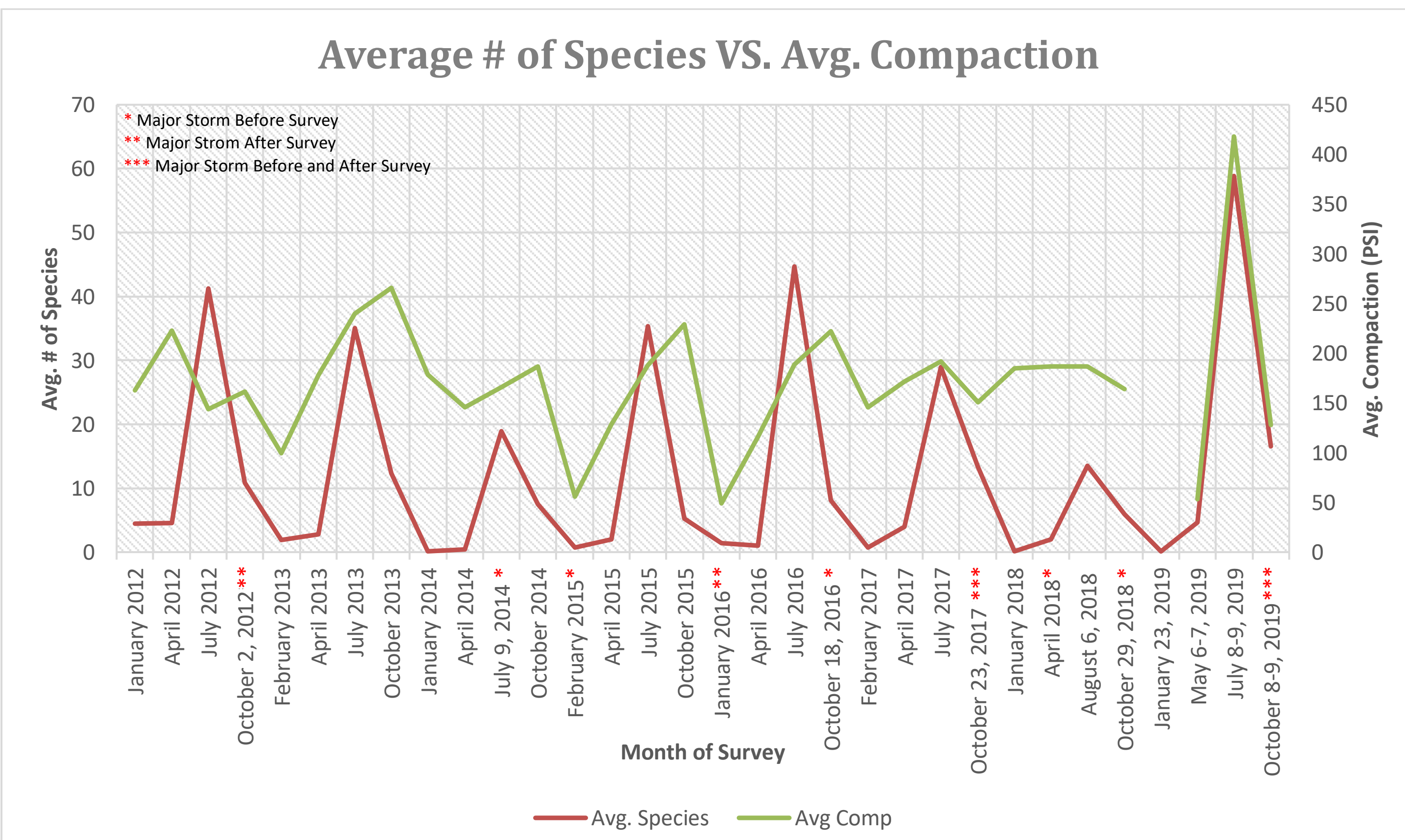


Fig. 8 – The comparison between the average number of species found per survey and the average compaction.

Note: January 2019 compaction data not available.

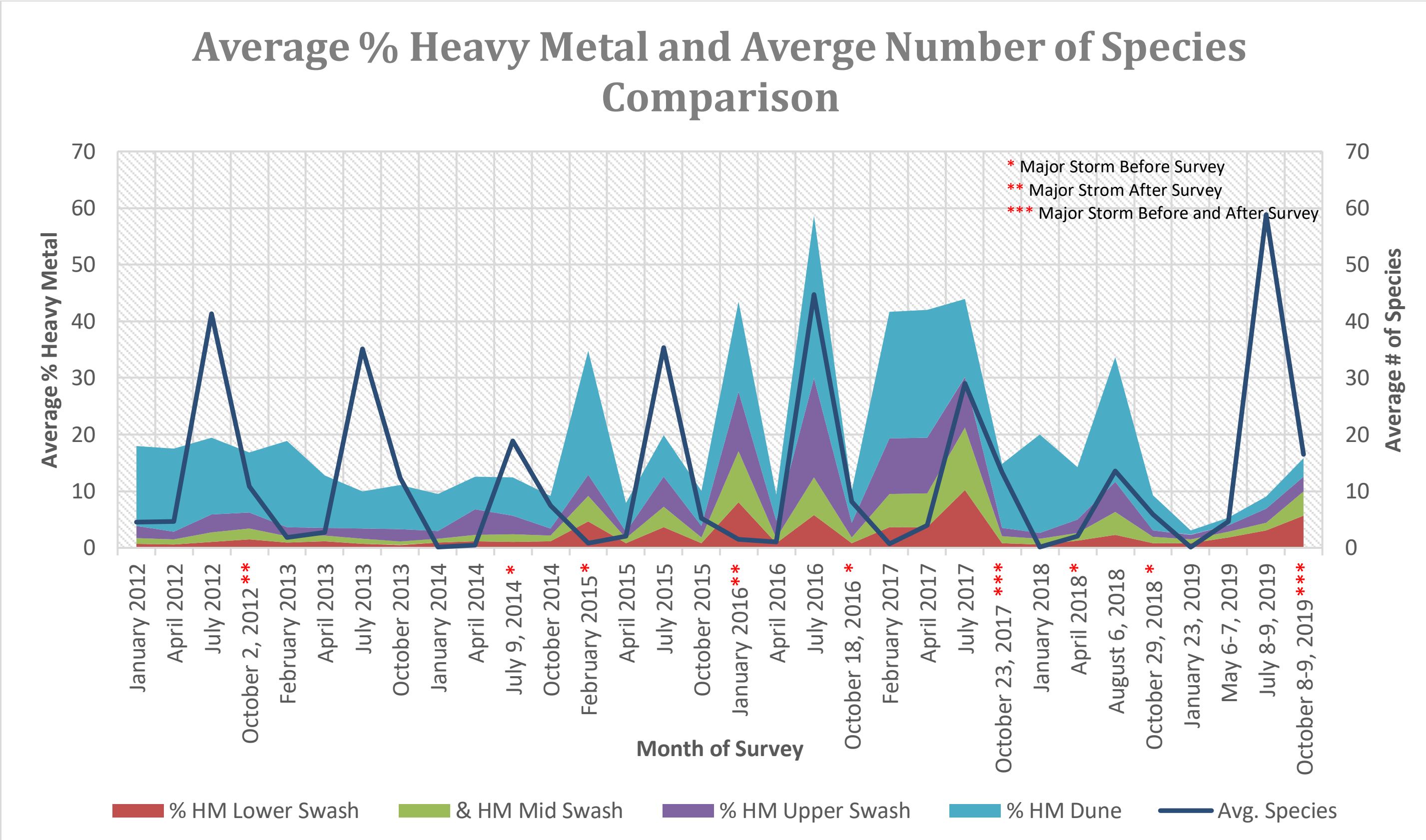


Fig. 9 – The comparison between the average percent heavy minerals and the average number of species found per survey.

Note: 2015 -2019 heavy mineral sand analysis was performed under different methods.

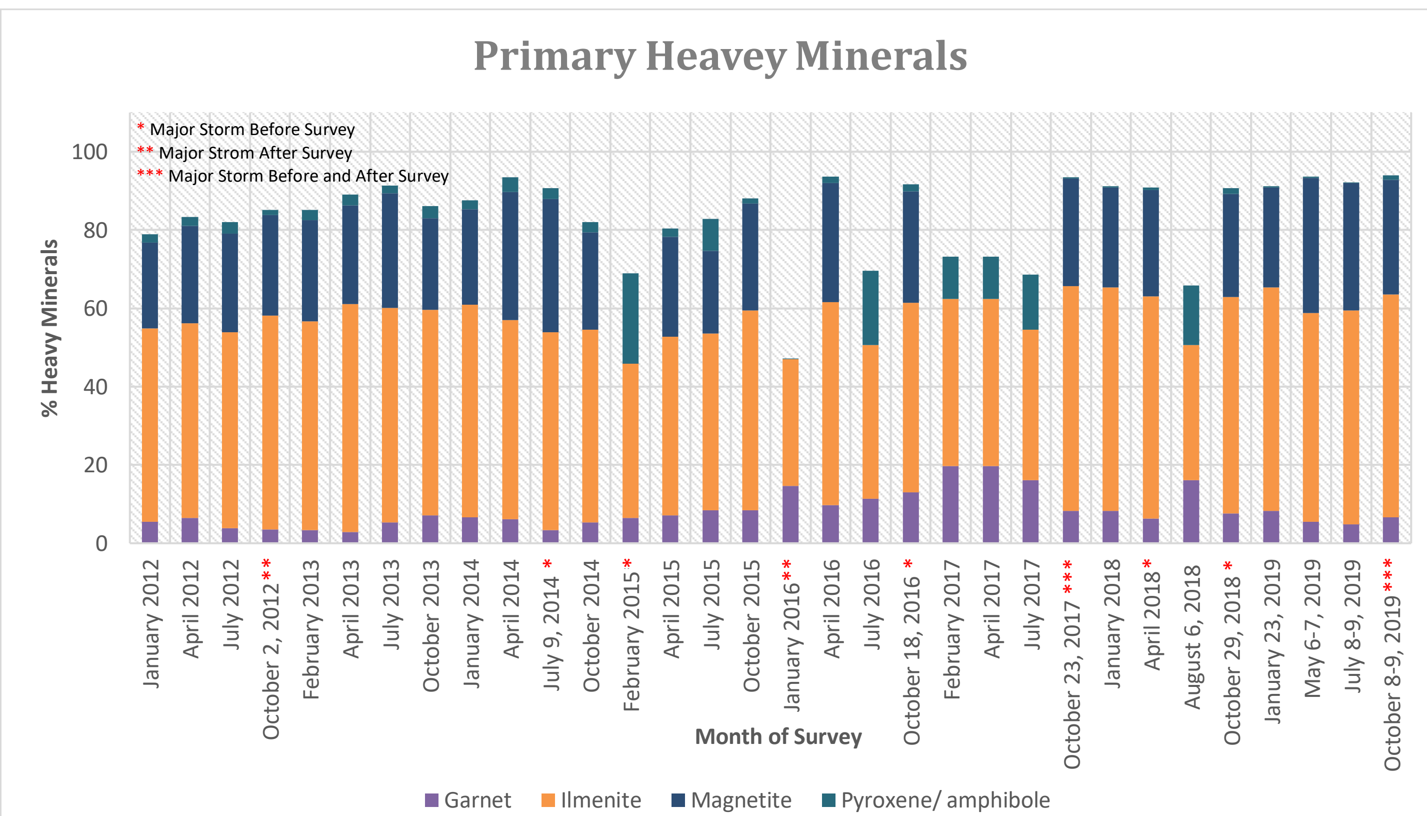


Fig. 10 – The primary heave minerals found in each survey.

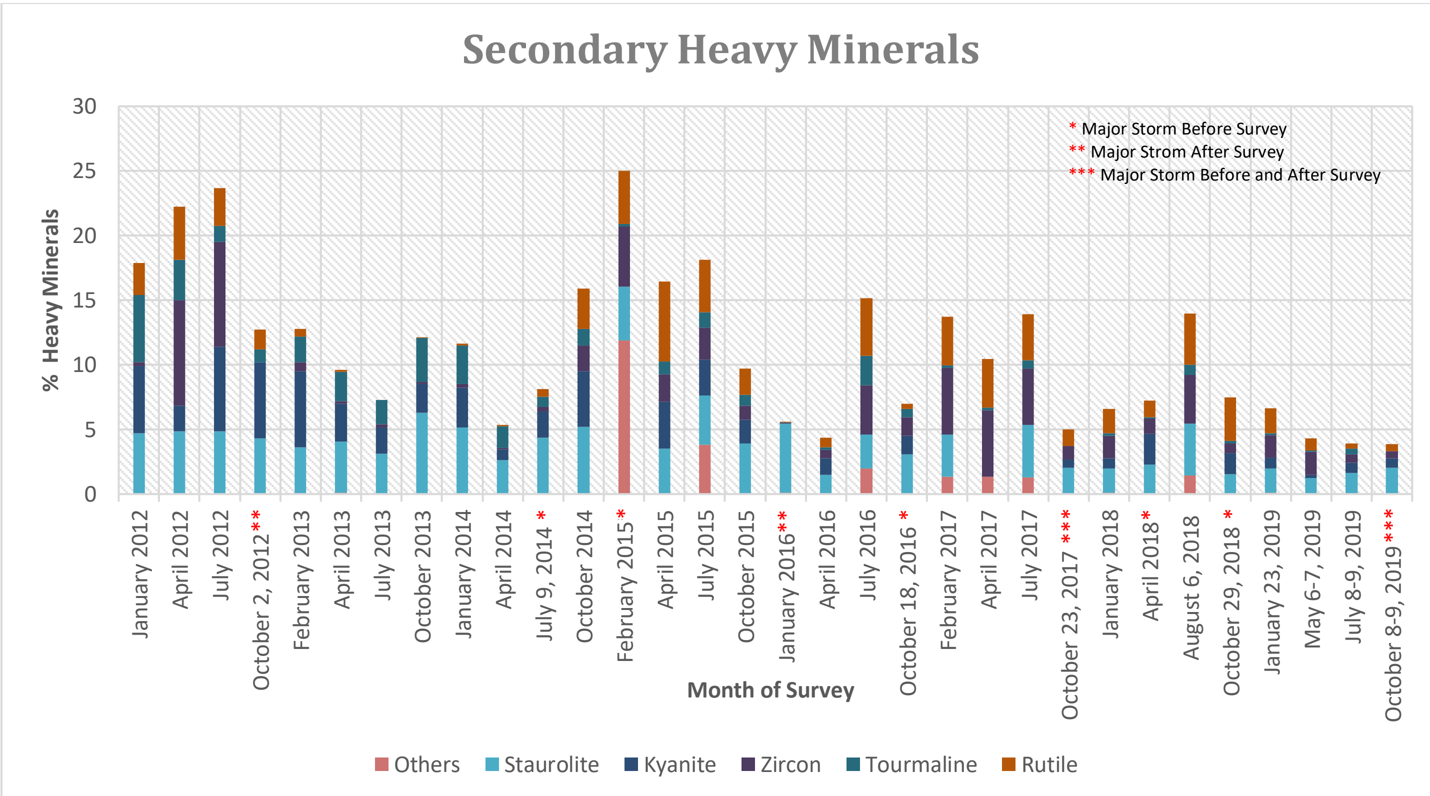


Fig. 11 – The secondary heavy minerals found at each survey.

2012 Sand Survey Statistics

	2012 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.03	0.17	0.03	0.64	0.46	0.85	0.38
Mean sand grain size lower swash (mm)	0.13	0.36	0.06	0.97	0.63	1.38	0.76
Mean sand grain size mid swash (mm)	0.04	0.19	0.03	0.67	0.54	0.96	0.41
Mean sand grain size upper swash (mm)	0.01	0.10	0.02	0.39	0.30	0.54	0.24
Mean sand grain size toe of dune (mm)	0.01	0.10	0.02	0.36	0.28	0.51	0.23
Total Benthos	1242991.6	1114.9	185.8	971.3	278.0	2618.0	2340.0
Avg. Species	309.0	17.6	2.9	15.3	4.5	41.3	36.8
Avg Slope Degrees	0.13	0.36	0.06	4.34	3.97	4.84	0.87
Avg Comp	1193.26	34.54	5.76	172.73	144.04	222.97	78.93
% HM Lower Swash	0.16	0.40	0.07	0.95	0.63	1.50	0.88
& HM Mid Swash	0.29	0.54	0.09	1.37	0.82	1.95	1.13
% HM Upper Swash	0.65	0.80	0.13	2.38	1.34	3.19	1.85
% HM Dune	3.39	1.84	0.31	13.24	10.57	14.72	4.15
Average %HM	0.08	0.28	0.05	4.49	4.21	4.86	0.65

Table 1 – The 2012 statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each survey (winter, spring, summer, fall).

2013 Sand Survey Statistics

	2013 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.00	0.06	0.01	0.71	0.63	0.76	0.13
Mean sand grain size lower swash (mm)	0.06	0.25	0.04	1.12	0.80	1.42	0.62
Mean sand grain size mid swash (mm)	0.00	0.04	0.01	0.73	0.70	0.79	0.09
Mean sand grain size upper swash (mm)	0.01	0.11	0.02	0.49	0.39	0.63	0.24
Mean sand grain size toe of dune (mm)	0.00	0.02	0.00	0.32	0.29	0.34	0.05
Total Benthos	981732.3	990.8	165.1	824.8	118.0	2245.0	2127.0
Avg. Species	239.0	15.5	2.6	13.0	1.9	35.1	33.2
Avg Slope Degrees	1.61	1.27	0.21	4.37	3.31	6.20	2.89
Avg Comp	5470.91	73.97	12.33	195.82	99.72	266.08	166.37
% HM Lower Swash	0.07	0.27	0.05	0.83	0.52	1.17	0.65
& HM Mid Swash	0.05	0.23	0.04	0.91	0.61	1.12	0.51
% HM Upper Swash	0.12	0.34	0.06	1.74	1.30	2.12	0.82
% HM Dune	14.65	3.83	0.64	9.68	6.46	15.15	8.69
Average %HM	0.98	0.99	0.17	3.29	2.48	4.71	2.23

Table 2 – The 2013 statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each survey (winter, spring, summer, fall).

2014 Sand Survey Statistics

	2014 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.01	0.12	0.02	0.80	0.64	0.89	0.25
Mean sand grain size lower swash (mm)	0.08	0.29	0.05	1.31	0.94	1.59	0.65
Mean sand grain size mid swash (mm)	0.05	0.22	0.04	0.78	0.59	1.09	0.51
Mean sand grain size upper swash (mm)	0.03	0.17	0.03	0.54	0.39	0.78	0.39
Mean sand grain size toe of dune (mm)	0.00	0.01	0.00	0.35	0.34	0.36	0.03
Total Benthos	303399.0	550.8	91.8	423.5	17.0	1191.0	1174.0
Avg. Species	77.1	8.8	1.5	6.8	0.2	18.9	18.7
Avg Slope Degrees	1.06	1.03	0.17	4.16	2.73	5.18	2.45
Avg Comp	322.98	17.97	3.00	169.12	145.47	186.66	41.19
% HM Lower Swash	0.01	0.10	0.02	1.07	0.92	1.14	0.23
& HM Mid Swash	0.05	0.22	0.04	1.04	0.74	1.25	0.52
% HM Upper Swash	2.59	1.61	0.27	2.62	1.23	4.52	3.29
% HM Dune	0.27	0.52	0.09	6.18	5.74	6.75	1.01
Average %HM	0.21	0.46	0.08	2.73	2.29	3.13	0.84

Table 3 – The 2014 statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each survey (winter, spring, summer, fall).

2015 Sand Survey Statistics

	2015 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.02	0.13	0.02	0.79	0.63	0.90	0.27
Mean sand grain size lower swash (mm)	0.12	0.34	0.06	1.23	0.80	1.61	0.81
Mean sand grain size mid swash (mm)	0.01	0.12	0.02	0.80	0.68	0.96	0.28
Mean sand grain size upper swash (mm)	0.03	0.18	0.03	0.57	0.41	0.81	0.40
Mean sand grain size toe of dune (mm)	0.00	0.02	0.00	0.35	0.34	0.38	0.04
Total Benthos	1039432.9	1019.5	169.9	671.8	47.0	2191.0	2144.0
Avg. Species	270.4	16.4	2.7	10.8	0.8	35.3	34.6
Avg Slope Degrees	1.97	1.40	0.23	5.23	3.93	7.19	3.26
Avg Comp	5664.01	75.26	12.54	150.30	55.81	228.91	173.09
% HM Lower Swash	3.89	1.97	0.33	2.46	0.76	4.66	3.90
& HM Mid Swash	3.39	1.84	0.31	2.53	0.91	4.53	3.61
% HM Upper Swash	3.50	1.87	0.31	3.03	1.05	5.29	4.24
% HM Dune	62.15	7.88	1.31	10.15	5.10	21.89	16.79
Average %HM	3.02	1.74	0.29	2.58	0.87	4.98	4.11

Table 4 – The 2015 statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each survey (winter, spring, summer, fall).

2016 Sand Survey Statistics

	2016 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.02	0.16	0.03	0.73	0.55	0.88	0.33
Mean sand grain size lower swash (mm)	0.13	0.35	0.06	1.14	0.75	1.53	0.77
Mean sand grain size mid swash (mm)	0.06	0.23	0.04	0.78	0.51	1.08	0.57
Mean sand grain size upper swash (mm)	0.01	0.10	0.02	0.48	0.39	0.57	0.18
Mean sand grain size toe of dune (mm)	0.00	0.03	0.00	0.34	0.31	0.36	0.06
Total Benthos	1672001.7	1293.1	215.5	855.5	62.0	2771.0	2709.0
Avg. Species	434.4	20.8	3.5	13.8	1.0	44.7	43.7
Avg Slope Degrees	2.07	1.44	0.24	4.34	2.85	6.15	3.29
Avg Comp	5973.63	77.29	12.88	143.95	49.11	222.44	173.34
% HM Lower Swash	13.04	3.61	0.60	3.86	0.81	8.03	7.21
& HM Mid Swash	17.10	4.14	0.69	4.42	0.89	9.07	8.18
% HM Upper Swash	49.30	7.02	1.17	8.38	2.58	17.42	14.84
% HM Dune	126.30	11.24	1.87	13.74	4.60	28.74	24.14
Average %HM	0.47	0.69	0.11	1.85	1.09	2.52	1.43

Table 5 – The 2016 statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each survey (winter, spring, summer, fall).

2017 Sand Survey Statistics

	2017 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.01	0.09	0.02	0.78	0.67	0.87	0.19
Mean sand grain size lower swash (mm)	0.05	0.22	0.04	1.10	0.83	1.32	0.49
Mean sand grain size mid swash (mm)	0.01	0.10	0.02	0.74	0.60	0.84	0.24
Mean sand grain size upper swash (mm)	0.00	0.07	0.01	0.51	0.45	0.61	0.16
Mean sand grain size toe of dune (mm)	0.00	0.03	0.00	0.35	0.33	0.39	0.05
Total Benthos	620117.6	787.5	131.2	727.3	45.0	1801.0	1756.0
Avg. Species	160.5	12.7	2.1	11.7	0.7	29.0	28.3
Avg Slope Degrees	0.21	0.46	0.08	3.83	3.32	4.32	1.00
Avg Comp	453.37	21.29	3.55	164.87	145.36	191.88	46.51
% HM Lower Swash	15.60	3.95	0.66	4.61	0.87	10.19	9.32
& HM Mid Swash	16.38	4.05	0.67	5.99	1.14	11.05	9.91
% HM Upper Swash	16.22	4.03	0.67	7.49	1.49	9.80	8.31
% HM Dune	34.09	5.84	0.97	17.52	11.28	22.61	11.33
Average %HM	12.20	3.49	0.58	8.92	3.69	10.98	7.29

Table 6 – The 2017 statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each survey (winter, spring, summer, fall).

2018 Sand Survey Statistics

	2018 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.01	0.10	0.02	0.70	0.59	0.79	0.20
Mean sand grain size lower swash (mm)	0.21	0.46	0.08	1.29	0.79	1.76	0.97
Mean sand grain size mid swash (mm)	0.01	0.09	0.02	0.60	0.47	0.70	0.23
Mean sand grain size upper swash (mm)	0.00	0.06	0.01	0.50	0.46	0.59	0.13
Mean sand grain size toe of dune (mm)	0.00	0.02	0.00	0.43	0.41	0.45	0.04
Total Benthos	130528.9	361.3	60.2	329.3	10.0	825.0	815.0
Avg. Species	35.1	5.9	1.0	5.4	0.2	13.5	13.4
Avg Slope Degrees	1.78	1.33	0.22	4.60	3.47	6.53	3.06
Avg Comp	125.54	11.20	1.87	180.66	163.93	187.06	23.13
% HM Lower Swash	0.54	0.73	0.12	1.25	0.64	2.29	1.65
& HM Mid Swash	2.18	1.48	0.25	1.87	0.97	4.07	3.09
% HM Upper Swash	3.84	1.96	0.33	2.44	0.98	5.24	4.25
% HM Dune	53.66	7.33	1.22	13.75	6.14	22.11	15.97
Average %HM	6.97	2.64	0.44	4.83	2.31	8.43	6.12

Table 7 – The 2018 statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each survey (winter, spring, summer, fall).

2019 Sand Survey Statistics

	2019 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.05	0.21	0.04	0.78	0.58	1.02	0.45
Mean sand grain size lower swash (mm)	0.35	0.59	0.10	1.31	0.63	1.96	1.33
Mean sand grain size mid swash (mm)	0.02	0.14	0.02	0.69	0.55	0.89	0.33
Mean sand grain size upper swash (mm)	0.04	0.19	0.03	0.64	0.46	0.83	0.38
Mean sand grain size toe of dune (mm)	0.00	0.06	0.01	0.49	0.44	0.58	0.14
Total Benthos	2667603.0	1633.3	272.2	1223.5	7.0	3590.0	3583.0
Avg. Species	716.9	26.8	4.5	20.1	0.1	58.9	58.7
Avg Slope Degrees	6.59	2.57	0.43	5.10	1.36	6.84	5.48
Avg Comp	37102.27	192.62	32.10	199.82	53.56	418.06	364.51
% HM Lower Swash	4.38	2.09	0.35	2.83	0.81	5.65	4.83
& HM Mid Swash	2.77	1.66	0.28	1.84	0.70	4.30	3.60
% HM Upper Swash	0.83	0.91	0.15	1.74	0.81	2.55	1.74
% HM Dune	1.19	1.09	0.18	1.88	0.75	3.29	2.54
Average %HM	1.94	1.39	0.23	2.07	0.77	3.95	3.18

Table 8 – The 2019 statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each survey (winter, spring, summer, fall).

Winter 2012-2019 Sand Survey Statistics

	Winter 2012-2019 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.04	0.19	0.03	0.75	0.54	1.02	0.48
Mean sand grain size lower swash (mm)	0.20	0.45	0.07	1.12	0.71	1.96	1.25
Mean sand grain size mid swash (mm)	0.02	0.13	0.02	0.69	0.51	0.89	0.38
Mean sand grain size upper swash (mm)	0.03	0.17	0.03	0.52	0.37	0.81	0.44
Mean sand grain size toe of dune (mm)	0.01	0.07	0.01	0.35	0.28	0.47	0.19
Total Benthos	8486.06	92.12	15.35	73.78	0.11	278.00	277.89
Avg. Species	2.15	1.47	0.24	1.21	0.11	4.48	4.37
Avg Slope Degrees	4096.36	64.00	10.67	26.34	1.36	184.72	183.36
Avg Comp	3242.57	56.94	9.49	125.14	49.11	184.72	135.61
% HM Lower Swash	7.33	2.71	0.45	2.54	0.64	8.03	7.39
% HM Mid Swash	9.90	3.15	0.52	3.00	0.70	9.07	8.37
% HM Upper Swash	15.76	3.97	0.66	3.87	0.81	10.45	9.64
% HM Dune	54.50	7.38	1.23	14.27	0.75	22.40	21.65
Average %HM	10.69	3.27	0.54	3.73	0.77	10.50	9.73

Table 8 – The statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each winter surveys between 2012-2019.

Spring 2012-2019 Sand Survey Statistics

	Spring 2012-2019 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.01	0.10	0.02	0.79	0.65	0.89	0.24
Mean sand grain size lower swash (mm)	0.08	0.28	0.05	1.35	0.94	1.61	0.66
Mean sand grain size mid swash (mm)	0.02	0.15	0.03	0.83	0.68	1.09	0.42
Mean sand grain size upper swash (mm)	0.01	0.11	0.02	0.59	0.46	0.83	0.37
Mean sand grain size toe of dune (mm)	0.00	0.07	0.01	0.39	0.32	0.51	0.19
Total Benthos	9939.0	99.7	16.6	166.9	30.0	292.0	262.0
Avg. Species	2.6	1.6	0.3	2.7	0.5	4.7	4.2
Avg Slope Degrees	8319.76	91.21	15.20	53.23	3.58	214.03	210.45
Avg Comp	2698.43	51.95	8.66	164.21	53.56	222.97	169.41
% HM Lower Swash	0.97	0.98	0.16	1.41	0.63	3.69	3.06
% HM Mid Swash	3.02	1.74	0.29	1.64	0.82	5.92	5.10
% HM Upper Swash	8.85	2.98	0.50	3.07	1.05	9.80	8.75
% HM Dune	45.91	6.78	1.13	9.10	1.37	22.61	21.24
Average %HM	8.24	2.87	0.48	3.80	1.32	10.50	9.18

Table 9 - The statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each spring surveys between 2012-2019.

