DRAFT: BEACH MANAGEMENT PLAN
CURRITUCK COUNTY, NORTH CAROLINA

PREPARED FOR
CURRITUCK COUNTY

PREPARED BY
COASTAL PROTECTION ENGINEERING OF NORTH CAROLINA, INC.
ENGINEERING LICENSE CERTIFICATE #: C-2331

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DATE

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EXECUTIVE SUMMARY

Currituck County commissioned this Beach Management Plan (Plan) to serve as a framework for the management, protection and restoration of the County's 22.6 miles of oceanfront beaches and dunes. The Plan addresses various coastal hazards including long-term erosion, storm impacts, and sea-level rise. The Plan provides a long-term vision for Currituck County to sustain the beaches that support a significant portion of their local economy and maintain the tax base located along the County's beaches.

The Plan recognizes that beaches are a critical economic asset, supporting tourism, property values, and the County's tax base. The overarching goal of the Plan is to preserve tourism-driven revenues while improving coastal resilience. To achieve this, the Plan specifically aims to:

- Reduce risk to oceanfront development from storm impacts
- Mitigate long-term erosion risk
- Prevent dune breaching and coastal flooding
- Protect critical infrastructure and evacuation routes
- Maintain sufficient recreational beach width
- Sustain ecological resources, including shorebird and sea turtle habitat

The Plan includes an in-depth evaluation of Coastal Hazards and Vulnerability (Section 2) and introduces a number of general management concepts that could be implemented by Currituck County (Section 3). Through the Feasibility Analysis (Section 4), four (4) separate reaches along the Currituck County oceanfront were identified for active beach management. Alternatives were developed for each of the Reaches and the feasibility of each of the Alternatives were weighed against each other to determine a recommended alternative for each.

This Plan is grounded in a detailed assessment of coastal hazards and the vulnerability. Coastal storms represent the most significant and immediate threat to the integrity of the beach and dune system. Hurricanes, nor'easters, and other tropical and extratropical storm systems generate elevated water levels and high-energy waves that can cause rapid erosion, undermine structures, and produce dune overwash or breaching. Historic storms such as Hurricane Isabel in 2003 provide a benchmark for understanding the magnitude of potential impacts. That event produced wave heights approaching 26 feet and water levels with return periods of up to 50–100 years. Even storms of lesser magnitude, when persistent or coinciding with elevated water levels, can produce substantial cumulative impacts to the shoreline.

Sea-level rise acts as a multiplier on these storm hazards. Observations from the NOAA tide gauge at Duck, North Carolina indicate a long-term rate of relative sea-level rise of approximately 4.99 millimeters per year, with projections suggesting an additional rise of between roughly two and nearly three feet by the year 2080. This gradual increase in water level effectively raises the baseline upon which storms act, increasing the likelihood of dune overtopping, expanding the zone of active erosion, and accelerating shoreline recession over time.

Long-term erosion represents another critical hazard, operating over decadal timescales and gradually reducing the buffer between oceanfront structures and the shoreline. Analysis of shoreline change between 2009 and 2025 indicates that shoreline change rates vary considerably across the County, with the highest average recession occurring in the Corolla and Reserve/Refuge Sections. An assessment of volumetric change trends reveals shorter-term fluctuations in sediment gain and loss, including a period of net accretion between 2020 and approximately 2022–2023 followed by a return to erosional conditions. This variability highlights the dynamic nature of coastal systems and the importance of evaluating both short-term and long-term trends in assessing vulnerability.

To quantify vulnerability in a more rigorous manner, the Plan incorporates multiple numerical modeling approaches, including Delft3D and XBeach, which simulate wave conditions, currents, sediment transport, and dune response during storm events. The Delft3D modeling consistently demonstrates that the southern portion of the County—particularly between Stations C-092 and C-114—is more exposed to higher wave energy and stronger currents during the simulated storms, relative to the rest of the County oceanfront.

The one-dimensional (1D) XBeach modeling approach was implemented along the cross-shore profiles south of the Horse Gate. These simulations focused on evaluating beach and dune response to extreme storm conditions under present-day (2025) conditions. After calibrating the model against Hurricane Matthew, production runs were conducted for Hurricane Isabel, the November 2009 Nor'easter, and a synthetic 25-year storm with adjustments for sea-level rise. Results indicated that Hurricane Isabel produced the most severe and spatially consistent impacts, with an average recession point approximately 8 feet landward of the dune crest and widespread dune erosion across nearly all profiles. In contrast, the 25-year storm generated moderate, spatially variable impacts with an average recession point slightly seaward of the dune crest, while the nor'easter produced the least severe response overall but still exhibited localized vulnerability. Several profiles, particularly between Stations C-060 and C-066, consistently demonstrated significant landward recession under all scenarios, reflecting vulnerability associated with low dune elevations and narrow beaches.

Building on the 1D analysis, the two-dimensional (2D) XBeach model was developed to better resolve alongshore variability and capture complex processes such as dune breaching, overwash pathways, and distributed sediment transport across the barrier island system. The 2D computational domain extended from Station C-048 to C-096, encompassing the most vulnerable central portion of the Corolla Section, including the Ocean Hills and Whalehead Beach communities. The model was calibrated using Hurricane Matthew (2016) with LiDAR-derived elevation change data. For production simulations, Hurricane Isabel and a synthetic 25-year return interval storm were selected, both adjusted for sea-level rise. Due to limits of availability of higher resolution topographic and bathymetric data, the production runs were limited to using high-resolution 2019 LiDAR topography. This means that results are reflective of impacts to the beach and dune based on 2019 conditions, not present day conditions. Results showed that Hurricane Isabel produced severe and widespread dune erosion, with dune crest elevations reduced below +10 ft NAVD88 across several reaches. Most notably, the dune elevations were lowered below the +10 ft. NAVD88 elevation along the south end of the Whalehead Beach community, the Crown Point community, and the north end of Ocean Sands (Stations C-080 and C-088) and in the vicinity of Station C-064 in Ocean Hills. The results indicate these areas are most conducive to overwash and potential breaching. In contrast, the synthetic 25-year storm resulted in substantially less impact, with dune crest elevations largely remaining above +10 ft NAVD88 elevation and erosion generally limited to less than approximately four feet, suggesting moderate resilience under more frequent storm conditions. Overall, the 2D analysis confirmed that while much of the study area exhibits resilience to moderate events, extreme storms have the potential to significantly degrade dune systems and expose landward infrastructure to flooding and wave attack, reinforcing the need for targeted management strategies in the most vulnerable reaches.

The analysis of shoreline change, volumetric change, and recreational beach width collectively indicates that Currituck County's beaches are experiencing spatially variable but persistent stress from both long-term and short-term coastal processes. Historical shoreline change rates between 2009 and 2025 show shoreline retreat across most stretches of the County's oceanfront. The highest recession rates have been measured in the Corolla (approximately -3.9 ft/yr) and Reserve/Refuge (-3.6 ft/yr) Sections. Projection analyses based on these trends reveal substantial variability in potential impacts to oceanfront homes over time, with the Corolla Section consistently accounting for the majority of projected impacts. Volumetric change analyses further highlight the dynamic nature of the system, showing a period of net sediment gain between 2020 and approximately 2022–2023 followed by an inflection to net erosion, suggesting that recent accretion was likely temporary and associated with post-storm recovery conditions rather than a long-term reversal of erosional trends. This shift is supported by wave climate observations, which indicate a relatively calm period followed by more energetic storm activity corresponding to renewed sediment losses. Finally, the assessment of recreational beach width demonstrates considerable spatial and temporal variability, with multiple locations falling below the approximate 65-foot threshold established as the width that supports recreational use. Narrower beaches tend to coincide with areas of higher erosion rates and increased vulnerability to storm damage. Together, these findings indicate that while short-term recovery cycles may occur, the dominant long-term trajectory for much of the County's shoreline is erosional, with implications for both infrastructure risk and the sustainability of tourism-dependent beach resources.

The findings of the various assessments of coastal hazards and vulnerability are integrated into a comprehensive vulnerability matrix presented in Section 2.4 of the Plan. The matrix evaluates five primary factors: storm-induced erosion, potential for breaching/overtopping, long-term shoreline change, volumetric erosion trends, and recreational beach width. Rather than relying on any single indicator, this multi-factor approach provides a holistic assessment of risk, allowing the County to identify areas where multiple stressors overlap and thus where management intervention is most urgently needed. The analysis shows that the highest vulnerability is concentrated in developed portions of the Corolla Section and in localized areas within the Spindrift and Pine Island reaches, while areas north of the Horse Gate generally exhibit lower structural vulnerability despite ongoing geomorphic changes.

Section 3 of the Plan evaluates a range of potential beach management concepts. These concepts span both structural and non-structural approaches, reflecting the complexity of coastal management in a setting where engineering, environmental, and regulatory considerations all play important roles. Non-structural approaches include the relocation or buyout of highly vulnerable oceanfront structures, which can reduce long-term risk and allow natural shoreline processes to occur without interference. Structural or semi-structural approaches include beach nourishment, which involves the placement of sand to widen the beach and enhance dune systems, and hybrid approaches that combine nourishment with coastal structures such as groins. Additional measures such as sand fencing and dune vegetation are considered as lower-cost methods for enhancing dune stability, while beach bulldozing is recognized as a short-term response to storm impacts.

To translate these concepts into actionable strategies, the Plan applies a feasibility analysis across four distinct shoreline reaches, namely the Central Reserve/Refuge Reach, the North Corolla Reach, the Spindrift Reach, and the South Pine Island Reach. Several alternatives were developed for each Reach and evaluated against a No Action alternative. The alternatives were then evaluated using a standardized framework that considers technical feasibility, economic and financial viability, legal and regulatory constraints, operational considerations, and implementation schedule.

In the area north of the Horse Gate, where development density is relatively low and access is limited, the analysis focused on an area between Stations C-041 and C-044 along Sandfiddler Road. This area is referred to as the Central Reserve/Refuge Reach. The analysis concludes that buyout and removal of vulnerable structures represents the most practical long-term strategy for this Reach. While beach nourishment could provide some protective benefits, the cost of such projects is difficult to justify in comparison to the limited economic value of development in this area. Consequently, the recommended approach emphasizes risk reduction through removal of exposure rather than ongoing maintenance of the shoreline.

The North Corolla Reach, which is more heavily developed and economically significant, stretches from the Horse Gate at the south end of the offroad portion of the County oceanfront, to Seabird Way in Ocean Sands (Stations C-059 to C-089). This Reach was identified as a candidate for beach nourishment. The feasibility analysis indicates that nourishment is the only alternative that effectively addresses storm risk, maintains recreational beach width, and supports the local economy. Although such projects require substantial initial investment and periodic maintenance, the benefits in terms of property protection and tourism support are considered to outweigh the costs.

The Spindrift Reach encompasses just the oceanfront properties in the Spindrift community east of Land Fall Court and north of the County Access in the vicinity of Station C-102. This Reach presents a more complex case, as it exhibits some of the highest levels of vulnerability within the County. It also poses challenges in terms of implementation and cost. Multiple alternatives, including nourishment and structural approaches, are technically capable of reducing risk; however, the economic justification for these measures is less clear, and regulatory barriers may limit the use of certain options. As a result, the Plan does not identify a single preferred alternative for this Reach but instead recommends additional analyses to better define the range of feasible solutions.

The South Pine Island Reach includes an approximately 3,000 foot long portion of the Pine Island Section, south of the Hampton Inn. The Reach covers the oceanfront from station C-114 to C-117, east of Hicks Bay Lane and Cottage Cove Road. The South Pine Island Reach is characterized by moderate vulnerability that becomes more pronounced under extreme storm conditions. While beach nourishment and structural measures could provide effective protection, the cost of implementing these strategies may exceed the expected benefits. Lower-cost approaches such as dune enhancement may provide incremental benefits but are unlikely to fully address the identified risks. As a result, the Plan does not identify a single preferred alternative for this reach but instead recommends additional analyses to better define the range of feasible solutions.

The following recommendations and considerations are provided to Currituck County elected officials, Currituck County staff, and the general public as they review what is intended to be a draft document. These recommendations are based on 1) an understanding of the current goals of the County for beach management; 2) the results of the vulnerability analyses described in Section 2 of this draft document; and 3) the feasibility assessment described in Section 4 of this draft document.

1. The XBeach 2D storm vulnerability analysis focused on overtopping added considerable value to the assessment of storm vulnerability. However, as described in Section 2.1.4.2, the analysis was limited by two factors. The first was the model domain, which was budget limited and focused mostly on the North Corolla Reach. The second was the availability of higher resolution topographic/bathymetric Lidar data of which the most recent dataset reflected conditions from 2019. An update of the XBeach 2D storm vulnerability analysis would provide additional value to the development of Alternatives and for the feasibility analyses. As part of the proposed 2026 Currituck County Monitoring scheduled for Spring 2026, Lidar data will be acquired along the entire oceanfront of Currituck County. The proposal includes costs for processing sub-sections of that data and re-running the XBeach 2D storm vulnerability assessment within the same limited model domain (C-048 to C-096). It is recommended that all of the data collected south of the Horse Gate be processed and that the XBeach 2D storm vulnerability model be re-run using the updated 2026 conditions.
2. As Currituck County elected officials and staff, as well as the general public, review this draft document, consideration should be given to the Alternatives evaluated in Section 4 for the various Reaches. Feedback is requested on whether other reasonable alternatives should be considered in the feasibility analyses of the four (4) reaches identified for active beach management.
3. Furthermore, as this draft document is reviewed by County elected officials and staff, and the general public, consideration should be given to the assumptions made in the

Feasibility Analysis included in Section 4. While evaluation of technical aspects of the engineering and environmental impacts have been made based on considerable experience working on similar projects, general assumptions have been made using best judgment on potential monetary losses on behalf of the County and private property owners. If reviewers believe that additional considerations should be made in these assessments, comments submitted will be considered.

4. Spindrift Reach – While the Alternatives described in Section 4.2.3.1 of this draft document were assumed to have a 30-year life cycle cost greater than the benefits realized over the same period, further analysis of the cost and benefits of these alternatives are warranted. This additional analysis would focus on more accurately quantifying the cost of losses under the No Action Alternative, and to further assess the 30-year life cycle cost of Alternative 2 (Buyout and Removal of threatened Oceanfront Structures), Alternative 3 (Beach Nourishment) and Alternative 4 (Beach Nourishment with Coastal Structures). Additional engineering analysis such as more detailed analysis of diffusion losses and the recommended updates for the XBeach 2D storm vulnerability model discussed in Item #1 above, are expected to provide a more accurate assessment of the benefit to cost ratio. Further consideration may also be warranted for the level of storm to which the Alternatives for the Spindrift Reach are designed. Designing to the Hurricane Isabel storm scenario may not result in an alternative for which benefits outweigh the costs of no action. However, designing to a less extreme storm may result in a positive benefit to cost ratio.

5. South Pine Island Reach – Similar to the Spindrift Reach, the Alternatives described in Section 4.2.4.1 of this draft document for the South Pine Island Reach, were assumed to have a 30-year life cycle cost greater than the benefits realized over the same period. For this Reach, further analysis of the cost and benefits of the alternatives considered are also warranted. This additional analysis would focus on more accurately quantifying the cost of losses under the No Action Alternative, and to further assess the 30-year life cycle cost of both Alternatives 3 (Beach Nourishment) and Alternative 4 (Beach Nourishment with Coastal Structures). Additional engineering analysis such as more detailed analysis of diffusion losses and the recommended updates for the XBeach 2D storm vulnerability model discussed in Item #1 above, are expected to provide a more accurate assessment of the benefit to cost ratio. Further consideration may also be warranted for the level of storm to which the Alternatives for the South Pine Island Reach are designed. Designing to the Hurricane Isabel storm scenario may not result in an alternative for which benefits outweigh the costs of no action. However, designing to a less extreme storm may result in a positive benefit to cost ratio.

6. The Beach Management Plan intended to establish thresholds for when beach management plans should be initiated. Based on the vulnerability analysis included in this draft document, depending on the storm scenario for which the County desires to design, the four Reaches defined in Section 4 require beach management actions now to achieve

the stated goals of this plan. However, as indicated in the previous bullets, consideration is still being given to the appropriate design storm to consider. Once there is agreement on the design storm(s) to be considered, existing data from the storm vulnerability analyses and annual beach profile monitoring data can be used to establish thresholds and monitor the beach relative to those thresholds to track areas that may need active beach management in the future.

7. Once preferred alternatives have been finalized for each of the Reaches, cost estimates will be developed. Once these cost estimates have been developed, additional public engagement will be needed to evaluate the level of cost sharing required to implement the preferred alternatives. Most successful beach management programs require a combination of funding streams including state funding, general funds from Counties/municipalities, room occupancy funds through Counties/municipalities, and funding paid by individual homeowners through either municipal service districts that levy a higher ad valorem tax for those that benefit from the projects or direct assessments. External funding sources can also be considered such as grants for coastal resilience and pre-disaster mitigation.

Once the County has had the opportunity to review this information, solicit public input on the recommendations, and provide feedback to the authors, a final section of the Plan will be added that will provide final recommendations for the proposed Beach Maintenance Plan including conceptual drawings and cost estimates for the recommended beach management alternatives.

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1 INTRODUCTION

Currituck County authorized Coastal Protection Engineering of North Carolina, Inc. (CPE) to develop a Beach Management Plan (Plan) to serve as a framework for the management, protection and restoration of the County's beaches and dunes. The Plan addresses various coastal hazards including long-term erosion storm impacts and sea-level rise. The Plan presented in this document provides a long-term vision for Currituck County to sustain the beaches that support a significant portion of their local economy and maintain the tax base located along the County's beaches.

1.1 Project Location

Currituck County is located on the Outer Banks of North Carolina just south of the Virginia border. The County encompasses approximately 527 square miles, which includes a large portion of the Currituck Sound. This geographical division creates two distinct regions namely, the Currituck Mainland, and the Currituck Barrier Island Beaches. The Currituck Barrier Island Beaches extend approximately 22.6 miles along the Atlantic Ocean. The beaches extend from the North Carolina/Virginia border south-southeast to the Town of Duck in Dare County, North Carolina. A location map is provided in Figure 1.

In 2020, Currituck County initiated an annual beach monitoring program. Through the development of this monitoring program, the Currituck County beaches were divided up into four sections based on differences in land use, land management, and geomorphology (changes in the dune and beach slope configuration over time). The nomenclature developed for those various Sections has been utilized in this Plan. The northernmost section is referred to as the Carova Section, which encompasses approximately 4.9 miles of the oceanfront from the northern County boundary to the northern boundary of the Currituck National Wildlife Refuge. The approximately 6.0-mile section of the oceanfront beaches that includes the Currituck National Wildlife Refuge, the Currituck Banks Estuarine Reserve, and the developed area along Sandpiper Road and Ocean Pearl Road is referred to as the Reserve/Refuge Section. The largest section, referred to as the Corolla Section, extends approximately 8.2 miles from approximately 250 feet south of the Horse Gate to approximately 500 feet north of Yaupon Lane. The southernmost 3.5 miles of the Assessment Area is referred to as the Pine Island Section. The sections are shown in Figure 1, and the length, geographical limits, and baseline stations for each section are provided in Table 1.

Throughout this report, segments or reaches of the shorelines are described in terms of stations established along a baseline along the Currituck County oceanfront from the Virginia/North Carolina border to the Currituck County/Dare County border. The stations are spaced approximately 1,000 feet apart and run from Station C-001 at the north end to C-120 on the south end. These stations are referenced in Table 1 and maps showing the locations of each baseline station are provided in Figure 2 through Figure 9.

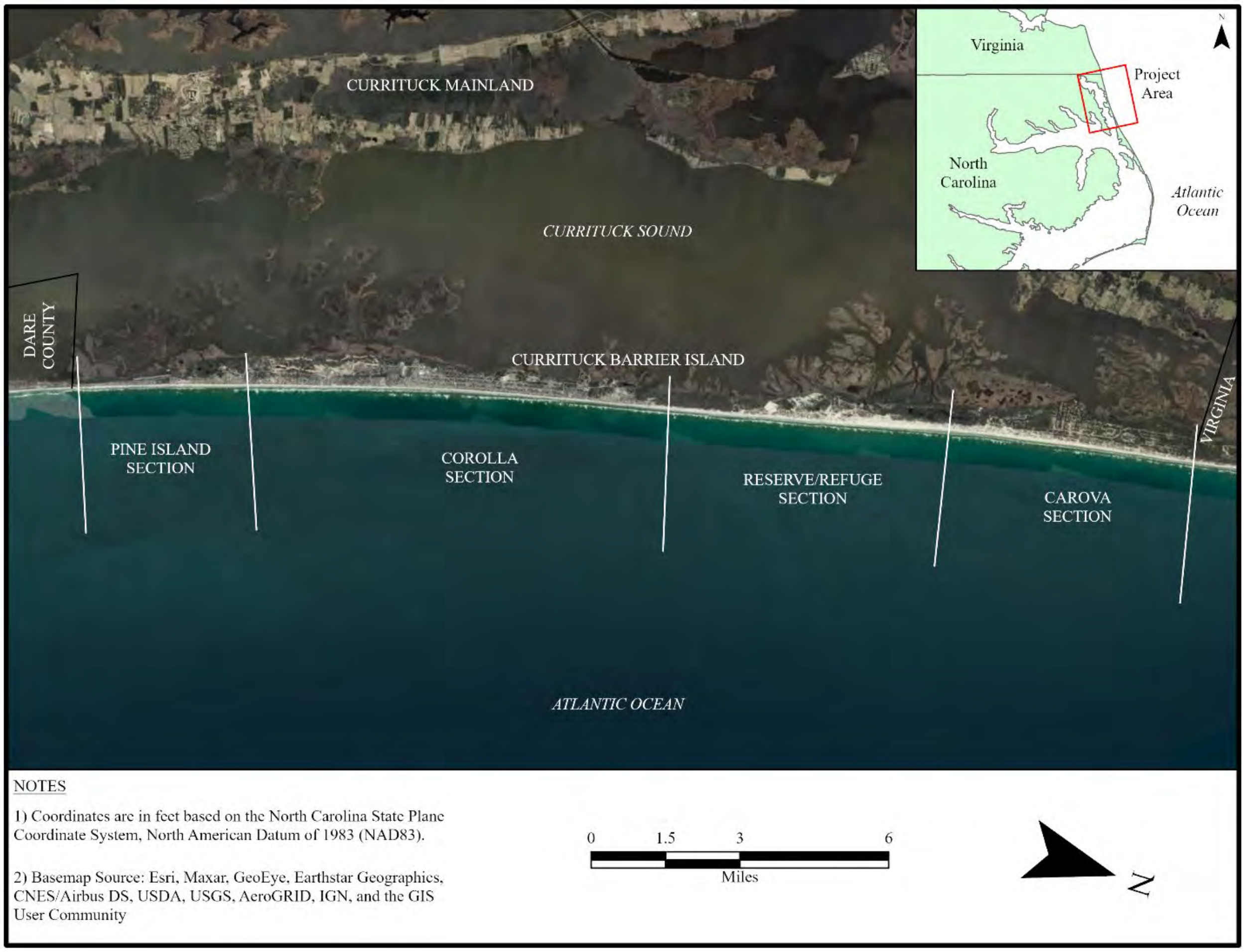


Figure 1. Currituck Project Location Map

Table 1. Section Descriptions

Section Name	Approximate Length	Geographic Extent	Baseline Stations
Carova	4.9 Miles	Northern County Boundary to Currituck Wildlife Refuge	C-001 to C-027
Reserve/Refuge	6.0 Miles	Northern boundary of Currituck Wildlife Refuge to 250 feet south of Horse Gate	C-027 to C-059
Corolla	8.2 Miles	250 feet south of Horse Gate to 500 feet north of Yaupon Lane	C-059 to C-102
Pine Island	3.5 Miles	500 feet north of Yaupon Lane to southern County boundary	C-102 to C-120

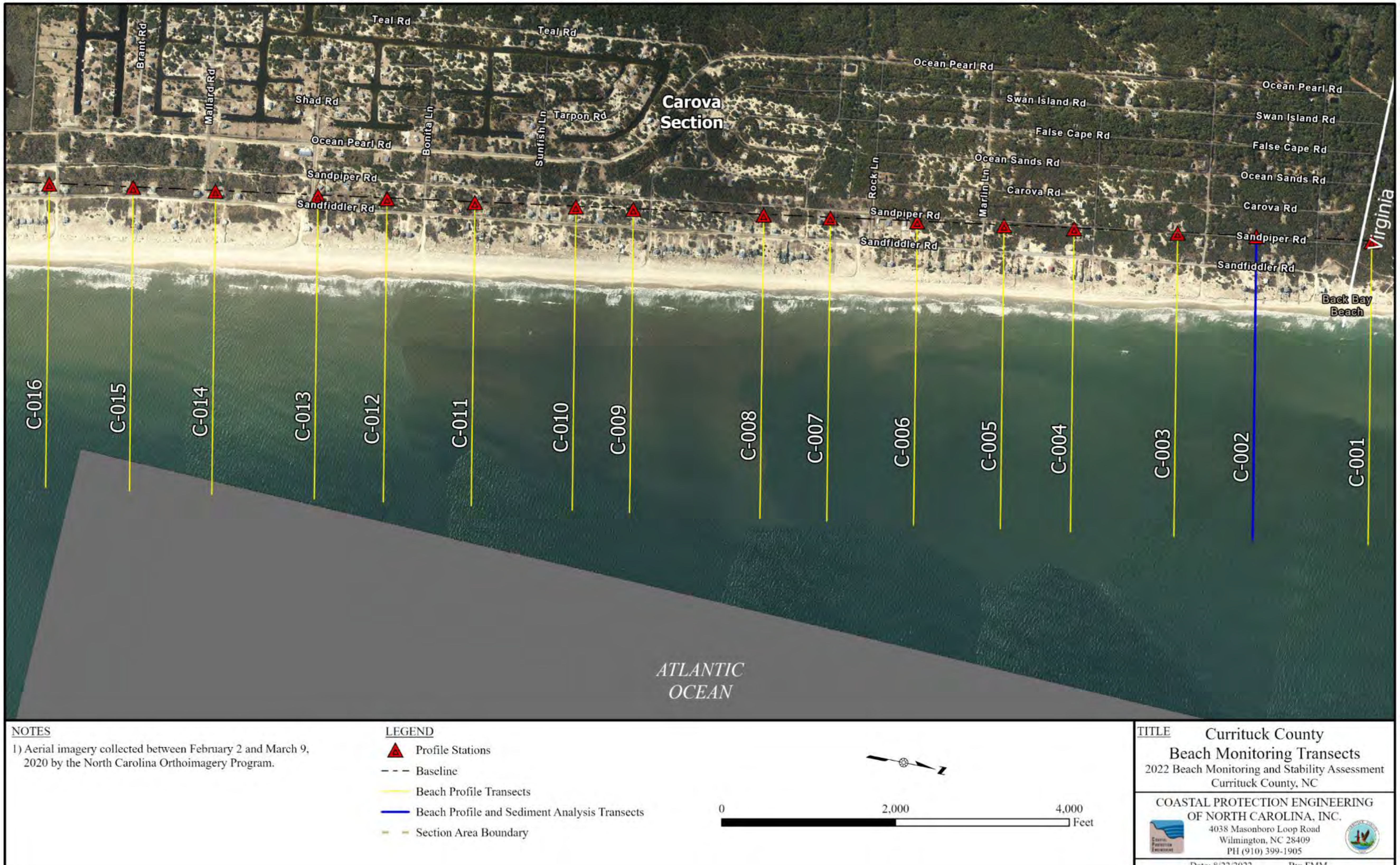


Figure 2. Monitoring Transects Map Stations C-001 to C-016

Figure 3. Monitoring Transects Map Station C-016 to C-031

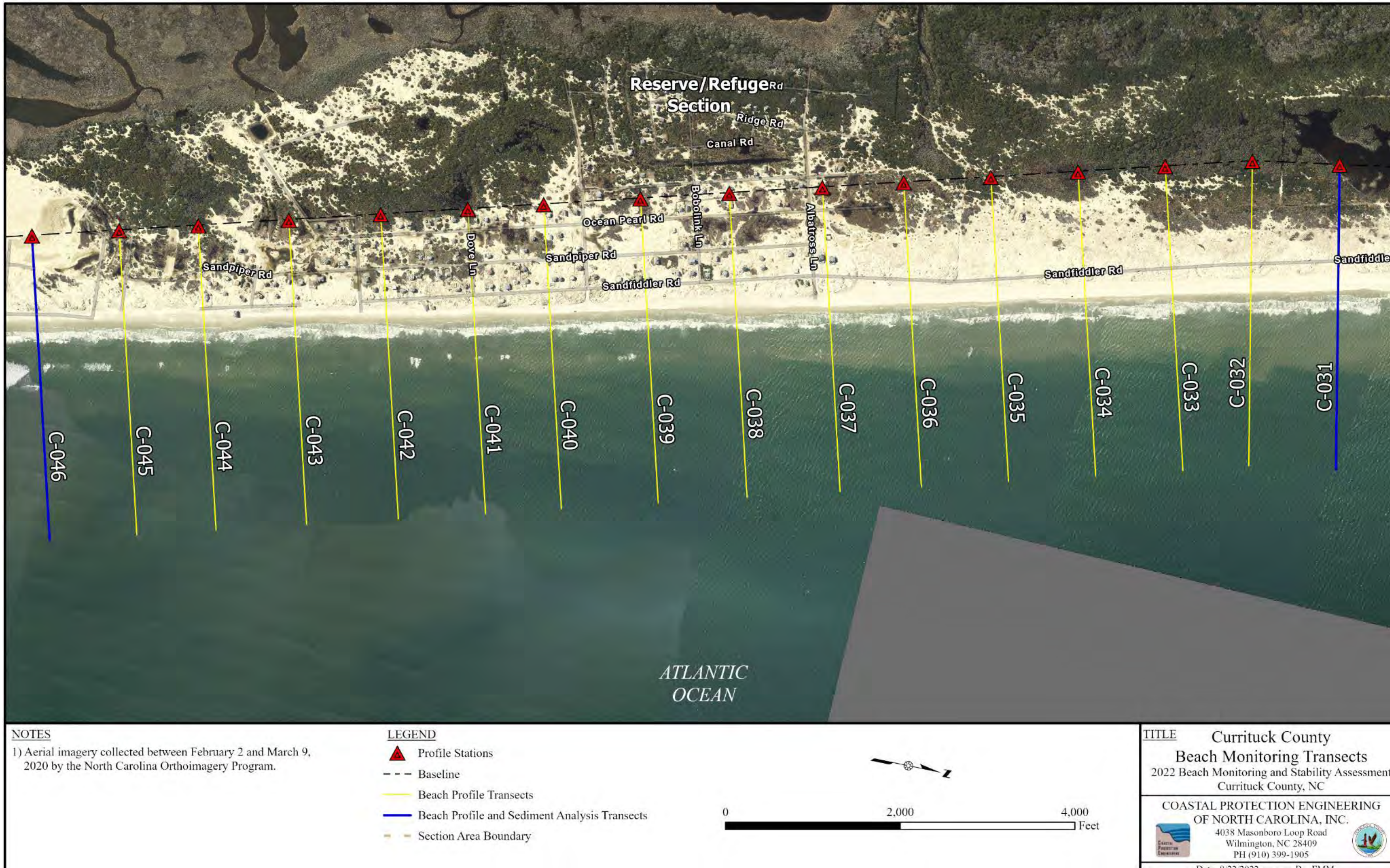


Figure 4. Monitoring Transects Map Station C-031 to C-046

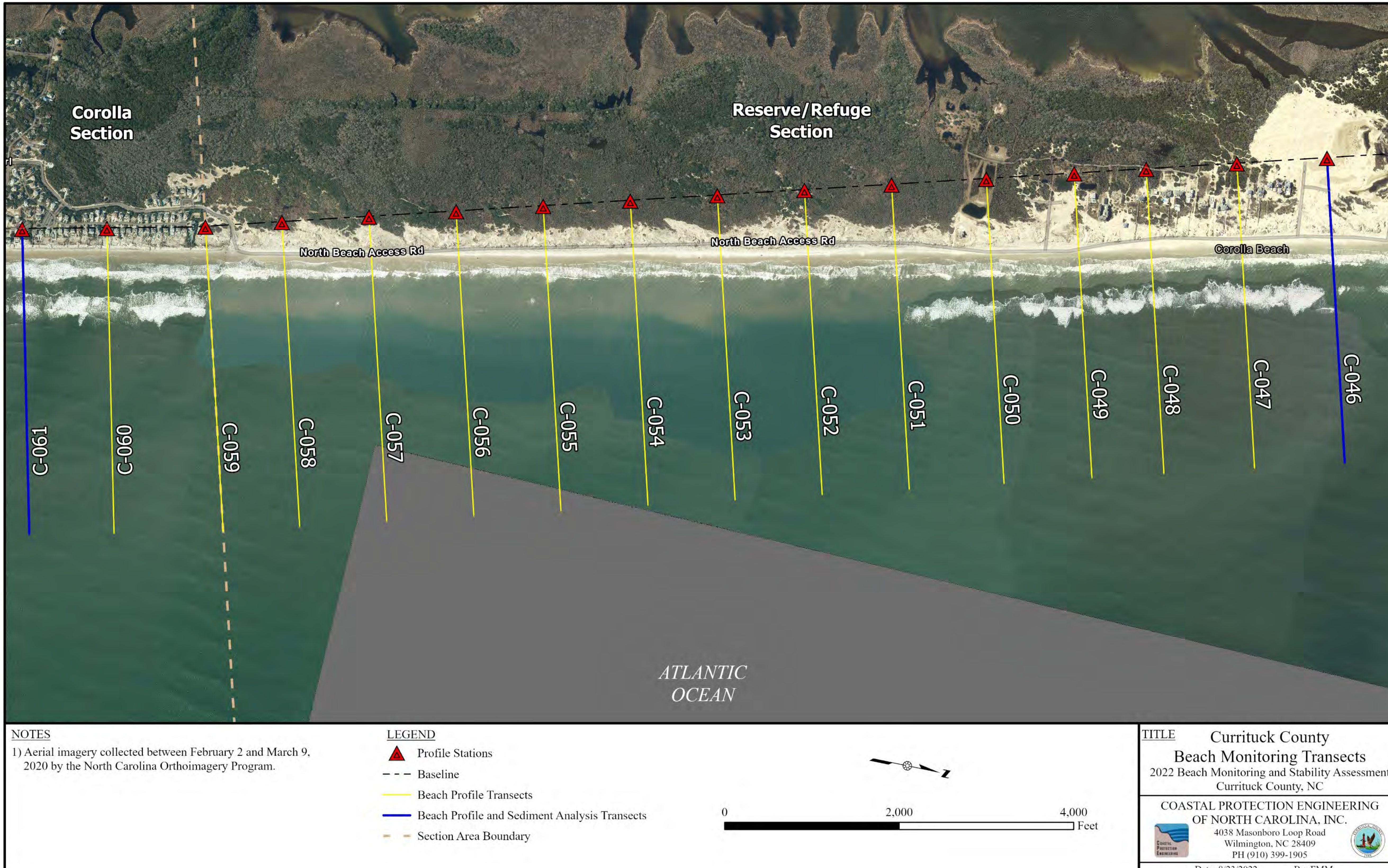


Figure 5. Monitoring Transects Map Station C-046 to C-061

Figure 6. Monitoring Transects Map Station C-061 to C-076

Figure 7. Monitoring Transects Map Station C-076 to C-091

Figure 8. Monitoring Transects Map Station C-091 to C-106

Figure 9. Monitoring Transects Map Station C-106 to C-120

Several papers have described historical inlets that had existed along the Currituck County beaches (Mallinson et al., 2008 and Moran et al., 2015). Like many modern day, unmanaged inlets, these features were likely not stationary but rather migrated throughout their history. Though the exact locations of these inlets are unknown, the southernmost inlet, known as Caffey's Inlet, is believed to have existed in the area between the Hampton Inn (Station C-110) and the southern County boundary (Station C-120). Caffey's Inlet is believed to have been open between 1770 and 1811. Though little is known of the specifics of the inlet, it has been theorized that the extensive back barrier marsh west of this portion of the barrier beach is built upon the relic flood tide delta system of Caffey's Inlet. Research conducted by Moran et al., (2015) suggested that Caffey's Inlet "accommodated a significant tidal prism", meaning that it was a significant inlet for the region.

1.2 Beach Management Goals

Prior to developing this Beach Management Plan, Currituck County carefully considered and established specific goals for which the Beach Management Plan would focus. The County's overall goal is to preserve tax revenues (sales taxes, bed taxes, and ad valorem taxes) generated from tourism associated with the beaches of Currituck County. To preserve these tax revenues both directly and indirectly, the County's Beach Management Plan focuses on maintaining the beaches in such a way as to:

1. Reduce risk to oceanfront properties from coastal storms;
2. Mitigate risk to oceanfront properties from long-term erosion;
3. Reduce the risk of dune breaching which can cause considerable flooding of beachfront communities;
4. Maintain/Protect public roads/emergency evacuation corridors; and
5. Provide sufficient recreational beaches that promote and encourage tourism

Recognizing that the County, like most coastal communities, is vulnerable to accelerated sea-level rise and intense coastal storms, Currituck County has developed this Plan such that a pronounced emphasis has been placed on bolstering resilience and resilience planning.

While discussing the established goals of the Beach Management Plan, the County also stated its interest in pursuing legislative changes to the prohibition of permanent shorelines stabilization. This plan explores concepts that include implementation of such permanent shoreline stabilization measures and provides recommendations on pursuing legislative changes.

2 COASTAL HAZARDS AND VULNERABILITY

This Beach Management Plan serves as a component of Currituck County's comprehensive resilience planning efforts. Beach management typically falls into a sub-set of resilience known as coastal resilience. The National Oceanic and Atmospheric Administration (NOAA) defines coastal resilience as "the ability of populations, ecosystems, and economies to prepare for, absorb, respond to, recover from, and successfully adapt to the impacts of natural and human-caused hazards" (NCCOS, 2024). This Beach Management Plan deals primarily with the hazards of coastal storms and long-term erosional trends and considers what impact sea level rise may have on these hazards over time. The following sections describe these coastal hazards and describe the analyses used to identify and quantify vulnerabilities associated with these hazards.

2.1 Coastal Storms

Extratropical storms, tropical storms, and cold fronts frequently produce severe wind events that result in storm surge and waves that can have a considerable impact on the beach and dune system. A sufficiently high and wide beach and dune system can effectively absorb the impact of these hazards, which are collectively referred to as coastal storms. However, in the absence of such sufficiently high and wide beach and dune systems, these coastal storms can cause significant beach erosion that may undermine oceanfront structures. In locations where a sufficient beach and dune system does exist, coastal storms can significantly reduce the amount of protective beach available in the future. These storm hazards can also cause dune breaching and or dune overtopping, which may result in flooding of coastal areas landward of the beach and dune.

The influence of sea level rise can exacerbate the impacts of coastal storms. The increase in relative sea level measured at a given location inherently increases the risk of flooding from dune overtopping, surge, and inundation to low lying areas associated with the storm's water level. The NOAA tide gauge (8651370) located on the pier at the U.S. Army Corps of Engineers Field Research Facility in Duck, North Carolina, has shown a relative sea level rise rate of 4.99 mm/year based on monthly sea level data from 1978 to 2024. This is equivalent to a rate of 1.64 feet over 100 years. Future sea level rise rates are anticipated to accelerate over time. NOAA's most recent projections for relative sea level rise at the tide gauge in Duck, suggests that between 2005 and 2080, relative sea level may rise between 2.1 and 2.7 feet according to their "intermediate low" and "intermediate" sea level rise scenarios, respectively (NOAA, 2022).

In terms of sediment loss and erosion of the dunes and beach, the impacts of sea level rise are more nuanced. A beach's ability to adapt to relative sea level rise is highly dependent on the sediment budget of a particular stretch of beach. The sediment budget is an evaluation of the amount of sand that is being transported to the beach vs. the amount of sand that is transported away from the beach. A beach where more sediment is flowing to the beach than from the beach may accrete and has the ability to keep up with modest sea level rise. Conversely, a beach where more sediment is flowing off of and away from the beach than is being transported to the beach, may experience higher rates of dune loss and erosion due to sea level rise. Furthermore, the amount of development proximate to the beach and dune can cause a phenomenon known as coastal squeeze, whereby beach and dune habitat is lost due to the beach's inability to migrate landward due to development.