Summer 2012-2019 Sand Survey Statistics

	Summer 2012-2019 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.01	0.10	0.02	0.73	0.63	0.87	0.24
Mean sand grain size lower swash (mm)	0.10	0.31	0.05	1.12	0.80	1.76	0.96
Mean sand grain size mid swash (mm)	0.01	0.10	0.02	0.62	0.47	0.78	0.31
Mean sand grain size upper swash (mm)	0.00	0.04	0.01	0.43	0.36	0.48	0.13
Mean sand grain size toe of dune (mm)	0.00	0.04	0.01	0.38	0.32	0.44	0.12
Total Benthos	893553.1	945.3	157.6	1712.6	58.9	2771.0	2712.2
Avg. Species	208.3	14.4	2.4	34.6	13.5	58.9	45.3
Avg Slope Degrees	3673.52	60.61	10.10	26.82	2.73	176.77	174.04
Avg Comp	848.50	86.25	14.37	215.32	144.04	418.06	274.03
% HM Lower Swash	11.40	3.38	0.56	3.92	0.75	10.19	9.44
% HM Mid Swash	12.43	3.53	0.59	3.83	0.87	11.05	10.18
% HM Upper Swash	26.30	5.13	0.85	5.97	1.85	17.42	15.57
% HM Dune	80.28	8.96	1.49	12.62	2.12	28.74	26.61
Average %HM	11.04	3.32	0.55	4.82	1.47	10.98	9.52

Table 10 - The statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each summer surveys between 2012-2019.

Fall 2012-2019 Sand Survey Statistics

	Fall 2012-2019 Statistics						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.02	0.13	0.02	0.70	0.46	0.88	0.41
Mean sand grain size lower swash (mm)	0.12	0.34	0.06	1.13	0.63	1.53	0.90
Mean sand grain size mid swash (mm)	0.03	0.16	0.03	0.75	0.60	1.08	0.48
Mean sand grain size upper swash (mm)	0.02	0.14	0.02	0.52	0.30	0.78	0.48
Mean sand grain size toe of dune (mm)	0.01	0.09	0.01	0.37	0.32	0.58	0.26
Total Benthos	70789.6	266.1	44.3	492.4	16.6	819.0	802.4
Avg. Species	15.6	4.0	0.7	10.0	5.2	16.6	11.3
Avg Slope Degrees	4045.16	63.60	10.60	26.47	2.85	183.87	181.02
Avg Comp	2181.11	46.70	7.78	188.47	127.84	266.08	138.25
% HM Lower Swash	2.87	1.69	0.28	1.52	0.52	5.65	5.12
% HM Mid Swash	1.41	1.19	0.20	1.52	0.61	4.30	3.69
% HM Upper Swash	0.40	0.63	0.11	2.00	1.19	2.80	1.61
% HM Dune	7.18	2.68	0.45	7.09	3.29	11.28	7.99
Average %HM	0.62	0.79	0.13	3.03	2.29	4.21	1.91

Table 11 - The statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each fall surveys between 2012-2018.

Overall Sand Survey Statistics Between Seasons 2012-2019

	Overall Stats Between Seasons 2012-2019						
	VAR	STD	STE	mean	Min	Max	Range
Avg. Grain Size	0.02	0.13	0.01	0.74	0.46	1.02	0.56
Mean sand grain size lower swash (mm)	0.12	0.35	0.01	1.18	0.63	1.61	0.98
Mean sand grain size mid swash (mm)	0.02	0.15	0.01	0.72	0.47	1.09	0.62
Mean sand grain size upper swash (mm)	0.02	0.13	0.01	0.52	0.30	0.81	0.51
Mean sand grain size toe of dune (mm)	0.00	0.07	0.00	0.37	0.28	0.51	0.23
Total Benthos	912698.2	955.4	39.8	753.3	7.0	2771.0	2764.0
Avg. Species	236.7	15.4	0.7	12.1	0.1	44.7	44.6
Avg Slope Degrees	1.69	1.30	0.05	4.50	1.36	7.19	5.83
Avg Comp	4732.04	68.79	2.87	171.27	49.11	266.08	216.98
% HM Lower Swash	5.53	2.35	0.10	2.23	0.52	10.19	9.66
% HM Mid Swash	7.01	2.65	0.11	2.50	0.61	11.05	10.44
% HM Upper Swash	13.77	3.71	0.15	3.73	0.81	17.42	16.61
% HM Dune	50.70	7.12	0.30	10.77	0.75	28.74	27.99
Average %HM	7.33	2.71	0.11	3.84	0.77	10.98	10.22

Table 12 – The overall statistics analyzing the variance, standard deviation, standard error, mean, minimum, maximum, and ranges of the mineral and benthic data collected from each survey between 2012-2018.

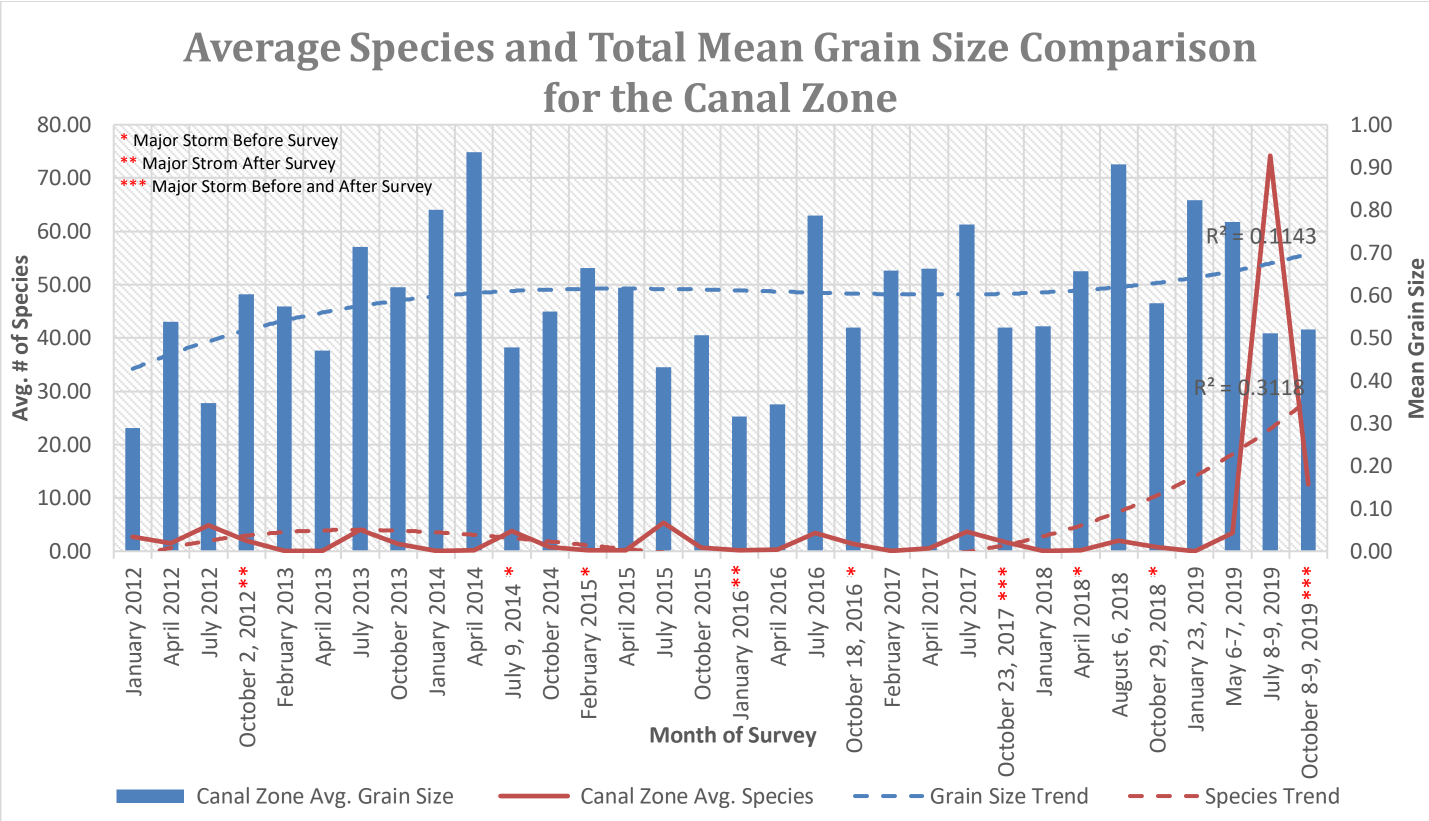


Fig. 12 – Average species and total mean grain size comparison for the Canal Zone.

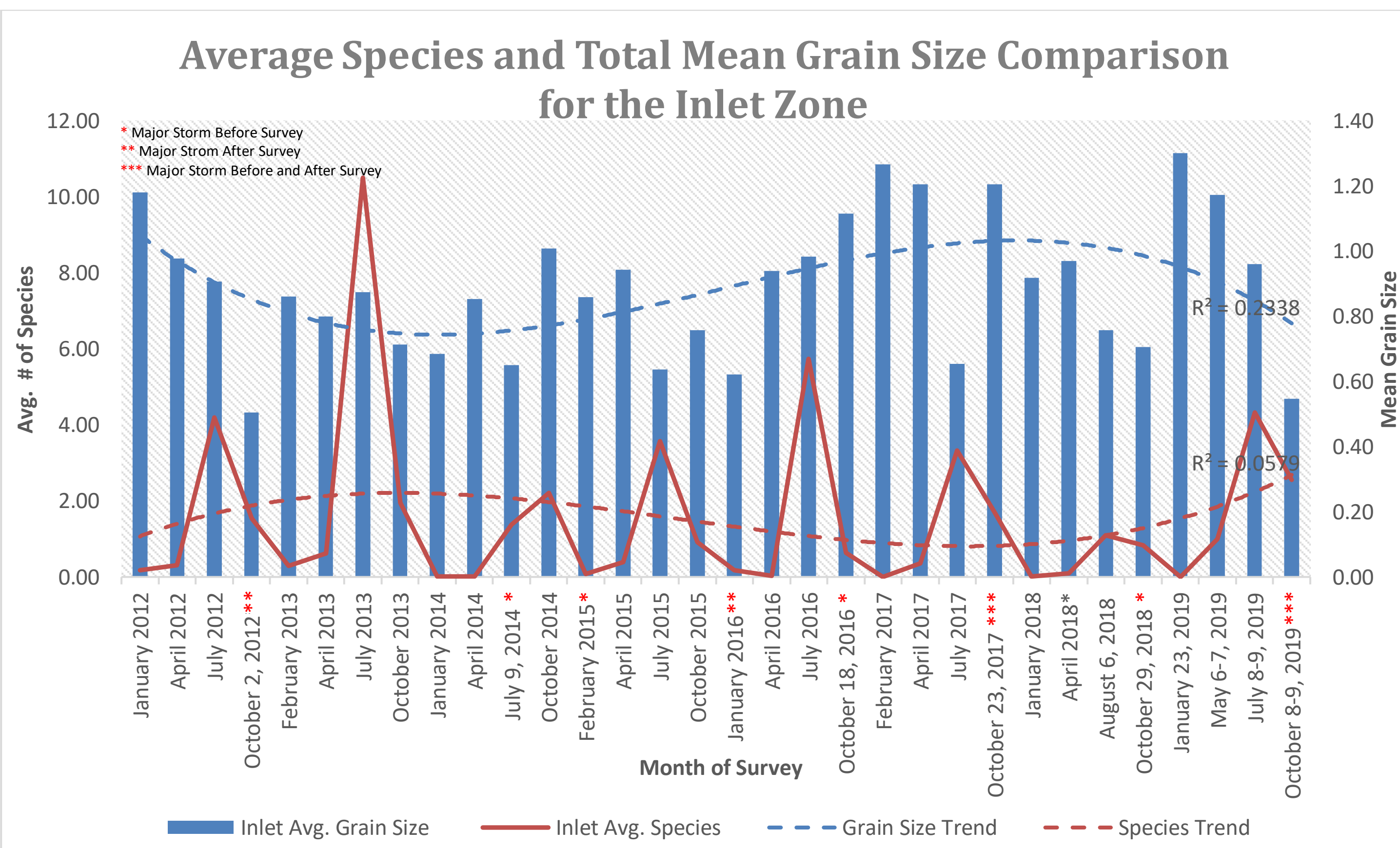


Fig. 13 – Average species and total mean grain size comparison for the Inlet Zone.

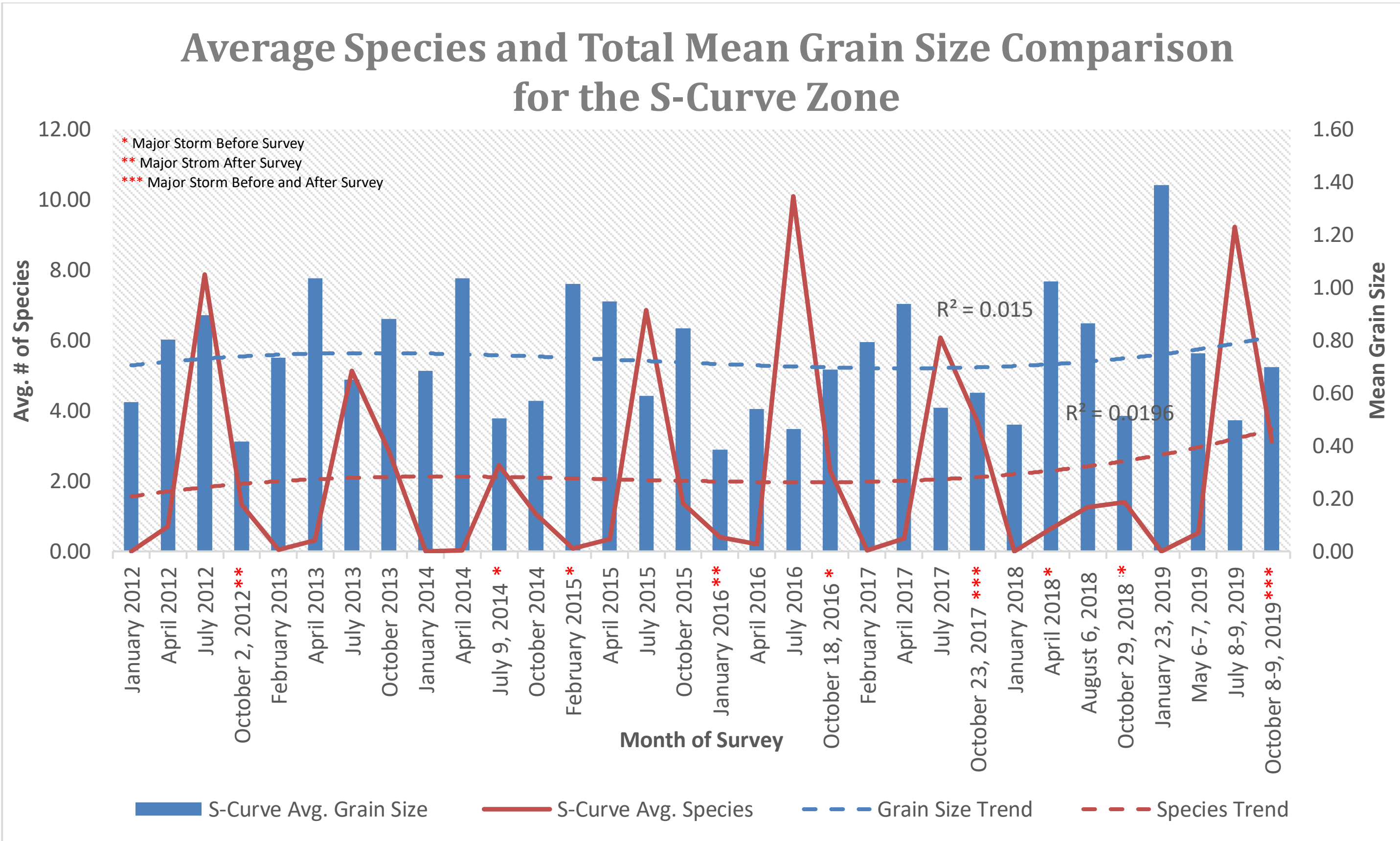
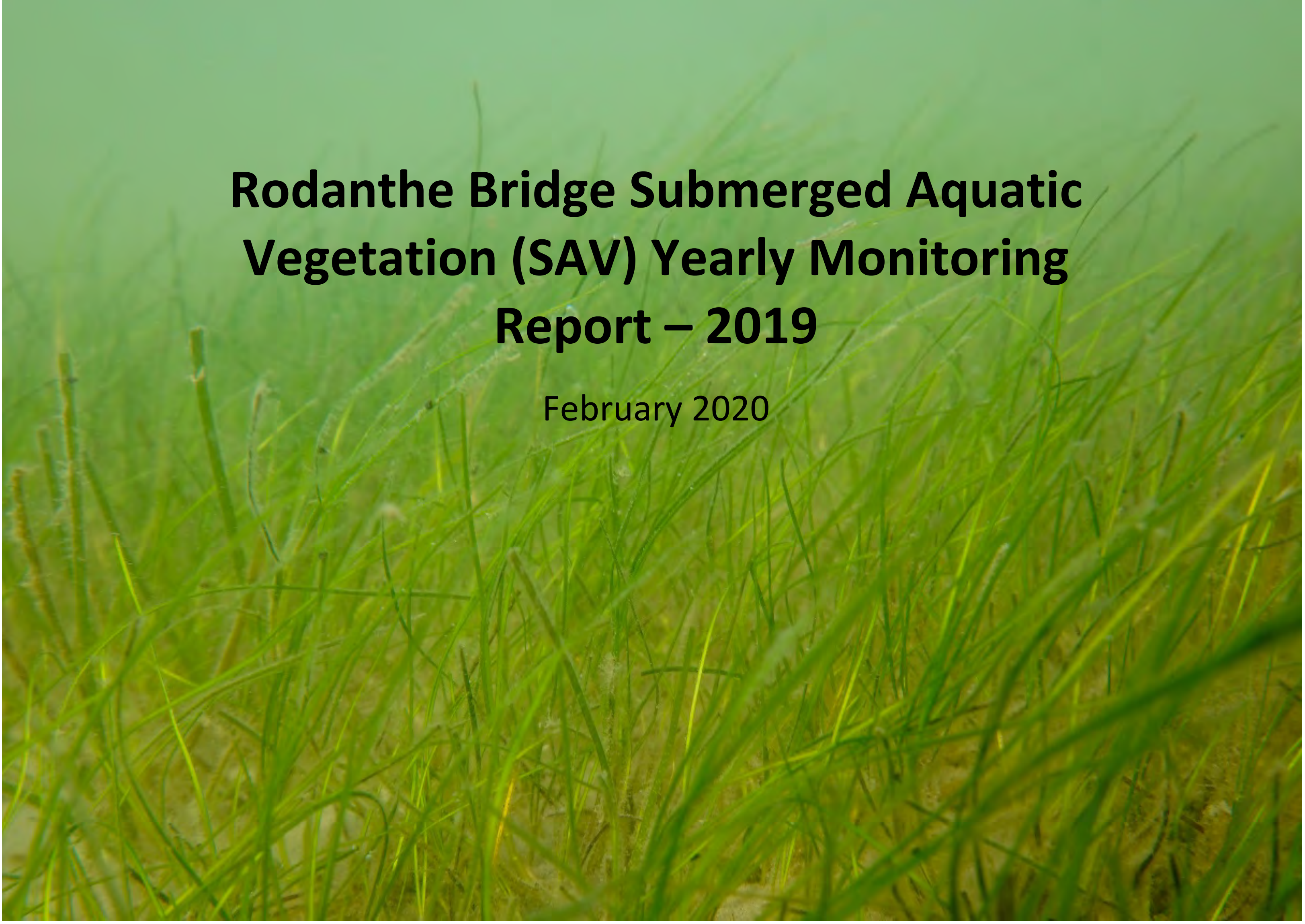


Fig. 14 – Average species and total mean grain size comparison for the S-Curve Zone.



Rodanthe Bridge Submerged Aquatic Vegetation (SAV) Yearly Monitoring Report – 2019

February 2020

Prepared for:

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Rodanthe Bridge Submerged Aquatic Vegetation (SAV) Yearly Monitoring Report - 2019

DOCUMENT NO. CSA-RKANDK-FL-20-80726-3291-04-REP-03-FIN-REV01

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01	12/20/2019	Draft	E. Hodel	M. Fonseca	E. Hodel
FIN	01/10/2020	Final	E. Hodel	M. Fonseca	E. Hodel
FIN-REV01	02/19/2020	Revised Final (client comments)	E. Hodel		E. Hodel

Table of Contents

List of Tables

List of Figures

BACKGROUND

In order to evaluate potential impacts of the Rodanthe Bridge on submerged aquatic vegetation (SAV), a long-term SAV monitoring and mitigation program has been established, with baseline data collection initiated in 2018. The North Carolina Department of Transportation (NCDOT) contracted Rummel Klepper and Kahl (RK&K) to lead this assessment. CSA Ocean Sciences Inc. (CSA) was subcontracted by RK&K to support the monitoring survey design and perform delineation of SAV cover from remotely-sensed data provided by RK&K. RK&K also conducted *in situ* SAV coverage and abundance surveys. This report also serves as the After Action report for the fall survey; the After Action report was delayed due to the need to re-acquire data following Hurricane Dorian and has consequently been subsumed in this report.

METHODS

SAV monitoring began in May 2018 and was repeated in spring and fall through fall 2019. Henceforth, monitoring will be conducted twice annually (spring and fall) and will end in 2025 or five years post-construction as per permit conditions. This time period will allow 1 to 2 years of baseline monitoring prior to bridge construction and will continue through the construction period to post-construction, capturing any direct impacts of the construction process and subsequent impacts to SAV, particularly from shading.

The monitoring area includes the proposed bridge dripline, forecasted adjacent shading areas, and reference areas (**Figure 1**). Specific study area width will be determined after the initial bridge shadow modeling has been completed, using the recently developed Shading Tool[1] . Currently, the study area has been organized into the following five strata based on an initial rough estimate of the potential bridge shadow width[2]:

1. Bridge dripline (42 feet wide) centered on the bridge alignment
2. Potential shading area east (200 feet east of dripline)
3. Potential shading area west (200 feet west of dripline)
4. Reference area east (100 feet east of shading area)
5. Reference area west (100 feet west of shading area)

---

[1] CSA Ocean Sciences Inc. 2019. CSA Ocean Sciences Inc. (CSA). 2019. Shadow toolbox user manual. ST_01_ver02. Submitted to Rummel, Klepper and Kahl, Raleigh, North Carolina. June 2019. CSA Document number CSA-RKK-NCDOT-FL-19-80763-3289-06-REP-01-VER02

[2] Using a freely available website (https://planetcalc.com/1875/ [last accessed 13 December 2019]), a latitude of 35 degrees, 45 seconds (N) and a longitude of 75 degrees and 33 minutes (W) and a day of the year of December 21st at 4pm (solstice setting sun) a sun angle of 8.05 degrees was computed. Using the formula $L = h/\tan\alpha$ where L = shadow length, h = bridge height (here 24 feet) and α = solar angle, and shadow length of 170 feet was computed. This was rounded up to 200 feet as a conservative estimate of the extreme distance affected by the bridge's shadow.

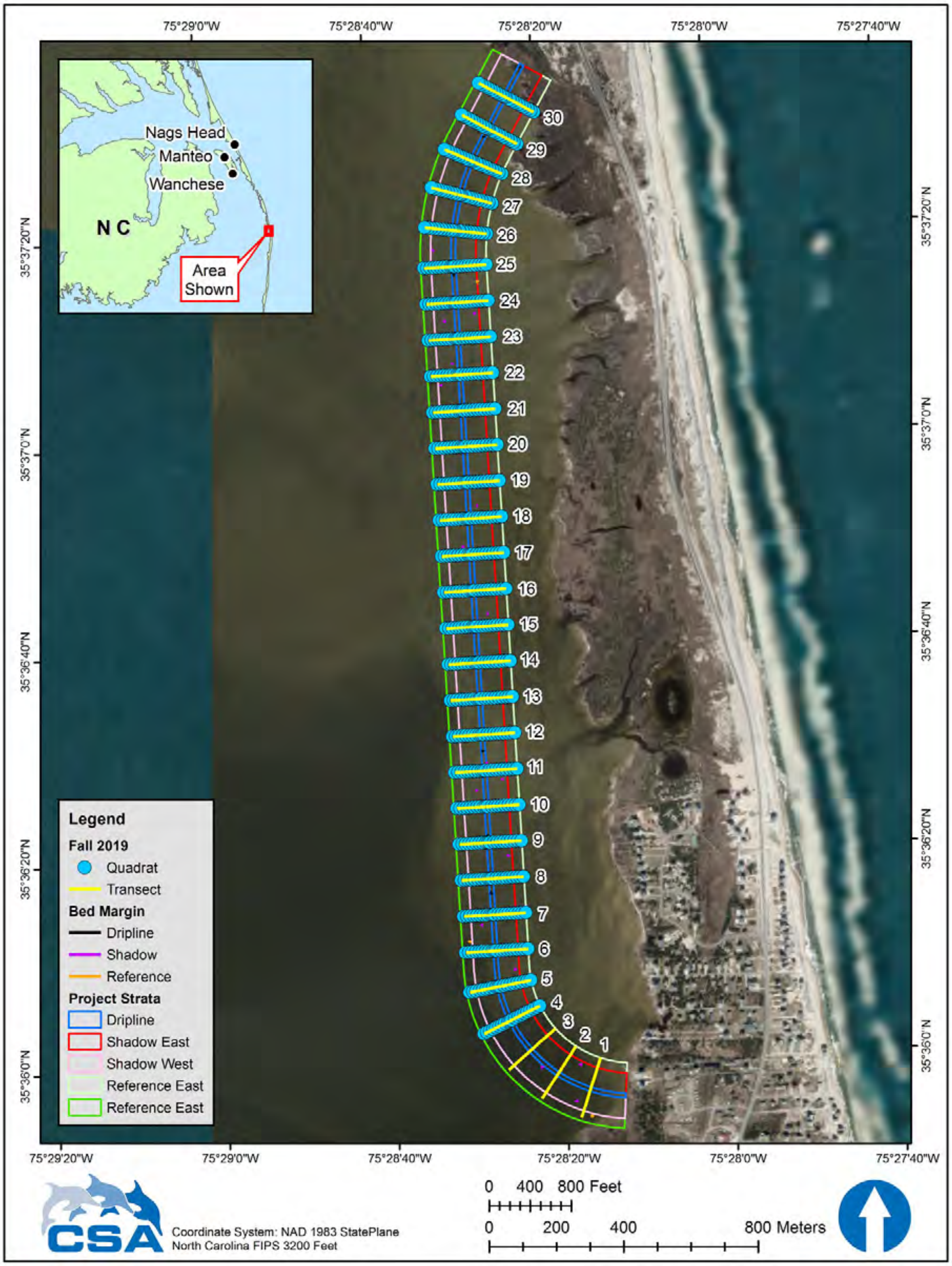

Figure 1. Project area and strata with field survey transects and BBL quadrat locations for Rodanthe Bridge corridor submerged aquatic vegetation (SAV) monitoring for Fall 2019. (Note in this image that quadrat surveys were not performed on Transects 1 to 3 due to safety issues arising from construction in the area).

SAV monitoring had two primary components: data acquisition to build a geospatially accurate map of SAV resources across all survey strata and a field survey of SAV status. RKK provided the datasets for May and September 2018 and November 2019 interpretations. Datasets were collected in May and September 2018 and May 2019. The Fall 2019 dataset was originally collected in September; however, artifacts of heavy detritus as a result from Hurricane Dorian which passed over the Outer Banks 5-6 September 2019, were present and would have confounded the SAV interpretation, therefore data was re-collected 7 November 2019. The dataset was mosaicked by RK&K and provided to CSA for SAV interpretation using a geographic information system (GIS). CSA completed the interpretation of the November dataset on 5 December 2019.

Associated field-based SAV surveys were conducted in July 2018 (to support the May 2018 dataset), October 2018 (to support the September 2018 dataset), May 2019 (to support the May 2019 dataset) and September 2019 (to support the November 2019 dataset).

To provide a baseline for shading effects, 30 equally spaced transects (75 m apart) were placed centered on and running perpendicular to the bridge, extending through the dripline strata, across the shading strata and on to the distal end of the reference areas which lie beyond the shading strata on either side (east or west) of the bridge (**Figure 1**). Line intercept and Braun-Blanquet (BBL) quadrat surveys are to be performed along the transects. During the September 2019 survey, line intercept data were collected along all 30 transects, however, due to bridge construction and safety concerns, BBL quadrat surveys were not performed on the southernmost 3 transects (Transects 1 to 3) (**Figure 1**).Along each transect, quadrat surveys were performed at approximately 10 m increments, numbering up to 20 quadrats per transect. The first three quadrat stations from either end of the transect were reference stations, the next six in from either side were within the predicted shading area and the middle two were under the dripline of the proposed bridge location. These surveys were augmented by the line intercept surveys of SAV presence along each transect for an estimate of SAV percent cover, if necessary. SAV presence or absence data from 200 randomly-selected BBL quadrat stations was utilized by GIS analysts for ground-truthing of spatial data. The small temporal difference between field surveys in late September and data collection in early November was not considered substantial enough to introduce meaningful error in representing the SAV distribution.

RESULTS and DISCUSSION

The results of the GIS-based SAV distribution interpretation from each survey to date are shown in **Figures 2** through **5**. SAV are present throughout the bridge corridor (study area) which covered a maximum total area of 160 acres[3] distributed among the five survey strata (**Table 1**). A confusion matrix to document accuracy of the GIS-based SAV delineation process (e.g., errors of Omission and Commission) was developed for the November 2019 survey (**Table 2**). Total Classification Accuracy was very acceptable 94% (overall measure of discrepancy in predicted vs. observed values) supporting the assumption that the temporal difference among field surveys did not contribute meaningful error. The Producer's Accuracy was 90% (10% omission error; omitting possible SAV from classification) and the User's Accuracy was 97% (3% commission error; assigning SAV classification to actual sand or other areas); all of which are generally considered acceptable levels of accuracy. The Kappa Coefficient was 0.8701 meaning that the actual classification was 87% better agreement than by chance alone.

[3] Based on the corrected survey areas for the five strata starting with the September 2018 survey.

Table 1. Percent cover of submerged aquatic vegetation (SAV) from spatial data and field-collected data (BBL quadrat stations) for all surveys to date. Strata are: bridge = area under the dripline of the proposed bridge; ref_east = 100' wide reference zone to east of bridge; ref_west = 100' wide reference zone to west of bridge; shade_east = 200' wide projected shading zone to east of bridge; shade_west = 200' wide projected shading zone to west of bridge. Scaled data bars (red, blue) added to percent cover columns to aid comparison.