2.1.1 2022 Beach Vulnerability Analysis

As part of a study completed for the County in 2022, a vulnerability analysis was conducted to determine the degree to which oceanfront development may be vulnerable to a specific design storm (CPE, 2023a). The vulnerability analysis was patterned after similar analyses employed in the evaluation of storm vulnerability for the neighboring Outer Banks communities of Duck (CPE-NC, 2013), Southern Shores (APTIM, 2018), and Kill Devil Hills (CPE-NC, 2015). The approach focused on potential damage associated with a "design storm" or a range of potential "design storms". The analysis utilized the Storm Induced Beach Change Model, SBEACH, developed by Larson and Kraus (Larson and Kraus, 1989) for the US Army Corps of Engineers (USACE). SBEACH is a two-dimensional model which simulates changes in the beach profile that could result from coastal storms of varying intensity in terms of storm tide levels, wave heights, wave periods, and storm duration. Information required as input to run the SBEACH model includes the beach cross-section, the median sediment grain size, and time series of the wave height, wave period, and water elevation for the design storm.

The results of the SBEACH model were used to assess the relative health of the beach and dune system in terms of providing a particular level of storm damage reduction to public and private development along the County's oceanfront shoreline. This analysis only identified which houses could experience damage due to storm induced erosion caused by a storm having similar characteristics to Hurricane Isabel under 2022 conditions. The analysis did not include specific evaluations of damages to individual houses due to direct flooding, wave impacts, or wind impacts, nor did it quantify the economic impacts resulting from the damage or loss of such houses.

The design storm used in the vulnerability analysis was based off Hurricane Isabel which impacted the Outer Banks in early September 2003. The relatively recent occurrence of this particular storm, which resulted in widespread impacts to the Outer Banks, provided those with firsthand knowledge of the event, a tangible frame of reference to put this vulnerability analysis in perspective. A multistep process was developed to account for variability in wave characteristics offshore of Currituck County. This process is documented in detail in the 2022 Beach Monitoring and Beach Stability Assessment (CPE, 2023a).

The SBEACH model was then run for each profile along the County's oceanfront based on 2022 conditions. These output data, which represented post-storm conditions, were evaluated to identify the most landward point of the profile at which the post-storm profile elevation was one (1) foot lower in elevation than the pre-storm profile. A one (1) foot vertical change in profile elevation from the pre-storm to the post-storm condition has been identified as a reasonable threshold for estimating when structures become vulnerable to wave damage, including undermining and/or inundation (Larson and Kraus, 1998). This analysis identified a house as "impacted" if any part of the structure was within 15 feet of the landward most location where the profile was lowered by 1-foot in the storm simulation. Comparing the location of this "impact point" to the position of oceanfront houses and public infrastructure, provided insight into the vulnerability of said houses and infrastructure to the design storm conditions.

The SBEACH analysis completed in 2022 indicated that 43 oceanfront houses were at risk of damage due to a storm similar to Hurricane Isabel. Four (4) houses along the Reserve/Refuge Section were identified as vulnerable. These houses were located seaward of Sandfiddler Road along an approximately 4,000-foot portion of the oceanfront south of Canary Ln. (between Station C-040 and Station C-044). The largest concentration of houses identified included 29 houses spanning along an approximate 1.0-mile portion of the Corolla Section between the northern end of Atlantic Avenue and Corolla Village Road (between Stations C-061 and C-066). Farther south, all nine (9) of the oceanfront houses along Land Fall Court in the Spindrift community are also indicated as vulnerable. Four (4) of the houses are located in the Corolla Section and four (4) are located in the Pine Island Section, and the ninth house falls right on Station C-102. That house is counted as one of the 34 houses listed in the Corolla Section in Table 2. One additional house was indicated as vulnerable within the Pine Island Section near the north end of Salt House Road (Station C-117). The number of vulnerable houses identified in each of the four Sections of the Assessment Area in 2022 are provided in Table 2.

Table 2. Number of Vulnerable Houses by Project Section

Section	Number of Houses Impacted
Carova (C-001 to C-027)	0
Reserve/Refuge (C-027 to C-059)	4
Corolla (C-059 to C-102)	34
Pine Island (C-102 to C-120)	5
Total Assessment Area (C-001 to C-120)	**43**

2.1.2 Extreme Storm Analysis

A return period analysis for historical storms was conducted as part of the development of this Plan. The analysis consisted of evaluating water levels and waves to characterize recent significant storms that occurred from 2000 to 2023 in terms of storm frequency and intensity. From this assessment, three (3) storms were selected for simulation using the state-of-the-art Delft3D model described in Section 2.1.3. These simulations were used to analyze the variability of wave heights, currents, and beach erosion, with the goal of identifying vulnerable areas along the Currituck County shoreline.

Water level return periods were derived from an extreme water level analysis using data from NOAA Station 8651370 at Duck, NC. This analysis includes the highest recorded monthly water levels from 1978 to 2024, as well as annual exceedance probability levels of 1%, 10%, 50%, and 99%. Water levels are provided in both meters and feet, referenced to Mean Higher High Water (MHHW) (Figure 10). By examining the peak values within this dataset, return periods were determined for all major storms occurring between 2000 and 2023.

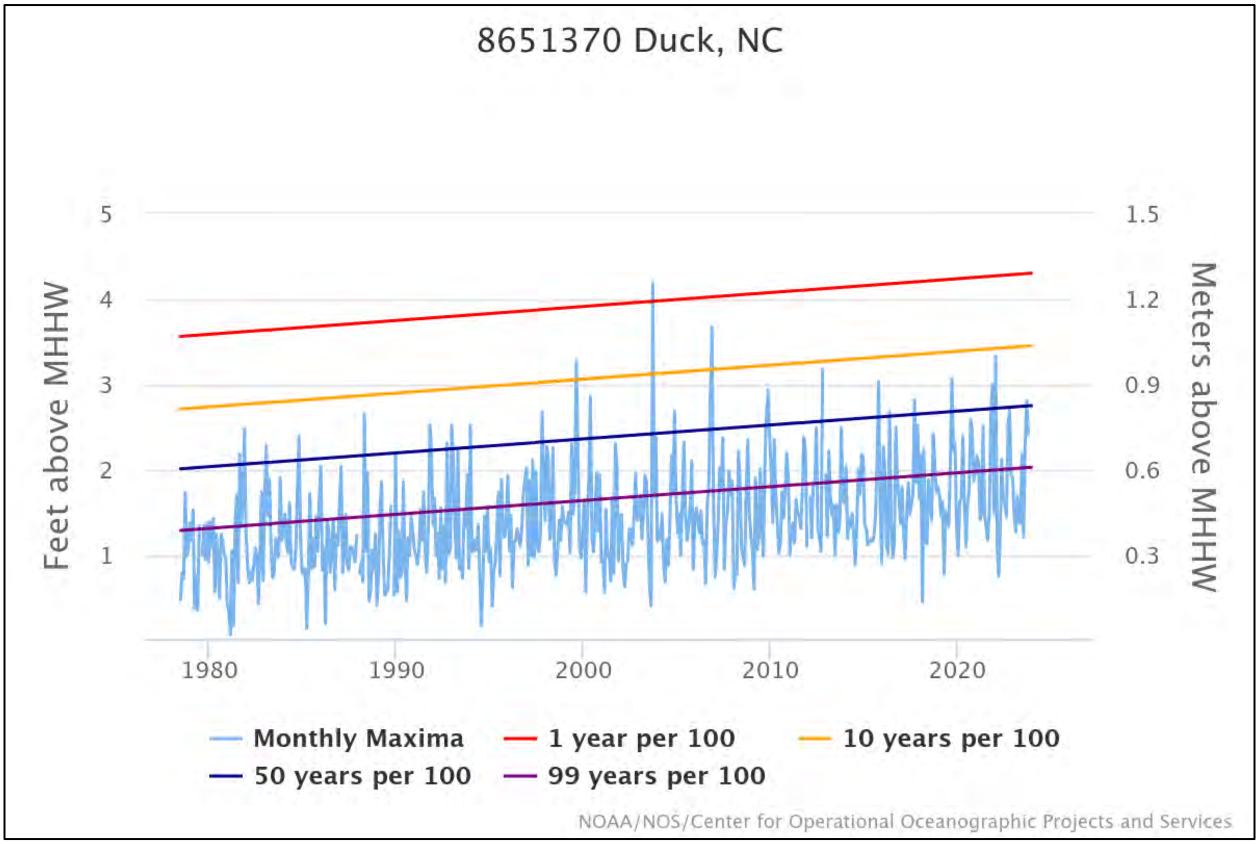


Figure 10. Monthly highest water levels at NOAA Station 8651370 at Duck, NC, along with 1%, 10%, 50%, and 99% annual exceedance probability levels shown in red, orange, blue, and purple, respectively. Source: https://tidesandcurrents.noaa.gov/map/index.html?id=8651370.

The wave height return period analysis utilized the extreme analysis table and extreme analysis plot from the Wave Information System (WIS) Station ST63217, located at a depth of 82 feet (Lat: 36.333°, Lon: -75.583°) directly east of Whalehead Beach. The extreme analysis table provides an assessment of peak wave heights recorded over a 43-year period (1980–2022), ranking them accordingly. The extreme analysis plot illustrates peak wave heights (in meters) plotted against return periods (in years) (Figure 11).

The return periods for several storms of interest were determined using the peak values obtained from the graph shown in Figure 11. Table 3 presents a summary of the wave height as well as water level return periods for eight (8) of the highest energy events that occurred from 2000 to 2023.

Hurricane Isabel (2003) had the highest peak wave height at 25.9 ft. with a 40-50-year return period and highest water level at 4.1 ft. (50-100 yr). Some storm events had higher return periods for wave heights than for water levels, indicating more extreme wave conditions relative to water level rise (e.g., Tropical Storm Ophelia). In contrast, other events, such as Hurricane Isabel and the November 2006 Nor'easter, had higher return periods for peak water levels, suggesting more significant coastal flooding despite less extreme wave conditions.

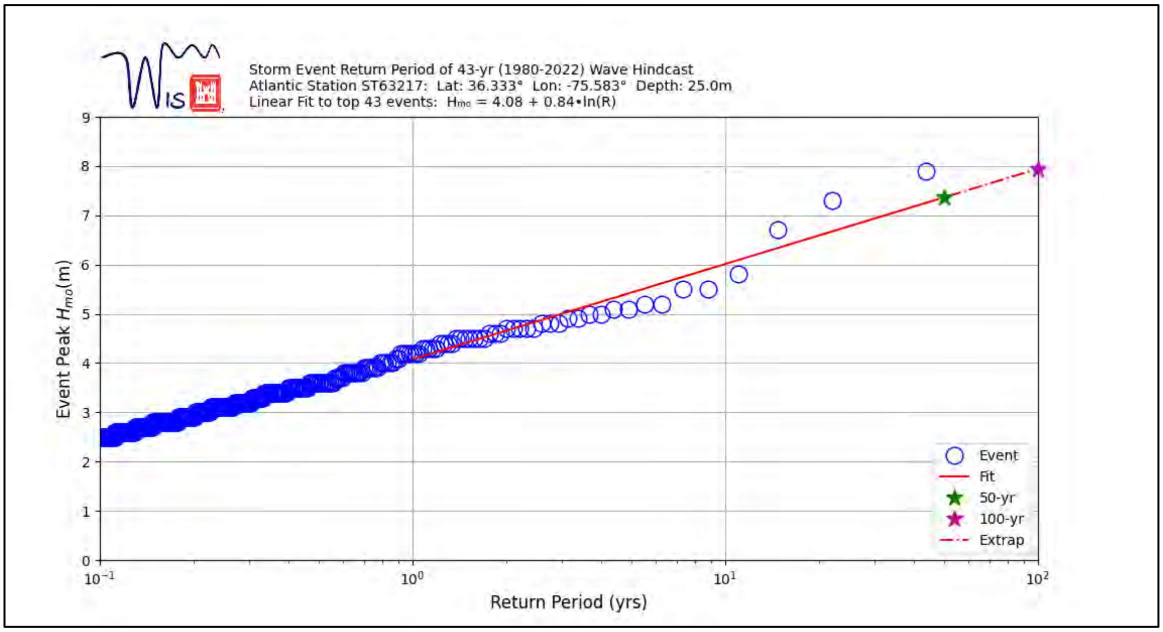


Figure 11. Peak wave heights (in meters) for extreme events plotted against wave return period (in years) for WIS Station ST63217. Source: https://wisportal.erdc.dren.mil/.

Table 3. Summary of key hydrodynamic parameters for select storms

Storm	Peak Wave Height (ft) and Return period (years)	Peak Wave Period (s)	Dominant Wave Direction	Dominant Wind Direction	Peak Water Level (ft, MHHW) and Return period (years)	Storm Duration (days)
Hurricane Isabel (2003)*	25.9 ft (40-50 yr)	16.0	E - SE	NE	4.1 ft (50-100 yr)	7 days
November 2006 Nor'easter	18.0 ft (8-10 yr)	12.5	NE	NE	3.5 ft (10-25 yr)	8 days
November 2009 Nor'easter*	16.4 ft (4 yr)	13.3	NE	NE	3.0 ft (5-10 yr)	6 days
Hurricane Irene (2011)	21.9 ft (10-20 yr)	16.0	SE	E	1.5 ft (<1 yr)	4 days
Hurricane Sandy (2012)	17.1 ft (6-7 yr)	13.0	NE	NE	3.0 ft (5-10 yr)	5 days
Hurricane Matthew (2016)**	16.7 ft (4-5 yr)	11.0	NE - E	NE	1.9 ft (<1 yr)	12 days
Hurricane Dorian (2019)*	15.4 ft (1-2 yr)	15.0	E - SE	SE	3.0 ft (5-10 yr)	3 days
TS Ophelia (2023)	21.1 ft (~10 yr)	12.0	E - SE	E	1.7 ft (<1 yr)	3-days

* Storms selected for production runs.
**Storm selected for model calibration.

From the listed storms, three (3) were selected for production runs based on the following criteria:

1. Representation of a diverse range of hydrodynamic conditions, including extreme tropical storms and extratropical cold fronts.
2. Storms exhibiting both high significant wave heights and elevated water levels.
3. Events characterized by longer durations.
4. Recent storms to ensure relevance to present-day conditions.

Based on these criteria, the storms selected for production runs were Hurricane Isabel (2003), the November 2009 Nor'easter, and Hurricane Dorian (2019). The November 2009 Nor'easter was chosen over the November 2006 Nor'easter because it featured both high waves and elevated water levels for six consecutive days, whereas the 2006 Nor'easter had high waves for eight days but elevated water levels for only two. Additionally, Hurricane Matthew (2016) was chosen for model calibration, which is discussed in Section 2.1.3. Details of each storm are provided below.

Hurricane Isabel (2003)

Hurricane Isabel presented the highest return periods for both wave height and water level. Although Hurricane Isabel (2003) made landfall approximately 110 miles south of Currituck County, as shown in Figure 12, the storm's indirect impact on Currituck County was exacerbated by its broad wind field, which drove storm surge and high waves into the region despite the storm's distant track. The prolonged period of strong onshore winds contributed to coastal flooding and severe beach erosion, causing damage to dunes and weakening the natural defenses of the shoreline. Figure 13 shows post-Hurricane Isabel imagery revealing severe scarping and dune washout along the Ocean Hills Community. The event highlighted vulnerabilities throughout the northern Outer Banks in local coastal infrastructure, necessitating long-term planning and investment in beach nourishment and dune restoration to prevent similar damage from future storms.

During Hurricane Isabel, the peak wave height reached 25.9 feet (7.9 m) (Figure 14), corresponding to a return period of 40–50 years, while the peak water level was 4.1 feet, MHHW (Figure 15), with a return period of 50–100 years. The dominant wave direction was from E-SE, and the dominant wind direction was from NE which can be seen in the wave and wind roses (Figure 16).

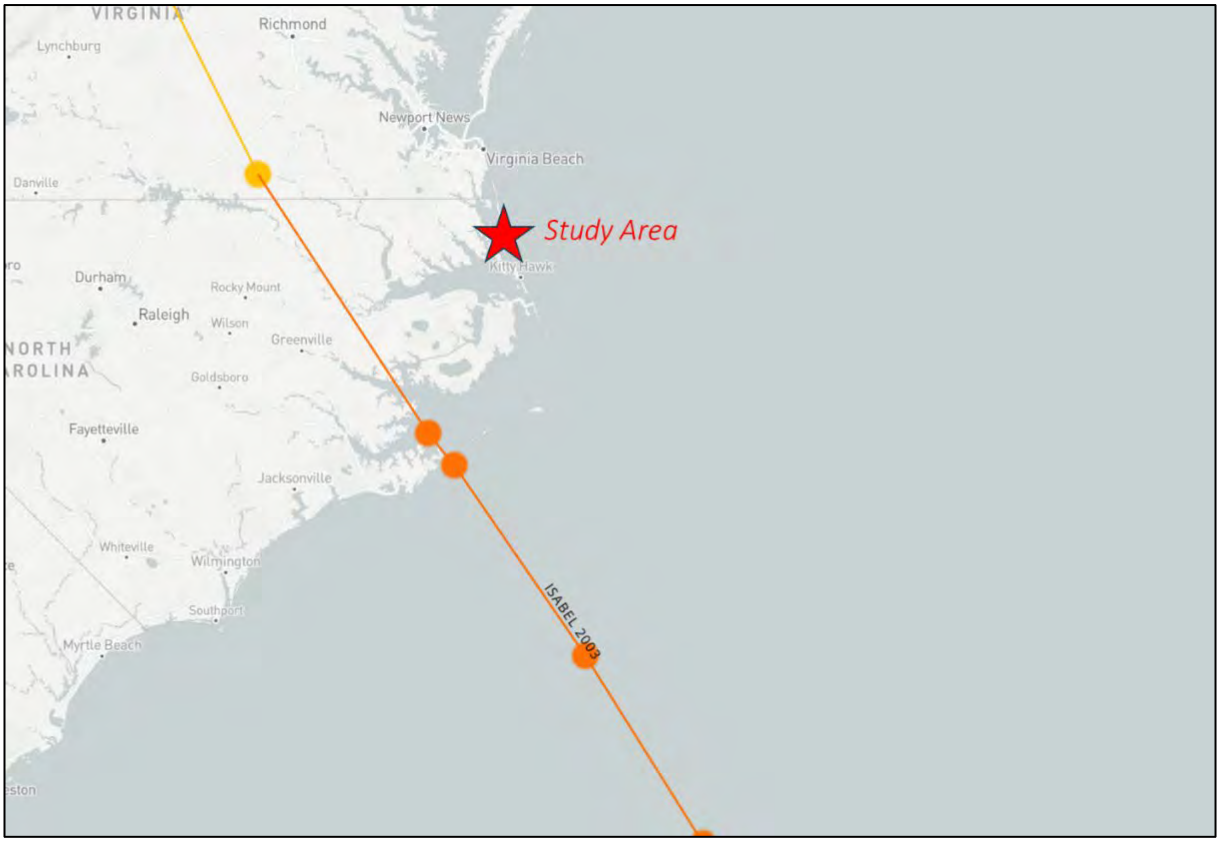


Figure 12. Hurricane Isabel (2003) track. Source: https://coast.noaa.gov/hurricanes/.

Figure 13. Post Hurricane Isabel Imagery showing severe scarping and dune washout along the Ocean Hills Community following Hurricane Isabel (2003). Source: National Geodetic Survey - Emergency Response Imagery Index.

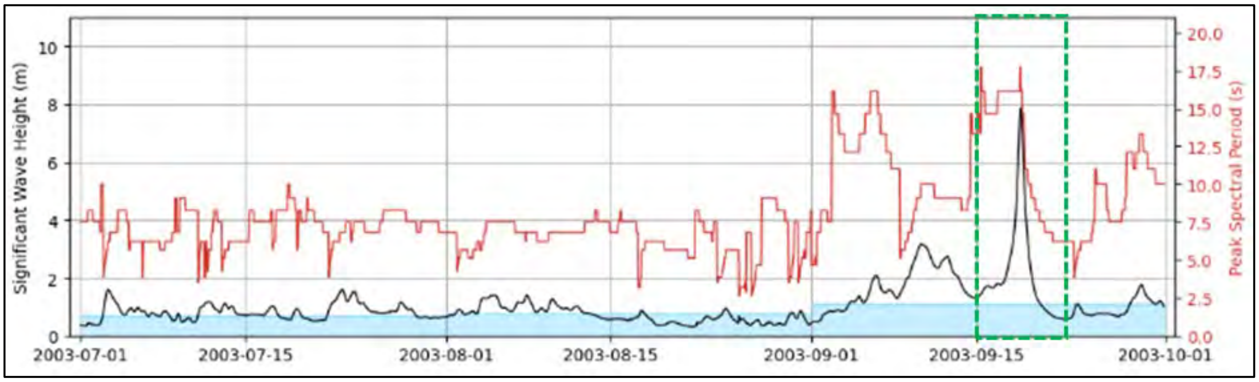


Figure 14. Significant wave height (in black) and peak period (in red) obtained from WIS Station ST63217 for the months of July to September (2003). The green box represents Hurricane Isabel (2003) timeframe. Source: https://wisportal.erdc.dren.mil/.

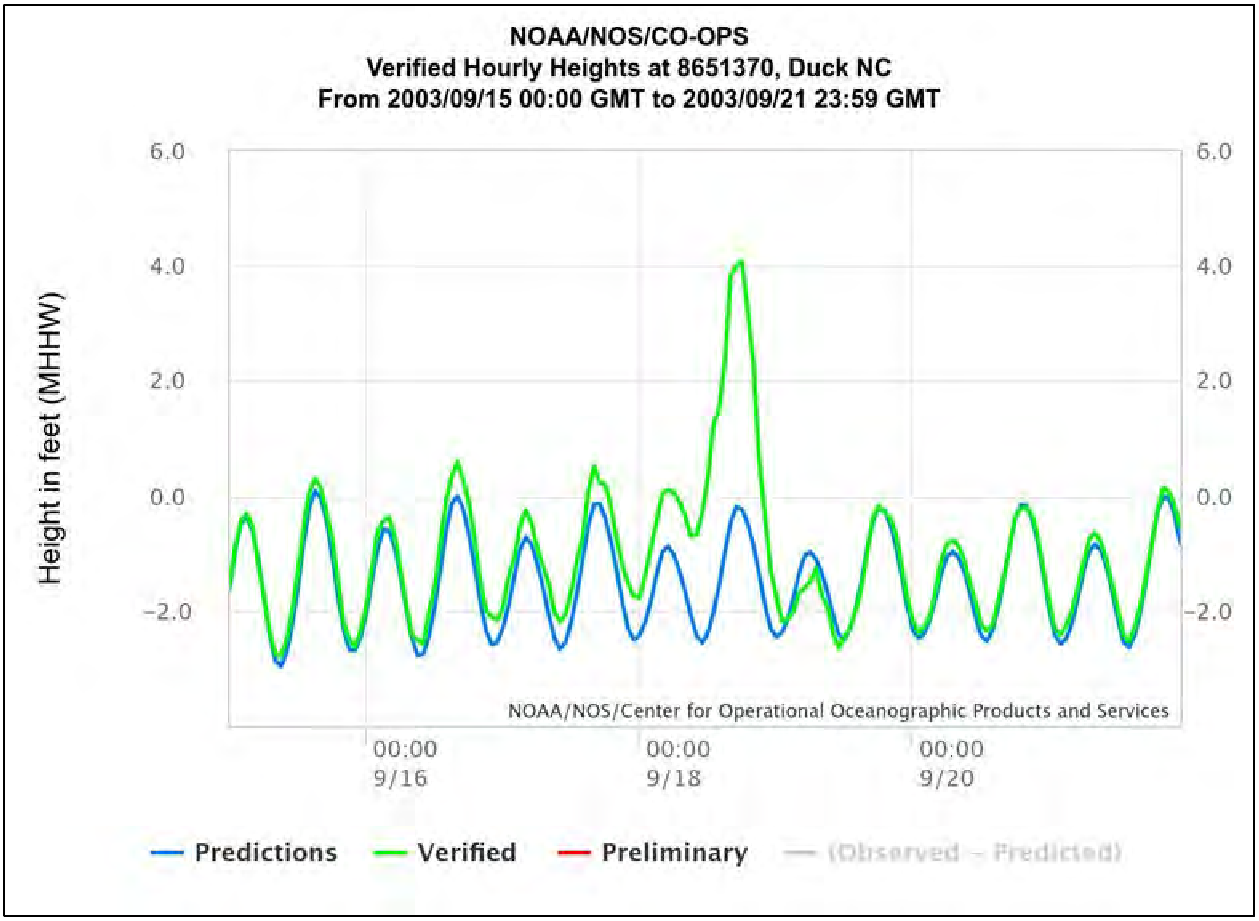


Figure 15. Water levels measured at NOAA Station 8651370 at Duck, NC during Hurricane Isabel (2003). Source: https://tidesandcurrents.noaa.gov/map/index.html?id=8651370.

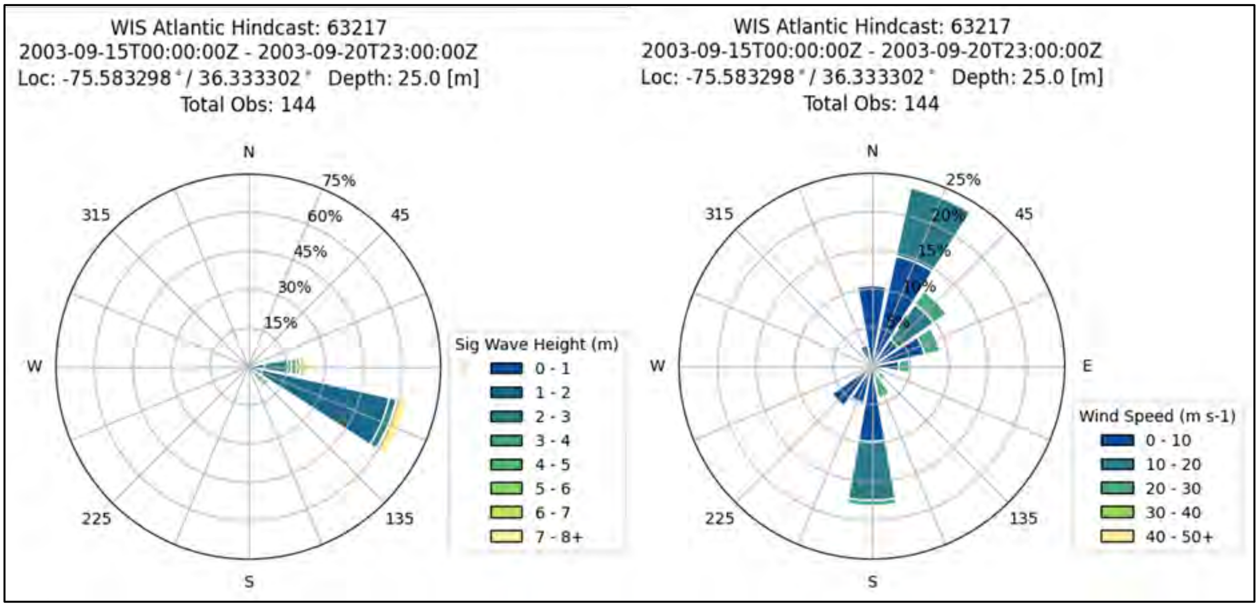


Figure 16. Wave rose (left) and wind rose (right) for WIS Station ST63217 for Hurricane Isabel (2003). Source: https://wisportal.erdc.dren.mil/.

November 2009 Nor'easter

The November 2009 Nor'easter was an extratropical cold front that occurred in the study area. This storm persisted for several days, generating sustained high winds and prolonged wave action. The verified water levels were higher than the predicted water levels by approximately +2 ft for almost 5 consecutive days. The extended duration of the storm played a crucial role in intensifying its impacts, as persistent onshore winds kept water levels elevated over an extended period, contributing to coastal flooding and erosion.

For the November 2009 Nor'easter, the peak wave height reached 16.4 feet (5.0 m) (Figure 17), corresponding to a return period of 4 years, while the peak water level was 3.0 feet (Figure 18), MHHW, with a return period of 5–10 years. The dominant wave direction was from NE, and the dominant wind direction was also from NE which can be seen in the wave and wind roses (Figure 19).

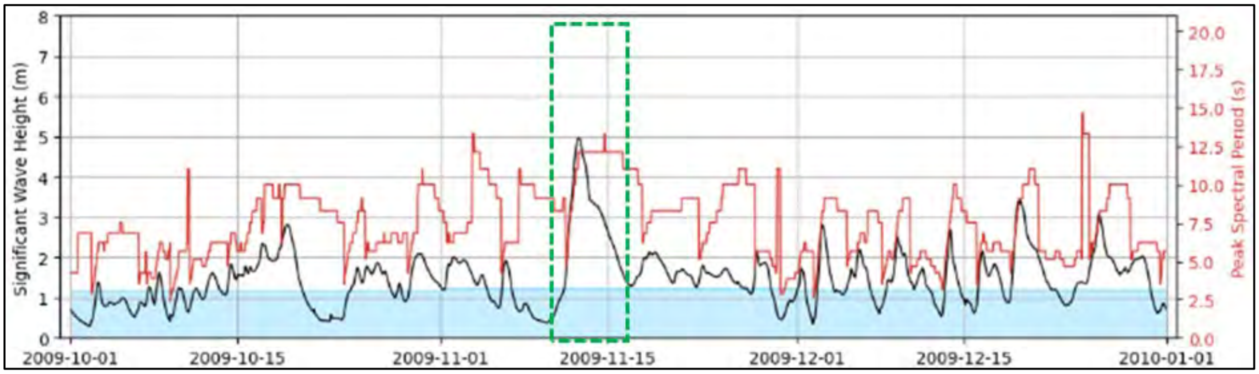


Figure 17. Significant wave height (in black) and peak period (in red) obtained from WIS Station ST63217 for the months of October to December 2009. The green box represents the November 2009 Nor'easter timeframe. Source: https://wisportal.erdc.dren.mil/.

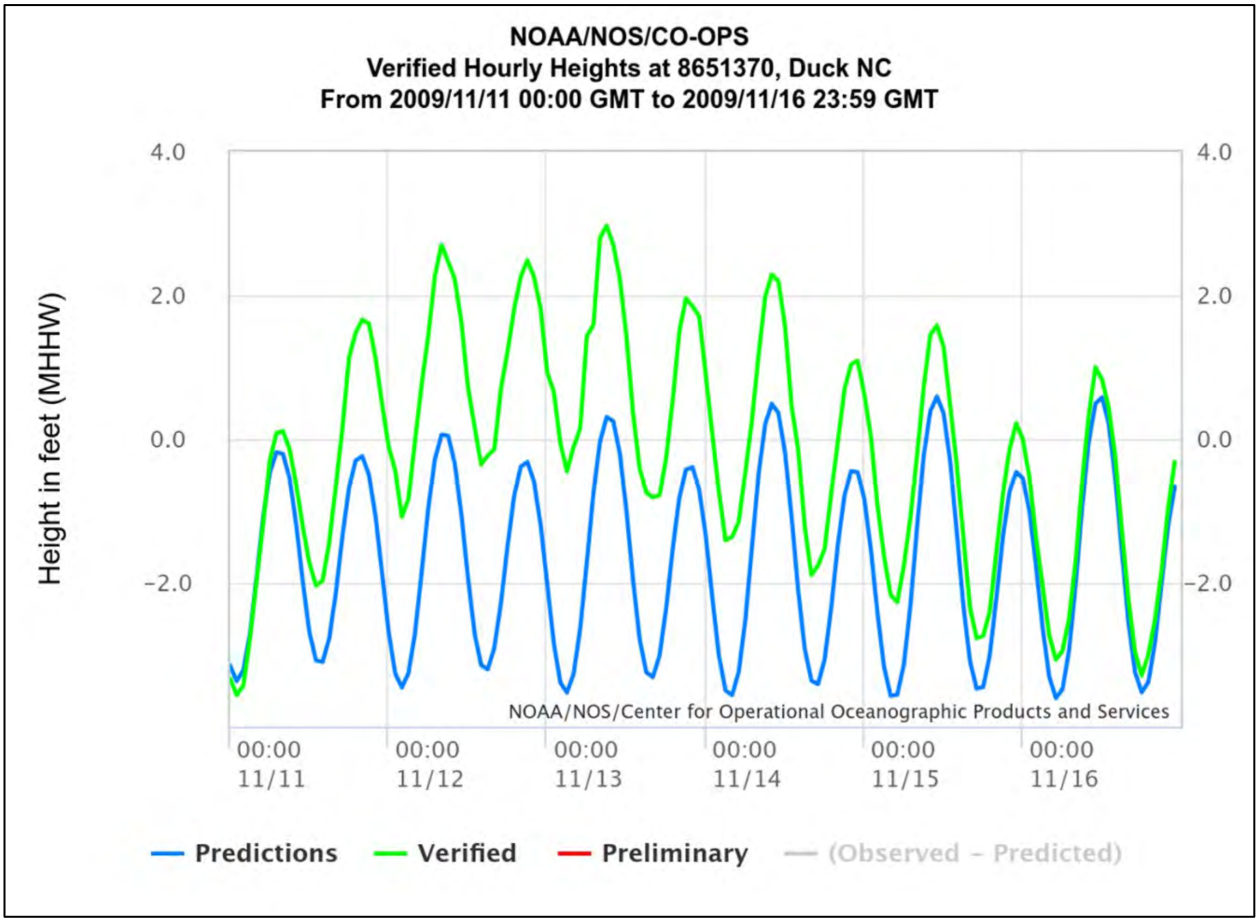


Figure 18. Water levels measured at NOAA Station 8651370 at Duck, NC during November 2009 Nor'easter. Source: https://tidesandcurrents.noaa.gov/map/index.html?id=8651370.

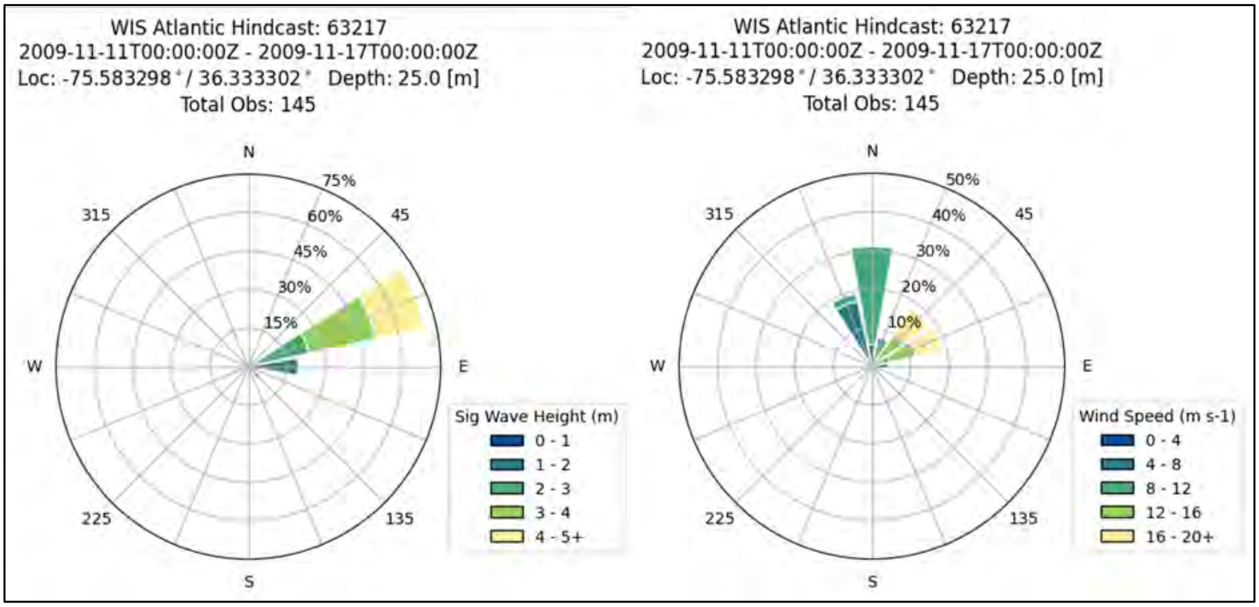


Figure 19. Wave rose (left) and wind rose (right) for WIS Station ST63217 for November 2009 Nor'easter. Source: https://wisportal.erdc.dren.mil/.

Hurricane Dorian (2019)

Hurricane Dorian (2019) was a recent storm that had a notable impact on Currituck County. Despite not making direct landfall as shown in Figure 20, the storm brought strong winds, high waves, and elevated water levels, resulting in widespread beach erosion. Flooding in low-lying areas affected roadways and infrastructure, disrupting local communities and businesses. The storm's impact, although less severe than previous hurricanes like Isabel (2003) or Sandy (2012), demonstrated how even moderate-intensity storms can have severe impacts on the coastal environment.

For Hurricane Dorian (2019), the peak wave height reached 15.4 feet (4.7 m) (Figure 21), corresponding to a return period of 1–2 years, while the peak water level was 3.0 feet, MHHW (Figure 22), with a return period of 5–10 years. The dominant wave direction was from E-SE, and the dominant wind direction was from SE, observed in the wave and wind roses plots shown in Figure 23.

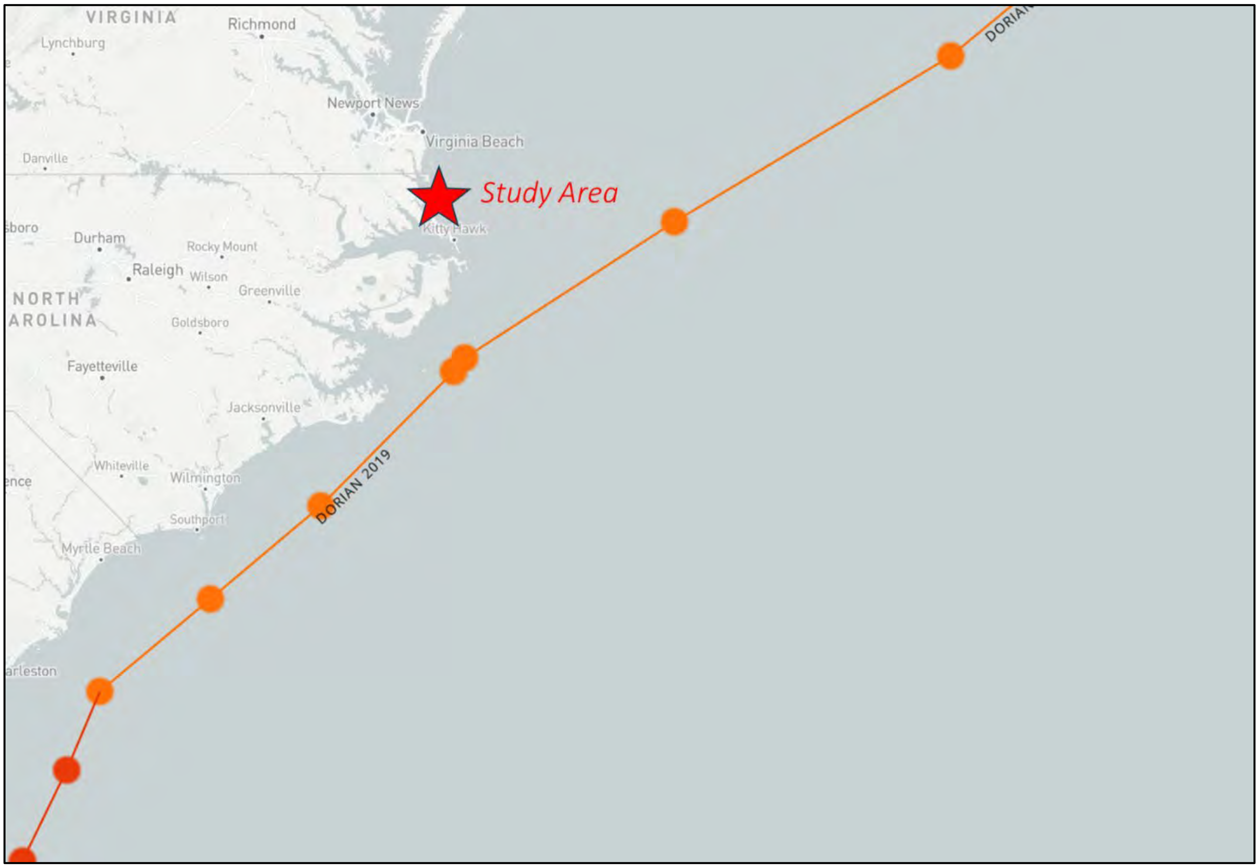


Figure 20. Hurricane Dorian (2019) track. Source: https://coast.noaa.gov/hurricanes/.

Figure 21. Significant wave height (in black) and peak period (in red) obtained from WIS Station ST63217 for the months of July to September 2019. The green box represents the Hurricane Dorian (2019) timeframe. Source: https://wisportal.erdc.dren.mil/.