Dates	Strata	Area of Dataset (acres)	GIS derived SAV (acres)	GIS derived SAV Percent Cover	Field Survey Mean Percent Cover	Field Survey Specific (only within seagrass beds) Mean Percent Cover
May 2018 (GIS) & July 2018 (Field Survey)	bridge	10.5	4.2	39.7	39.8	42.4
	ref_east	5.3	2.0	38.2	33.8	36.7
	ref_west	9.4	3.6	38.5	35.6	37.9
	shade_east	49.0	16.7	34.0	31.3	36.7
	shade_west	51.2	20.9	40.7	37.5	42.1
Sept 2018 (GIS) & October 2018 (Field Survey)	bridge	10.5	6.6	62.9	40.5	41.1
	ref_east	23.8	12.1	50.8	29.0	29.7
	ref_west	26.3	16.7	63.7	35.6	39.3
	shade_east	49.0	26.5	54.1	31.0	31.9
	shade_west	51.2	33.1	64.6	34.4	36.6
May 2019 (GIS & Field Survey)	bridge	10.5	4.5	42.9	13.6	14.9
	ref_east	23.8	7.7	32.3	16.3	17.2
	ref_west	26.3	12.9	49.1	18.0	19.7
	shade_east	49.0	17.7	36.2	13.9	14.4
	shade_west	51.2	24.5	47.9	17.8	19.4
Nov 2019 (GIS) & Sept 2019 (Field Survey)	bridge	10.5			36.0	36.2
	ref_east	23.8			30.8	32.5
	ref_west	26.3			29.7	32.9
	shade_east	49.0			30.7	33.1
	shade_west	51.2			33.9	36.4

Table 2. Confusion matrix on ground-truthed points provided by the field team (data collected in September 2019 data) for confirmation by the interpreter in the data (data collected in November 2019).

Classification	SAV	Other (not SAV)	Row Total
SAV	92	3	95
Other	10	95	105
Column Total	102	98	200

Yellow boxes show the number of occurrences where points were correctly classified; gray boxes show the number of occurrences where points were incorrectly classified.
SAV = submerged aquatic vegetation.

The SAV survey boundaries were somewhat truncated in the first (May 2018) survey, resulting in smaller reference areas as compared to subsequent surveys (**Table 1**). In September 2018 the survey area was expanded and covered the full extent of all five strata; consequently, more SAV acreage was detected (**Table 1**). SAV coverage from the spatial interpretation has shown varying levels of percent cover over time ranging from 32.3 to 64.6 (grand mean 45.846.4 [SD 9.8910.9]). Percent cover was similar in the two May surveys but had approximately 20% additional cover in the September 2018 survey, likely due to seasonality and the peak of *Halodule wrightii* biomass. Percent cover in the November 2019 survey was approximately 15% less versus the September 2018 survey, potentially due in part to data collection later in the year, after the peak of the SAV growing season (Thayer et al., 1984) (grand means by survey: May 2018 = 38.2 [SD 2.57], September 2018 = 59.2 [SD 6.32], May 2019 = 41.7 [SD 7.31]), November 2019 = 45.8 [SD 9.89].

Initial findings from the July and October 2018 and May and September 2019 field-based fixed BBL quadrat station data (**Figure 6**) revealed a mean percent cover per strata ranging from 13.6 to 40.5 (**Table 1**). The grand mean percent cover did not change appreciably among the first two survey dates; 35.6 [SD 3.3] in July versus 34.1 [SD 4.4] in October 2018. Yet, an across-the-board reduction of over 50 percent cover occurred with the May 2019 survey (grand mean percent cover = 15.9 [SD 2.1]) as compared to the previous two surveys. Cover in September 2019 returned to 2018 levels (grand mean percent cover = 34.2 [SD 1.89]). However, substantial variability within strata remained evident as evidenced by the proportionally (to mean value per transect) high standard deviations (**Figure 6**).

While the area of seafloor covered by SAV fluctuated somewhat seasonally as seen in the spatial surveys, the abundance of SAV within the boundaries of SAV-colonized space (specific cover) did not behave similarly and instead decreased dramatically in May 2019 as compared to similar abundances throughout 2018. However, similar to areal cover, specific cover in September 2019 returned to levels observed in the 2018 surveys (grand means by survey: May 2018 = 39.2 acres [SD 2.9], September 2018 = 35.7 [SD 4.8], May 2019 = 17.1 [SD 2.5]), September 2019 = 34.2 [SD 1.9]). From personal observation, such year-to-year fluctuations in SAV abundance within the boundaries of colonized habitat is not unusual and can be driven by interannual variability in the onset of the growing season and shifting proportions of different SAV species found in this area (*H. wrightii, Ruppia maritima, Zostera marina).* The lowered abundance of SAV within areas of colonization, operating apart from seasonal fluctuation in overall seafloor coverage of SAV, is not a typical mechanical response to storm events. However, hurricanes Florence and Dorian may have had indirect effects on SAV abundance that cannot be ruled out arising from prolonged water quality changes, exposure at low water, reduced salinity, etc.

Monitoring will continue to be conducted biannually in and the spring and fall (April-May and September-October, respectively) which captures both seasonal and interannual variation. Sampling across the study area and updated shading zone (based on results from the Shading Tool) will provide the basis for determining any project-related impacts. Sampling areas may continue to may be periodically be altered to accommodate safety requirements of the bridge construction.

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Thayer, G.W., W.J. Kenworthy, and M.S. Fonseca. 1984. The ecology of eelgrass meadows of the Atlantic coast: a community profile. U.S. Department of the Interior, Fish and Wildlife Service, Division of Biological Services, Research and Development, National Coastal Ecosystems Team. FWS/OBS-84/02. 147 pp.

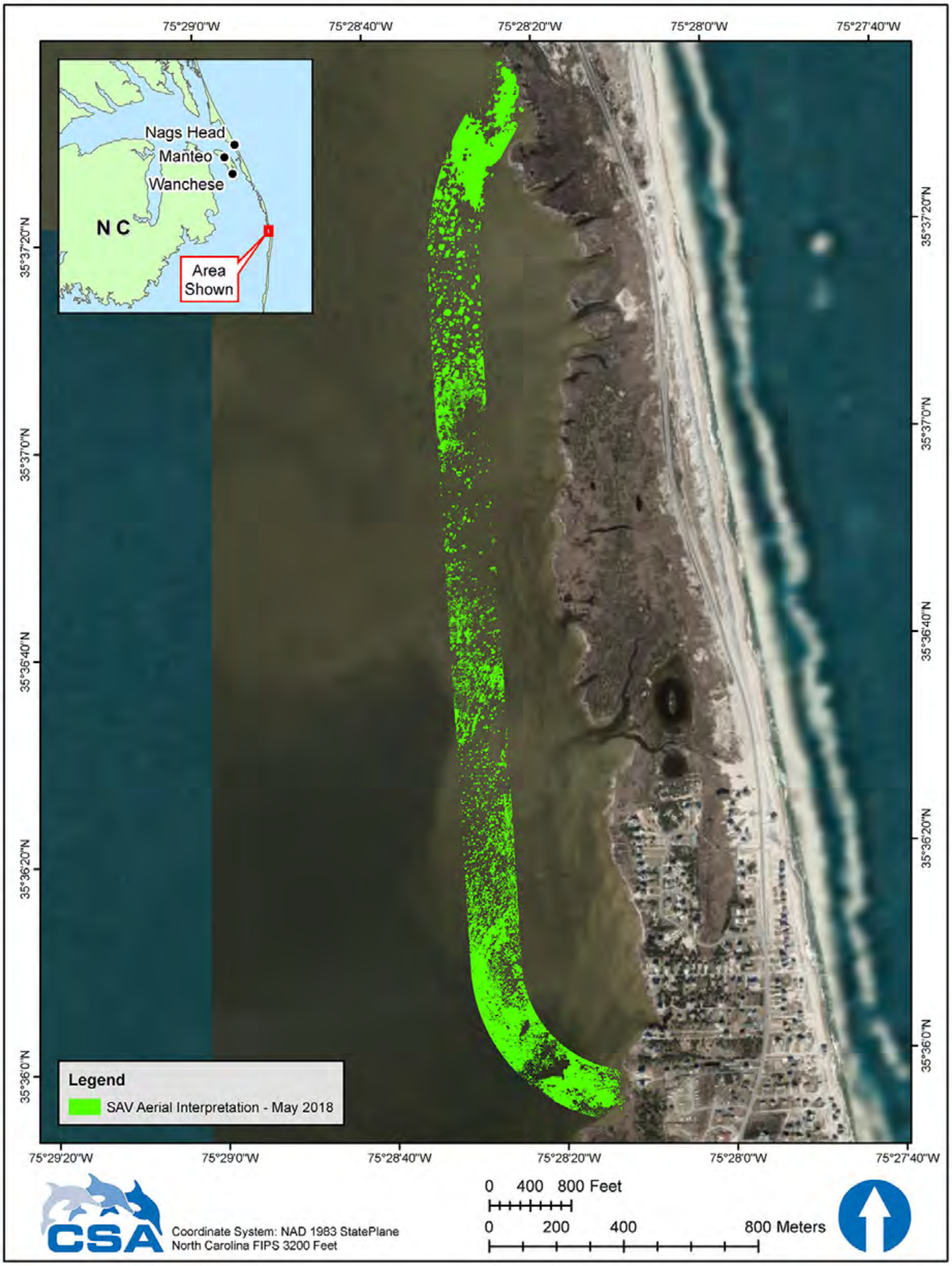

Figure 2. GIS-based interpretation of submerged aquatic vegetation (SAV) cover within the study area (bridge alignment, shading, and reference strata) for the May 2018 survey.

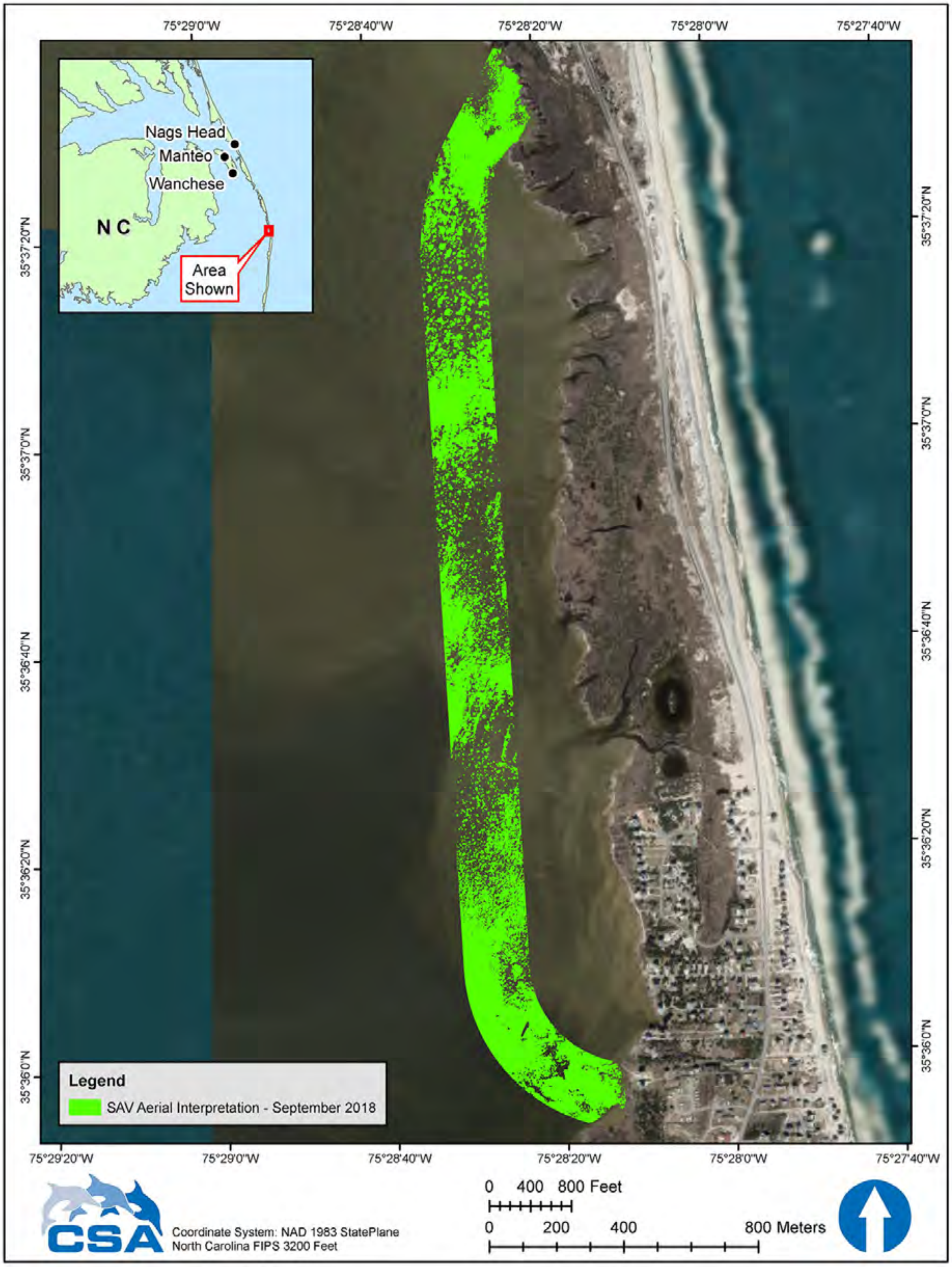

Figure 3. GIS-based interpretation of submerged aquatic vegetation (SAV) cover within the study area (bridge alignment, shading and reference strata) for the September 2018 survey.

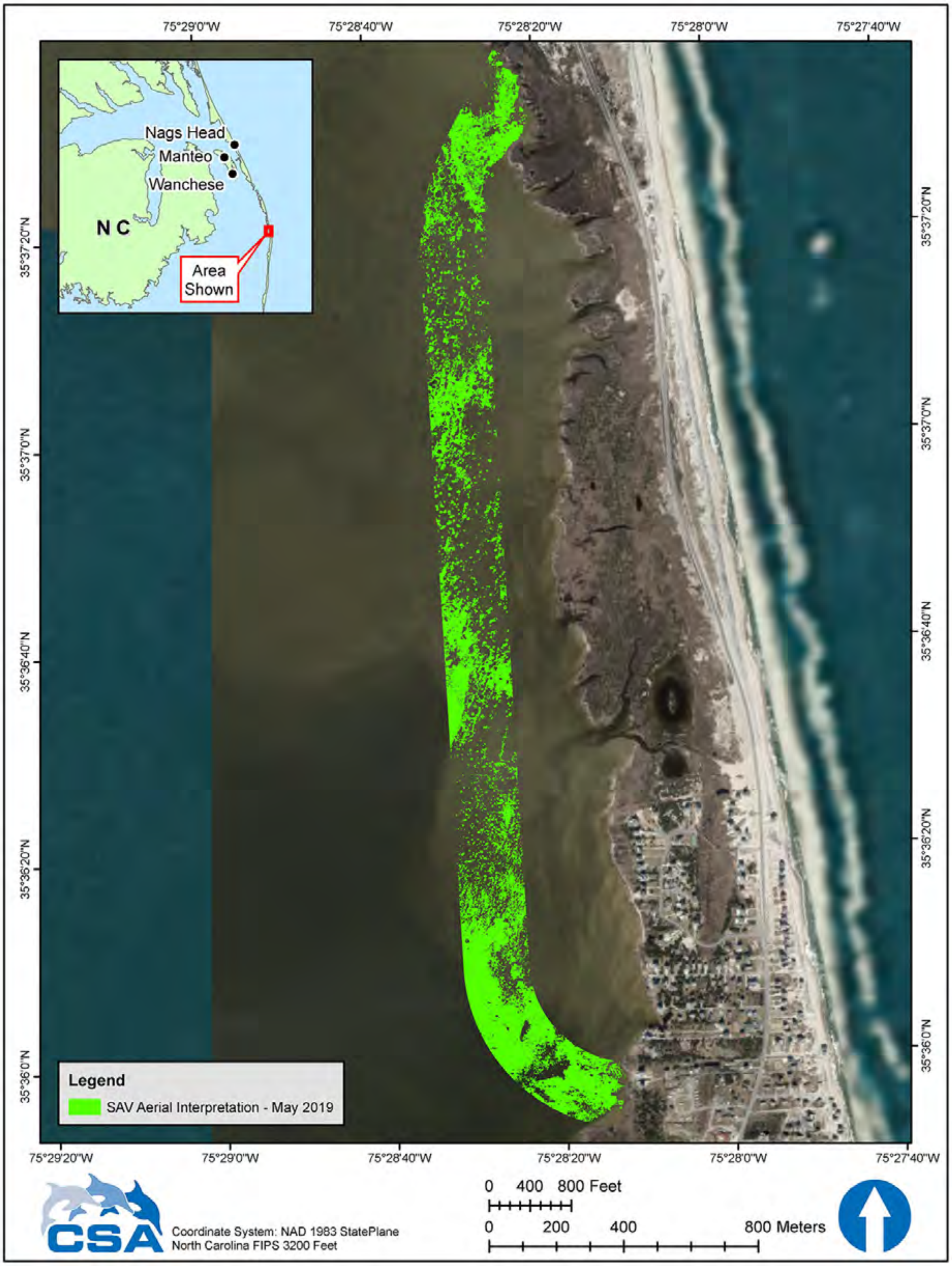

Figure 4. GIS-based interpretation of submerged aquatic vegetation (SAV) cover within the study area (bridge alignment, shading and reference strata) for the May 2019 survey.

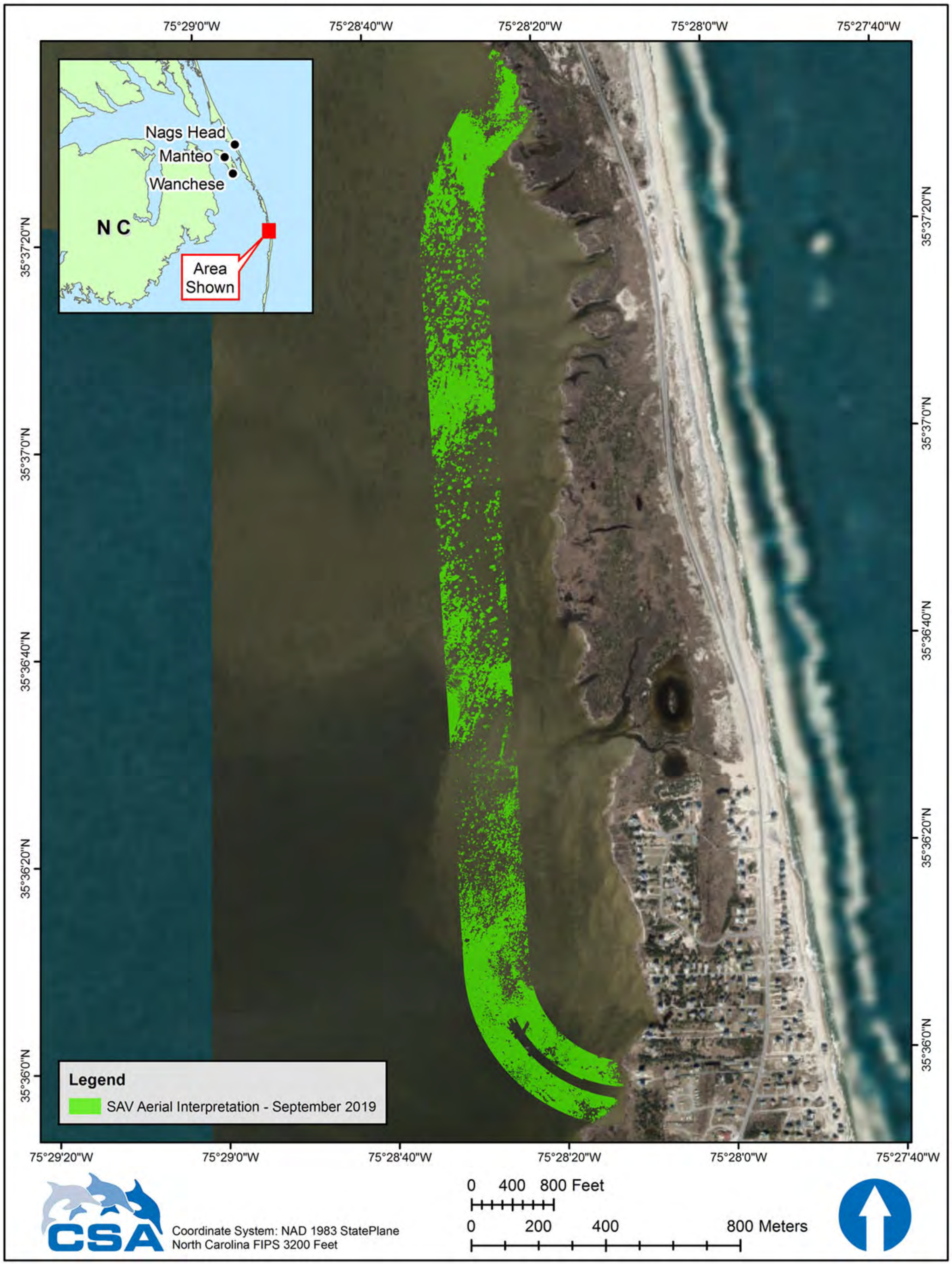

Figure 5. GIS-based interpretation of submerged aquatic vegetation (SAV) cover within the study area (bridge alignment, shading and reference strata) for the November 2019 survey.

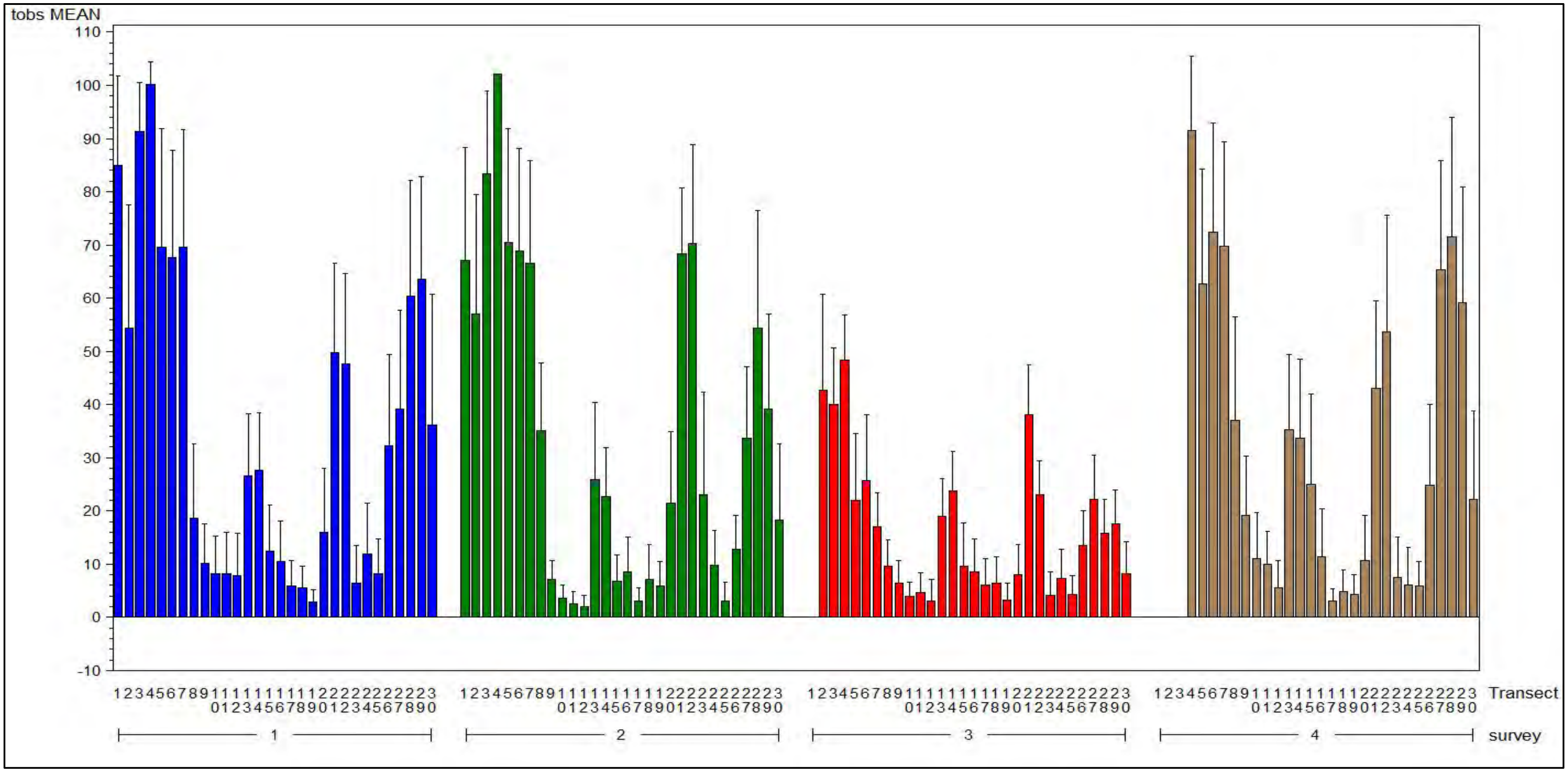

Figure 6. Means and standard deviations of percent cover of submerged aquatic vegetation (SAV) (Y-axis) from quadrat samples taken along Transects 1 to 30. Survey 1 = July 2018; Survey 2 = October 2018; Survey 3 = May 2019; Survey 4 = September 2019. Note the absence of data from transects in Surveys 3 and 4 due to safety requirements associated with bridge construction.

B-2500 Bonner Bridge Seagrass Mitigation Site

Year 3 Annual Survey Report

December 2019

Prepared for:

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B-2500 Bonner Bridge Seagrass Mitigation Site
Baseline Monitoring Survey

DOCUMENT NO.CSA-NCDOT-FL-19-1830-2845-11-REP-01-FIN

Version	Date	Description	Prepared by:	Reviewed by:	Approved by:
01	07/20/19	Initial draft for review	M. Fonseca	E. Hodel	E. Hodel
02	08/07/19	Revised draft	M. Fonseca	K. Metzger	E. Hodel
FIN	12/17/19	Final	M. Fonseca	E. Hodel	E. Hodel

Table of Contents

List of Tables

Table **Page**

List of Figures

Figure **Page**

List of Photos

List of Photos
(Continued)

Photo **Page**

1.0 Introduction

The North Carolina Department of Transportation (NCDOT) contracted CSA Ocean Sciences Inc. (CSA) in 2012 (Contract No. 6300032017) to conduct in-kind seagrass (mixed *Halodule wrightii, Ruppia maritima, Zostera marina*) mitigation of 1.28 acres (0.52 hectares) to compensate for losses anticipated to occur during the replacement of the Herbert C. Bonner Bridge over Oregon Inlet, North Carolina (**Photo 1**). The Bonner Bridge provides the only highway connection for Hatteras Island to the mainland in Dare County, North Carolina and its replacement is currently under construction. Based on previous published research in North Carolina (Fonseca et al., 1998, Fonseca et al., 2000, Kelly et al., 2001, Fonseca et al., 2002) CSA conceptualized creating a wavebreak structure to modify existing, patchy seagrass habitat by attenuating wave activity to promote more continuous, persistent seagrass coverage. This subsequent increase in seagrass acreage was expected to meet NCDOT's seagrass mitigation requirements while enhancing ecosystem services for the surrounding area.

Photo 1. Aerial image of Bonner Bridge.
Source: http://www.kdhnc.com/667/Herbert-C-Bonner-Bridge-Replacement-Project.

CSA conducted the first Biannual Monitoring Survey (Year 1) for the Bonner Bridge Seagrass Mitigation Site from 2 to 4 October 2017. The Year 1 Biannual Monitoring Survey was initially scheduled for August 2017; however, due to tropical storm and hurricane activity and subsequent above-average water depths in Pamlico Sound at the site, the survey was not conducted until early October 2017. In 2018, the spring survey (May – June) was conducted from 13 to 17 May. In 2019 the survey was conducted from 14 to 17 May and provides the most recent data included in this Year 3 Annual Survey Report. **Table 1** has been updated and describes CSA's previous activities and future scheduled surveys.

Table 1. Activity and monitoring survey schedule for the Bonner Bridge Seagrass Mitigation Site. Construction refers to the installation of the wavebreak structure.

Task	Date	Status
Pre-construction		
Site Selection Survey	April 2015	Complete
Seagrass Transplantation and Bioturbation Experiment Initiation	May 2016	Complete
Sediment Digital Elevation Survey (USV)	June 2016	Complete
Construction		
Wavebreak Structure Installation	18 Nov. 2016 to 18 Jan. 2017	Complete
Post-construction		
Baseline Monitoring Survey	14 to 18 Jan. 2017	Complete
Year 1 Biannual Monitoring Survey	2 to 4 Oct. 2017	Complete
Year 2 Annual Monitoring Survey	13 to 17 May 2018	Complete
Year 2 Biannual Monitoring Survey	6 to 8 October 2018	Complete
Year 3 Annual Monitoring Survey	May 2019	Complete
Year 3 Biannual Monitoring Survey	October 2019	Scheduled
Year 4 Annual Monitoring Survey	July 2020	Scheduled
Year 5 Annual Monitoring Survey	July 2021	Scheduled

USV = unmanned surface vehicle.

2.0 Methods

The Year 1 Baseline and Biannual Survey Reports included:

- Observations of conditions
- Monitoring of relocated seagrass in two planted areas and reference areas;
- Monitoring of selected bioturbation experiment stations and removal of mesh when found;
- Collection of sediment elevation data;
- Download of long-term wave data and maintenance of wave sensors;
- Collection of wave sensor data throughout the site for future WEMo validation; and
- Maintenance of epibiota monitoring stations on the wavebreak structure.