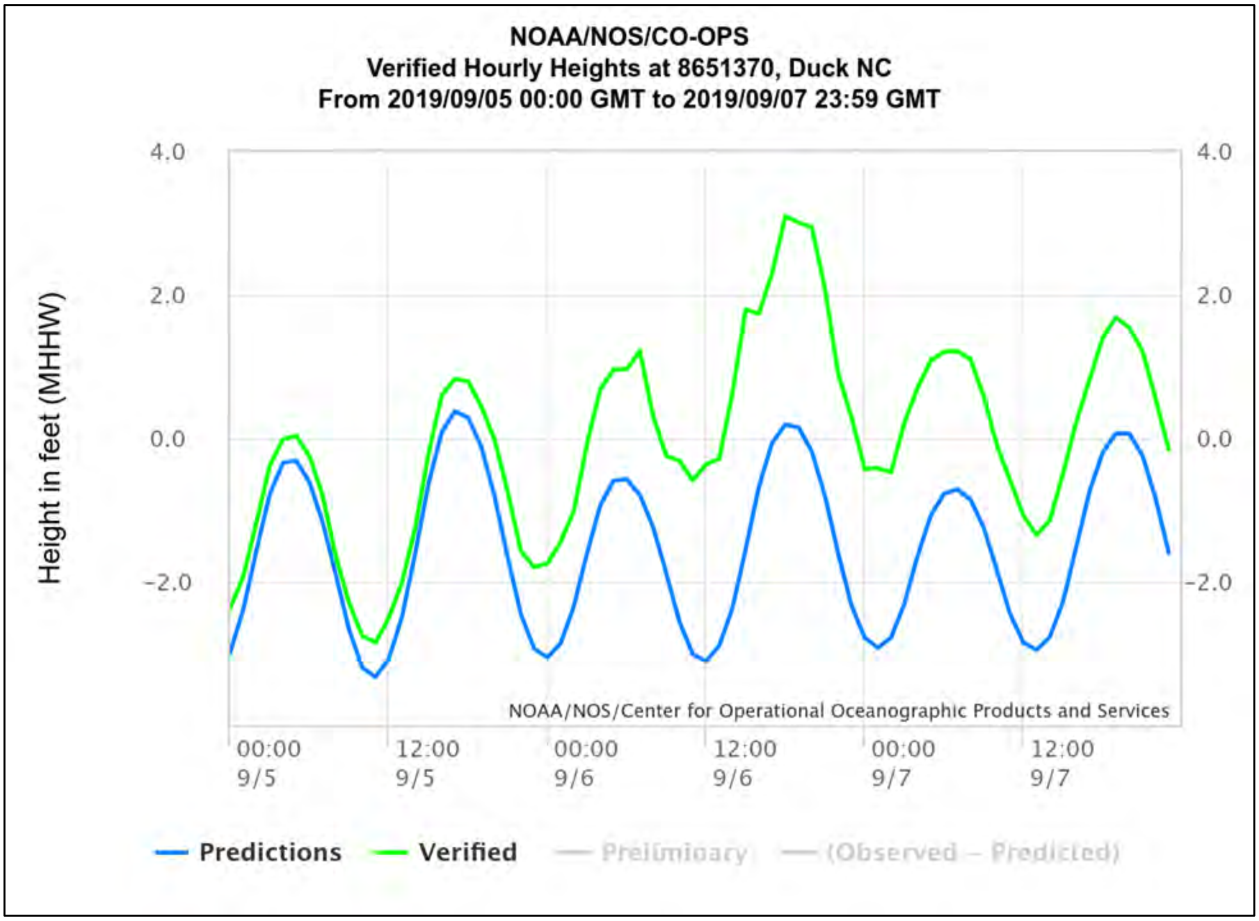


Figure 22. Water levels measured at NOAA Station 8651370 at Duck, NC during Hurricane Dorian (2019). Source: https://tidesandcurrents.noaa.gov/map/index.html?id=8651370.

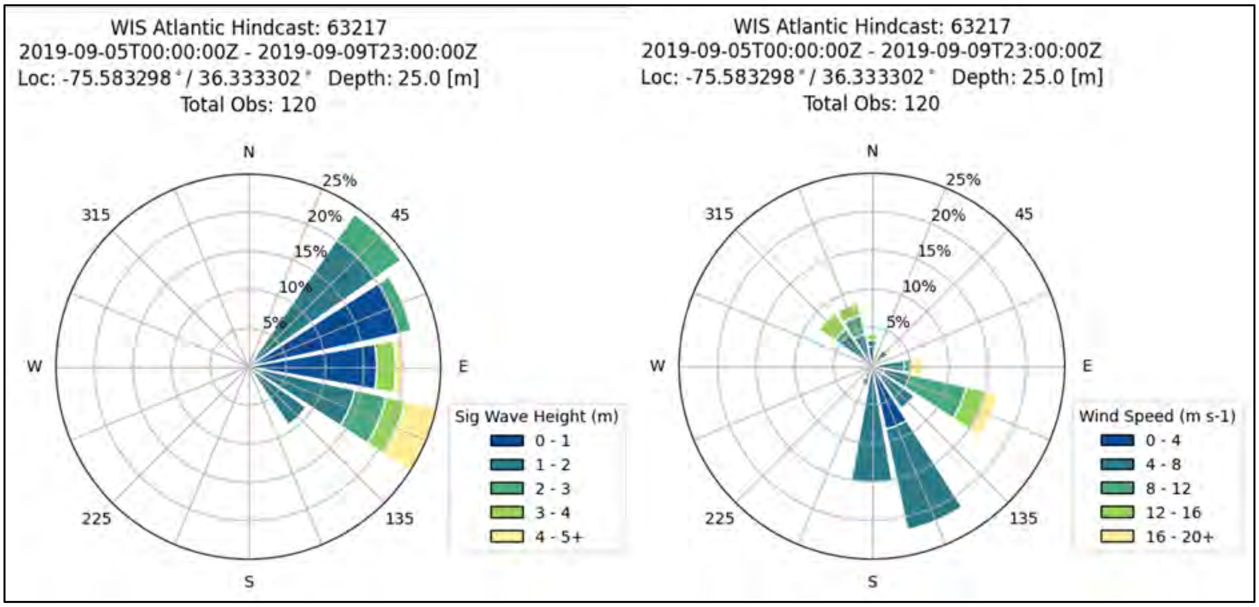


Figure 23. Wave rose (left) and wind rose (right) for WIS Station ST63217 for Hurricane Dorian (2019). Source: https://wisportal.erdc.dren.mil/.

Hurricane Matthew (2016)

Hurricane Matthew (2016) brought significant coastal impacts to Currituck County, primarily through heavy rainfall and high waves. Although the storm did not make direct landfall in the region, as shown in Figure 24, its effects were strongly felt along the shoreline.

For Hurricane Matthew (2016), the peak wave height reached 16.7 feet (5.1 m) (Figure 25), corresponding to a return period of 4–5 years, while the peak water level was 1.9 feet, MHHW (Figure 26), with a return period of <1 year. The dominant wave direction was from NE-E, and the dominant wind direction was from NE which can be seen in the wave and wind roses (Figure 27).

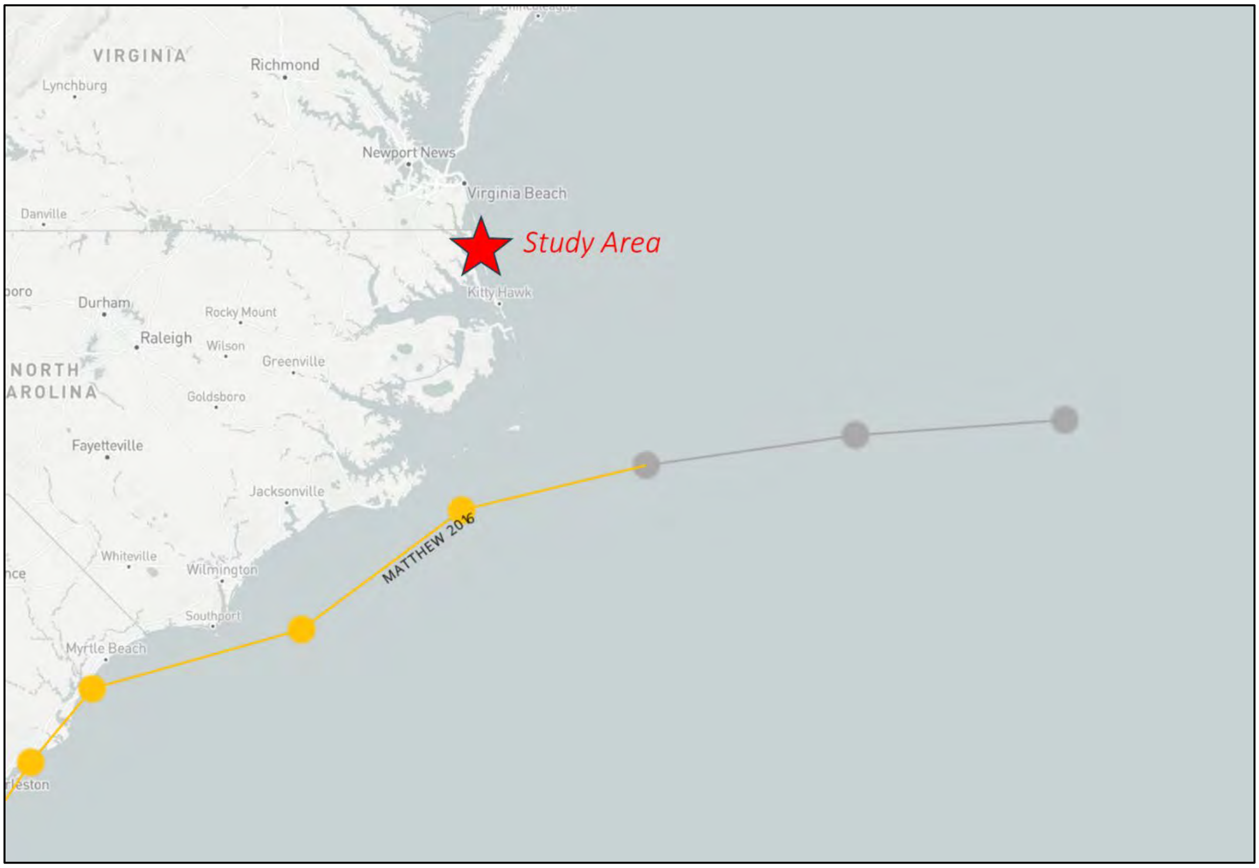


Figure 24. Hurricane Matthew (2016) track. Source: https://coast.noaa.gov/hurricanes/.

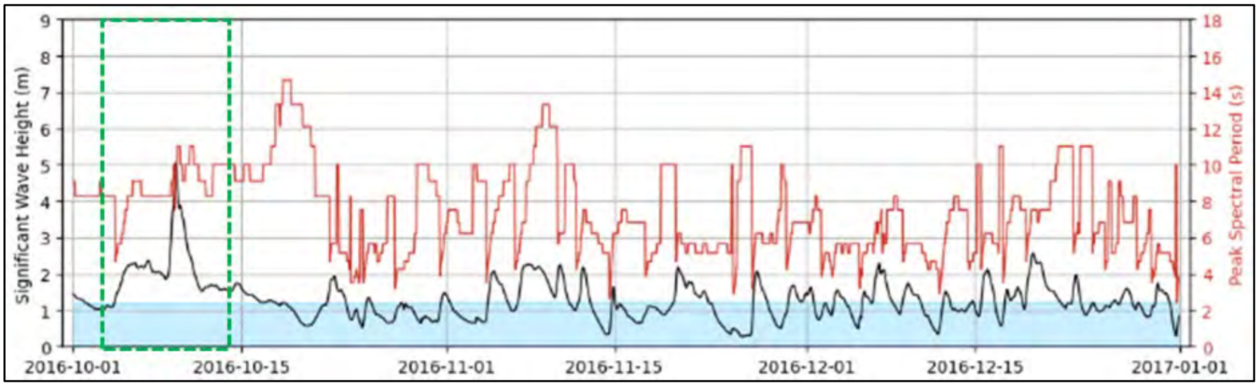


Figure 25. Significant wave height (in black) and peak period (in red) obtained from WIS Station ST63217 for the months of October to December 2016. The green box represents the Hurricane Matthew (2016) timeframe. Source: https://wisportal.erdc.dren.mil/.

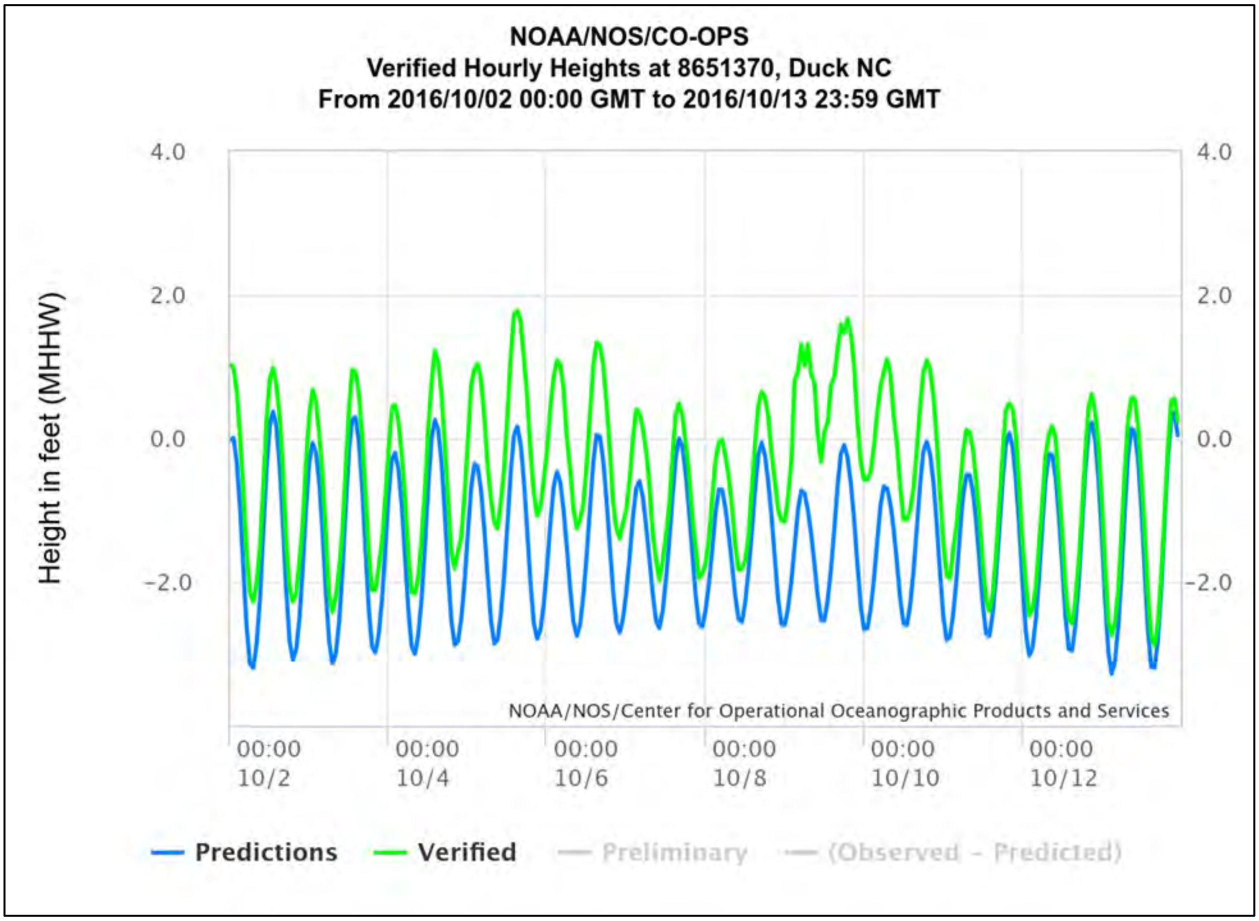


Figure 26. Water levels measured at NOAA Station 8651370 at Duck, NC during Hurricane Matthew (2016). Source: https://tidesandcurrents.noaa.gov/map/index.html?id=8651370.

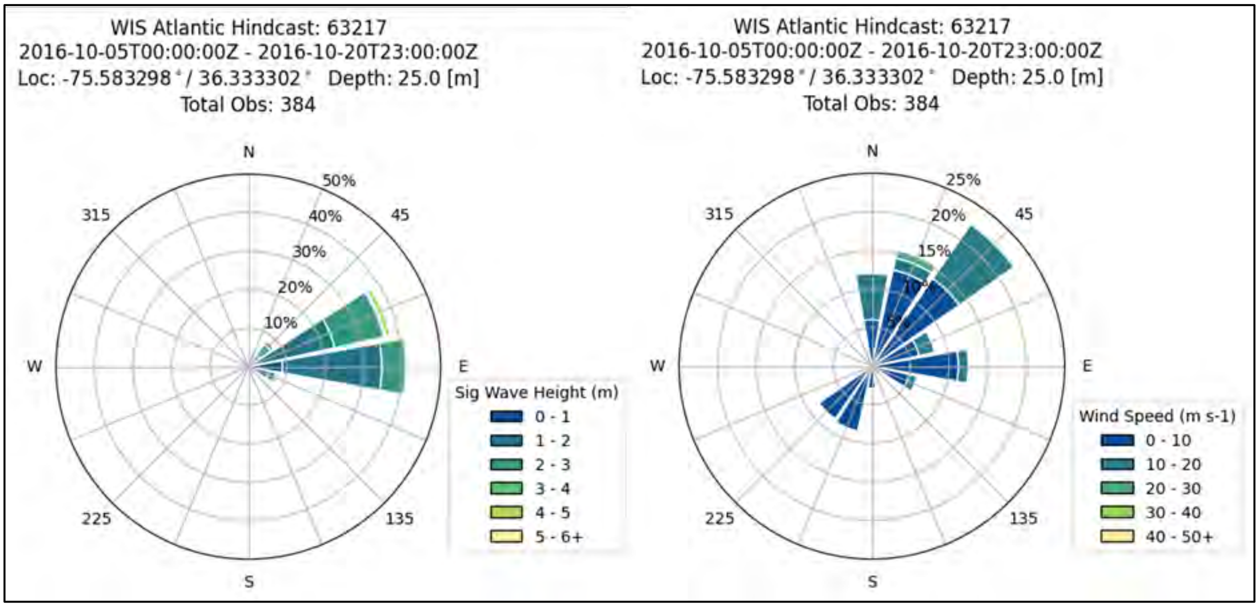


Figure 27. Wave rose (left) and wind rose (right) for WIS Station ST63217 for Hurricane Matthew (2016). Source: https://wisportal.erdc.dren.mil/.

2.1.3 2024-2025 Delft3D Erosion Hot Spot Analysis

Delft3D is a leading 3D modeling suite developed by Deltares for simulating hydrodynamics, sediment transport, and morphological change in coastal environments. For this study, Delft3D was used to identify erosion hotspots in the project area by evaluating wave conditions, current patterns, and volumetric changes across the active beach profile from the dry beach to the offshore bar. The software has been extensively applied to coastal engineering projects and research initiatives worldwide, including numerous beach morphology studies in the United States. Additional details of the model can be found at:
https://oss.deltares.nl/web/delft3d/about.

2.1.3.1 Morphology Model Setup and Calibration

The Delft3D model consists of two main modules: Delft3D-FLOW (Deltares, 2018a) and Delft3D-WAVE (Booij et al., 1999; Deltares, 2018b), which were dynamically coupled to simulate hydrodynamics, sediment transport, and beach morphology changes such as erosion and deposition.

Computational Grids

During the initial stages of model development, a regional model domain was planned alongside two separate local model domains: the north domain and the south domain. The north domain covered a portion of the Corolla Section, extending from Stations C-059 to C-084 (Horse Gate to Albacore St.), a length of approximately 4.7 miles. The south domain encompassed areas within the Corolla and Pine Island Sections, extending from Stations C-092 to C-110, covering approximately 3.5 miles. These domains were selected based on the results of the 2022 storm vulnerability analysis discussed in Section 2.1.1, the shoreline change projections described in Section 2.2.1, and general erosion trends summarized in Section 2.2.3 (CPE, 2023a).

As the model development progressed, the proximity of these two local domains led to them being merged into a single high-resolution local model domain. This merged domain extended 12.5 miles from Stations C-052 to C-118. Expanding this domain beyond Station C-110 allowed for the inclusion of areas experiencing higher sediment volume losses and significant offshore features, enhancing the model's accuracy in simulating coastal processes.

Three (3) computational grids were created for the project area, each with a different modeling objective described below.