The Year 2 Baseline and Biannual Survey Reports included:

- Observations of conditions
- Monitoring of relocated seagrass in two planted areas and reference areas;
- Collection of sediment elevation data
  - o Seagrass patch elevation rods
  - o SEPI near-field wavebreak surveys
- Download of long-term wave data and maintenance of wave sensors;
- Collection of wave sensor data throughout the site for future WEMo validation
- Reporting of wave sensor data throughout the site over this and the past surveys for WEMo validation; and
- Monitoring of epibiota monitoring stations on the wavebreak structure

This Year 3 Annual Survey Report includes:

- Observations of conditions
- Monitoring of relocated seagrass in two planted areas and reference areas;
- Collection of sediment elevation data
    - o Seagrass patch elevation rods
    - o SEPI near-field wavebreak surveys
- Download of long-term wave data and maintenance of wave sensors;
- Collection of wave sensor data throughout the site for future WEMo validation
- Reporting of wave sensor data throughout the site over this and the past surveys for WEMo validation; and
- Monitoring of epibiota monitoring stations on the wavebreak structure

CSA's methods followed the accepted monitoring plan (STIP B-2500 Bonner Bridge Phase I seagrass Mitigation Plan, Pamlico Sound, Dare, County, North Carolina; September 2015) referenced in the permit (Permit Modification No. 106-12) to ensure all monitoring requirements were met.

During the October 2017 survey, scientists observed patchy seagrass habitat consisting of three species of seagrass (*Z. marina*, *H. wrightii*, and *R. maritima*). *Halodule wrightii* was the most prevalent species, followed by *Z. marina* and then *R. maritima*. The major substrate type observed throughout the site was fine sand. Limited vessel traffic was observed during on-site surveys within the immediate vicinity. Site conditions were relatively consistent during the survey, with slight variations due to direction and strength of the wind. Average daily water temperatures during the survey ranged from 22°C (72°F) to 23°C (73°F), with wind speeds ranging from 26.5 to 31.3 kph (16.4 to 19.5 mph). Wind direction was predominately out of the north.

In May 2018, scientists again observed patchy seagrass habitat consisting of three species of seagrass (*Z. marina*, *H. wrightii*, and *R. maritima*). *Halodule wrightii* and *Z. marina* were both commonly observed while *R. maritima* was rarely observed. The major substrate type observed throughout the site was fine siliceous sand. Limited vessel traffic was observed during on-site surveys within the immediate vicinity. Site conditions were relatively consistent during the survey, with slight variations due to direction and strength of the wind. Average daily water temperatures during the survey ranged from 23.4°C (74.2°F) to 24.8°C (76.7°F), with wind speeds ranging from 7.6 to 41.1 kph (4.7 to 25.5 mph). Wind direction was predominately south-southwest.

During the October 2018 survey, scientists observed patchy seagrass habitat consisting of two species of seagrass (*H. wrightii* and *Z. marina*). *Halodule wrightii* was the most prevalent species, followed by *Z. marina*. *Ruppia maritima*, as distinguished by presence of flowering shoots, was not observed during this survey. The major substrate type observed throughout the site was fine sand. Limited vessel traffic was observed within the immediate vicinity of the wavebreak structure. Site conditions were relatively consistent during the survey, with slight variations due to direction and strength of the wind. Average daily water temperatures during the survey ranged from 25.7°C (78.3°F) to 27.4°C (81.3°F), with wind speeds ranging from 7.6 to 27.7 kph (4.7 to 17.2 mph). Wind direction was predominately out of the east-northeast.

During the May 2019 survey, scientists observed patchy seagrass habitat consisting of three species of seagrass (*H. wrightii*, *R. maritima*, and *Z. marina*). *Halodule wrightii was* the most prevalent species, closely followed by *Z. marina*. *Ruppia maritima* was rarely observed but present. The major substrate type observed throughout the site was fine sand. Limited vessel traffic was observed within the immediate vicinity of the wavebreak structure. Site conditions were relatively consistent during the survey, with slight variations due to direction and strength of the wind. Average daily water temperatures during the survey ranged from 17.0°C (62.6°F) to 19.6°C (67.3°F), with wind speeds ranging from 1.6 to 45.1 kph (1 to 28 mph). Wind direction was predominantly out of the west.

Sections of this report that refer to construction and engineering activities or permits where originally developed using English units, will follow the convention of reporting first in English units and then parenthetically in metric units. For the sections of the report not directly associated with structural engineering, the convention of reporting will be metric units followed by English units parenthetically.

Sections of the early reports describing initial project activities have now been moved to Appendices in order to focus on long-term post-construction monitoring. Project Site Selection and Project Engineering and Design sections were initially described here in previous reports. This historical material has now been moved to **Appendix I**. Additionally, the description of an attempted experiment to assess the relative contribution of bioturbation to patch maintenance (versus wave energy) has been moved to **Appendix II**.

MONITORING OF RELOCATED SEAGRASS

In 2016, prior to installation of the wavebreak structure, the State of North Carolina Department of Environmental Quality and Coastal Resources Commission permit (Permit Modification No. 106-12) required any seagrass within the structure footprint and the construction corridor to be moved to the lee side of the structure onsite. In May 2016, seagrass patches within the structure footprint and construction corridor were relocated to two planting areas on the south side of the construction footprint (**Figure 1**).

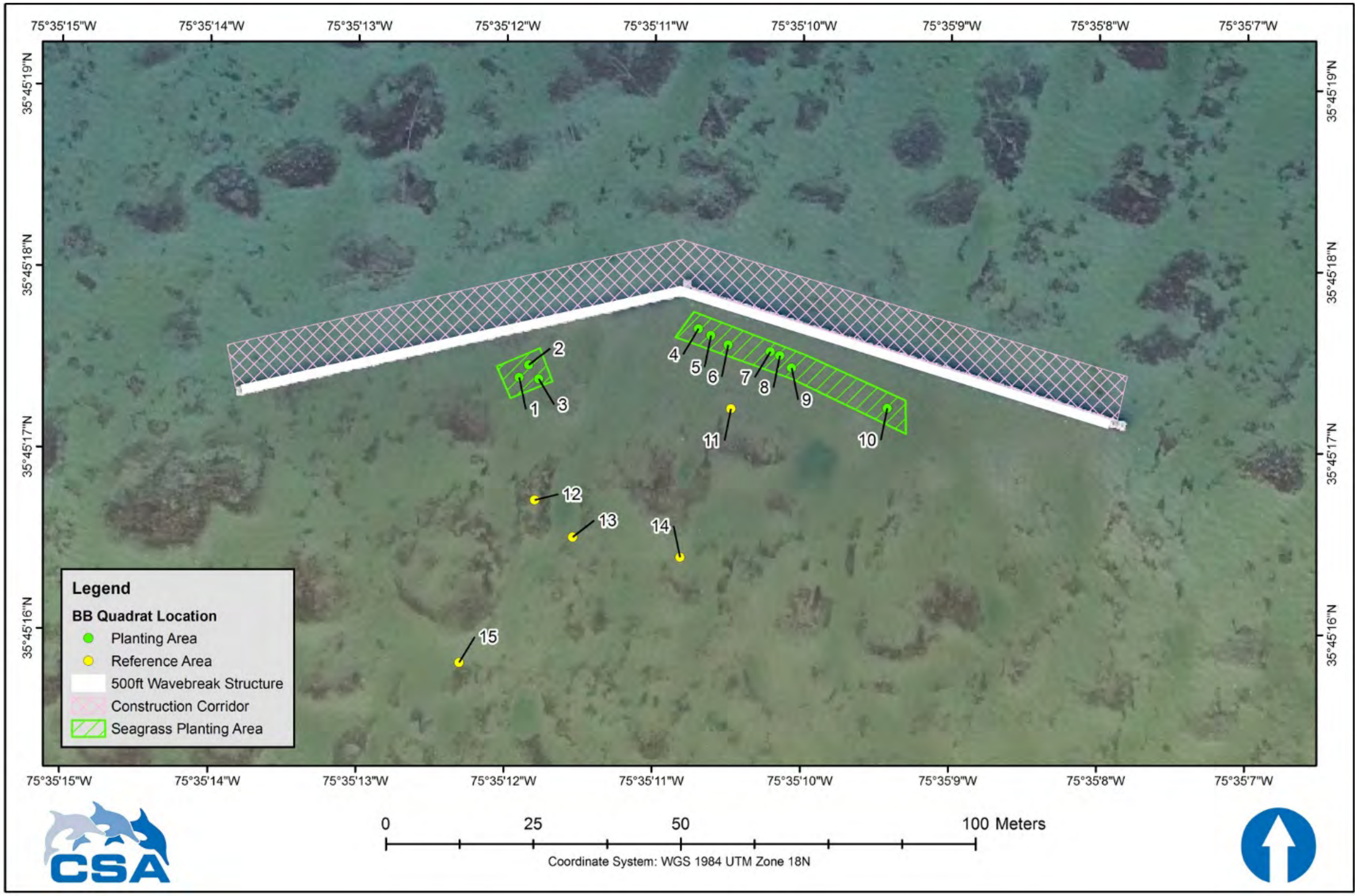

Figure 1. Aerial image of the wavebreak area at the Bonner Bridge Seagrass Mitigation Site, showing the position of the seagrass planting areas, the construction corridor, and the structure itself. Examples of randomly selected seagrass survey points are shown for surveys within the planted areas and nearby reference locations.

Percent cover of seagrass within relocation areas was evaluated immediately after transplanting. Each time, scientists navigated to 10 pre-selected locations (proportionally assigned to seven locations in the larger eastern relocation area and three in the smaller western relocation area) within the planting areas using the Trimble Geo XH GeoExplorer 2008 Series GPS.

To compare the colonization of the planted areas to the surrounding natural areas, five additional random locations were selected in the surrounding natural areas (reference area) within a 50-meter (164-foot) distance of the planting areas (**Figure 1**). At each location, a 1-m^2 (11-ft^2) quadrat was centered over each point and percent cover of seagrass was assessed using a modified Braun-Blanquet (BB) cover and abundance technique (Braun-Blanquet, 1972; Kenworthy and Schwarzchild, 1997; Fourqurean et al., 2001). Within the quadrat a BB scale value (**Table 2**) was independently evaluated for percent cover of each seagrass species as well as total seagrass. Average BB scores were then converted to percent cover for each area to allow interpolation of averaged BB scores that fall between BB scale values (conversion is conducted by regressing the mid-point of percent cover associated within the range covered by each BB scale value, on the associated BB scale value:
Percent Cover = $2.8108*[BB]^{2.2325}$).

Table 2. Braun-Blanquet scale (score) and percent cover scale values (Braun-Blanquet, 1972).

Braun-Blanquet Scale (Score)	Percent Cover (%)
0.0	Not present
0.1	Solitary specimen
0.5	Few with small cover
1	Numerous, but <5
2	5 to 25
3	25 to 50
4	50 to 75
5	75 to 100

SEAGRASS COVER

Seagrass cover was determined by classifying areas of seagrass occurring within the Bonner Bridge Seagrass Mitigation Site based on aerial imagery. A georeferenced, high-resolution mosaicked aerial image (collected by NCDOT on 18 April 2018) was used for the first classification of seagrass areas. The aerial image was color-infrared (CIR) with a resolution of 0.08 m (0.25 ft). The image was subdivided into separate classification areas of interest (AOI) based on similar pixel spectral signature ranges. Separate classification of each AOI helped to eliminate variations in reflectance and environmental conditions across the entire project area in order to reduce classification confusion. An unsupervised classification was then performed on each classification AOI using a combination of iso cluster and maximum likelihood techniques using ESRI ArcGIS 10.4 software. After running the unsupervised classifications, each AOI was manually interpreted by denoting visually apparent classes of seagrass and classes of non-seagrass. Spectral noise and holes within the classification results were removed and corrected using a combination of majority filter, region group, set null (enhanced boundary edges and removed groups of small non-contiguous pixels that were smaller than a specified value), and eliminate polygon part (eliminated areas that were less than a specified value) tools in ArcGIS. Lastly, a manual classification technique was then applied to the classification with guidance from a GIS analyst.
This consisted of removing areas of over-classification and adding-in (digitizing) areas where

under-classification occurred, again based on visually apparent seagrass cover. Following the 18 April 2018 overflight, no further overflight data are being processed under this award.

SEDIMENT ELEVATION

Sediment elevation is being documented with three methods:

1. **Rod Heights** - measurements of sediment height relative to 2 m long rods installed to near the sediment surface in seagrass patches used for the previous bioturbation studies,
2. **USV Digital Elevation Model** - a broad-scale digital elevation model created using an RTK-equipped (real-time kinematic) unmanned surface vehicle (USV), and
3. **Near-field Transect Sediment Elevation Survey** - Near-field sediment elevation measurements along transects north and south of the wavebreak.

Rod Heights: This method utilized during all monitoring surveys was by direct measurement of the height of the center rod above the sediment at each of the 40 stations originally established for the bioturbation experiment (see **Appendix II**). At each station, the rod height above the sediment was measured using a meter stick fastened to a piece of wood (24 cm × 5 cm × 5 cm [18 in × 2 in × 2 in]). The 0-mark on the meter stick was attached to the center of the wood piece creating an inverted "T" shape (**Photo 2**). The wood was laid flush against the seafloor to provide more surface area to avoid the ruler sinking into the substrate. The meter stick was placed next to the rod to obtain the measurement of the rod height above the substrate. In addition to the 40 center rods, four additional sediment rods (one per wave energy regime) were installed in sandy substrate and rod height above the substrate was measured for each.

This monitoring is continuing, and updated results are provided in this report. Change in sediment elevation among surveys and across the wave energy strata was computed for each combination of survey times (survey 1 vs 2, 1 vs 3, 1 vs 4, 2 vs 3, 2 vs 4 and 3 vs 4). The differences in change in sediment elevation among strata for each comparison of survey times were compared in a 1-way ANOVA using PROC GLM in SAS 9.2 after ln + 10 transformation (to avoid negative numbers and address any non-normality of the data).

USV Digital Elevation Model: A second method was employed to evaluate the entire area forecast to be affected by the wavebreak. In June 2016, CSA used a USV to develop a sediment digital elevation model to document changes in shoal elevation associated with the wavebreak installation. The USV (**Photo 3**) was pre-programmed to run a pre-selected geographic grid at 50-m (164-ft) spacing which encompassed the entire site. Bathymetry data was collected using duel frequency, single beam sonar at a rate of 220 to 224 kHz. A Trimble RTK system (RTK) was mounted on the USV to integrate real time navigation while the USV ran the pre-programmed grid lines (speed of approximately 9 kph [5.7 mph]). The RTK had a horizontal and vertical accuracy of 2 cm (± 0.787 in) and real-time tidal corrections were applied to accurately determine water levels across the site. This survey will be repeated at the end of the five-year monitoring period in 2021.

Photo 2. Inverted "T" shape ruler used to measure rod height above or below the substrate at the Bonner Bridge Seagrass Mitigation Site.

Photo 3. Unmanned surface vehicle (USV) collecting bathymetry data across the Bonner Bridge Seagrass Mitigation Site.

Near-field Transect Sediment Elevation Survey: In June 2017, a third method of sediment elevation assessment was initiated. SEPI Engineering Inc. (SEPI) was contracted by NCDOT to conduct high density, near-field sediment elevation measures in the vicinity of the wavebreak structure. North-south oriented transects were established at five equally spaced locations centered on the wavebreak (**Figure 2**) and sediment elevations corrected to MLLW surveyed (June 2017, September 2017 and then monthly starting January 2018; reported here through June of 2018). Transects were placed on both the north and south side of the wavebreak. In 2017, elevations at distances of 0 (at the edge of the wavebreak structure), 5, 10, 20, 50, 75, and 100 ft were recorded. In January of 2018 that changed to increments of 5 feet out to 50 ft and then at 75 and 100 ft to improve sensitivity of detecting any systematic change in sediment elevation. Starting in June of 2018, distances of 125 and 150 ft were added to ensure elevation samples were taken beyond the apparent apron of recently moved sand seen in aerial images (**Figure 3**). These data have been provided to CSA and were analyzed for this report. Elevations were compared in a 2-way ANOVA using PROC GLM in SAS 9.2 after ln + 10 transformation (to avoid negative numbers and address any non-normality of the data). Main effects were distance from the wall and side of the wall, tested at individual dates along with assessment for interaction of main effects.

WAVE REGIME AND MODEL VALIDATION

Long Term Wave Regime: Long-term wave energy regime monitoring stations were placed at the Bonner Bridge Seagrass Mitigation Site in "Month Year" using pressure sensor loggers to record wave characteristics. Starting in January 2017 two pressure sensors (RBR*virtuoso* models) were deployed at stationary locations 25 m (82 ft) in front (north) of and behind (south) the wavebreak structure (**Figure 4**). Pressure sensors were cylindrical and approximately 5 cm (2 in) in diameter by 25 cm (10 in) long and were mounted in a locked casing horizontally on the seafloor approximately 15 cm (6 in) above the substrate on a solid base, concrete-filled pillar set 0.91 m (3 ft) into the seafloor (**Photo 4**). Pressure sensors were set to record bursts of pressure data every 30 minutes at a sampling rate of 4 Hz for 128 seconds. These data also provide water level and tide documentation specifically for the site in order to evaluate the wave energy regime impinging on the north and south faces of the wavebreak structure.

In November 2017, the sensors were removed and sent back to the manufacturer (RBR) for calibration and assessment of impacts from sand impaction and biofouling that had occurred around the wave sensor port. This servicing caused the sensors to be out of service until their re-deployment on 16 January 2018. Communication with the RBR technical representatives indicated that the sediment impaction and biofouling did not affect the detection of wave characteristics. Nonetheless, upon redeployment, the sensor brackets were revised to hold the sensors in a vertical posture and with the wave sensor window down-facing (**Photo 5**) in order to minimize sand collection in the sensor port through gravity. The sensors were re-deployed in January 2018 and have been recording continuously since that time. The entire January 2017 – May 2019 data are reported here.

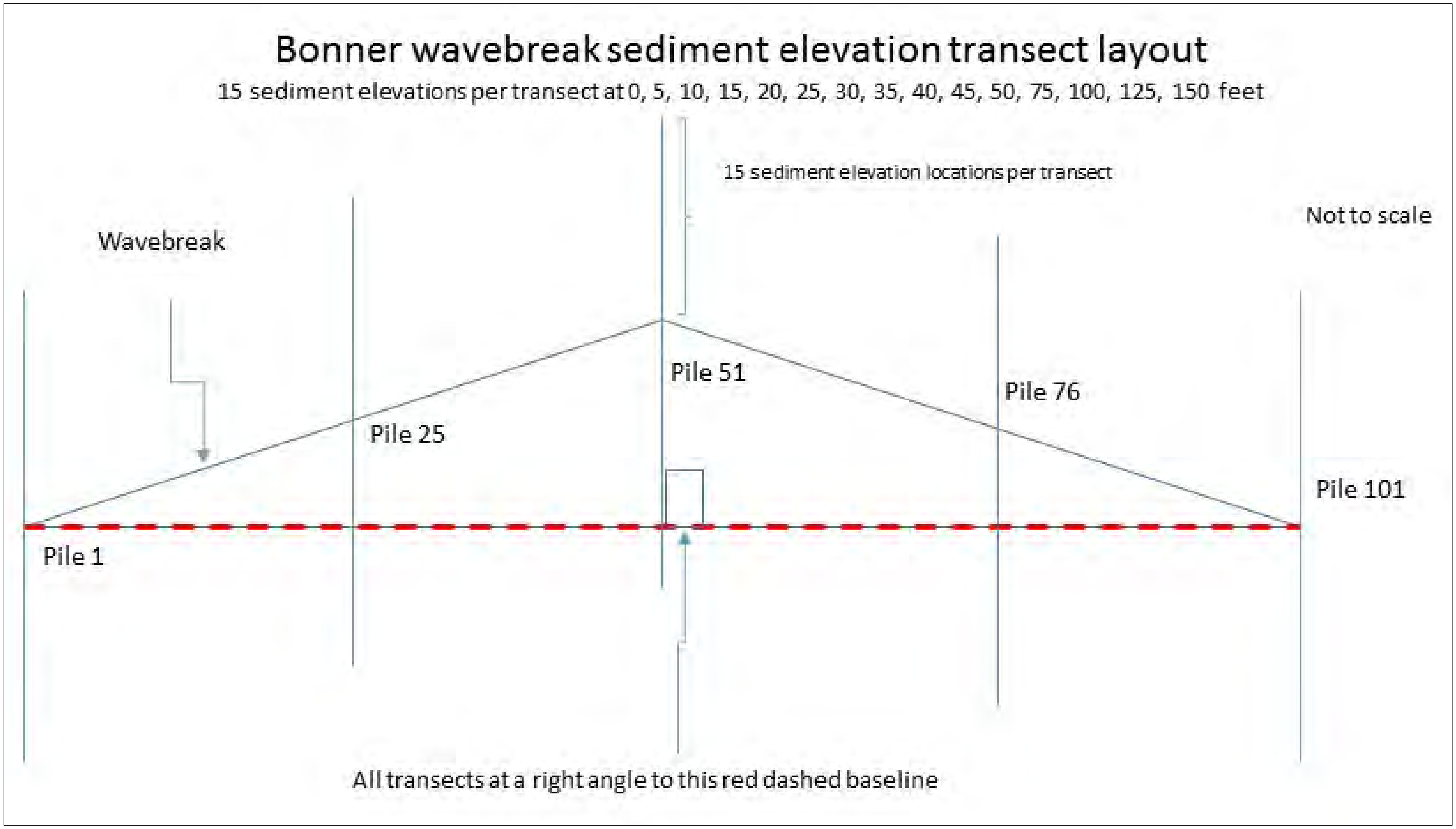

Figure 2. Schematic (not to scale) layout of the near-field (to wavebreak) sediment elevation transects.

Figure 3. Sand apron south of wall visually outlined. 18 April 2018.

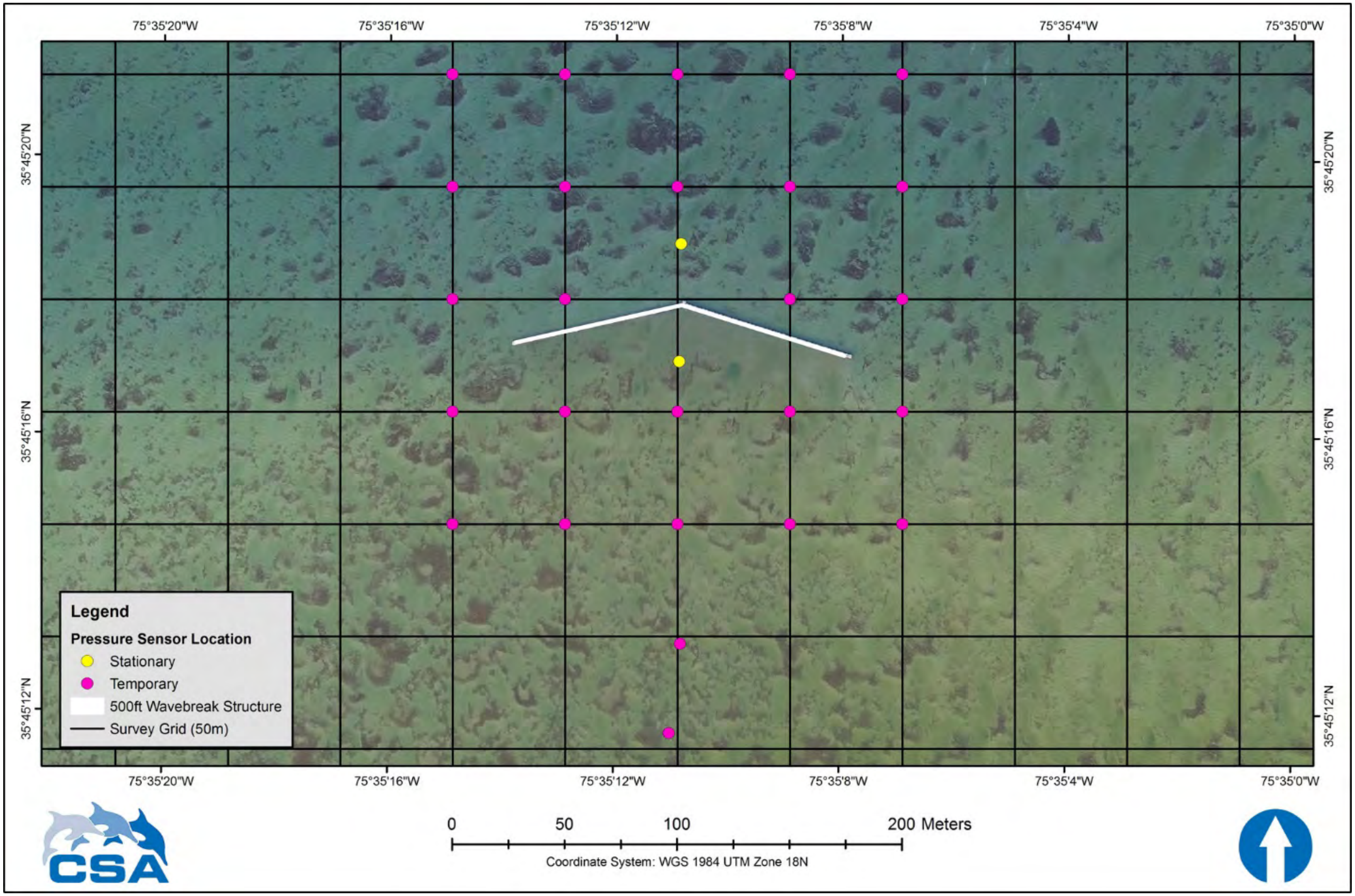

Figure 4. Stationary and temporary locations of the pressure sensors at the Bonner Bridge Seagrass Mitigation Site.

Photo 4. Photograph of one of the two wave sensor brackets cemented into its base, prior to installation at the Bonner Bridge Seagrass Mitigation Site. The hinged bracket is shown being lifted; a disposable padlock is installed through the hinged piece to keep the sensor secure.

Photo 5. Re-engineered wave sensor bracket installed in January 2018 to hold the sensor vertical and further away from the sand surface.

WEMo model validation: This is being developed through opportunistic sampling. During times of onsite monitoring surveys, an RBR sensor was systematically but temporarily relocated across the site in a grid pattern (**Figure 4**) to obtain a spatial assessment of predicted (WEMo computation to follow based on water depth and wind conditions of the survey date) versus observed wave heights from the mobile sensor. This spatial assessment was performed on 18 May 2016; 15 January 2017; 4 October 2017; 15 May 2018; 7 October 2018; and 16 May 2019 to provide a geographically articulated assessment of wave energy distribution with regard to prevailing conditions. The relocated pressure sensor was set to record bursts of pressure data at a sampling rate of 4 Hz for 128 seconds during this sampling. During these surveys one of the long-term RBR sensors was used. During each survey, a scientist recorded the wind speed using hand-held anemometers as well as wind direction prior to sampling and again after sampling was complete. Wave data from pressure sensors were downloaded into Ruskin software (V1.13.7) and exported to Microsoft Excel for analysis. Analysis will be comprised of simple univariate statistics of wind speed and predicted versus observed regression to determine the ability of the WEMo-derived forecast to downscale to the 50 m scale.

EPIBIOTA MONITORING

Epibiota monitoring on the wavebreak was initiated in January 2017 through the establishment of randomly-placed, permanent monitoring stations (**Figure 5**). Digital photographs were recorded at each station as a time-zero (uncolonized) baseline against which subsequent epibiota colonization will be compared for each survey time. Stations were stratified by the sides of the wavebreak (30 on the exposed side [north] and 30 on the sheltered [south] side) at different vertical elevations related to the individual wave attenuator unit placement (high, middle, and low). Ten replicate stations were randomly assigned per elevation on either side of the wavebreak for a total of 60 monitoring stations. Random locations were selected along the wavebreak and a vertical elevation was randomly assigned to each location. Scientists used the Trimble GPS to navigate to the pre-selected random monitoring station/elevation replicate along the wavebreak. Monitoring stations were separated by a minimum of one Reefmaker unit. The exact horizontal location of the monitoring station on a wave attenuator unit was visually determined where rock placement was closest to the edge of the concrete, making them easier to photograph. Some wave attenuator units had smaller rock embedded in the concrete, so often two small rocks were selected for monitoring. To identify the precise monitoring location and allow precise alignment for subsequent photographs, a numbered tag was installed on the rock immediately to the right of the selected rock(s) to be monitored (**Photo 6**) and alignment points marked on the concrete surface.

A Sony A5000 digital camera in an underwater housing was installed on a PVC camera mount framer to photograph the concrete and rock(s) at each monitoring station. The PVC frame (**Photo 7**) was included in every photo to ensure standardization of photo size (dimension of the frame was 20.3 cm × 30.5 cm [8 in × 12 in]). The camera housing was fixed to the framer with a distance of 25.7 cm (10 in) from the housing lens to the outer edge of the frame.

To photograph the concrete portion of the wave attenuator units, the entire framer was placed flush with the side of the concrete, so the bottom edge of the concrete was included within the frame. To photograph the rock(s), the bottom of the framer was placed flush with the top edge of the concrete layer (where the selected rock was embedded) and the top of the framer rested on the concrete layer located above the selected rock(s) (approximately 15º angle).

During the May 2018 survey, the low elevation strata monitoring stations were entirely submerged during all observed tidal stages. This coupled with high turbidity levels, reduced visibility to less than one foot. As a result, the method used to photograph the low elevation stations was slightly modified. The camera was removed from the framer to allow capture of close-up photos within visibility limits. The framer was still held against the concrete as described previously, yet due to the decreased distance between the camera and the rock or concrete, multiple photographs were collected to image the entire area within the framer (typically four photos). The multiple photographs were then stitched together using Adobe® Photoshop® to create a single photograph of each low strata rock or concrete monitoring station. This methodology was not necessary in subsequent surveys (October 2018 and May 2019) as visibility was sufficient for photographing the original area contained within the framer, resulting in one image.

One photo of the concrete and one photo of the rock(s) were collected for all 60 monitoring stations, resulting in 120 digital images. Digital images were processed and analyzed using Coral Point Count with Microsoft Excel extensions (CPCe) V4.1 software analysis program (Kohler and Gill, 2006). CPCe utilizes the random point count method described by Bohnsack (1979) to accurately estimate percent cover of benthic organisms and substrate from digital images. Because the rocks were all different sizes, it was necessary to assign a number of random points that was proportional to the size of the rock (i.e., a larger rock would have a greater number of random points assigned). The total area of evaluated rock was calculated for each image using the measurement tool in CPCe. For purposes of this assessment, we assumed that all rocks were equidistant from the camera lens. From these calculations, average rock size was determined to be 112.4 cm^2 and was assigned 10 random points. The number of random points assigned to each image was then increased or decreased proportionally to the size of the rock(s); the number of random points for rock images ranged from four to 22. Because the area of concrete assessed was the same in each photo, all concrete images were assigned the same number of random points (41), and points were restricted to the area of the photograph containing concrete. Random points were projected on each image, and the biota or substrate located beneath each point was identified to the lowest possible taxonomic level (for the time-zero images, no biota were detected). Data from each image were assembled in a spreadsheet for percent cover calculations and subsequent comparative analysis.

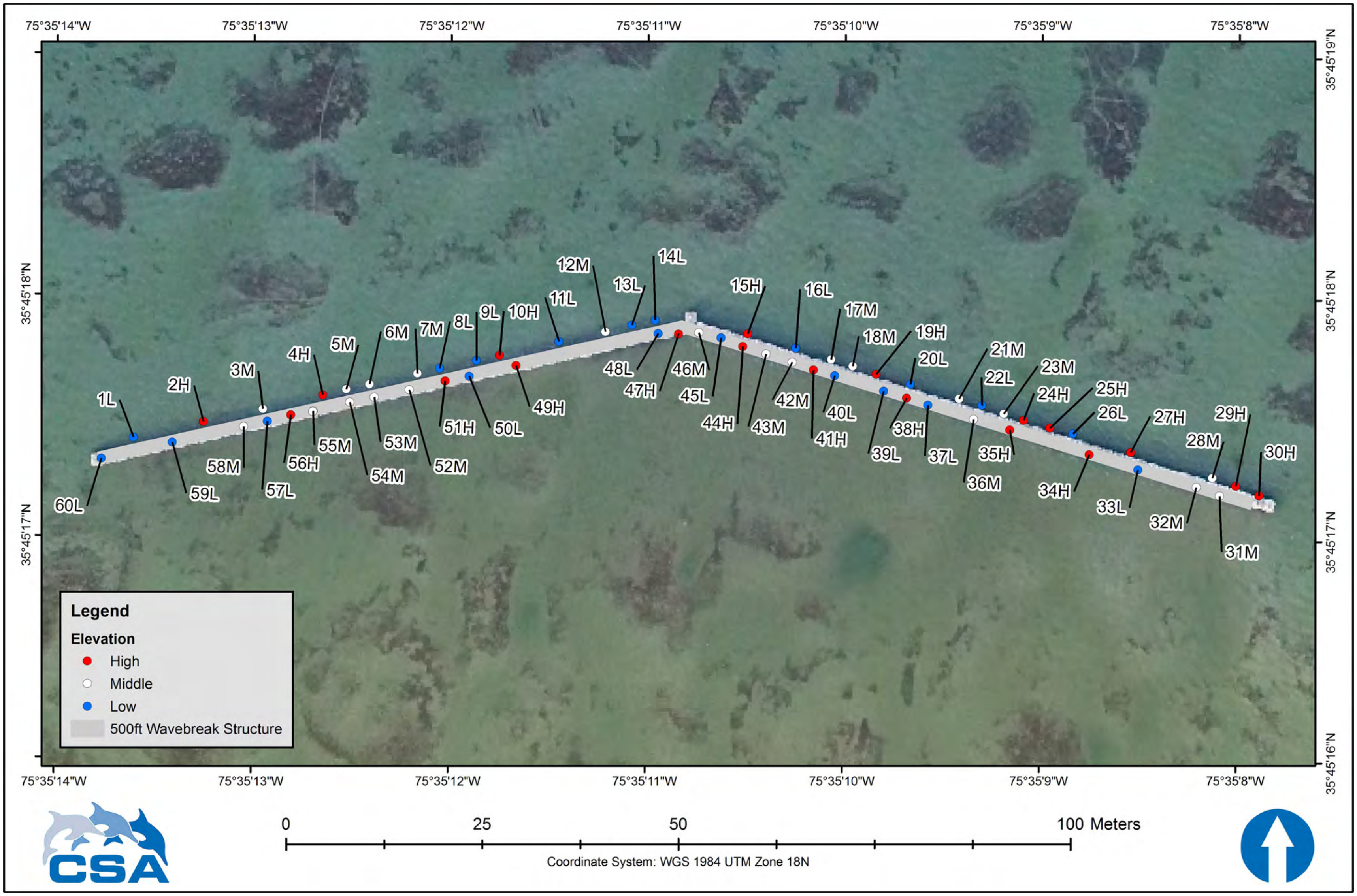

Figure 5. Epibiota monitoring stations on the wavebreak at the Bonner Bridge Seagrass Mitigation Site.

Photo 6. Example of numbered tag installed at every monitoring station on the wavebreak at the Bonner Bridge Seagrass Mitigation Site.

Photo 7. PVC camera mount framer used to photograph every monitoring station on the wavebreak at the Bonner Bridge Seagrass Mitigation Site.

3.0 Results

During visits to the site, scientists have consistently observed that the Bonner Bridge Seagrass Mitigation Site was composed of patchy seagrass habitat consisting of multiple species including *Z. marina*, *H. wrightii*, and *R. maritima*. Very fine sand (visual observation) sediments has consistently been the dominant substrate type observed. Limited vessel traffic has been observed during onsite surveys within the immediate vicinity although small commercial crabbing vessels have been observed crossing the general shoal area.

Site conditions varied during each survey and were largely driven by direction and strength of the wind. Strong northeasterly winds on site resulted in lowered water level at the site and strong southwesterly winds resulted in higher water levels. Current speeds have been consistently low, ranging only between 9.8 and 12.9 cm s^{-1}, with a mean of 11.2 cm s^{-1}. During the May 2019 survey average current speed was 10.3 cm s^{-1}.

During the May 2019 survey, scientists again observed patchy seagrass habitat consisting primarily of two species of seagrass (*H. wrightii* and *Z. marina*). *Halodule wrightii* was the most prevalent species, followed by *Z. marina*. *Ruppia maritima*, was only rarely during this survey. The major substrate type observed throughout the site was fine sand. Limited vessel traffic was observed within the immediate vicinity of the wavebreak structure. Site conditions were relatively consistent during the survey, with slight variations due to direction and strength of the wind.

Average daily water temperatures during monitoring surveys (May and October) have ranged from 17°C (62.6°F) to 24.8°C (76.6°F). During the May 2019 survey water temperature ranged from 17.0°C (62.6°F) to 19.6°C (67.3°F). Average wind speeds during surveys have ranged from 12 to 30 kph (7.5 to 18.5 mph) with maximum wind speeds ranging from 15 to 34 kph (8 to 21.3 mph) from either northeast or west and south-southwest directions. During the May 2019 survey wind speeds ranged from 10.3 to 13 kph (6.4 to 8.1 mph) predominantly from the west.

MONITORING OF RELOCATED SEAGRASS

Prior to construction, seagrass patches within the structure footprint and construction corridor were relocated to two planting areas on the lee side of the wavebreak structure (**Figure 1**). In May 2016, immediately after relocation, the percent cover[1] of seagrass was evaluated within the relocation areas and within the surrounding reference area. Upon completion of relocation, percent cover of seagrass was 32.7% for the relocation areas and 49.1% for the reference area (BB scores of 3.0 and 3.6, respectively[2]). Transplanted seagrass within the relocation areas appeared similar to the surrounding natural seagrass and the borders of the planting areas were visibly indistinguishable (**Photo 8**). All seagrass blades were bright green and visibly clear of epiphytic growth.

In January 2017, immediately following construction of the wavebreak structure, the percent cover of seagrass within the planting areas was evaluated again. The planting areas had a percent cover of 0.2% and the natural reference areas had a percent cover of 7% (BB scores of 0.2 and 1.5, respectively)

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[1] Cover is 'specific cover' as quadrats are placed only within areas colonized by seagrass (as opposed to 'areal cover' which would include any unvegetated seafloor arising from random placement of quadrats)

[2] The average BB scores were converted to percent cover for each area to allow interpolation of averaged BB scores that fall between BB scale values (conversion was conducted by regressing the mid-point of percent cover associated within the range covered by each BB scale value, on the associated BB scale value: Percent Cover = $2.8108*[BB]^{2.2325}$).

(**Table 3**). In January 2017, a brown epiphytic layer covered the majority of the visible seagrass blades and small tufts of brown macroalgae were observed colonizing the substrate often mixed in with seagrass (**Photo 9**). Seagrass cover declined by 32.5% in the planting areas and 42.1% in the reference areas, indicating a substantial overall drop in coverage.

In October 2017, no seagrass was observed in the planted areas. Cover in the reference areas was approximately 62% (**Table 3**), well above the baseline cover of 49% observed in May 2016. Seasonality in seagrass growth may be responsible for the higher cover observed in October, with higher cover expected at the end of growing season in October versus the beginning of growing season in May.

In May 2018, sparse seagrass was observed in the planted areas, but cover was still <1%, marking a decrease of approximately 32% since the initial survey in May 2016 (**Table 3**). Cover in the reference area was approximately 40% (**Photo 10**), similar to the cover observed in May 2016.

In October 2018, at the time of the Year 2 Biannual Monitoring Survey, seagrasses were present within both planted areas, but cover was relatively low at 14.9%, and dominated by *H. wrightii* (**Table 3**; **Photo 11**). Average percent cover of total seagrass in reference areas was high at approximately 100% (**Table 3**; **Photo 12**), where *H*. *wrightii* was also dominant.

In May 2019 (this report) seagrasses were again present within both planting areas but no discernable cover was found in the easternmost planting block and percent cover in the western block was 15.8% (**Table 3, Photo 13**). The reference cover was down to 23.7% (from 100% in the previous survey; **Table 3, Photo 14**).

Table 3. Braun-Blanquet (BB) scores and associated percent cover for seagrass within the planting and reference areas for the Bonner Bridge Seagrass Mitigation Site by survey.

Survey	Planting Area		Reference Area	
	Average Seagrass BB	Average Percent Cover	Average Seagrass BB	Average Percent Cover
May 2016	3.0	32.7	3.6	49.1
January 2017	0.3	0.2	1.5	7.0
October 2017	0.0	0.0	4.0	62.1
May 2018	0.55	0.7	3.3	40.4
October 2018	2.11	14.9	5.0	100
May 2019	0.65	1.1	2.6	23.7

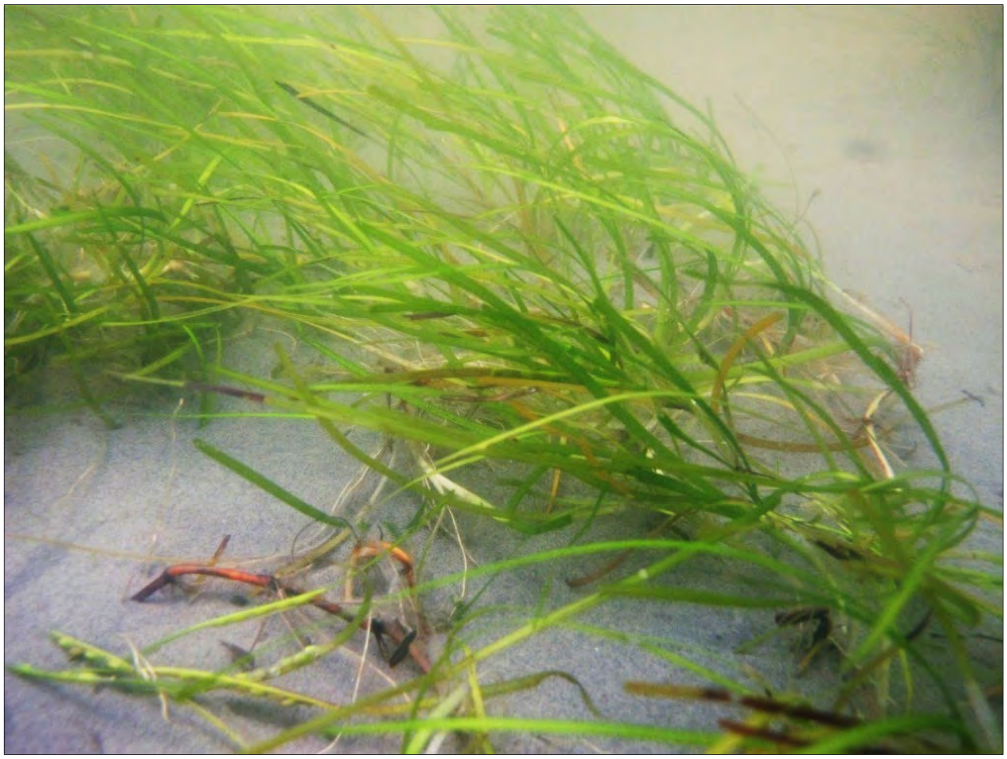


Photo 8. Transplanted seagrass with clean blades appearing similar to surrounding natural seagrass at the Bonner Bridge Seagrass Mitigation Site during the May 2016 survey.

Photo 9. Natural seagrass in the reference area showing blades covered with a layer of epiphytes at the Bonner Bridge Seagrass Mitigation Site during the January 2017 survey.

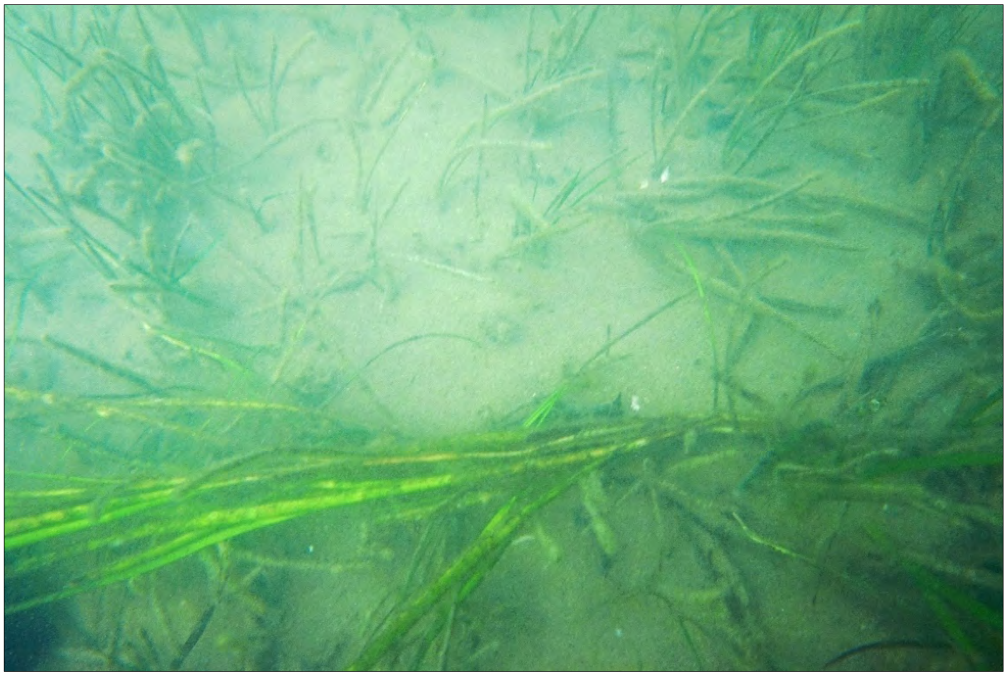


Photo 10. Natural seagrass in the reference area at the Bonner Bridge Seagrass Mitigation Site during the May 2018 survey.

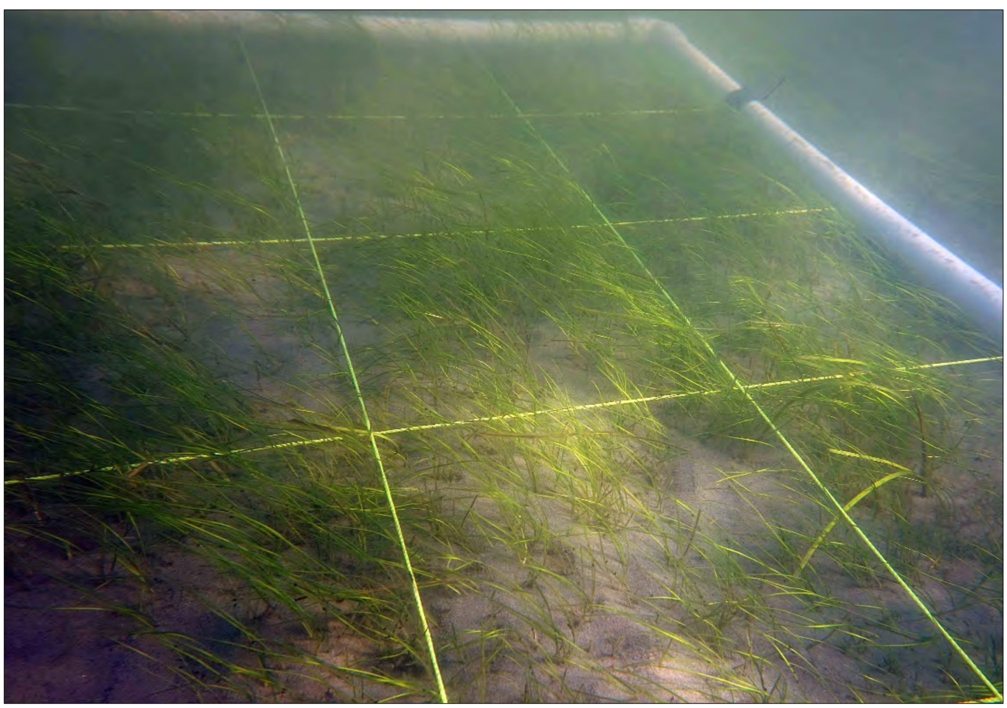


Photo 11. Representative image of *in situ* quadrat surveyed for percent cover in the planted areas. Photo taken in the eastern planted area on 7 October 2018.

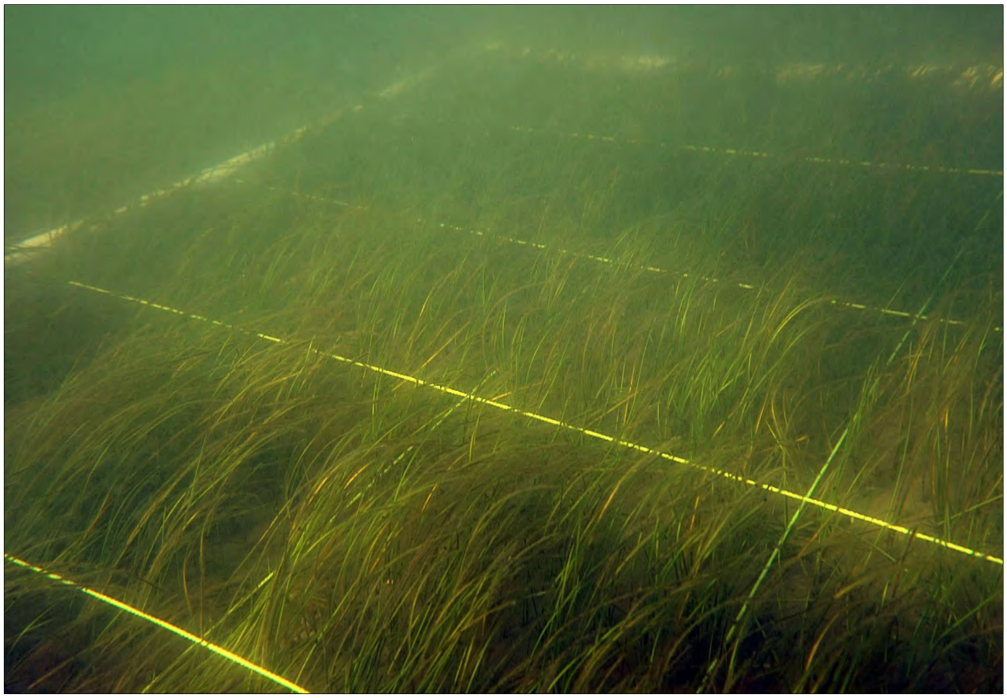


Photo 12. Representative image of *in situ* quadrat surveyed for percent cover in the reference area. Photo taken in the reference area on 7 October 2018.

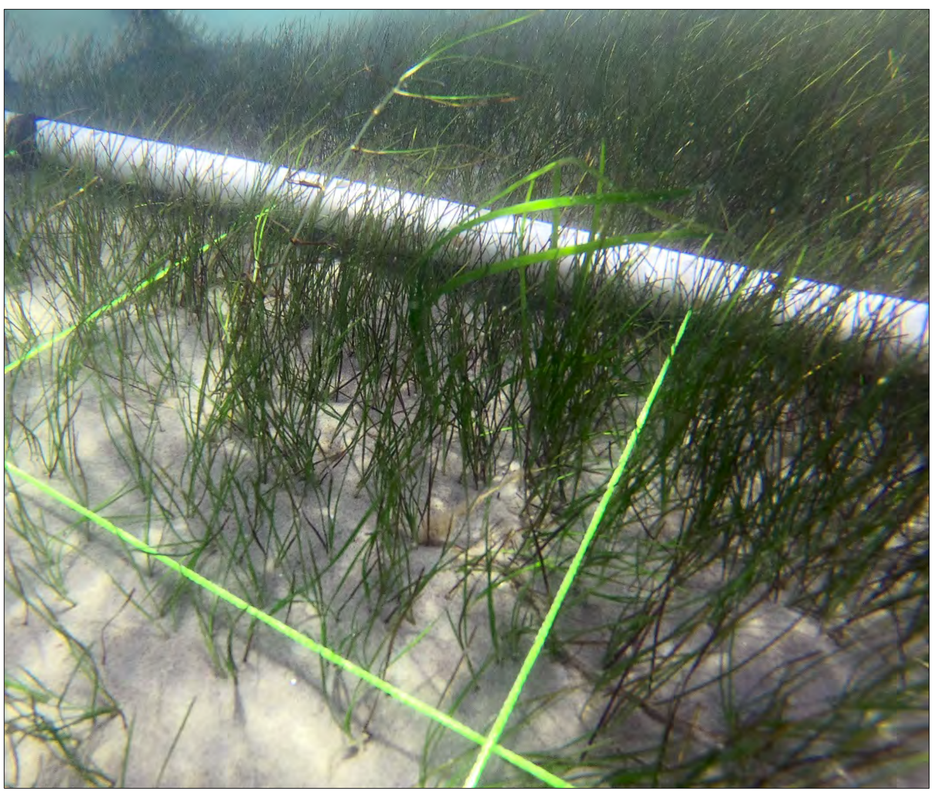


Photo 13. Representative image of *in situ* quadrat surveyed for percent cover in the planted areas. Photo taken in the western area on 14 May 2019.

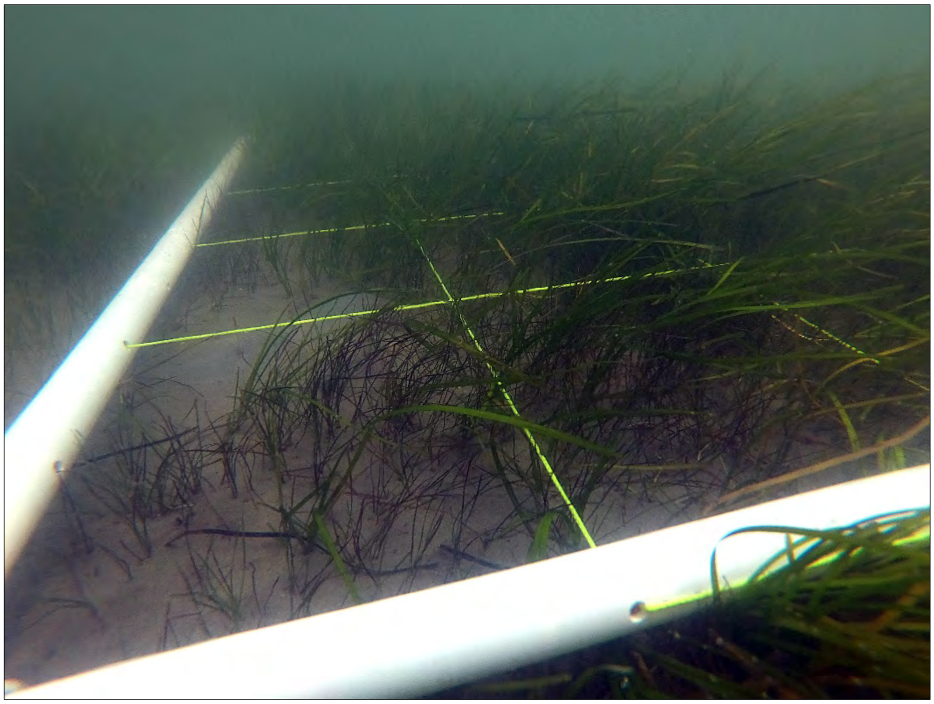


Photo 14. Representative image of *in situ* quadrat surveyed for percent cover in the reference area. Photo taken in the reference area on 14 May 2019.

Several factors may have contributed to the loss of seagrass within the planted areas that was initially observed in January 2017. Seagrass was relocated to gaps within natural seagrass patches in May 2016 prior to installation of the wavebreak structure. Construction was originally scheduled for June 2016 but delayed until November 2016 and completed in January 2017. Previous studies have shown if seagrass is relocated to areas naturally devoid of seagrass without modifying the existing environment, natural processes will continue to preside and the relocated seagrass should not necessarily persist (Fonseca et al., 1998). Additionally, Hurricane Matthew passed through the Pamlico Sound and surrounding areas on 8 and 9 October 2016, five months after seagrass relocation, prior to the installation of the wavebreak structure. The hurricane had average wind speeds ranging from 32 to 64 kph (20 to 40 mph) with maximum wind speeds of 129 kph (80 mph) initially from the north, and then switching direction out of the southeast as the storm passed. Severe flooding occurred along the coast with an average rainfall of 22.1 cm (8.7 in) (http://www.weather.gov/mhx/MatthewSummary). It is possible that the relocated seagrass had not fully established a sufficiently robust root and rhizome system during the five months from relocation to the storm event, leaving them susceptible to erosion. Additionally, sand accumulation on the south side of the structure due to scouring has been observed in physical monitoring surveys and may be inhibiting seagrass survival in the immediately adjacent planted areas.

Seagrass cover in coastal North Carolina naturally declines in winter months (Thayer et al. 1984) and therefore lower cover was expected during the January 2017 survey. Cover in the reference area was also very low at this time (7%), which also may have been attributable to Hurricane Matthew and/or the sampling event occurring in winter. Since the January 2017 survey, seagrass in the planted areas has not recovered and cover remains <1%. However, seagrass in the reference area has recovered and percent cover is similar to that observed during the initial survey in May 2016.

With this survey, seagrass monitoring has now been performed for three years post-relocation. At this point, the dramatic fluctuation of cover among surveys in both the planted blocks and reference areas is likely the result of storm impacts and a highly patchy and shifting seagrass distribution. Percent cover has thus far averaged 8.3% in the planted areas and 46.8% in the reference areas.

SEAGRASS COVER

The Bonner Bridge Seagrass Mitigation Site was forecast to include 301.6 acres (122.1 hectares), and boundaries were determined by using the wave forecast model prediction. Seagrass cover within these boundaries was determined by classifying areas of seagrass based on aerial imagery provided by NCDOT. In 2018, classification resulted in 24.9 acres (10.1 hectares (versus 33.4 acres [13.5 hectares] in 2017) of seagrass cover over the 301.6-acre (122.1-hectare) site (**Figures 6** [**2017**] and **7** [**2018**]). By visual estimation it appears that seagrass cover was lost in the patchy areas north and east of the wavebreak.

In aquatic systems, classification methods rarely achieve 100% accuracy. This is because, unlike terrestrial systems, whose classification is limited primarily by atmospheric conditions, classification of aquatic systems, especially benthic components, is limited by both atmospheric and water conditions. Thus, the accuracy of seagrass classification largely depends on water clarity and sea surface condition at the time of imagery acquisition. Weather events affect waves on the water surface which actively degrade visualization of the seafloor, as well as water clarity. In addition, wind events occurring immediately prior to imagery collection may cause latent sediment suspension that negatively impact results. Finally, many seagrass patches were interdigitated with sand and often non-contiguous, which complicates precise delineation. In addition to atmospheric and water column effects, mosaicking of the image produced shading gradients which interfered with seagrass classification accuracy of the seagrass areas and appeared to be the source of most inaccuracy. An absence of ground control points taken in association with the imagery impeded further accuracy assessment. In both 2017 and 2018, interpretation of seagrass cover was compromised by the generally poor quality of the imagery. Large areas of high surface reflectance and presence of white 'flecks' in the imagery over much of the AOI impaired or completely prevented interpretation of seagrass cover. Discrimination of seagrass cover apart from sand was also made difficult because of low contrast among the two habitat types. This may have resulted from high water levels, high visibility, low sun intensity or some combination thereof. Upcoming utilization of low-altitude, high resolution imagery should improve seagrass cover delineation. Following the 18 April 2018 overflight, no further overflight data are being processed under this award.