- **Regional Wave Grid**: A Regional Wave Grid was created to calculate regional wave transformation processes from deeper waters along the model's offshore boundary (located at depths ranging from -70 ft. to -90 ft. NAVD88) to the nearshore wave model domain (located at a depth of approximately -50 ft. NAVD88) (Figure 28). The Regional Wave Grid extended from Currituck County Stations C-010 to C-120 and also included a portion of the area offshore Dare County.

- **Local Wave Grid**: A Local Wave Grid was created to calculate detailed shallow water wave propagation processes. The Local Wave Grid was nested within the Regional Wave Grid. Depth at the offshore boundary of the Local Wave Grid was approximately -50 ft. NAVD88, and the alongshore extent was 12.5 miles, extending from Stations C-052 to C-118 (Figure 28). Higher resolution was applied to the northern (C-059 to C-084) and southern (C-092 to C-110) sections, where the most vulnerable areas had been previously identified.

- **The Local Flow/Morphology Grid**: A high-resolution Local Flow/Morphology Grid was created to simulate currents, sediment transport, morphology change (erosion and sedimentation), and evaluate morphology changes under storm conditions. The Local Flow/Morphology Grid is very similar to the Local Wave Grid as both grids were coupled, enabling a more comprehensive simulation of coastal processes by considering the interactions between waves, currents, sediment transport, and morphological changes. The Local Flow Grid and the Local Wave Grid along with the north and south domain extents are provided in Figure 29.

The coordinate system used in the model is the North Carolina State Plane Coordinate System, North American Datum of 1983 (NC NAD83). Grid characteristics are summarized in Table 4.

Table 4. Grid characteristics, Currituck County.

Characteristics	Regional Wave Grid	Nearshore Wave Grid	Morphology Grid
Number of Cells	30,000	88,000	86,000
Longshore Grid Resolution (ft)	490 to 525	65 to 165	65 to 165
Cross-Shore Grid Resolution (ft)	515 to 600	40 to 165	40 to 165

Figure 28. Regional Wave Grid (yellow) and Local Wave Grid (red).

Figure 29. Local Wave Grid (red) and Local Flow Grid (green).

Topography and Bathymetry

The topographic and bathymetric Digital Elevation Model (DEM) was created by integrating the following three datasets:

1. **Pre-Hurricane Matthew Topobathy Data**
   - Derived from the 2016 USACE National Coastal Mapping Program (NCMP) Topobathy Lidar DEM for Duck, NC, collected by NOAA in July 2016.
   - Covered elevations from approximately +30 ft. to -35 ft. NAVD88.
   - Alongshore coverage extended between Stations C-062 to C-118.
2. **NOAA NCEI Continuously Updated Digital Elevation Model (CUDEM) – 1/3 Arc-Second**
   - Used to supplement areas outside the 2016 topobathy dataset.
3. **NOAA NCEI Continuously Updated Digital Elevation Model (CUDEM) – 1/9 Arc-Second**
   - Provided additional bathymetric and topographic coverage for the remaining portions of the model grid.

The datasets used are summarized in Table 5.

Table 5. Topographic and bathymetric datasets used for Delft3D modeling.

Date	Source	Type	Location	Resolution (ft)
July 2016 (Pre-Matthew)	USACE NCMP	Topobathymetric LiDAR	Currituck County Stations C-063 to C-120	10
November 2016 (Post-Matthew)	USACE	Topographic LiDAR	Currituck County Stations C-059 to C-120	10
June 2024	CPE	Beach Profiles	Currituck County Stations C-059 to C-120	N/A
Multiple	NOAA NCEI	1/3 Arc-Second Continuously Updated Digital Elevation Model (CUDEM)	Atlantic Coast of North Carolina	35
Multiple	NOAA NCEI	1/9 Arc-Second Continuously Updated Digital Elevation Model (CUDEM)	Atlantic Coast of North Carolina	10

By integrating these datasets, a comprehensive high-resolution DEM was developed, ensuring the study area's topographic and bathymetric features are well represented. The interpolated bathymetry for the Regional Wave Grid and the Local Wave Grid are shown in Figure 30 and Figure 31. The model results were compared against the November 2016 USACE Post-Matthew Topobathy Lidar DEM.

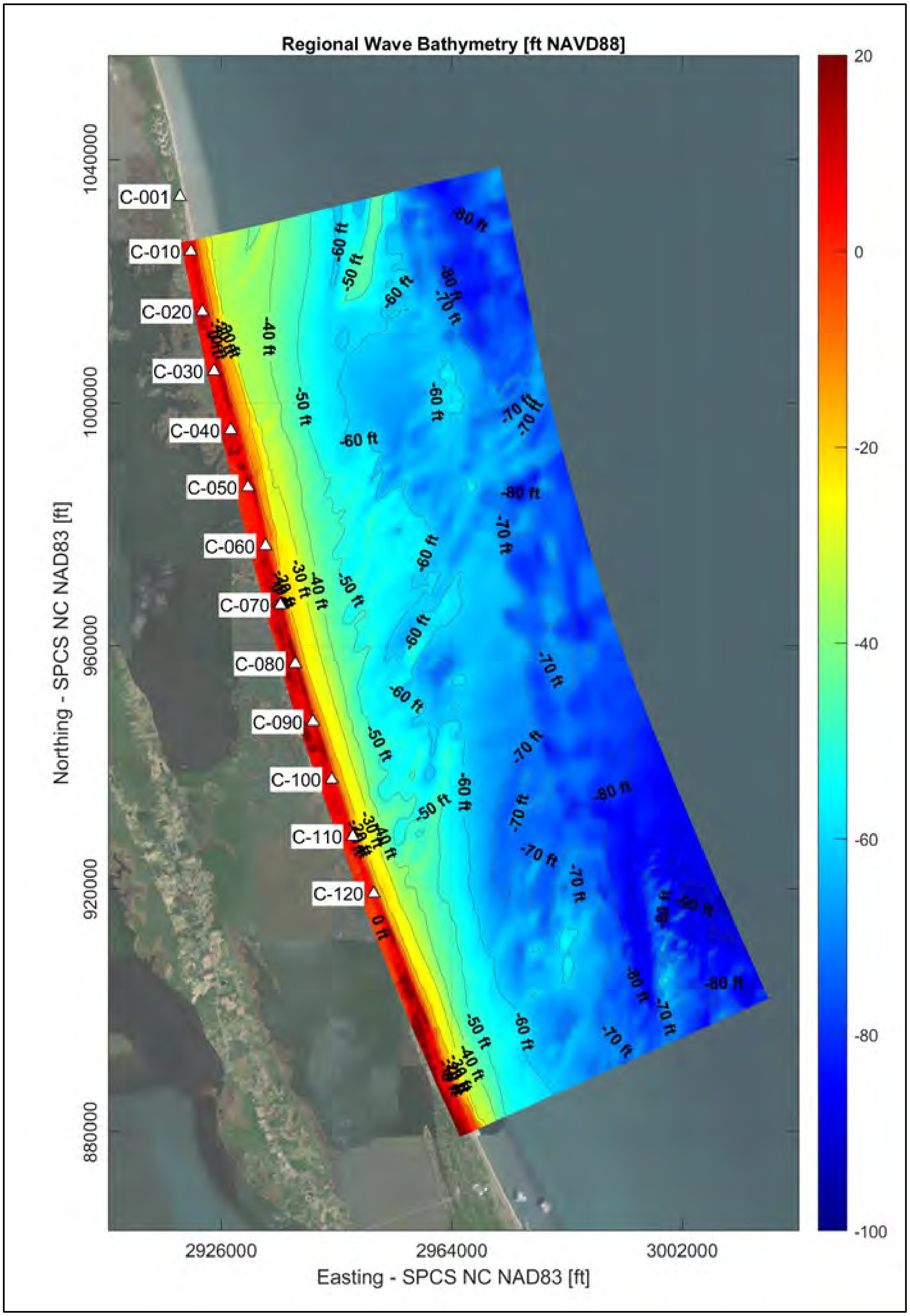


Figure 30. Bathymetry surface of the Regional Wave Grid.

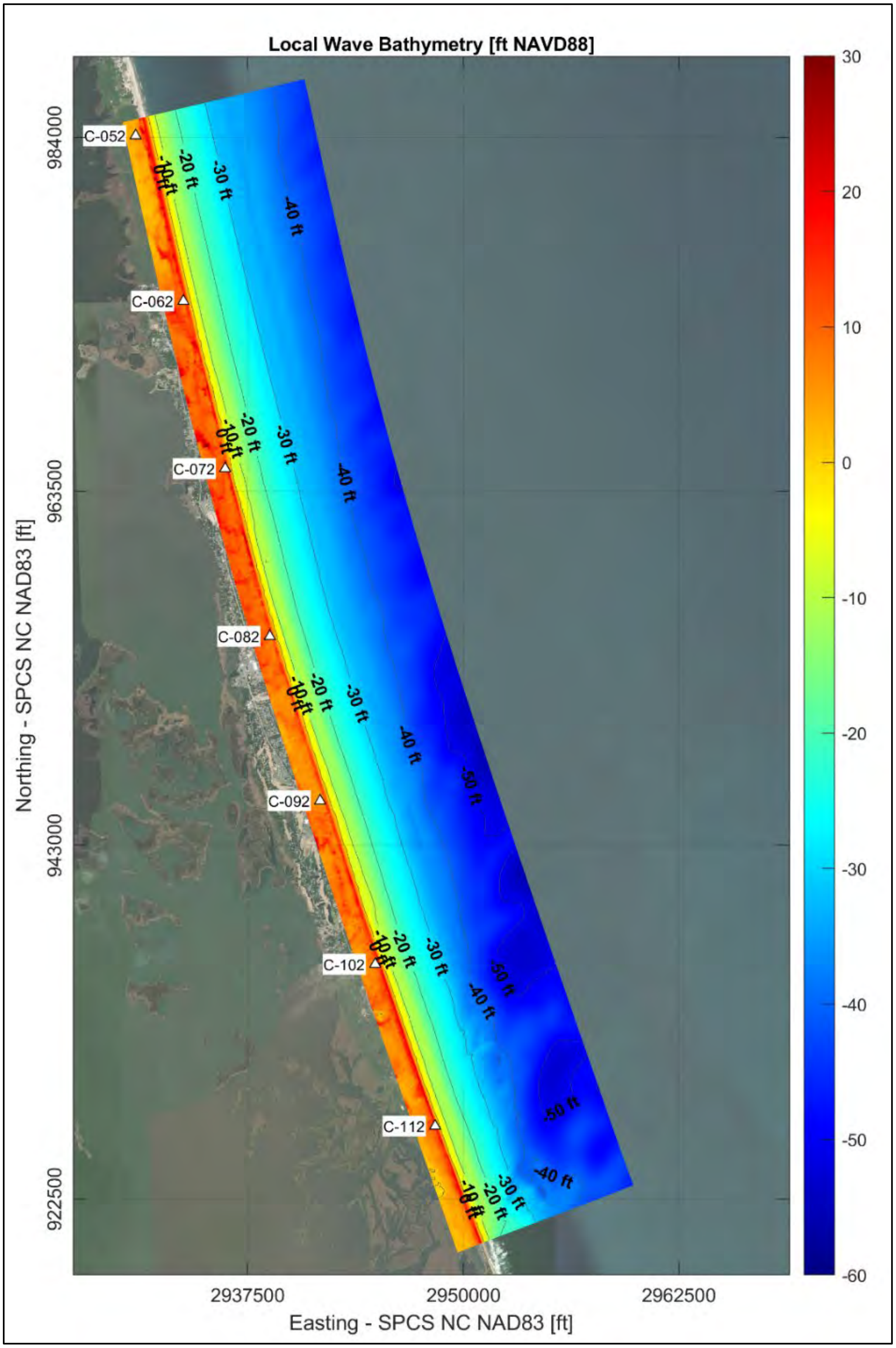


Figure 31. Bathymetry surface of the Local Wave Grid.

Boundary Conditions and Forcings

Existing water level, wind field, and wave data were used as boundary conditions for the model. Publicly available sources of input data used include:

- **Waves** – Wave input for the model was obtained from WIS Station ST63217. Time series of wave parameters, including significant wave height (Hs), peak period (Tp), and wave direction (Dir) were used to force the offshore boundary of the Regional Wave Grid.
- **Water Level** – Water level boundary conditions for the model were obtained from the NOAA Station 8651370 at Duck, NC.
- **Wind Fields** – Wind Fields for the model were obtained from the NOAA Station 8651370 at Duck, NC.

Morphology Model Calibration

The goal of the morphology calibration was to qualitatively reproduce the morphologic response of the dry beach and dunes to storms in the project area. Based on pre-and post-storm measured topobathy data availability, Hurricane Matthew (October 2016) was selected for model calibration.

The model was implemented in 3D mode using five (5) vertical sigma layers to accurately represent vertical hydrodynamic and sediment transport processes. A morphological acceleration factor of 1 was applied, as the model was run in 'brute force' mode without acceleration techniques. Beach sediments were represented as a single sediment fraction with a median grain size (D50) of 0.19 mm, based on sediment measurements conducted by CPE in Currituck County (CPE, 2020).

The model was initialized using the pre-Hurricane Matthew 2016 USACE NCMP Topobathy Lidar DEM (Duck, NC). Simulation results were compared against the 2016 USACE Post-Matthew Topobathy Lidar DEM (Southeast Coast: VA, NC, SC, GA, and FL), summarized in Table 5. However, the post-Matthew dataset contained elevation data only for the dry beach and did not include underwater bathymetric data. Consequently, model calibration was conducted exclusively for dry beach elevations. The model simulation was conducted for a 12-day period, from October 2, 2016, to October 14, 2016.

At the beginning of the calibration process, the previously developed Delft3D models for the Outer Banks, for the design of projects in northern Dare County, were used, incorporating the parameter settings from those calibrated models. Based on the initial model results, sediment transport parameters and other model settings were adjusted to achieve a reasonable simulation of dry beach morphology changes during the storm. The main adjustment made to the model was adding a wave setup to the water levels. Delft3D does not incorporate long waves (infragravity waves) within its suite of coastal processes. During extreme events, swash motions and runup are primarily driven by infragravity waves. These motions replicate the effects of wave "sets" or surf beat on water levels and wave runup. To include wave setup in the calculations, FEMA highwater marks were considered. FEMA provides measured high-water marks which are the maximum recorded water level for different storms and inherently include the wave setup on top of the water levels and were used as the model input boundary condition. However, in case of Hurricane Matthew, a high-water mark elevation was not available, so the wave setup was determined with the help of an empirical equation (Guza and Thornton, 1981) shown below. The wave setup obtained from this equation was added to the water levels obtained from the NOAA Station 8651370 at Duck, NC and used as model input.

Wave Setup = 0.17 x Offshore Significant Wave Height

Model Calibration Results

The model calibration process aimed to replicate the measured changes through both qualitative and quantitative comparisons of the model results. The qualitative morphology changes analysis focused on replicating the most prominent morphological changes, particularly for the dry beach and dune. This involved the comparison of erosion and sedimentation maps between the measured and modeled data along the extent of the north and south domains. Figure 32 and Figure 33 show measured and modeled erosion and sedimentation for the north domain extents for Hurricane Matthew (2016), respectively. Figure 34 and Figure 35 show measured and modeled erosion and sedimentation for the south domain extents for Hurricane Matthew (2016), respectively.

From the measured and modeled erosion and sedimentation plots, overall, the model was able to reproduce the main morphological changes that occurred during Hurricane Matthew. This includes the depiction of the erosion and sedimentation patterns between C-062 and C-084 for the north domain and between C-092 and C-110 for the south domain. The landward extent of erosion was also well represented, showing the model's capability to simulate extreme events.

The quantitative morphology change analyses focused on determining whether volumetric changes in the model are within a similar range as the measured data. The measured and modeled volume changes (sedimentation and erosion) for Hurricane Matthew (2016) were calculated within the blue polygons depicted in the erosion-sedimentation plots (Figure 32 to Figure 35).

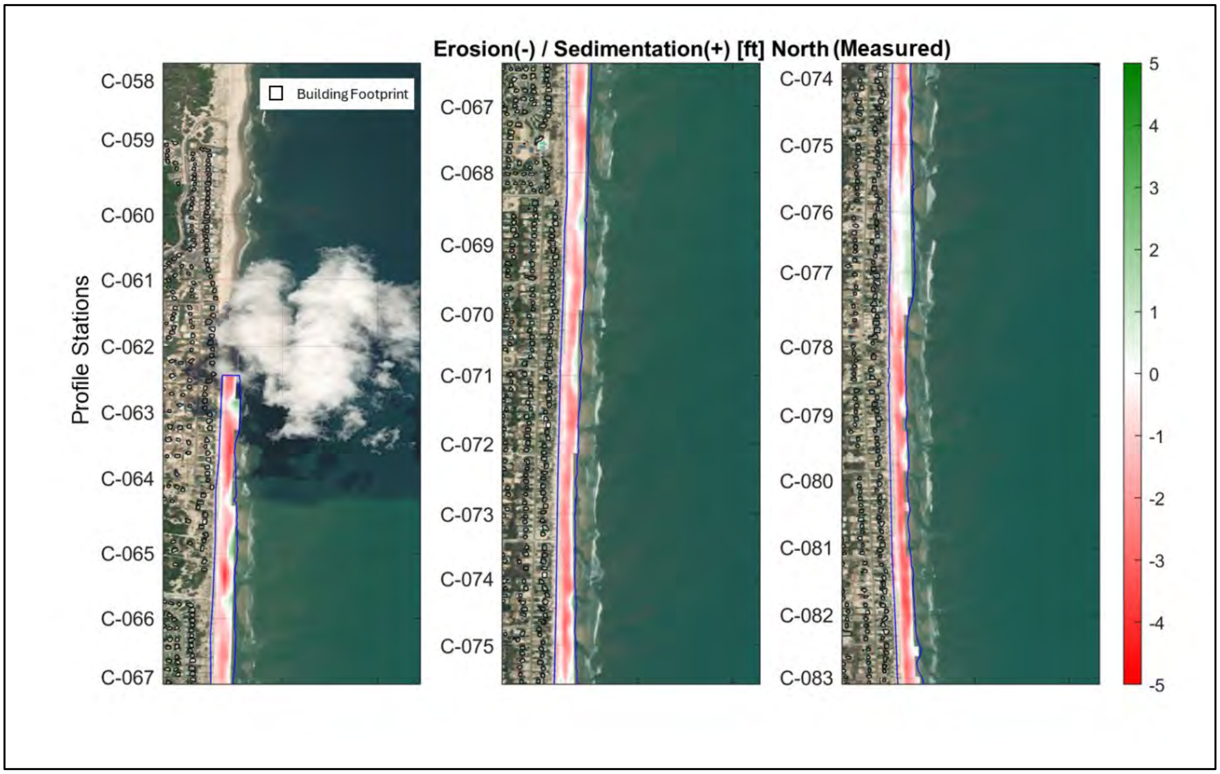


Figure 32. Measured erosion and sedimentation for the north domain extent for Hurricane Matthew. The blue polygon represents the extents of the measured data.