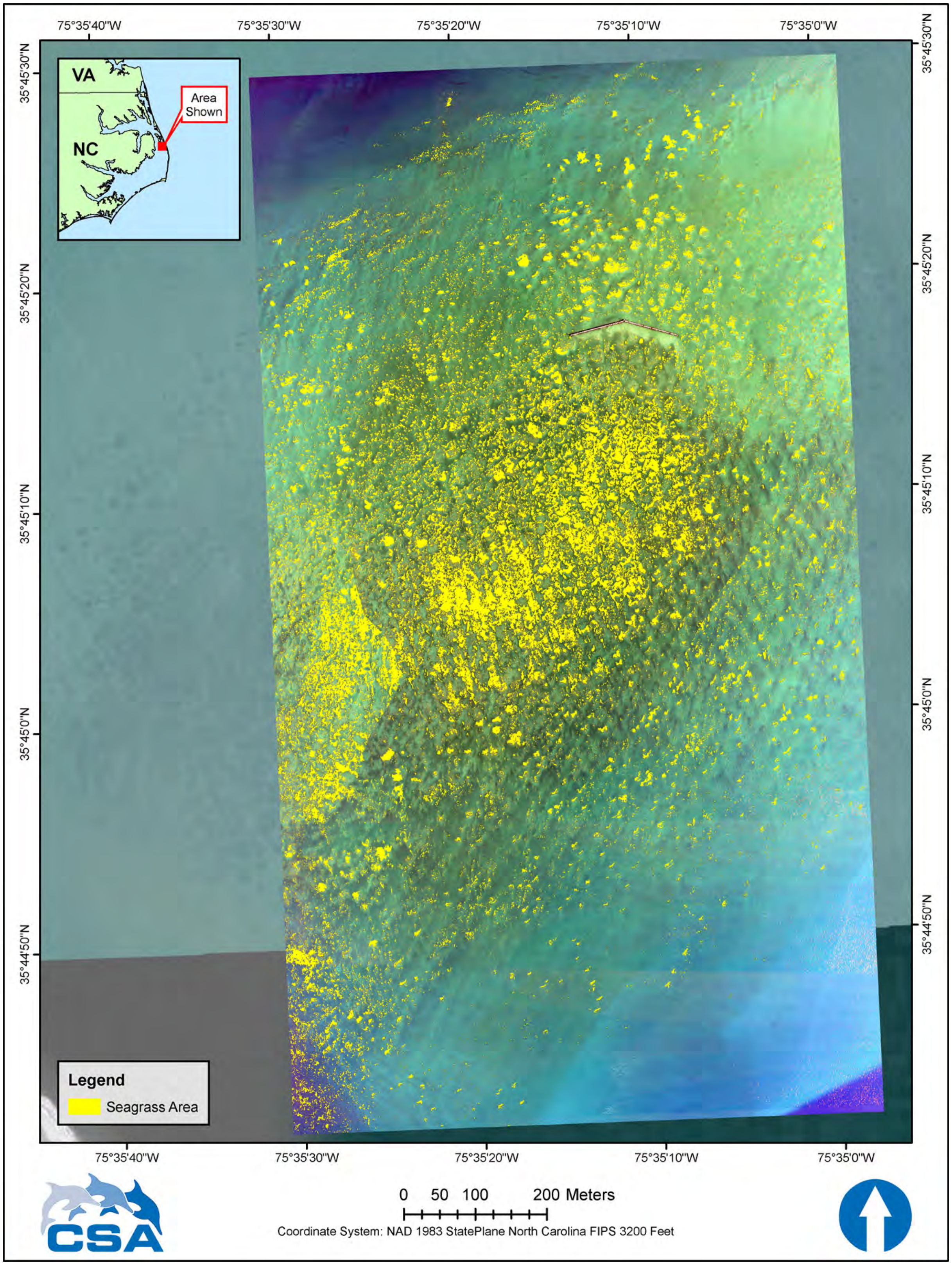


Figure 6. Baseline classification results identifying areas of seagrass (yellow) within the Bonner Bridge Seagrass Mitigation Site for the 24 March 2017 overflight.

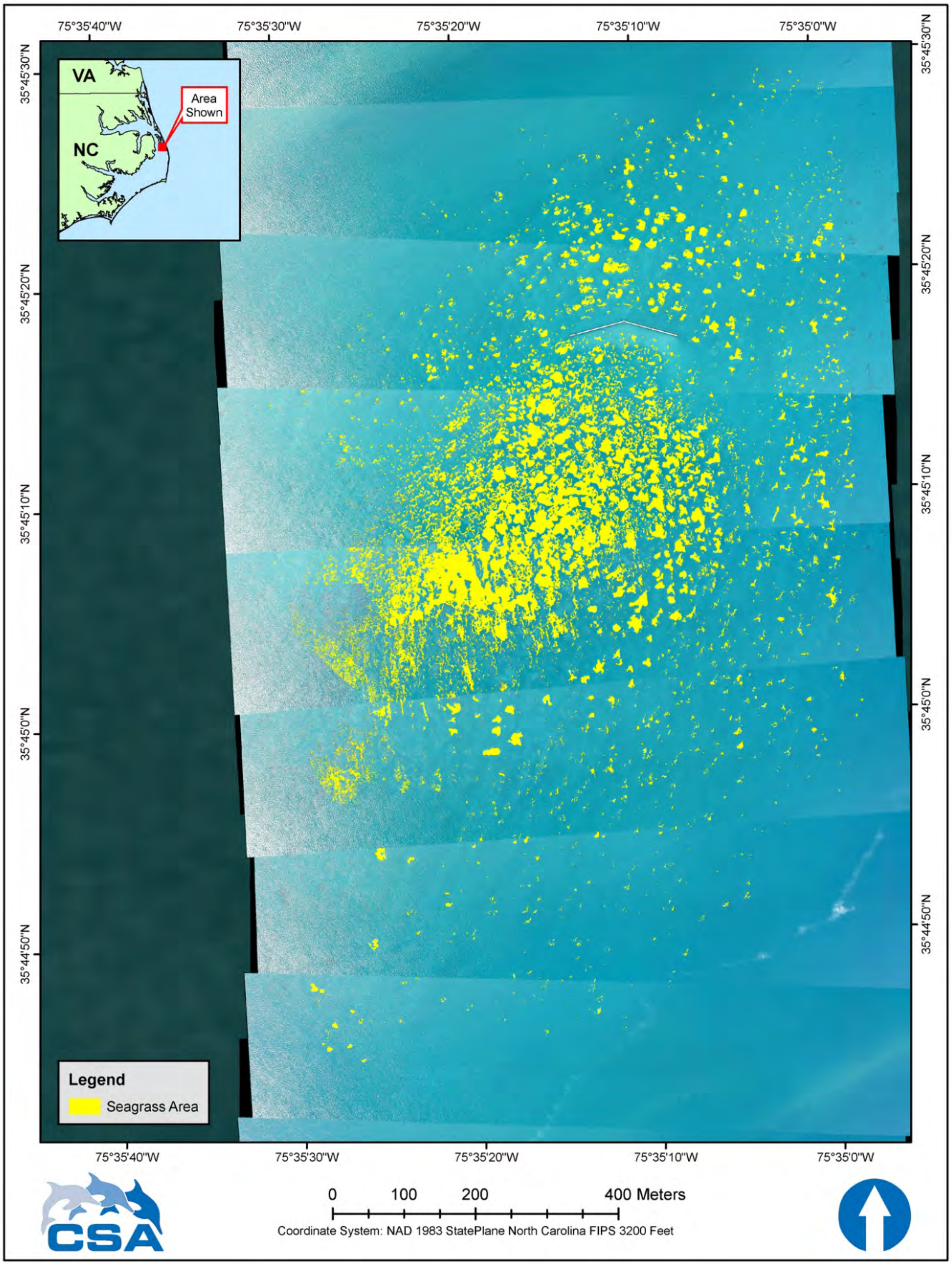


Figure 7. Enlarged view of baseline aerial imagery (left) and classification results (right) identifying areas of seagrass (yellow) within the Bonner Bridge Seagrass Mitigation Site for the 18 April 2018 overflight.

SEDIMENT ELEVATION

Rod Heights: Sediment elevation was monitored across the entire site by measuring the center rods at 40 seagrass patches selected for a bioturbation study (see **Appendix II** for description of this since-terminated experiment) and four additional sediment rods placed in sandy substrate. These 40 rods were installed in May 2016 at locations randomly selected from within strata (10 per strata) defined by the forecasted wave reduction pattern following wavebreak placement (high wave energy reduction = >66%; moderate reduction = 34 to 66%, low reduction = 5 to 33%, and ambient or reference = <5% reduction (**Appendix Figure II-1**). Across all surveys, no rods were located that were below the sediment surface despite extensive searching and probing. If buried rods were not located, this would suggest that the surveys were potentially biased towards measurements indicating a lower elevation of the sediment surface.

The average rod height above the sediment in May 2016 was 6.8 cm (2.7 in). The average height of the four sediment rods above the sediment was 6.9 cm (2.7 in). In January 2017, a total of 32 center rods were relocated and the average rod height was 11.0 cm (4.3 in). Two of the four sediment rods were relocated, and the average rod height was 12.4 cm (4.9 in). The eight center rods not located may be deeply buried and future attempts will be made to locate them. If they were deeply buried, then the average rod height would decrease.

In October 2017, sediment elevation was monitored at the center rod of the 14 patches monitored for bioturbation in addition to the original 4 rods in sandy substrate. The center rod was not located (likely due to burial) at 3 of the 14 seagrass patch locations and 1 sandy substrate location. The average height of center rods in seagrass patches was 16.5 cm (6.5 in.) and 12.0 cm (4.7 in.) at sandy substrate stations. Sediment depth had decreased (increased rod height) within seagrass patches and remained similar at the sandy substrate locations since the Baseline Survey in January 2017.

In May 2018, sediment elevation was again monitored at the center rod of the 14 patches monitored for bioturbation, in addition to the original 4 rods in sandy substrate. The center rod was not located (likely due to burial) at 3 of the 14 seagrass patch locations and 1 sandy substrate location. The average height of center rods in seagrass patches was 14.7 cm (5.8 in.) and 14.0 cm (5.5 in.) at sandy substrate stations. Sediment depth has decreased (increased rod height) within seagrass patches and remained similar at the sandy substrate locations since the Baseline Survey in January 2017.

Change in sediment elevation was computed among the replicate rods in each of the wave energy reduction strata among all combinations of survey dates (**Figure 8**). *In lieu* of survey to survey changes which revealed no clear pattern of change over time, comparisons with the first survey time were performed. A one-way ANOVA revealed that only comparisons among Survey 1 and Surveys 5 and 6 had differences in sediment elevation among Reference and the High wave reduction zone and Reference and Low and High wave reduction zones (**Table 4**). Differences were driven by the sediment accumulation in the High wave reduction zone, closest to the wavebreak. With the elimination of the survey to survey comparisons a clear pattern of sediment accumulation across wave energy strata emerged from this analysis. Sediment accumulated most in the High wave energy reduction zone closest to the wavebreak with decreasing sediment accumulation with decreasing wave energy reduction and distance from the wavebreak (**Figure 8**). This pattern has remained consistent among the surveys, corroborating the near-field survey work (below).

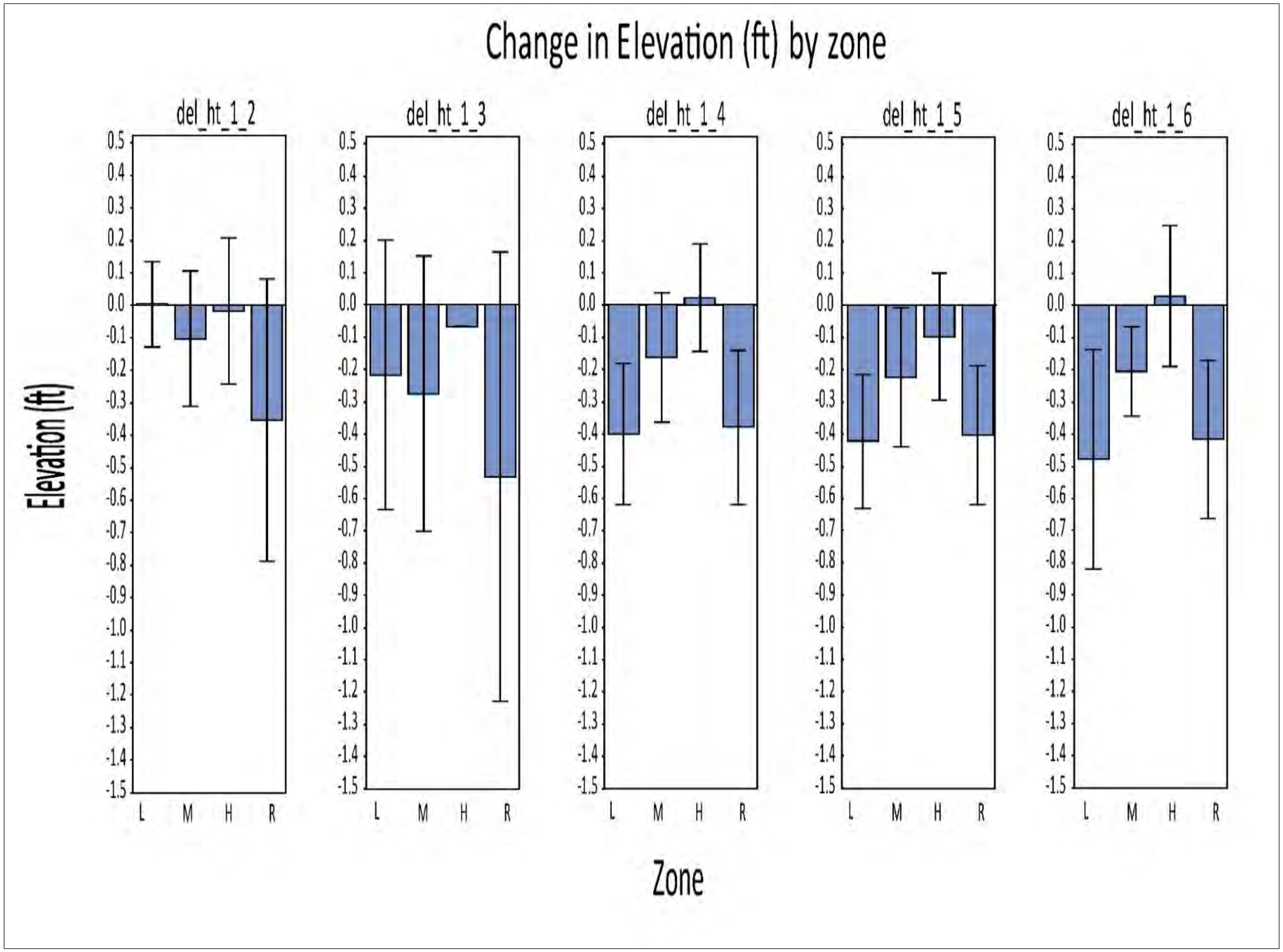


Figure 8. Change in sediment elevation (del_ht in ft, MLLW) over time monitored at rods installed in previous bioturbation study. H= area of high wave energy reduction by the wavebreak; M = medium; L = low; R = reference (no wave energy reduction). Error bars represent ± one standard deviation. The comparisons (e.g., 1_2, 1_3, etc. refer to comparisons among the first survey and subsequent surveys.

Table 4. One-way ANOVA testing differences in sediment elevation (ft, MLLW) from rods installed at previous bioturbation patches between Survey 1 and subsequent surveys. Survey 1 = May 2016, Survey 2 = January 2017, Survey 3 = October 2017, Survey 4 = May 2018, Survey 5 = October 2018, Survey 6 = May 2019.

Wave energy reduction	Survey 1 → 2	Survey 1 → 3	Survey 1 → 4	Survey 1 → 5	Survey 1 → 6
Reference (none)	ND	ND	R,H	ND	R,H
Low	ND	ND	L,H	ND	L,H
Medium	ND	ND	ND	ND	ND
High	ND	ND	ND	ND	ND

Shaded bars = significant effect at P ≤ 0.05; comparisons with the same letters are not significantly different. ND = no significant difference. Cells with no information represent strata where rods could not be located, presumably due to excessive sediment deposition. R = reference, H = high wave energy reduction zone, M = medium wave energy reduction zone, L = low energy wave reduction zone.

USV Digital Elevation Model: The USV collected bathymetry data across the entire site in June 2016 (**Figure 9**). The survey was conducted during both flood and ebb tides and real-time tidal corrections were made to data collected. Water depths ranged from 0.7 to 1.6 m (2.3 to 5.2 ft) across the site. The western portion of the site was notably shallower than the eastern portion. The USV will collect bathymetry data during the final monitoring survey and data will be compared to this baseline bathymetry.

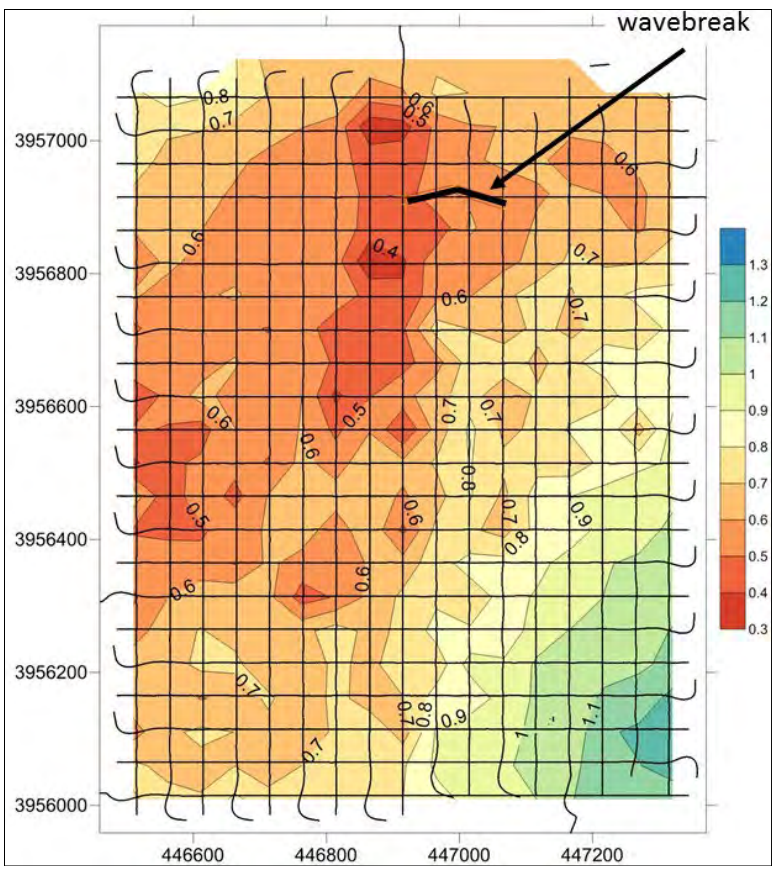


Figure 9. Track lines traveled by the Unmanned Surface Vehicle (black lines) and digital elevation model at the Bonner Bridge Seagrass Mitigation Site prior to construction of the wavebreak (ultimate location of wavebreak shown). Soundings are in MLLW.

Near-field Wall Sediment Elevation Survey: The surveys conducted by SEPI revealed significant scour pits having formed under the wavebreak units themselves. This sediment is suspected to be the source of the light-colored band visible to the south of the wall in aerial images (**Figure 3**). The 5 transects were treated as replicates for evaluating sediment elevation on both the north and south sides of the wavebreak, by distance. A comparison of sediment elevations by distance and side of wall (north vs south) shows a generally consistent pattern of erosion in the immediate proximity of the wall but with little change in sediment elevation with distance on either side of the wavebreak (**Figure 10**). There, transects on the south side of the wall however, generally appeared to be shallower. Upon examination under 2-way ANOVA (**Table 5**) there was no significant interaction of the main effects (distance, side), allowing each main effect to be re-tested independently. The effect of distance irrespective of side was significant ($p < 0.05$) at every survey time. However, the visually apparent difference in elevation among the north and south sides of the wall was statistically significant beginning in January of 2018 and remained different (but for April of 2018) through September of 2018, with the southern side being consistently shallower. From October 2018 through March 2019 there was no significant difference in sediment elevation among sides of the wall. Only in April 2019 (and May) did a significant difference re-emerge with the south side being significantly shallower. In general, it was noted that the 0 distance (immediately abutting the wall structure) was always the deepest, followed closely by the 5-foot distance being the next deepest among all surveys (**Figure 10**). While statistically different, the elevation differential among the north and south side was in the range of about 6 inches. Despite being shallower, the south side was still within the range of seagrass growth as attested by the presence of numerous seagrass patches within this near-field survey.

Table 5. Results of 2-way ANOVA for the near-field sediment elevation (ft, MLLW) by survey. Blue shading indicates a statistically significant ($p < 0.05$) difference. Blank cells have not yet been surveyed.

Year	2017		2018					
Month	Jun	Sep	Jan	Feb	Mar	Apr	May	Jun
Distance	<.0001	<.0001	<.0001	0.0006	<.0001	<.0001	<.0001	0.0005
Side	0.7046	0.6983	0.0494	0.0011	0.0372	0.0608	0.0002	0.0002
Interaction	0.8913	0.9754	0.3347	0.777	0.118	0.0744	0.4098	0.8185

Year	2018						2019	
Month	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb
Distance	0.0025	0.0022	<00006	0.0006	0.0006	0.0002	0.0022	0.0086
Side	0.0029	0.0036	0.0042	0.5273	0.1684	0.0825	0.2117	0.1080
Interaction	0.9695	0.6937	0.9016	0.8492	0.9147	0.6512	0.4738	0.9404

Year	2019							
Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Distance	0.0024	0.0018	0.0010	--	--	--	--	--
Side	0.2650	0.0151	0.0170	--	--	--	--	--
Interaction	0.8691	0.8486	0.7329	--	--	--	--	--

Panel 1

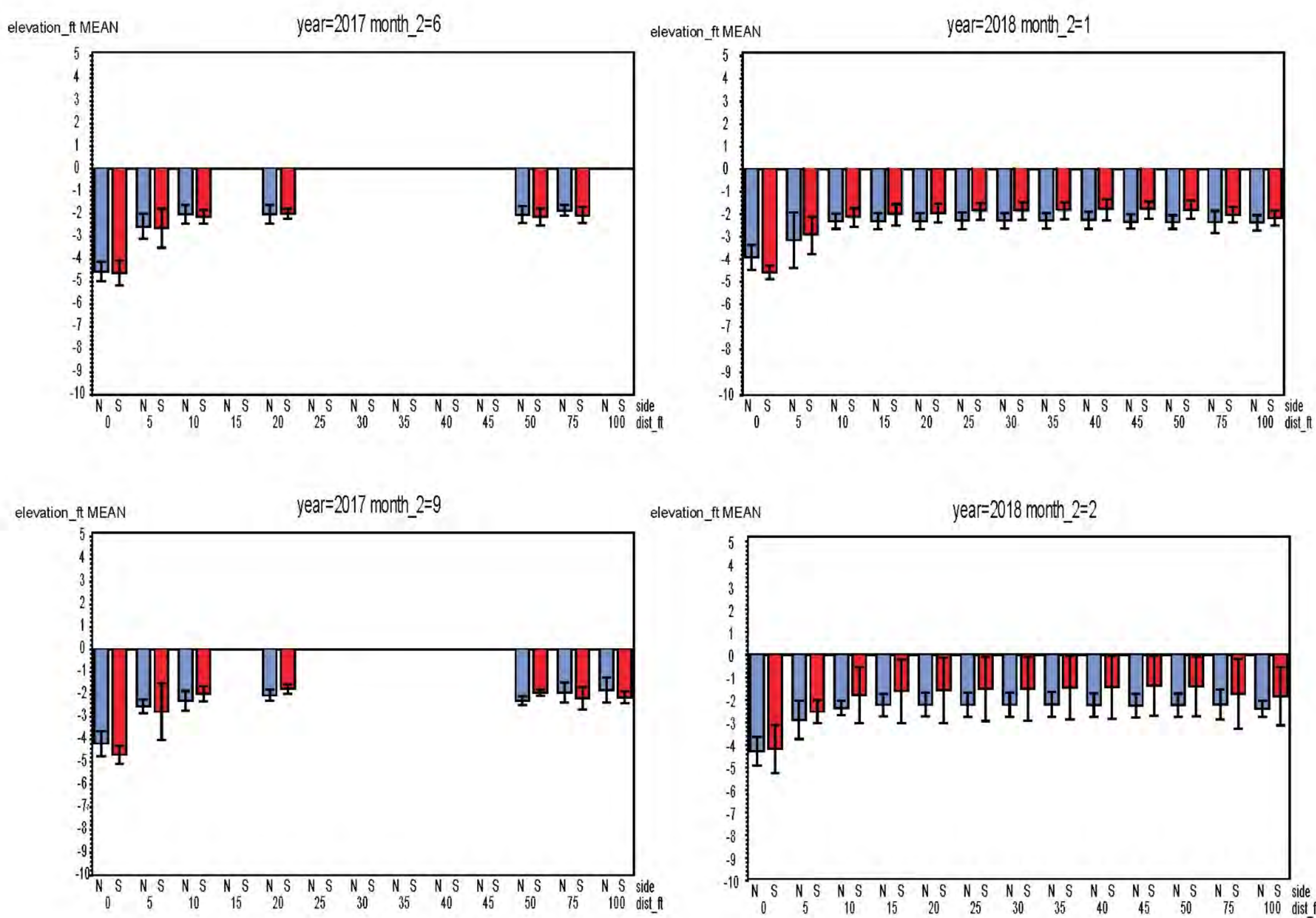


Figure 10. Panels 1-5; average sediment elevation (ft, MLLW) by side of wavebreak and distance over time. Error bars are ± 1 standard deviation.

Figure 10. (Continued).

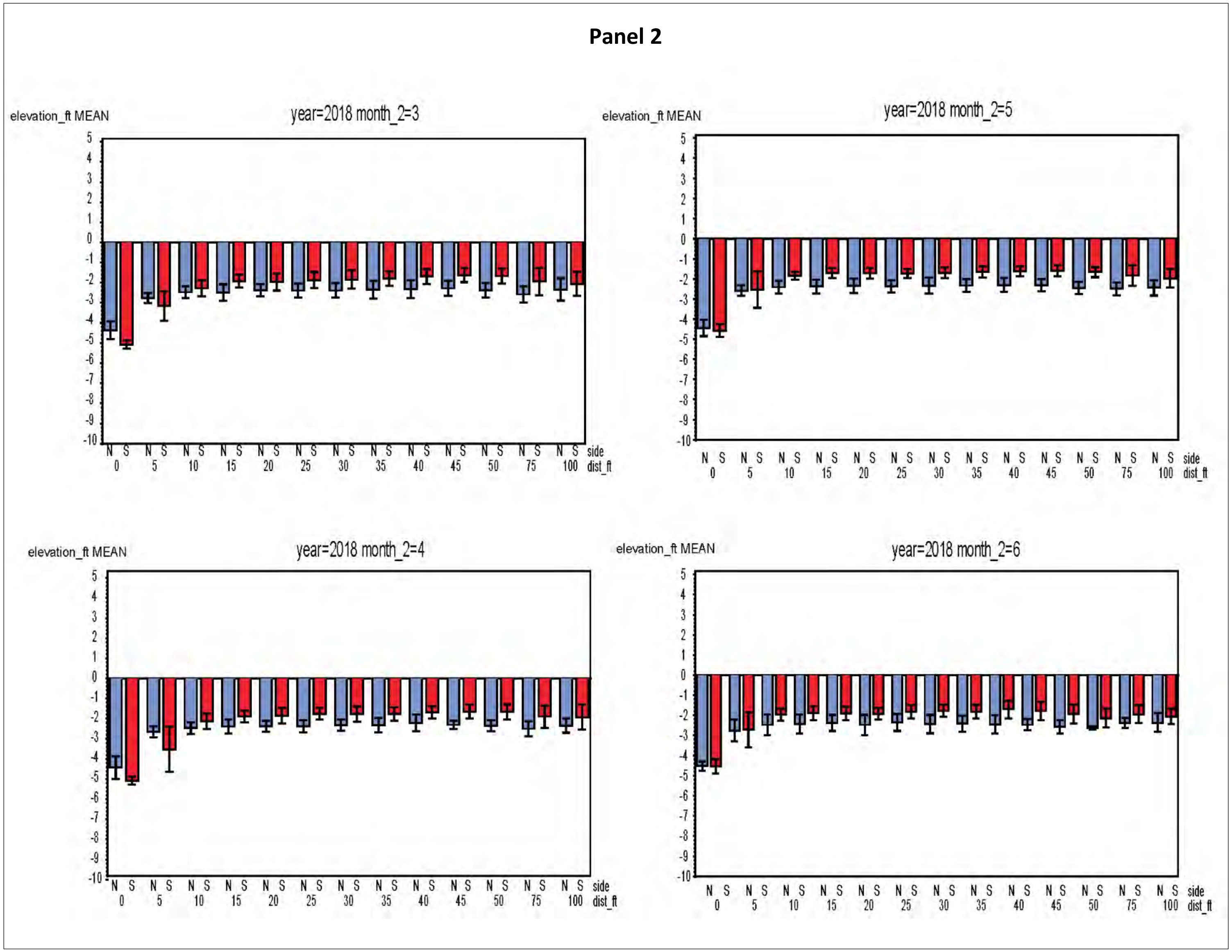


Figure 10. (Continued).

Panel 3

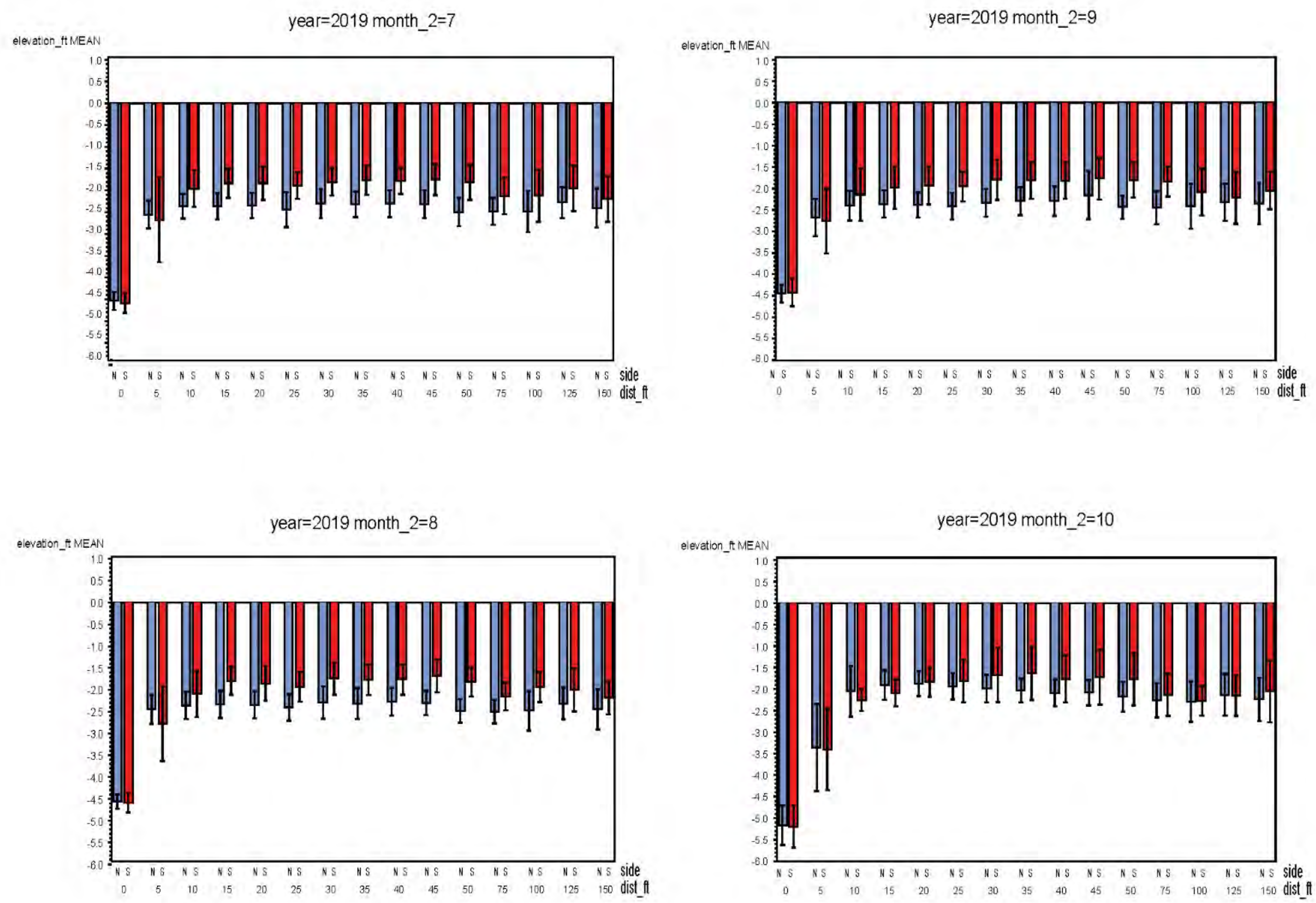


Figure 10. (Continued).

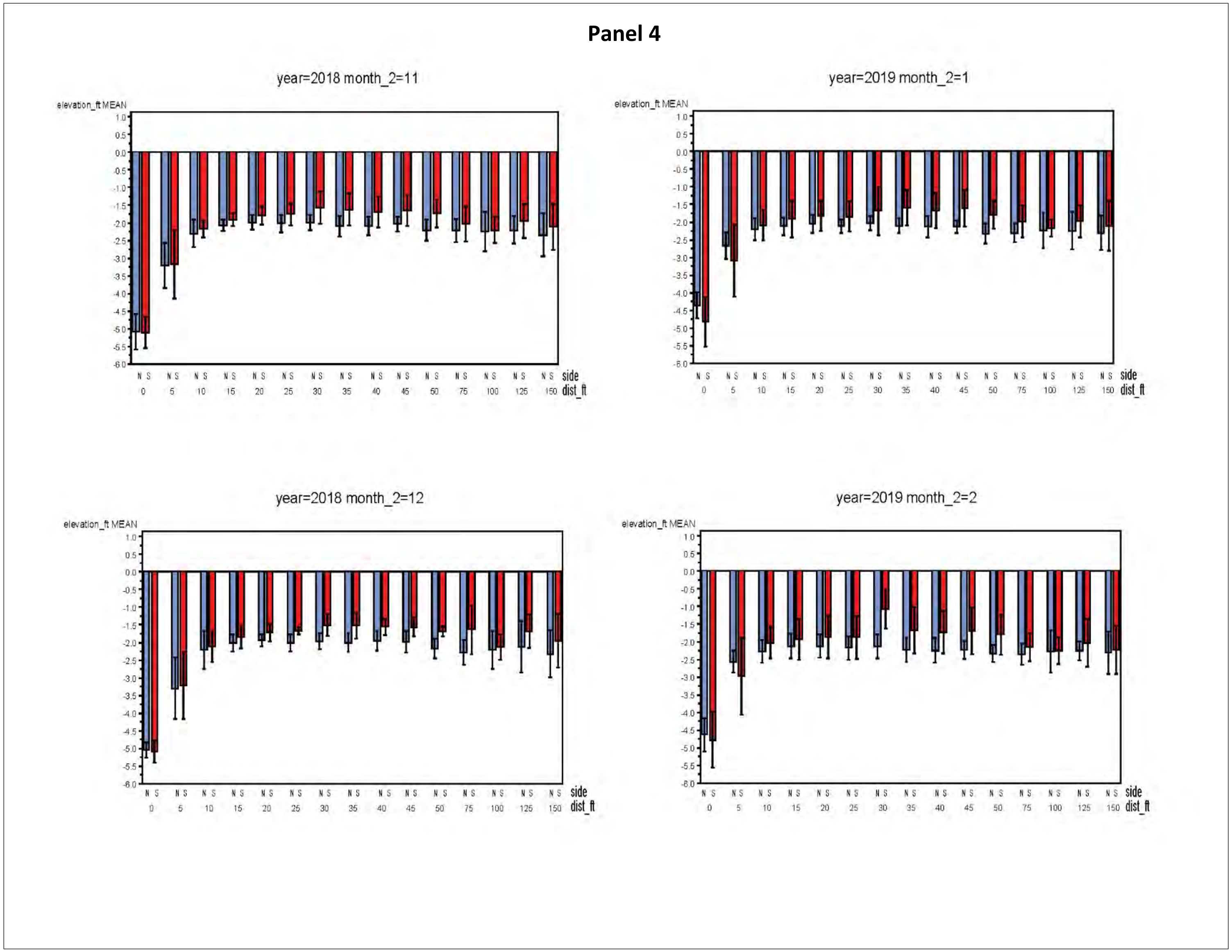
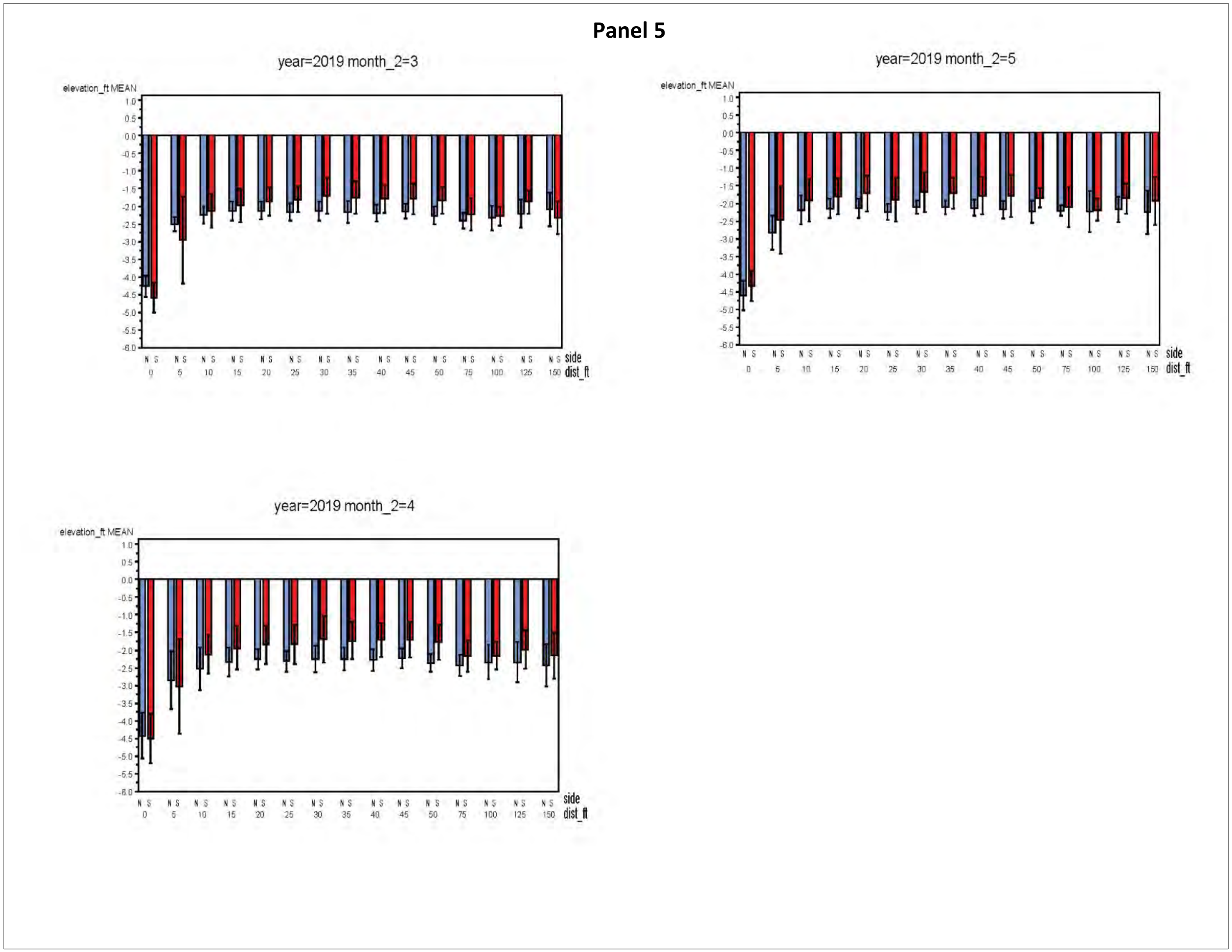


Figure 10. (Continued).



WAVE REGIME AND MODEL VALIDATION

Long Term Wave Regime: After the wavebreak was installed, pressure sensors were installed at specified stationary locations on both the north and south sides of the wavebreak to spatially assess significant wave height (highest 1/3 of waves) distribution arising from the top 5% of wind events between the two sides of the wavebreak. **Figure 11** shows the difference in the significant wave heights over elapsed time. During 2017, there did not appear to be a substantial difference in the significant wave heights among the two sides, whereas in 2018, events where the significant wave height was higher on the south side of the wall were more numerous and of greater difference over time. This indicates that wave events were often higher on the south side than the north, suggesting that the north side of the wall could also be receiving substantial sheltering from waves.

WEMo model validation: Wave forecast modeling using WEMo was initially conducted in January 2016 for different lengths of the wavebreak structure. Modeling was re-analyzed in January 2017 after installation of the 500 ft (152 m) wavebreak (**Appendix I**). As done previously, the model was run on 65-foot (20-meter) grid cells, as the bathymetric data which are an important driver of the calculations is not more resolved than that distance. Forecast acreage of seagrass was computed by regression from the relationship of wave energy to seagrass cover (Fonseca and Bell 1998). The area of the seafloor experiencing at least a 5% reduction in wave energy was computed. The total acreage associated with the zones of wave reduction beyond the 5% threshold is given in **Table 6**. Theoretically, this could result in an overall total of 1.78 acres (0.72 hectares) of new seagrass with the 10% reduction zone producing 1.13 acres (0.46 hectares) and the 5% reduction zone producing 1.50 acres (0.61 hectares).

Table 6. Areas for the wave energy reduction zones depicted in **Appendix I** in both acres and square meters.

Percent Representative Wave Energy Reduction	Square Meters	Acres
>66%	3,184	0.8
33% to 66%	21,153	5.2
5% to 33%	200,889	49.6
<5%	1,095,260	270.6

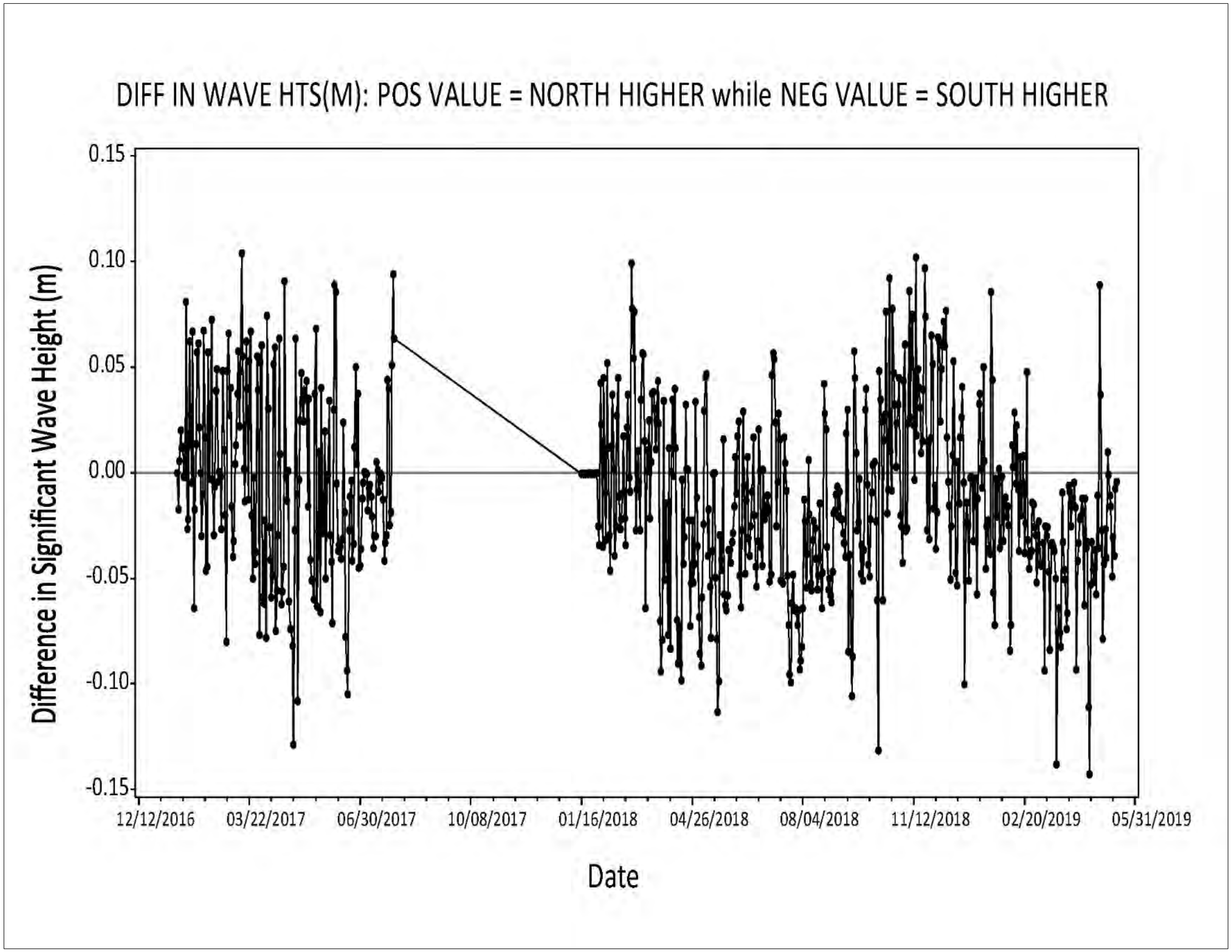


Figure 11. Difference in hourly significant wave heights (m) between and north and south side of the wavebreak structure for January 2017 through May 2019. A data gap (area of straight line) arose from need to reposition and recalibrate sensors. Positive values = wave heights higher on north side; Negative values = wave heights higher on south side.

After the model was run and a smoothing technique (krigging) applied (**Appendix I**), a disruption appeared in the wave reduction just south of the wall. However, this is a product of the krigging and a small zone of 33-66% wave reduction just south of the wall is a display artifact and was not part of the acreage calculations.

EPIBIOTA MONITORING

During the January 2017 baseline survey, ebb tides were extremely low and monitoring stations at all three elevation strata (high, middle, and low) were exposed above water. No biota had colonized the substrate and the percent cover of concrete and rock were both 100% during this survey.

During the May 2018 survey, there was a consistent south/southwest wind that resulted in high water levels at the structure, even at ebb tide. Monitoring stations at the high elevation were exposed above water but were primarily wet and regularly splashed by waves hitting the structure during all tidal stages observed. The middle elevation monitoring stations were exposed above water during all tidal stages observed, also primarily wet, and regularly splashed by waves hitting the structure. The low elevation monitoring stations were completely submerged at all tidal stages observed, even ebb tide. Due to high levels of turbidity in the water column during the survey, the low strata monitoring stations were photographed at a closer distance than the high and middle strata, requiring four close-up photographs per station which were later mosaicked together.

During the May 2019 survey, ebb tides were relatively high. Monitoring stations at the high elevation were exposed above water during all tidal stages observed but were primarily wet and regularly splashed by waves hitting the structure (**Photo 15**). The middle elevation monitoring stations were exposed above water during ebb tides, and regularly splashed by waves hitting the structure (**Photo 16**). The low elevation monitoring stations were completely submerged at all tidal stages observed, even ebb tide (**Photo 17**).

Photo 15. Representative photo of rock substrate for a high elevation monitoring station (Station 27) showing wet rock on the structure at the Bonner Bridge Seagrass Mitigation Site during the 2019 survey.

Photo 16. Representative photo of concrete substrate for a middle elevation monitoring station (Station 7) showing wet concrete, algae, and barnacle growth on the structure at the Bonner Bridge Seagrass Mitigation Site during the May 2019 survey.

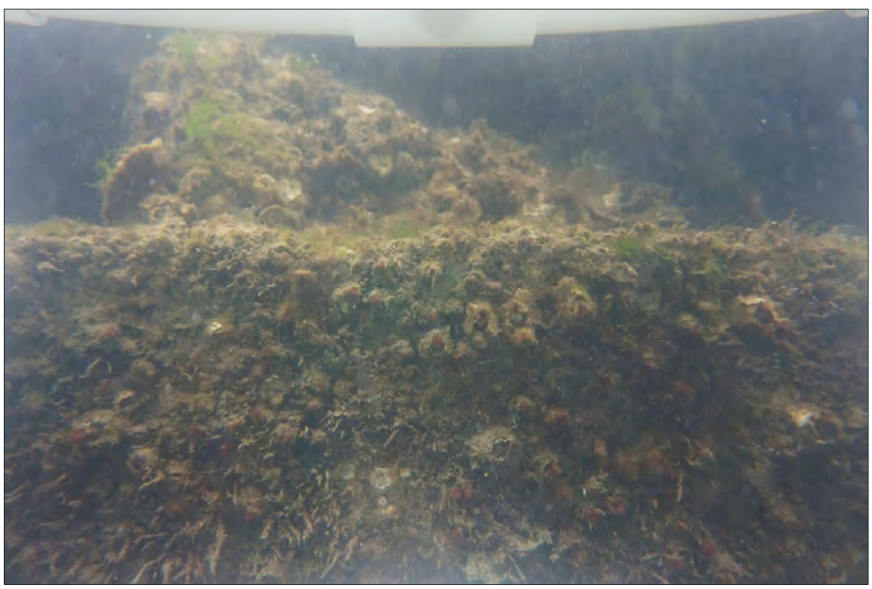


Photo 17. Representative photo of concrete substrate for a low elevation monitoring station (Station 8) showing submerged concrete and barnacle growth on the structure at the Bonner Bridge Seagrass Mitigation Site during the May 2019 survey.

As in previous surveys, the percent cover of colonizing biota were assessed at the 60 fixed monitoring stations along the wavebreak structure. Data was grouped first by substrate type (concrete or rock), then by strata (high, middle, or low), and also by orientation (north or south side of the structure). Data collected for concrete and rock monitoring stations are displayed in **Tables 7** and **8**, respectively. Representative photographs of colonized substrate and motile fauna from the May 2019 survey can be found in **Appendix III**.

Table 7. Percent cover of biota from concrete monitoring stations during the Baseline Monitoring Survey in January 2017, the Year 2 Annual Monitoring Survey in May 2018 and the Year 3 Annual Monitoring Survey in May 2019. Scaled color bars added for emphasis.

Biota or Non-Living Substrate	Concrete - North									Concrete - South								
	2017			2018			2019			2017			2018			2019		
	High	Middle	Low	High	Middle	Low	High	Middle	Low	High	Middle	Low	High	Middle	Low	High	Middle	Low
Biota																		
Macroalgae	0	0	0	34.12	41.11	20.14	78.04	64.27	81.75	0	0	0	14.51	14.49	16.81	75.57	38.71	66.26
Barnacle	0	0	0	5.51	37.61	64.03	2.84	30.26	15	0	0	0	0	46.67	73.01	0	34.14	24.94
Hydroid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.64	0	0	0
Oyster	0	0	0	0	0.58	0	0.26	1.44	2.75	0	0	0	0	0	0	0	1.61	8.8
Cyanobacteria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL BIOTA	0	0	0	39.63	79.3	84.17	81.14	95.97	99.5	0	0	0	14.51	61.16	96.46	75.57	74.46	100

Table 8. Percent cover of biota from rock monitoring stations during the Baseline Monitoring Survey in January 2017, the Year 2 Annual Monitoring Survey in May 2018 and the Year 3 Annual Monitoring Survey in May 2019. Scaled color bars added for emphasis.

Biota or Non-Living Substrate	Rock - North									Rock - South								
	2017			2018			2019			2017			2018			2019		
	High	Middle	Low	High	Middle	Low	High	Middle	Low	High	Middle	Low	High	Middle	Low	High	Middle	Low
Biota																		
Macroalgae	0	0	0	0	5.06	1.35	0	0	12.94	0	0	0	0	0	1.41	0	16.09	53.66
Barnacle	0	0	0	0	29.11	14.86	7	23.53	11.76	0	0	0	0	3.51	16.9	0	4.6	24.39
Hydroid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oyster	0	0	0	0	0	0	0	7.84	18.82	0	0	0	0	0	0	0	2.3	13.41
Cyanobacteria	0	0	0	0	0	0	0	4.9	34.13	0	0	0	0	0	0	0	0	0
TOTAL BIOTA	0	0	0	0	34.17	16.21	7	36.27	77.65	0	0	0	0	3.51	18.31	0	22.99	91.46

Colonizing biota observed on concrete substrate continued to include barnacles, macroalgae (primarily unidentified green hair algae), hydroids, and oysters. For concrete stations, biotic colonization was now dominated by macroalgae (versus barnacles in 2018) for the majority of strata. Percent cover of barnacles declined as compared to the 2018 particularly in the low strata with maximum percent cover down to 30.26% and 34.14% for the north and south sides, respectively (down from 64.03% and 73.0% in 2018; **Table 7**). Percent cover of macroalgae increased since 2018, doubling or tripling its percent cover in some cases. Macroalgae percent cover was greater than barnacles in all strata on both the north and south sides, with a maximum percent cover of 78% for high strata on the north side and 75.57 on the south side. The small numbers of hydroids observed in 2018 were not found in 2019 while oysters were now present in low cover in all strata on the north side and in the middle and low strata on the south side with a high (south side, low strata) of 8.8%, a clear increase overall since 2018.

Colonizing biota on rock substrate included barnacles and macroalgae and new since 2018, oysters; no hydroids were observed on either side of the structure. For rock stations, biotic colonization continued dominated by barnacles for the majority of strata, with maximum cover of 24.39% on low strata on the south side (**Table 8**). Unlike concrete, percent cover of macroalgae was generally low except for the low south strata which had the highest percent cover (53.66%) of any biota across strata and side thus far.

For all elevation strata, concrete exhibited greater total colonization by biota versus rock on both north and south sides of the structure, although the rock low strata on both the north and south sides were becoming more equivalent to concrete. Unlike 2018 where both concrete and rock, the middle and low strata generally showed greater colonization by biota than high strata, in terms of total biota all concrete substrate strata on both sides were now becoming much more equivalent, however, with the lowest strata still showing the highest percent cover of colonization. Rock colonization lagged behind concrete percent cover of colonization especially for the high and middle strata, irrespective of side. Only the rock substrate low strata, and particularly on the south side had become nearly equal to that of concrete.

While there a clear trend of increasing colonization is occurring, there is non-systematic fluctuations in cover among year, side and elevation strata, which is not uncommon for sessile intertidal communities. Concrete is supporting more macroalgae and barnacles while rock is supporting more oyster colonization. Hydroids and cyanobacteria continue to be rare, despite a pulse of cyanobacteria presence in the rock low north strata this survey.

4.0 Conclusions

The wavebreak was successfully installed in January 2017 (**Photo 18**) and passed its post construction engineering inspection. Monitoring will continue for an additional two years, through 2020 (**Table 1**) which will build off of this report.

Photo 18. North-oriented view of the wavebreak installed in January 2017 at the Bonner Bridge Seagrass Mitigation Site. The total structure length is 500 ft (152 m).

Seagrasses were successfully relocated from the construction corridor to two planting zones south of the wall footprint in May 2016. Seagrasses in the area are composed of all three of the marine species found in North Carolina (mixed *H. wrightii, R. maritima, Z. marina*). Seagrass cover measured within the confines of natural, colonized seagrass displayed dramatic change from May 2016 to January 2017 (-42%). The relocated seagrass area showed a similar decline of -35.0%. It cannot yet be determined if this change is a typical seasonal change in cover (spring versus winter) or if there was a contribution from Hurricane Matthew. The hurricane passed over this area on 9 October 2016, prior to the installation of the wavebreak structure; thus, the relocated area was highly exposed to an extreme wave event only 5 months after planting which could have led to disruption of the relocated material. In October of 2017 no seagrass was found in the randomly selected samples from both planting areas. Subsequent surveys found cover ranging from 0.7 to 14.9% in the planted areas while during the same time, cover in the reference areas ranged from 23.7 to 100% cover. At this point, the dramatic fluctuation of cover among surveys in both the planted blocks and reference areas is likely the result of storm impacts and a highly patchy and shifting seagrass distribution. Percent cover has thus far averaged 8.3% in the planted areas and 47.1% in the reference areas.

A bioturbation experiment to help determine the relative role of bioturbation versus wave energy reduction in seagrass space occupation was significantly disrupted by unknown sources. Only 20% of the mesh (8 out of 40 remesh sheets) was relocated during the January 2017 survey. The wavebreak was not present during this time so comparisons could only be tested among the remaining 8 remesh sheets and those edges that did not receive remesh. There was no significant difference ($p < 0.05$) among the change in distance between the remesh and no remesh treatments, preliminarily indicating that bioturbation was not strongly influencing the expansion of patch margins at that time. However, the passage of Hurricane Matthew may have obscured effects (disturbance effects like Hurricane Matthew erode seagrass patches from their edge, much like sting ray bioturbation; Fonseca et al., 2000).

Physical data collection of sediment elevation and wave energy has been completed. A digital elevation model of the site was collected using the USV and these data will be compared with an end-of-project survey conducted in the same manner to determine net sediment accumulation or loss in the project area. Sediment elevation stakes will also continue be monitored to gain an understanding of short-term fluctuations in sediment elevation. An overall change in sediment elevation (-4.1 cm) was detected in that survey which cannot be attributed to the wavebreak, as similar differences occurred across the entire shoal.

More detailed monitoring of the near-field sediment elevation (within 150 feet) and the far-field (spread over the entire wave energy forecast area) has shown a stable profile over time. With the near-field monitoring, the south side has consistently been approximately ½ foot shallower than the north but still within the range of colonization by seagrass as is evidenced by the continued presence of seagrass in this area, including the planting and reference sites.

The final wave modeling effort indicated that theoretically, the wavebreak influence on seagrass cover could result in a total of 1.78 acres (0.72 hectares) of new seagrass overall, with the 10% reduction zone producing 1.13 acres (0.46 hectares) and the 5% percent reduction zone producing 1.50 acres (0.61 hectares). The classification resulted in 33.4 acres (13.5 hectares) seagrass cover across the Bonner Bridge Seagrass Mitigation Site. Aerial imagery was collected and analyzed annually to capture changes in seagrass cover associated with the addition of the wavebreak structure. That collection has been terminated as of April 2018 and has been replaced by monthly surveys under another contract.

Finally, time-zero data collection for epibiotic colonization was completed using a stratified random, repeated measures design. As expected, there was no discernible epibiotic colonization in any of the 120 digital images recorded. Photographs of the exact locations on the structures, stratified by tidal elevation and north and south sides of the wall will be repeated over time to quantify epibiotic colonization trajectory, abundance and composition. The May 2018 data collection for epibiotic colonization was completed using a stratified random, repeated measures design. During the May 2018 survey, the percent cover of concrete and rock decreased from levels observed in January 2017 as epibiota colonized the structure. Concrete typically exhibited greater colonization by macroalgae and fauna than the rock substrate. The middle and low strata of both concrete and rock showed greater colonization than the high strata.

As of May 2019, a clear trend of increasing colonization continues with high levels of colonization among all elevations of the wavebreak structure, irrespective of side (north or south facing). The most frequently observed biotic cover on concrete portions has been macroalgae and to a lesser degree, barnacles and oysters. Oyster colonization has only occurred on the lowest elevation strata of the wavebreak structure. There are non-systematic fluctuations in cover among year, side and elevation strata, which is not uncommon for sessile intertidal communities. Concrete is supporting more macroalgae and barnacles while rock is supporting slightly more oyster colonization. Hydroids and cyanobacteria continue to be rare, despite a pulse of cyanobacteria presence in the rock low north strata this survey

This report occurs prior to the last survey (October 2019) of the twice-annual monitoring period of performance. Beginning in May 2020, annual surveys and reports will only occur in the May–July timeframe for the next two years to the end of the contract period.

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Appendices

Appendix I

Project Site Selection

In 2015, CSA completed the process of site selection ([Report] **Table 1**). Existing seagrass cover and site conditions were compared between potential mitigation sites within the Pamlico Sound in the vicinity (~ 8 km [~ 5 mi]) of the Oregon Inlet. The Bonner Bridge Seagrass Mitigation Site was identified on a historically stable shoal, where seagrass growth was evident, and had the most potential for increased seagrass cover with gap closure among existing patches of the sites examined. The site was located near dredge spoil islands approximately 4.8 km (3 mi) southwest of the existing Bonner Bridge at Oregon Inlet. Wave and seagrass response models were utilized to determine the length of the wavebreak forecast to achieve the 1.28 acres (0.52 hectares) of seagrass mitigation.