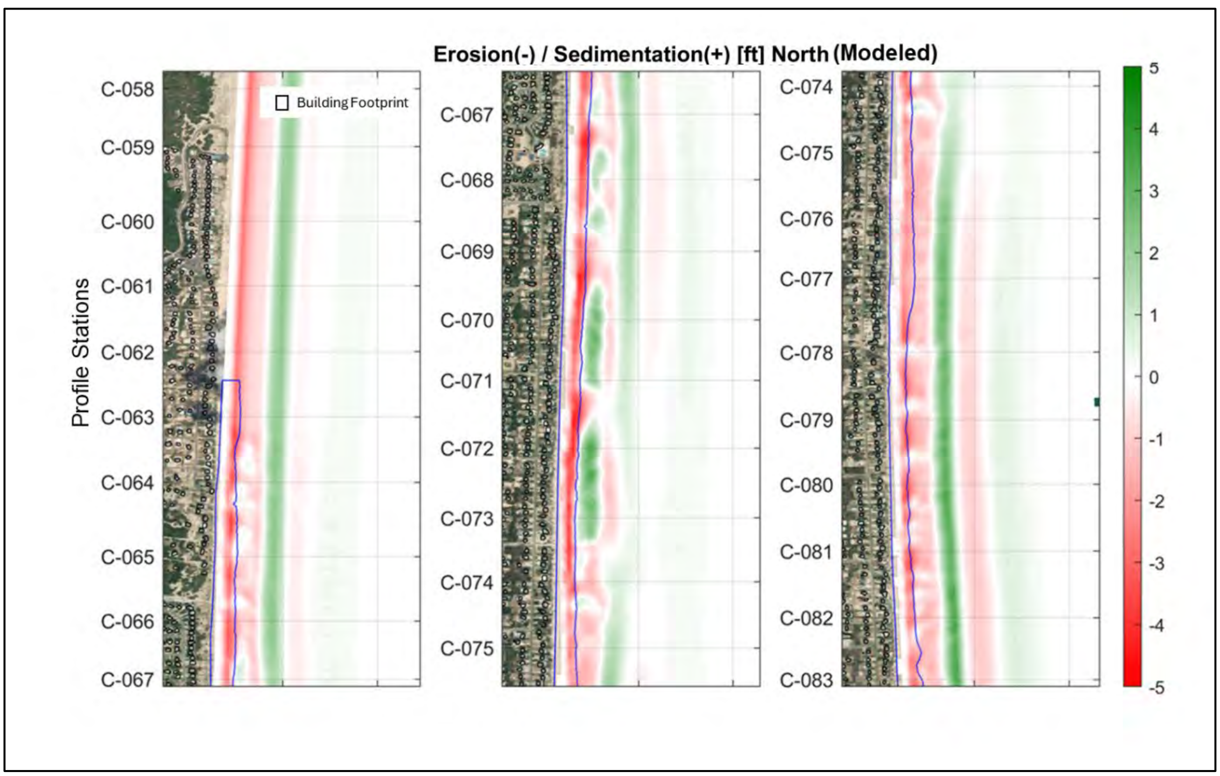


Figure 33. Modeled erosion and sedimentation for the north domain extent for Hurricane Matthew. The blue polygon represents the extents of the measured data.

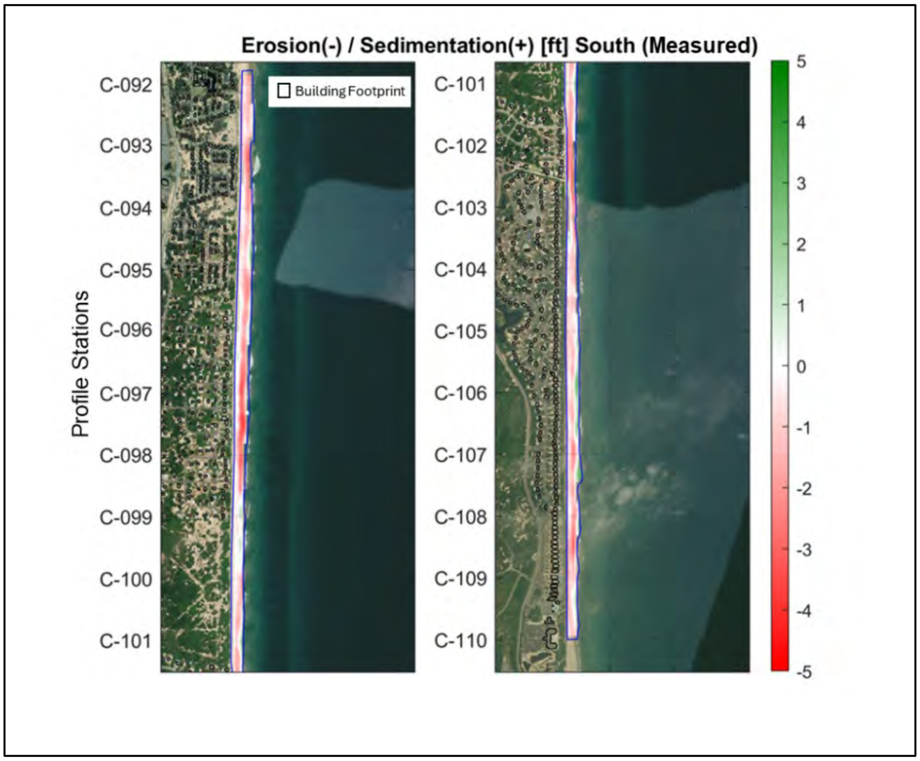


Figure 34. Measured erosion and sedimentation for the south domain extent for Hurricane Matthew. The blue polygon represents the extents of the measured data.

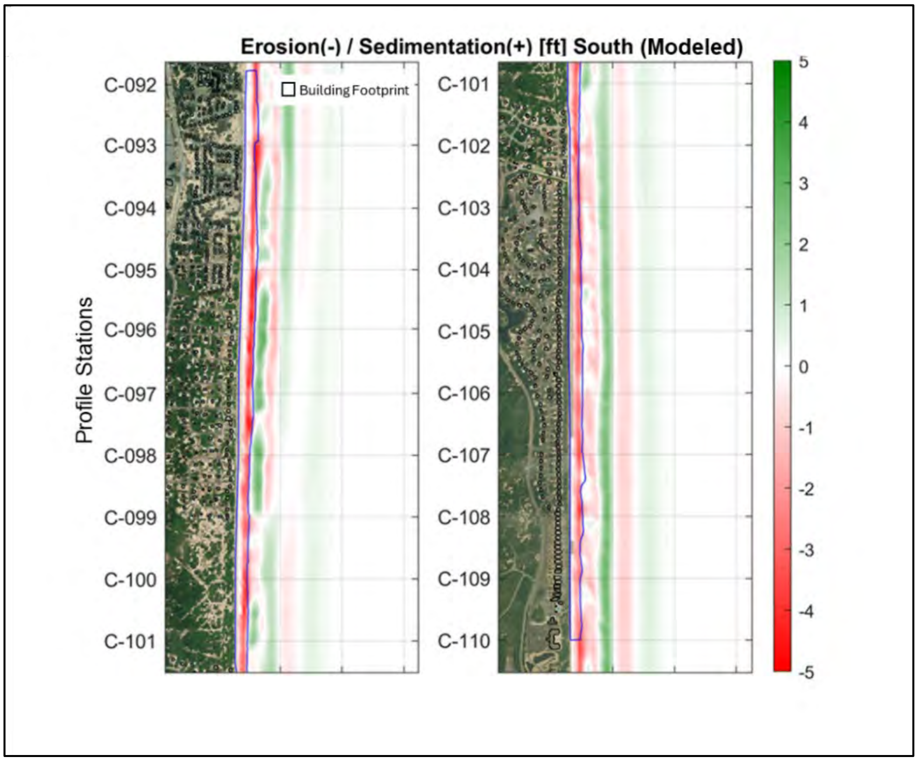


Figure 35. Modeled erosion and sedimentation for the south domain extent for Hurricane Matthew. The blue polygon represents the extents of the measured data.

Figure 36 provides a comparison of the gross sedimentation and gross erosion volumes between the measured and modeled data for each domain. The primary focus of calibration was to get the measured and modeled erosion volumes in the same order of magnitude. The accretion patterns observed in the measured data were generally very small and scattered, making them difficult for the model to replicate accurately due to grid refinement and bathymetric representation. Overall, the model exhibits a tendency to overestimate erosion volumes and underestimate the accretion volumes. However, there is generally a reasonable agreement within the calculation cells for both north and south domains, particularly in erosion volume estimates.

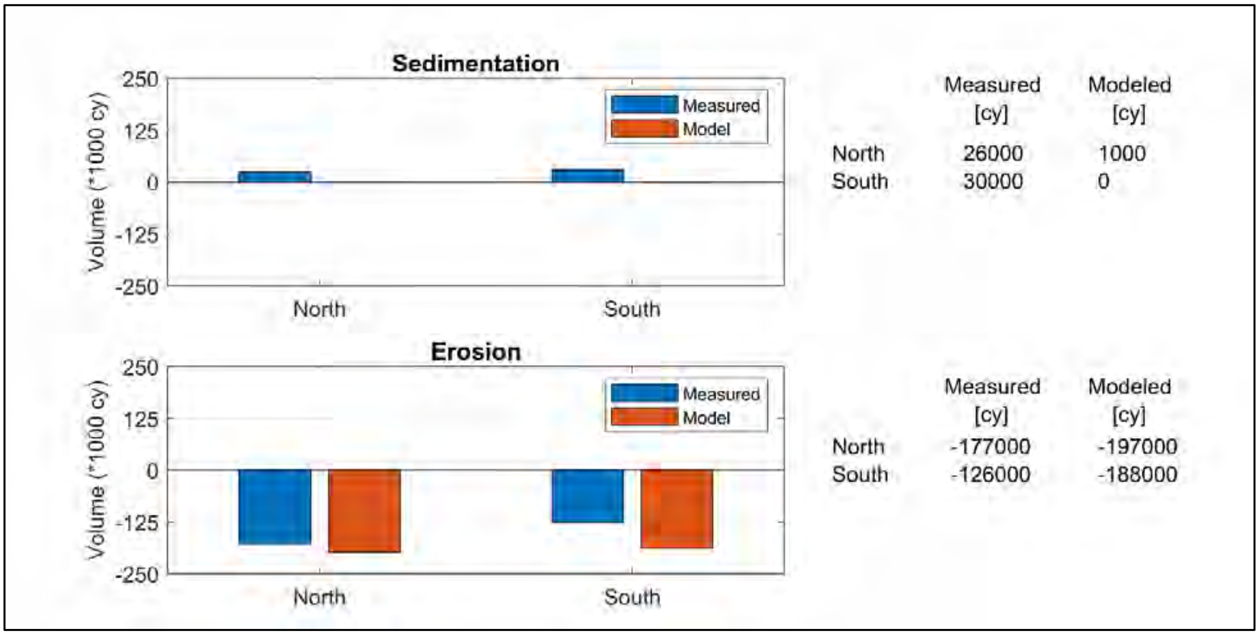


Figure 36. Volume Bar Plots and corresponding volumes (in cy) for measured and modeled data for Hurricane Matthew.

2.1.3.2. Simulation of Historical Storms

Based on the extreme analysis, three (3) storms were selected for production runs to evaluate erosion patterns along the domains based on 2024 beach conditions. The selected storms included Hurricane Isabel (2003), November 2009 Nor'easter, and Hurricane Dorian (2019), all described in detail in Section 2.1.2. All production runs used the same model setup as the calibration runs, described in Section 2.1.3.1.

During the production runs, adjustments were made to the initial model surface elevation. The June 2024 beach profile survey data collected by CPE along Currituck County, was utilized as the primary data source. Grid points outside the coverage of this survey were populated by the NOAA NCEI Continuously Updated Digital Elevation Model (CUDEM) 1/3 arc second and NOAA NCEI Continuously Updated Digital Elevation Model (CUDEM) 1/9 arc second datasets. The datasets are listed in Table 5.

FEMA's high-water marks are available for hurricanes Isabel and Dorian and were used as the water level boundary condition at the peak of the storms. For the November 2009 Nor'easter, FEMA's high-water mark was not available, and hence the empirical equation from Guza and Thornton (1981), described in the model calibration section, was used to calculate the wave setup, which was then added to the measured water level and used as model boundary condition.

The simulation time periods for the three storms are provided below.

- **Hurricane Isabel (2003)** - The model simulation was based on conditions measured over the 7-day period, from September 15, 2003, to September 22, 2003.
- **November 2009 Nor'easter** - The model simulation was based on conditions measured over the 6-day period, from November 11, 2009, to November 17, 2009.
- **Hurricane Dorian (2019)** - The model simulation was based on conditions measured over the 3-day period, from September 06, 2019, to September 09, 2019.

Model results from the simulation of the historical storms are summarized below.

Wave Analysis

The wave analysis, which focused on the variability of wave heights along Currituck County, involved determining wave heights at different depth contours to gain insight into wave transformation processes as waves propagate from deep to shallow water. This approach helped to identify how wave energy dissipates at different locations due to offshore bathymetric features, depth-induced breaking, bottom friction, and interactions with coastal features such as sandbars.

Wave field maps at storm peak for Hurricane Isabel (2003), November 2009 Nor'easter and Hurricane Dorian (2019) are presented in Figure 37 to Figure 39, respectively. Among the three events, Hurricane Isabel (2003) produced the highest wave heights, followed by November 2009 Nor'easter, and then Hurricane Dorian (2019). The wave propagation is highly dependent on the complex offshore bathymetric contours as shown in the wave filed maps. In general, the southern portion of the modeled Currituck shoreline (Stations C-092 to C-110) is exposed to higher wave heights due to a steeper nearshore slope. This topographic differential causes waves to break closer to shore and with greater energy, which may enhance sediment transport and contribute to localized erosion. In contrast, the northern portion of the domain (Stations C-059 to C-084) exhibits a wider and shallower nearshore zone, where the gentler slope facilitates greater wave energy dissipation before reaching the shoreline.

Significant wave height (Hs) results for the three storms were extracted from the models at two different depth contours, -1 ft. NAVD88 and -30 ft. NAVD88. The local wave map fields display both contours, while only the -30 ft. contour is shown on the regional wave map field for improved visibility (Figure 37 to Figure 39). These results were plotted against the Stations C-052 through C-114 along the model domain (Figure 40). Due to the boundary effects observed on the southern side of the model domain, the profiles at Stations C-114 to C-118 were excluded from the analysis. Consistent with the spatial patterns observed in the wave field maps, all three events exhibited a general increasing trend in wave heights from Station C-052 to C-114. This indicates that wave energy tends to intensify toward the southern portion of the domain, with the segment between Stations C-092 and C-110 appearing particularly susceptible to storm impacts. Additionally, complex nearshore bathymetric features, such as those between Stations C-094 and C-110, produce localized variations in wave propagation. These features influence wave gradients at the shoreline, resulting in the alternating increases and decreases in wave heights observed in the Hs contour plots within those areas.

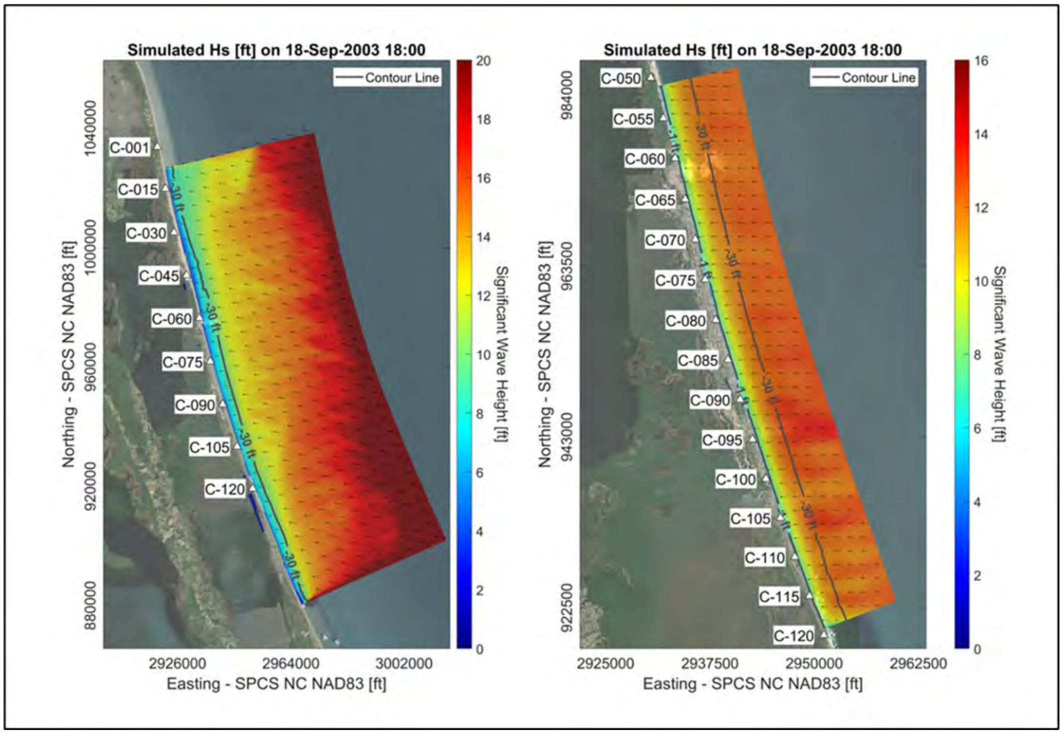


Figure 37. Highest simulated Significant Wave Height (ft) for Hurricane Isabel over the Regional Wave Grid (left panel) and the Local Wave Grid (right panel).

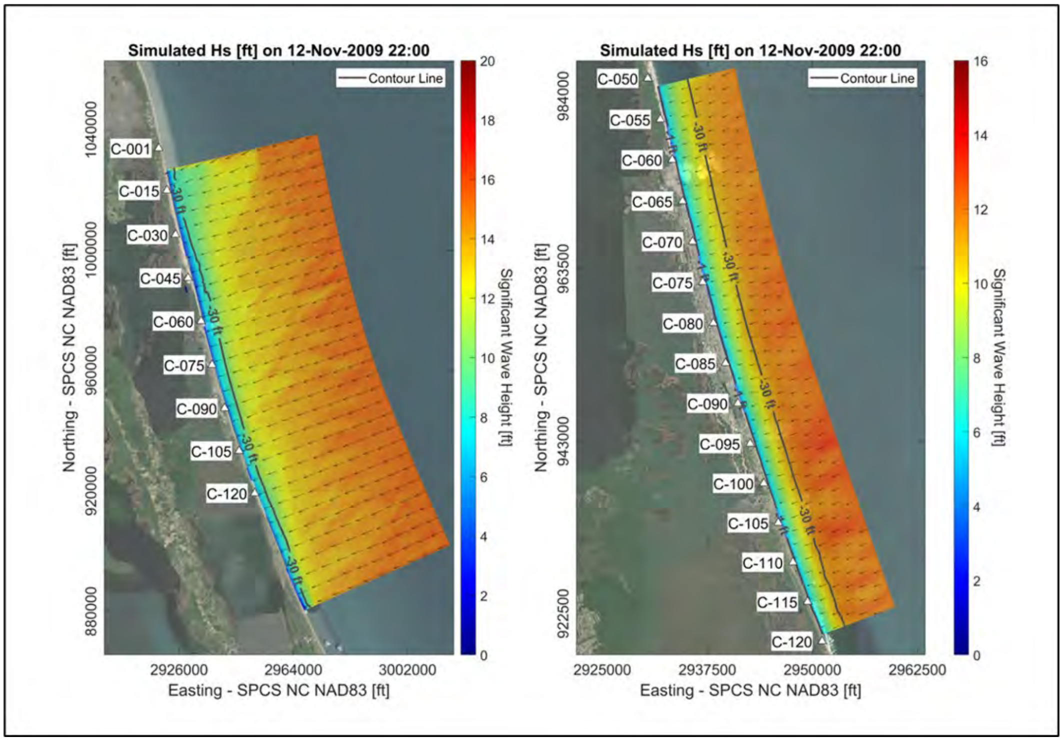


Figure 38. Highest simulated Significant Wave Height (ft) for November 2009 Nor'easter over the Regional Wave Grid (left panel) and the Local Wave Grid (right panel).

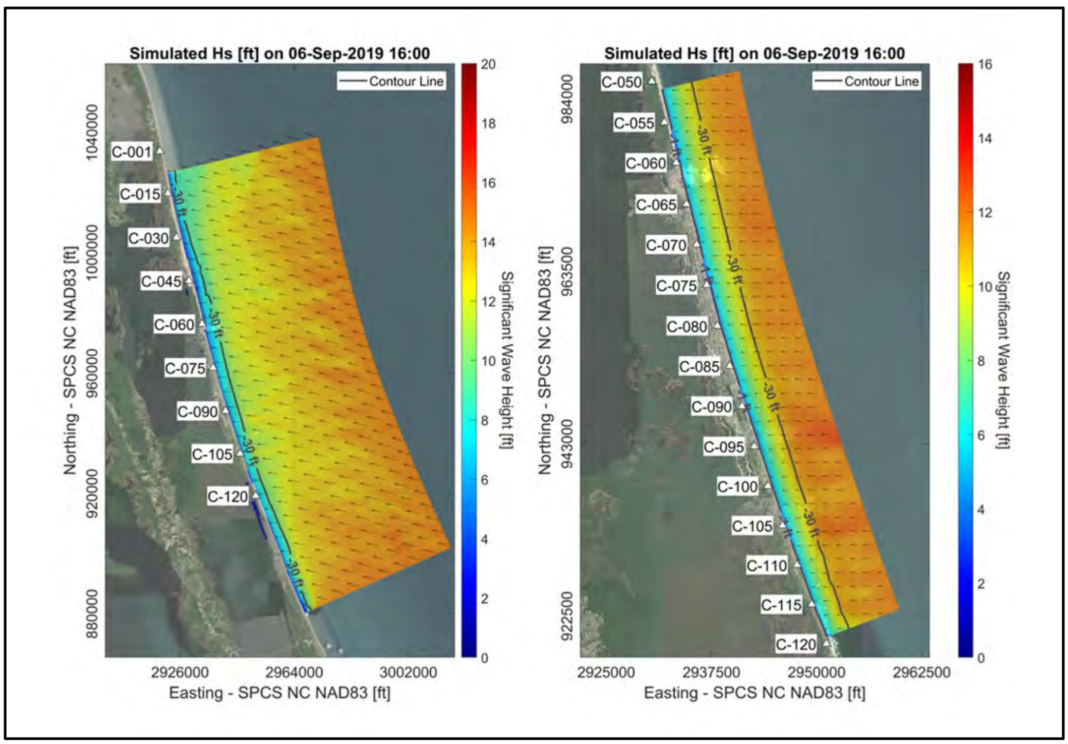


Figure 39. Highest simulated Significant Wave Height (ft) for Hurricane Dorian over the Regional Wave Grid (left panel) and the Local Wave Grid (right panel).