Also in 2015, CSA completed development of the wavebreak design and placement, a task which required both wave forecasting, seagrass recovery forecasting and engineering sub consultation for placement of the structure design. Wave forecast modeling (Malhotra and Fonseca, 2007) was utilized to estimate the wave reduction effects of the wavebreak structure. Percent wave reduction was computed from comparisons of no-wavebreak and wavebreak modeling scenarios for various length wavebreak structures. The percent wave energy reduction for a given length wavebreak was converted to percent seagrass cover (recomputed from Fonseca and Bell, 1998) to predict the overall increase in seagrass acreage across the site as the result of wave reduction. The 500-foot (152-meter) long wall was designed with an inverted “V-shape” consisting of two 250-foot (76.2-meter) sections.

The V-shape was a professional judgement on the part of the design team to mitigate wave impacts on the wall from the forecast direction of maximum wave height development (northerly). Thus, the wavebreak was oriented on the site to attenuate the dominant north and northeasterly exceedance event (wind events composing the local top 5% of all hourly wind speeds, along with their direction, over the preceding three years period) winds and create a calmer environment on the lee side (south facing side) of the structure to promote seagrass patch coalescence and new, permanent seagrass acreage.

Once the 500-foot (152-meter) wall length was selected by NCDOT (the wall length that most closely approximated the forecast 1.28 acres [0.52 hectares] of new seagrass cover), four wave energy regimes (treatments) were defined from a cumulative frequency analysis of the area covered by the modeling effort where greater than 5% energy reduction was forecast to occur as the result of the wavebreak (**Figure I-1**). The wave energy regimes represent high wave energy reduction (>66% forecast reduction), moderate reduction (34 to 66%), low reduction (5 to 33%), and ambient or reference (<5% reduction). These wave energy reduction regimes became strata for random selection of various sampling described below.

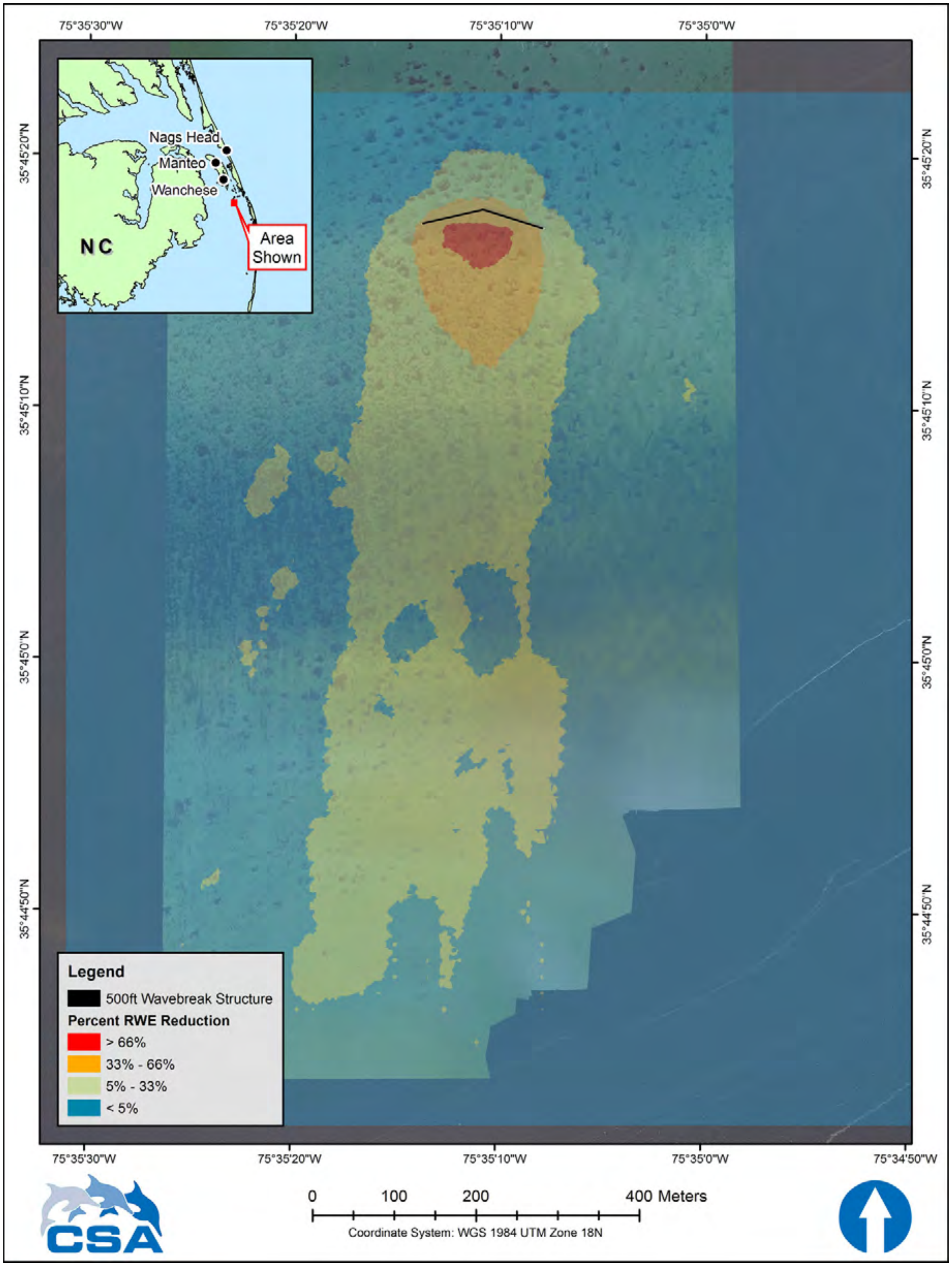

Figure I-1. Post-construction forecast of wave energy (RWE; representative wave energy [J m^{-1} wave crest]) based on 500-foot (152-meter) wavebreak structure, superimposed on image of seagrass cover.

Project Engineering and Design

CSA subcontracted SEPI Engineering to design the wavebreak and provide the engineering Signed and Sealed Design Plans. The wavebreak was designed based on wave height forecasts provided by CSA using the WEMo model (Malhotra and Fonseca, 2007) and the aforementioned exceedance event winds. To meet the 500-foot (152-meter) design length, the structure was composed of 101 individual "Reefmaker" units each containing a central piling, one concrete base unit, and three concrete wave attenuator units stacked on the base unit and each embedded with natural granite rock to increase surface area for epibiota colonization (each unit was 4.8 ft × 4.8 ft × 4 ft [1.46 m × 1.46 m × 1.22 m]) (**Photos I-1** and **I-2**). Granite rock was chosen to prevent bioerosion of the enhanced surface area. Each Reefmaker unit had a bottom clamp and a top collar installed to secure the concrete layers to the central piling to hold the base and wave attenuator units in a fixed vertical position on the piling, preventing settling into the sand substrate over time.

Photo I-1. East-facing view of installation of the central pilings with piling clamps at the Bonner Bridge Seagrass Mitigation Site. Yellow arrow points to an installed clamp.

Photo I-2. One Reefmaker unit consisting of one base unit on the bottom and three wave attenuator units containing granite rock. One hundred and one of these units were installed at the Bonner Bridge Seagrass Mitigation Site. For scale, the width of the units is 4.8 ft (1.46 m).

Appendix II

Bioturbation Experiment

To evaluate the influence of biological disturbance on seagrass patches at the site (*sensu* Townsend and Fonseca, 1998), CSA installed a bioturbation exclusion experiment in May 2016. There, 40 locations were randomly selected from within strata (10 per strata) defined by the forecasted wave reduction pattern following wavebreak placement (high wave energy reduction = >66%; moderate reduction = 34 to 66%, low reduction = 5 to 33%, and ambient or reference = <5% reduction) (**Figure II-1**). The nearest isolated seagrass patch to that location was then selected for application of the experimental treatment. At the center of all 40 patches, a 2.4-meter (8-foot) long stainless steel rod (**Photo II-1**) was driven into the sediment until only 3 to 10 cm (1 to 4 in) remained above the sediment. Five randomly selected patches were assigned wire mesh (wire remesh panels 1.07 m × 2.13 m [42 in × 84 in]) welded steel wire remesh sheet (with 0.106 m × 0.1.06 m [4 in × 4 in] mesh size) to exclude bioturbating sting rays and five were un-protected within each of the four wave energy regimes (total of 40 patches). At each of two randomly selected cardinal directions per patch, the distance from the center rod to the edge of the seagrass was measured in centimeters using a metric tape (**Photo II-2**). For patches receiving mesh, each of the cardinal directions received a wire mesh. The longest length of the mesh was positioned parallel to the patch edge approximately 1/3 on seagrass and 2/3 on sand to allow room for seagrass growth (**Photo II-3).** Two J-shaped rebar stakes 0.3 m (1 ft) long anchored the mesh so it was flush on the seafloor. Flush deployment on the seafloor and anchoring were performed to prevent entanglement by sea life, such as diving birds. Other information recorded for each patch included the treatment received (mesh or no mesh), elevation of the rod above the sediment, and seagrass species observed at each edge. Change in the distance from the center rod to the patch margin will be recorded over time. The statistical approach for this experiment is a repeated measures two-way analysis of variance with wave energy and patch protection as main effects. The mesh and stakes will be removed and disposed of appropriately when patch coalescence begins, at which time monitoring of these patches will cease.

During the May 2018 survey, scientists revisited each patch to collect data. Scientists navigated to the location of the center rod using the Trimble GPS. Once on location, they searched for the center rod using a glass bottom bucket and grazing a rake (tines up) on the seafloor. The distance from the center rod to the edge of the seagrass patch was re-measured along the same cardinal directions established during installation. The presence or absence of mesh, elevation of the rod above the sediment, and seagrass species observed at each edge was also noted for each patch.

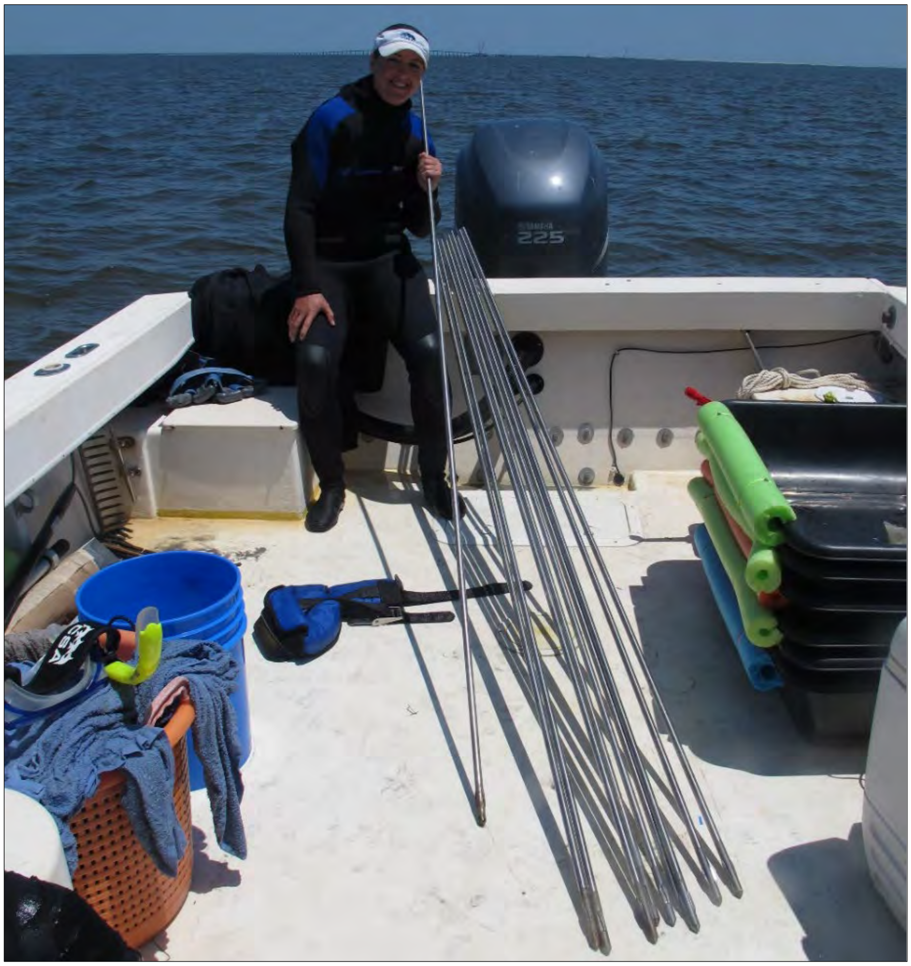

Photo II-1. Center rods (2.4 m [8 ft]) installed at each bioturbation experiment patch within the Bonner Bridge Seagrass Mitigation Site.

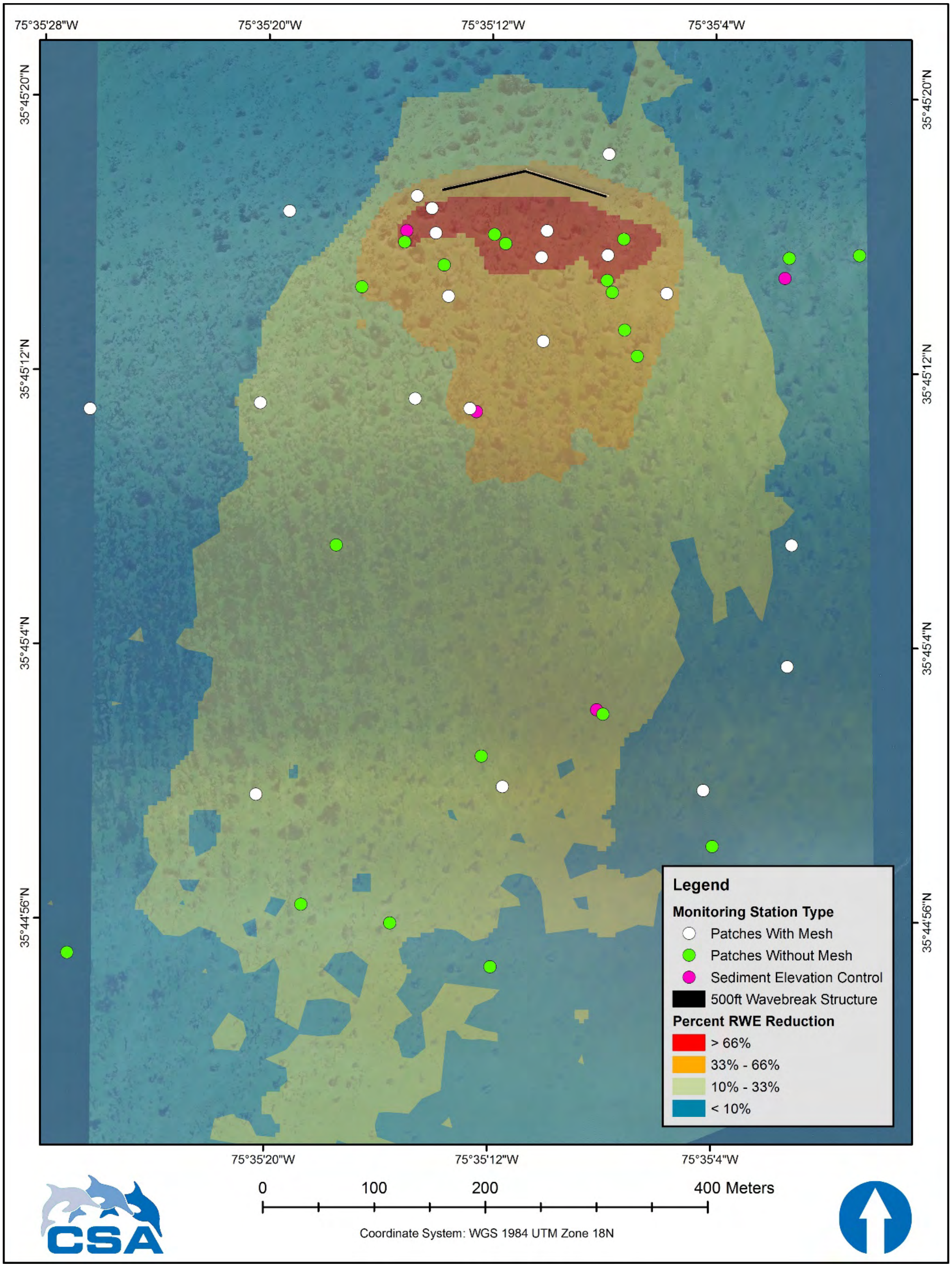

Figure II-1. Randomized distribution of the seagrass patches and the experimental treatments selected for use in the bioturbation study.

Photo II-2. Scientists measuring from the center rod to the edge of the seagrass patch on the randomly selected direction at the Bonner Bridge Seagrass Mitigation Site.

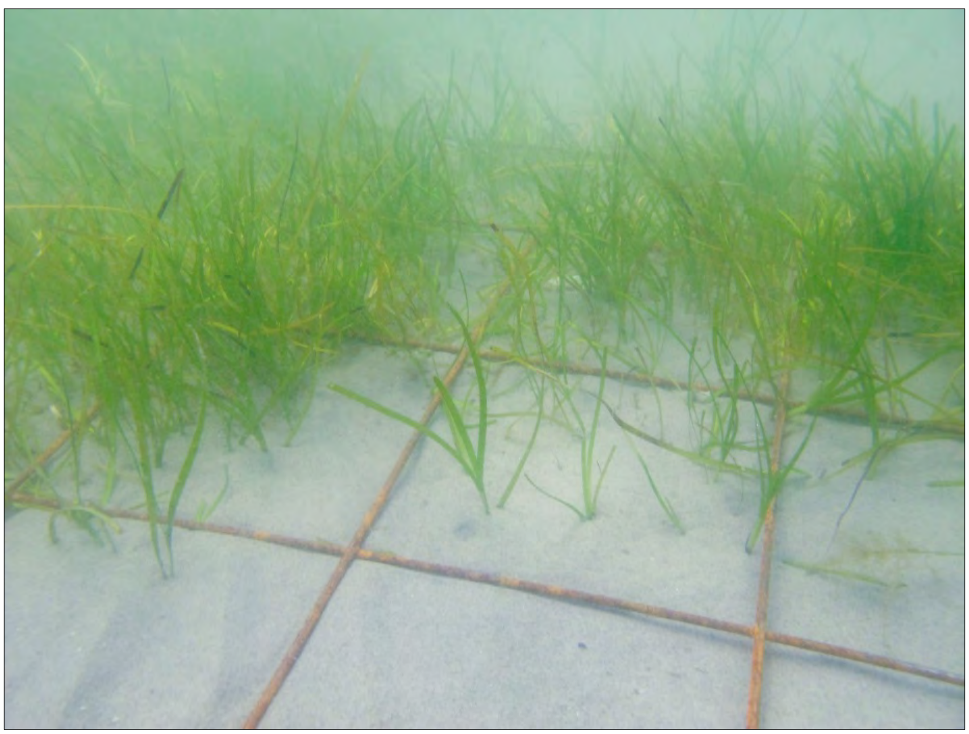

Photo II-3. Exclusion mesh installed flush on the seafloor on the edge of the seagrass patch within the Bonner Bridge Seagrass Mitigation Site. Mesh size is 0.106 m × 0.1.06 m (4 in × 4 in).

Bioturbation Experiment

At the time of setting out the experiment in May 2016, the average distance from the center rod to the edge of all 40 patches was 3.8 m (12.5 ft) (**Table II-1**). At the onset of the experiment patches with exclusion mesh had an average distance of 3.9 m (12.8 ft) and patches without exclusion mesh had an average distance of 3.7 m (12.1 ft).

Table II-1. Average distances in meters from the center rod to the edge of the patch for the bioturbation experiment. Updated July 2018; n/a = not applicable; meshes had been removed. ND = no data; distances not measured as experiment had ended.

Survey	All 40 patches (m)	Patches with exclusion mesh (m)	Patches without exclusion mesh (m)
May 2016	3.8	3.9	3.7
January 2017	3.5	3.7	3.3
October 2017	1.48	n/a	n/a
May 2018	ND	ND	ND

In January 2017, all 40 bioturbation patches were revisited and monitored. For all 40 patches, the average distance from the center rod to the edge of the patch was 3.5 m (11.5 ft). For all mesh treatment patches, the average distance to the edge of the patch was 3.7 m (12.1 ft) (however, mesh was only located at 8 locations within 7 patches at the time of the survey). Patches without exclusion mesh had an average distance of 3.3 m (10.8 ft). In October 2017, the number of monitored patches was reduced to 14 to revisit only those 7 patches that still contained mesh at the time of the January survey in addition to an equal number of non-mesh patches (n=7). Average distance from the center rod to the edge of all 14 monitored seagrass patches was 1.5 m (4.9 ft). For the 7 patches that contained mesh at the time of the January survey, the average distance to the edge of the patch was 0.5 m (1.6 ft). The 7 patches without exclusion mesh had an average distance of 1.9 m (6.2 ft). In October of 2017 the experiment had been terminated and only the distance to patch edges were measured. That distance had reduced from 3.5 to 1.48 m suggesting the dynamic nature of seagrass patch margins in this area.

Appendix III

Representative Images of Biota – May 2019

Image III-1. Blue crab (*Callinectes sapidus*) on wavebreak structure in the medium elevation strata.

Image III-2. Hydroids colonizing the lower edge of the wavebreak structure. Note support piling in background.

Image III-3. School of juvenile fish utilizing the shallow water column over a dropped wavebreak unit. Note the oyster colonization on the unit surface and discarded *Neverita* shell.

Image III-4.   Ruddy Turnstones roosting on top of the wavebreak structure.

Image III-5. Turf algae colonizing the concrete surface among embedded rocks on a medium elevation portion of the wavebreak structure.

Image III-6. Oysters colonizing a rock on a medium elevation portion of the wavebreak structure.

APPENDIX B

DEPARTMENT OF CIVIL ENGINEERING
NORTH CAROLINA STATE UNIVERSITY
RALEIGH, NC

EDGE OF PAVEMENT CHANGE
FEBRURARY 5, 2019

RUSSELL NASRALLAH

Due to significant changes in the right-of-way of Highway NC 12 along Pea Island, North Carolina, the Edge of Pavement (EOP) transects used to determine the beach profile volumes were updated to reflect the most current configuration.

It is noted that EOP updates have been made previously for the purposes of computing the 230 ft buffer for present and future conditions; however due to the desire to remain consistent in comparing volumes with past values the volume transects were not changed until 2019.

These changes affect two areas along the stretch of highway between Oregon Inlet and Rodanthe and will be detailed below (Fig 1). The offshore transect ends remained static while the onshore transect ends were extended or shortened to match the edge of pavement on February 5th, 2019.

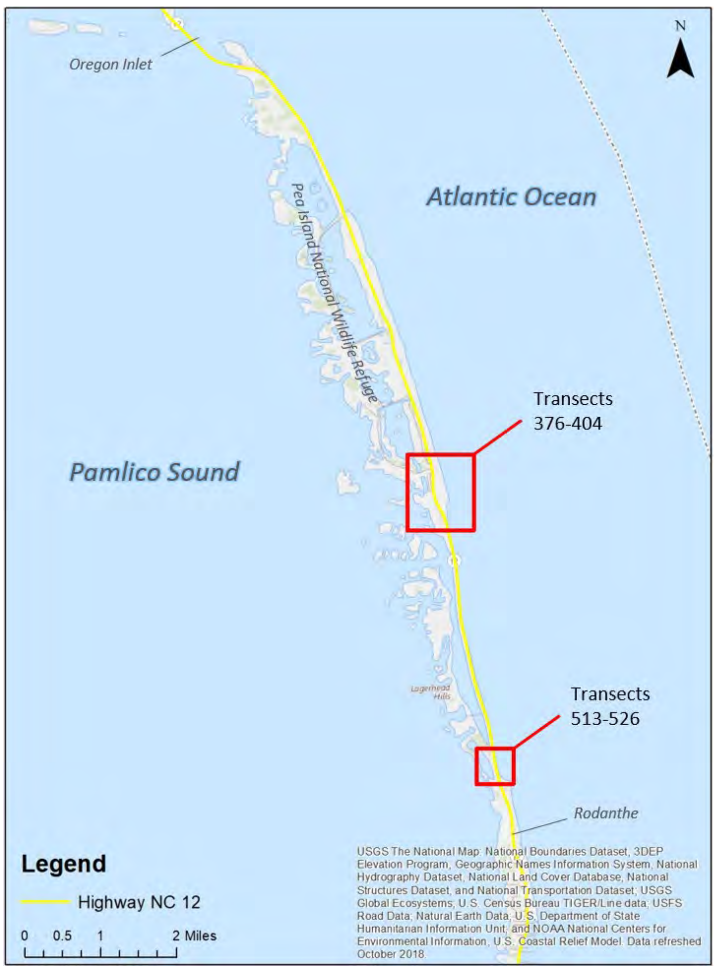

Figure 1 The regions outlined in red were altered due to changes in the edge of pavement (EOP) of Highway NC 12. These locations are near the Interim Bridge and the staging area for the new Jug Handle Bridge.

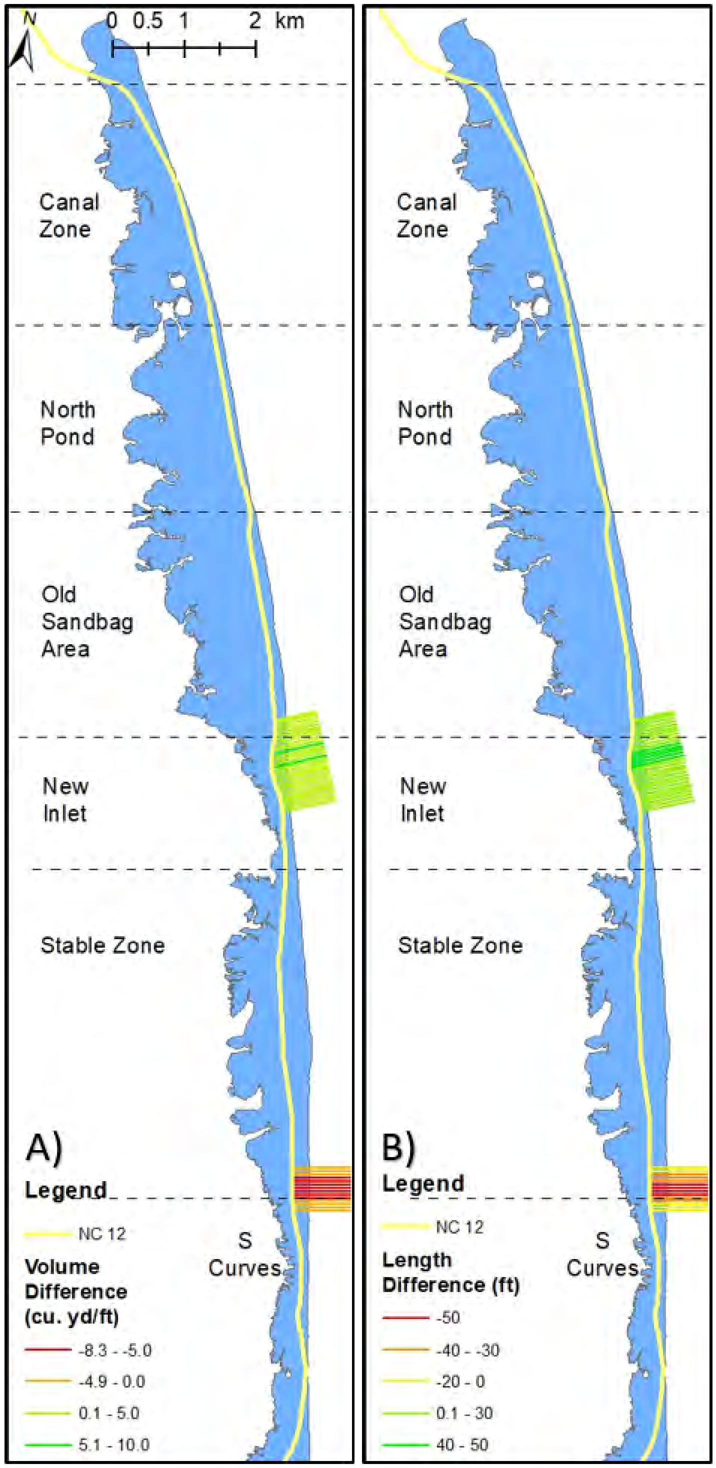

Figure 2 Locations of transects with A) volume differences (cu. yd/ft) and B) length differences (ft)

Table 1. Length and volume differences at affected transects.

Transect ID	Length Difference (ft)	Volume Difference (cu. yd/ft)
376	2.34	0.425
377	9.19	1.691
378	15.57	2.681
379	19.14	3.212
380	20	2.777
381	21.22	3.671
382	23.79	4.388
383	22.98	3.388
384	22.86	2.501
385	23.4	3.544
386	35.15	5.018
387	43.29	4.343
388	44.72	4.574
389	41.41	4.836
390	33.54	6.269
391	23.22	3.521
392	21.66	2.524
393	20.07	2.116
394	19.82	2.44
395	18.58	2.54
396	16.53	2.255

Transect ID	Length Difference (ft)	Volume Difference (cu. yd/ft)
397	16.99	3.211
398	18.02	2.979
399	20.6	3.463
400	18.7	2.334
401	19.12	3.058
402	22.87	3.498
403	19.51	3.101
404	11.67	1.98
513	-3.61	-0.278
514	-14.78	-1.496
515	-29.97	-3.765
516	-41.61	-6.025
517	-49.51	-8.133
518	-53.7	-8.348
519	-52.84	-7.957
520	-52.83	-7.158
521	-52.47	-6.846
522	-49.56	-5.725
523	-37.79	-3.897
524	-22.38	-2.734
525	-10.98	-1.627
526	-1.78	-0.38