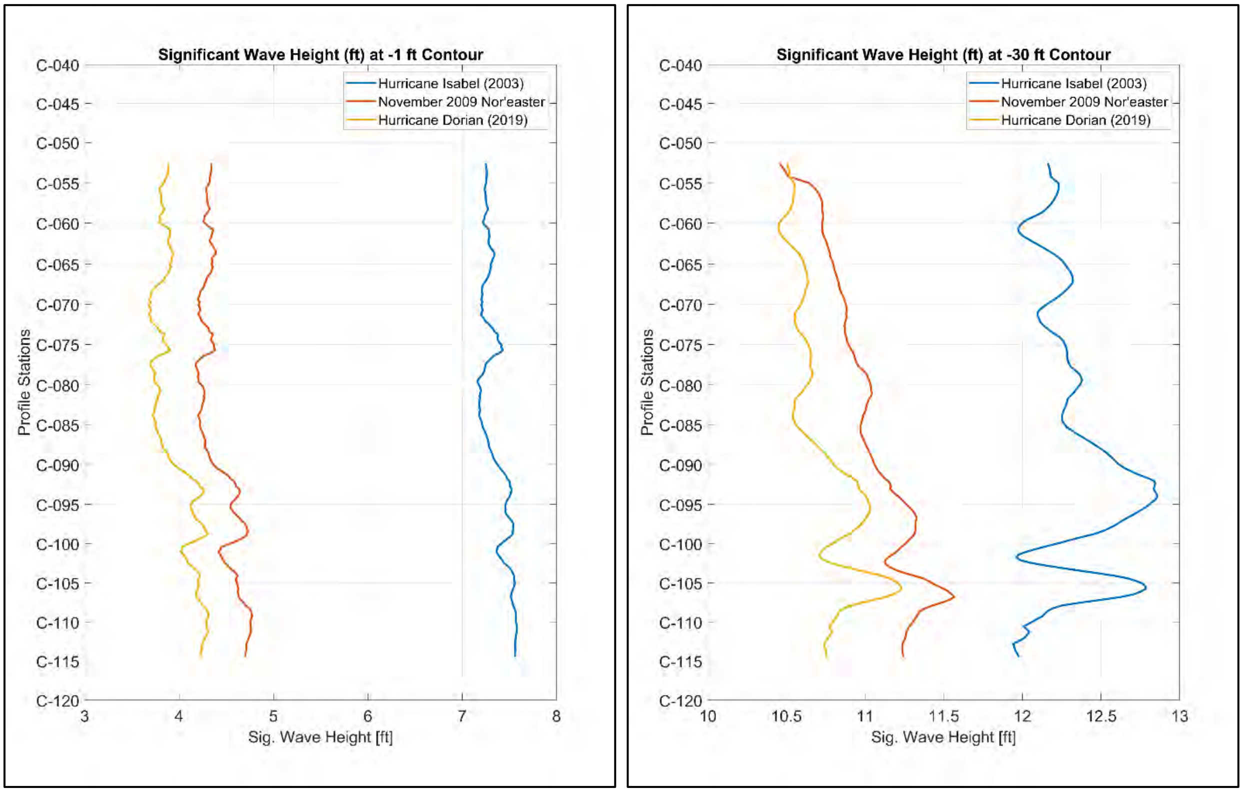


Figure 40. Highest simulated Significant Wave Height (ft) at -1 ft NAVD contour (left panel) and -30 ft NAVD contour (right panel) for Hurricane Isabel, the November 2009 Nor'easter, and Hurricane Dorian.

Currents Analysis

A current velocity analysis was conducted to assess the variability of current velocities along Currituck County. The analysis involved determining current velocities at different depth contours along Currituck County to gain insight into general trends/patterns.

Highest current velocities from Hurricane Isabel (2003), November 2009 Nor'easter and Hurricane Dorian (2019) are presented in Figure 41. The wave breaking patterns across the Currituck shoreline, discussed in the previous section, would generate gradients that directly influence wave-driven current velocities, especially in the nearshore zone. Along the southern shoreline, between Stations C-092 and C-110, the higher wave heights and waves breaking closer to shore result in stronger wave-induced currents. The more gradual bathymetry between Stations C-059 and C-084, along the northern Currituck County oceanfront, causes waves to break farther offshore, reducing the energy that reaches the shoreface, leading to weaker current velocities, due to greater wave dissipation.

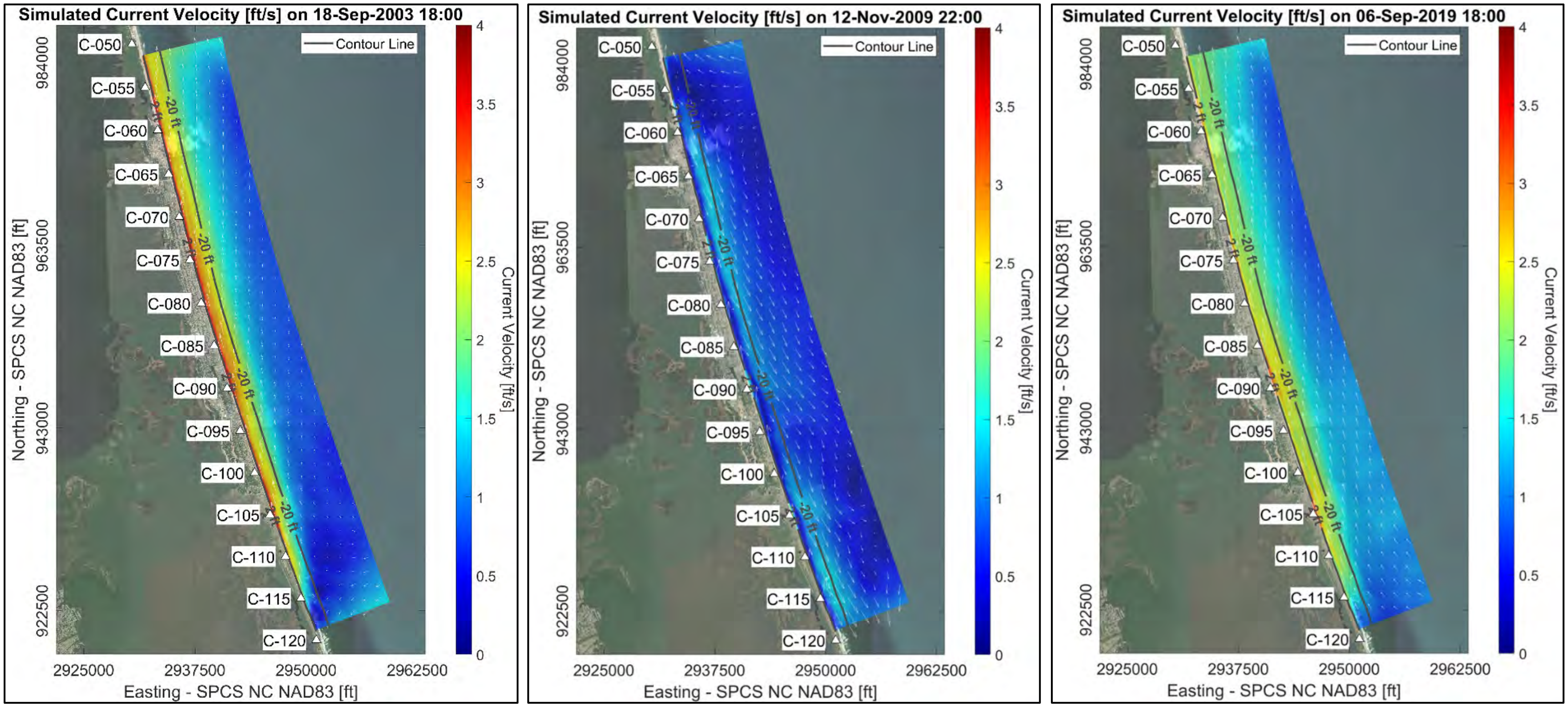
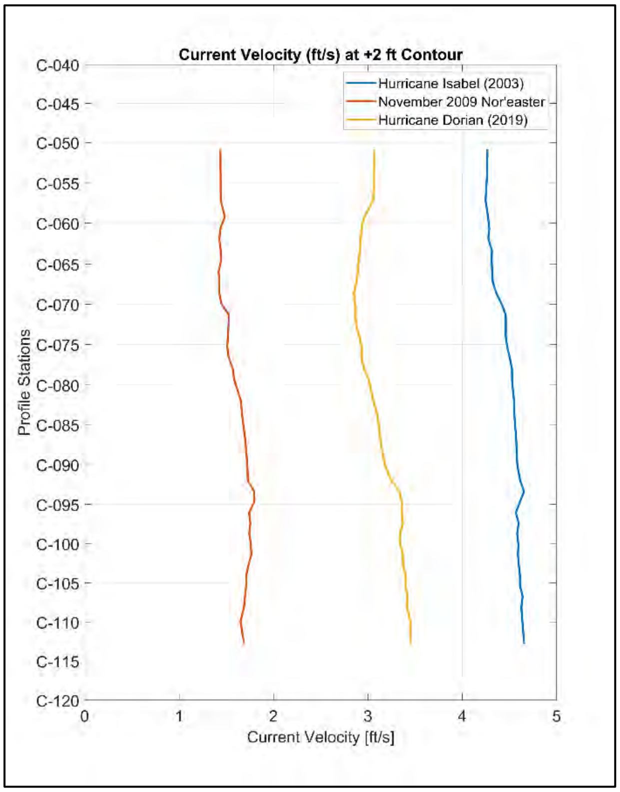


Figure 41. Highest simulated Current Velocities (ft/s) for Hurricane Isabel (left panel), November 2009 Nor'easter (central panel), Hurricane Dorian (right panel).

The current velocity results for the three storms were extracted from the models at two different depth contours: +2 ft. NAVD88 and -20 ft. NAVD88. The maps of local current fields display both contours, (Figure 41). These results were plotted against the Stations C-052 to C-114 along the model domain (Figure 42). Due to the boundary effects observed on the southern side of the model domain, the profiles at Stations C-114 to C-118 were excluded from the analysis. Similar to the significant wave height (Hs) results, all three storm events demonstrated a general upward trend in current velocities moving from C-052 to C-114, with current velocities tending to increase toward the latter profile stations. This is an indication that the southern domain between C-092 to C-114 could be more vulnerable to storm events. Hurricane Isabel (2003) had the highest current velocities; however, unlike for significant wave height, Hurricane Dorian (2019) had higher current velocities than the November 2009 Nor'easter.



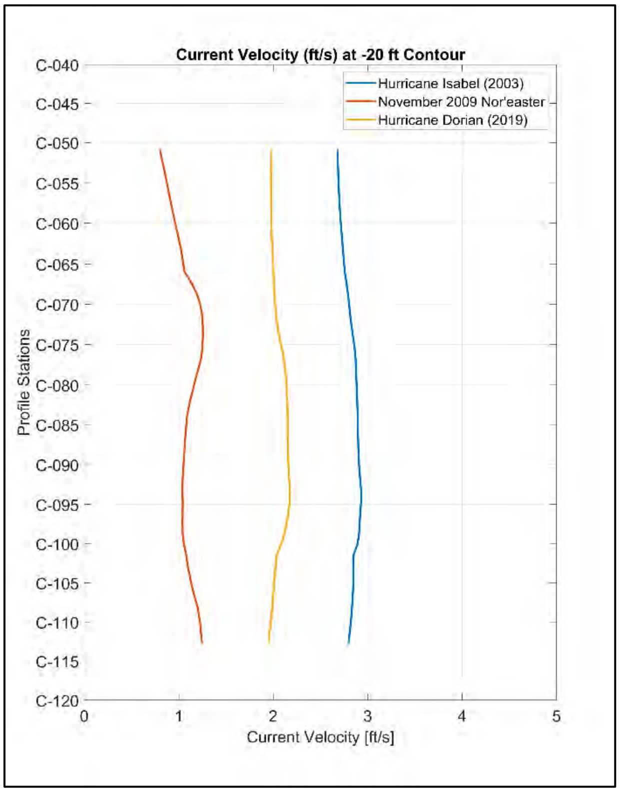


Figure 42. Highest simulated Current Velocities (ft/s) at +2 ft NAVD contour (left panel) and -20 ft NAVD contour (right panel) for Hurricane Isabel, the November 2009 Nor'easter, and Hurricane Dorian.

Volume Change Analysis

To evaluate volume losses in the active part of the beach profile, a volume change analysis was conducted for the three storms. Volumetric changes were measured between the +6 ft. NAVD88 contour, located on the berm, and the base of the offshore bar (-12 ft. NAVD88). The volume change results for the three storms are shown in Figure 43, Figure 44 and Figure 45, with values summarized in Table 6. The results are presented for Stations C-052 through C-114. Due to the boundary effects observed on the southern side of the model domain, the profiles at Stations C-114 to C-118 were excluded from the analysis. The model results indicated that the highest volume losses occurred in the southern domain (Stations C-90 to C-114) for all three storms. The average erosion measured between +6 ft. and -12 ft. contours over an approximately 1,000 ft. section of beach for the Hurricane Isabel storm simulation was -7,170 cy. The average erosion measured for the November 2009 Nor'easter and Hurricane Dorian storm simulations were -7,180 cy and -2,670 cy, respectively.

The results analysis show that for longer duration extra-tropical storms, such as the November 2009 Nor'easter (Figure 44), the most significant volume changes were observed between the +6 ft. NAVD88 contour and the base of the offshore bar. This pattern is attributed to the relatively prolonged duration of the event (6 days) with sustained high wave heights (Figure 38). The water level during this longer duration event ranged from 0 to +3 ft. above MHHW, resulting in the majority of erosion occurring in this area.

In contrast, faster-moving tropical storms such as Hurricane Isabel (2003) and Hurricane Dorian (2019) showed less erosion between the +6 ft. to -12 ft. contours (Figure 43 and Figure 45). Of these storms, Hurricane Isabel produced the most substantial morphological changes in the dune area (above +6 ft. NAVD88), which are discussed in detail in Section 2.1.4 (2026 XBeach Storm Vulnerability Analysis). These impacts were driven by higher peak water levels, reaching +4.1 ft. MHHW for Hurricane Isabel (2003) and +3 ft. MHHW for Hurricane Dorian (2019). These higher water levels shifted the majority of the erosion to occur in the dune area.

The stations that exhibited higher than average erosion during the simulated wave event were identified as the most vulnerable. The Stations exhibiting this trend across all the three simulated storms included C-066, C-078, C-082, C-093, C-097, C-106, C-111 and C-112.

2.1.3.3 Summary of Delft3D Hotspot Analysis

The modeling analysis of wave heights, current velocities, and volume changes along Currituck County's shoreline for simulated storms revealed that the southern shoreline, between Stations C-092 and C-114, is more exposed to higher waves, greater wave differentials, and higher currents which would all increase sediment transport. The steeper slope and topographic features cause waves to break closer to shore with greater energy, resulting in higher wave heights and stronger wave-driven currents compared to the northern shoreline from Stations C-059 to C-084. Along this section a gentler slope allows for greater wave dissipation. Wave and current velocities consistently increased from Station C-052 to C-114, with the highest values observed in the southern domain, correlating with greater erosion risks. As a result of the increased wave heights and current velocities along the southern portions of the domain, the model indicated higher volume losses in these areas for all three storms simulated. While the general trend observed indicated greater erosion along the southern domain than the north, volume change analysis identified numerous stations throughout the area as having relatively higher erosion potential. Stations C-066, C-078, C-082, C-093, C-097, C-106, C-111 and C-112 were shown to have the highest potential of storm erosion.

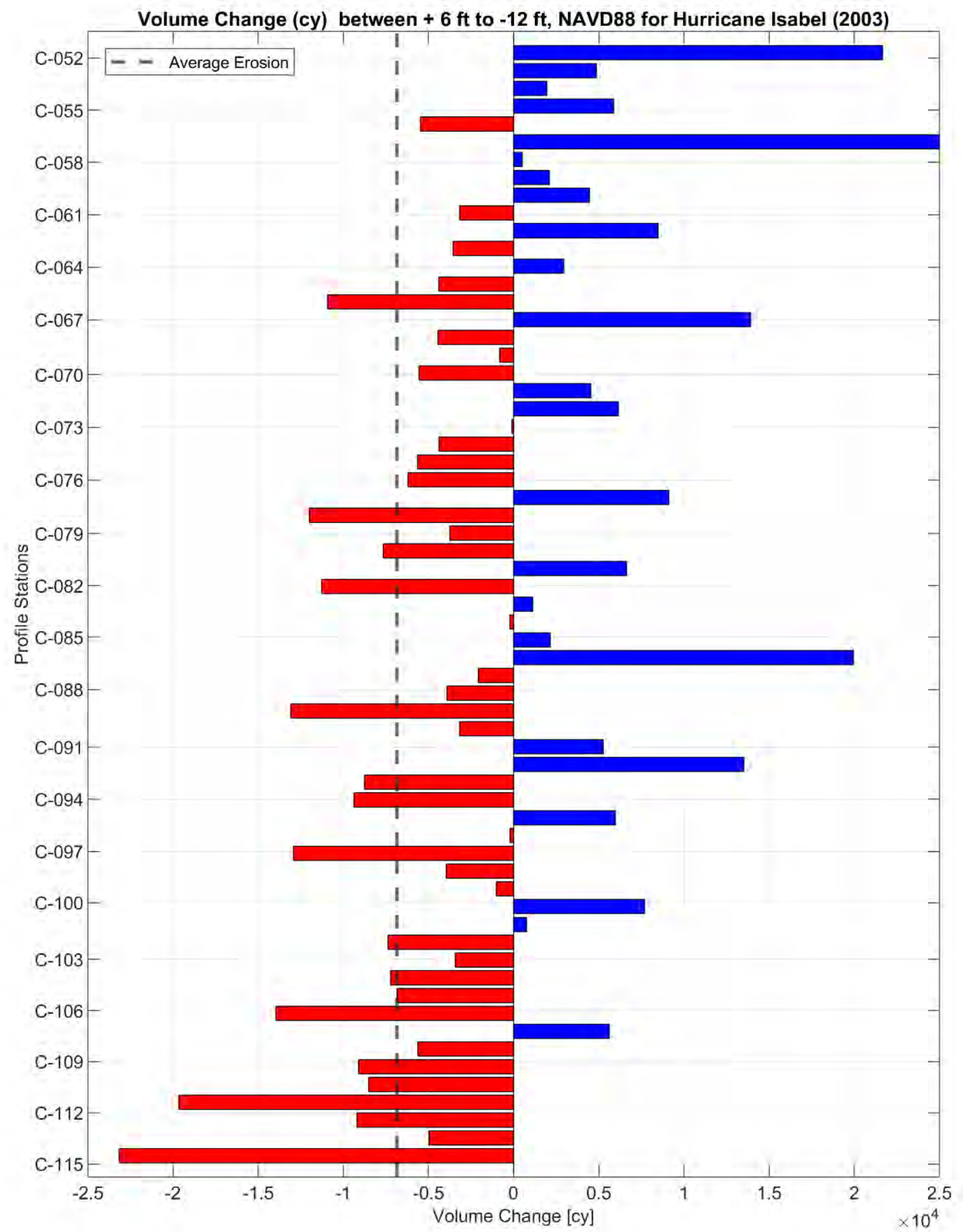


Figure 43. Volume change model results (in cy) between +6 ft to -12 ft, NAVD88 for Hurricane Isabel. The dashed black line represents the average erosion associated with the event.

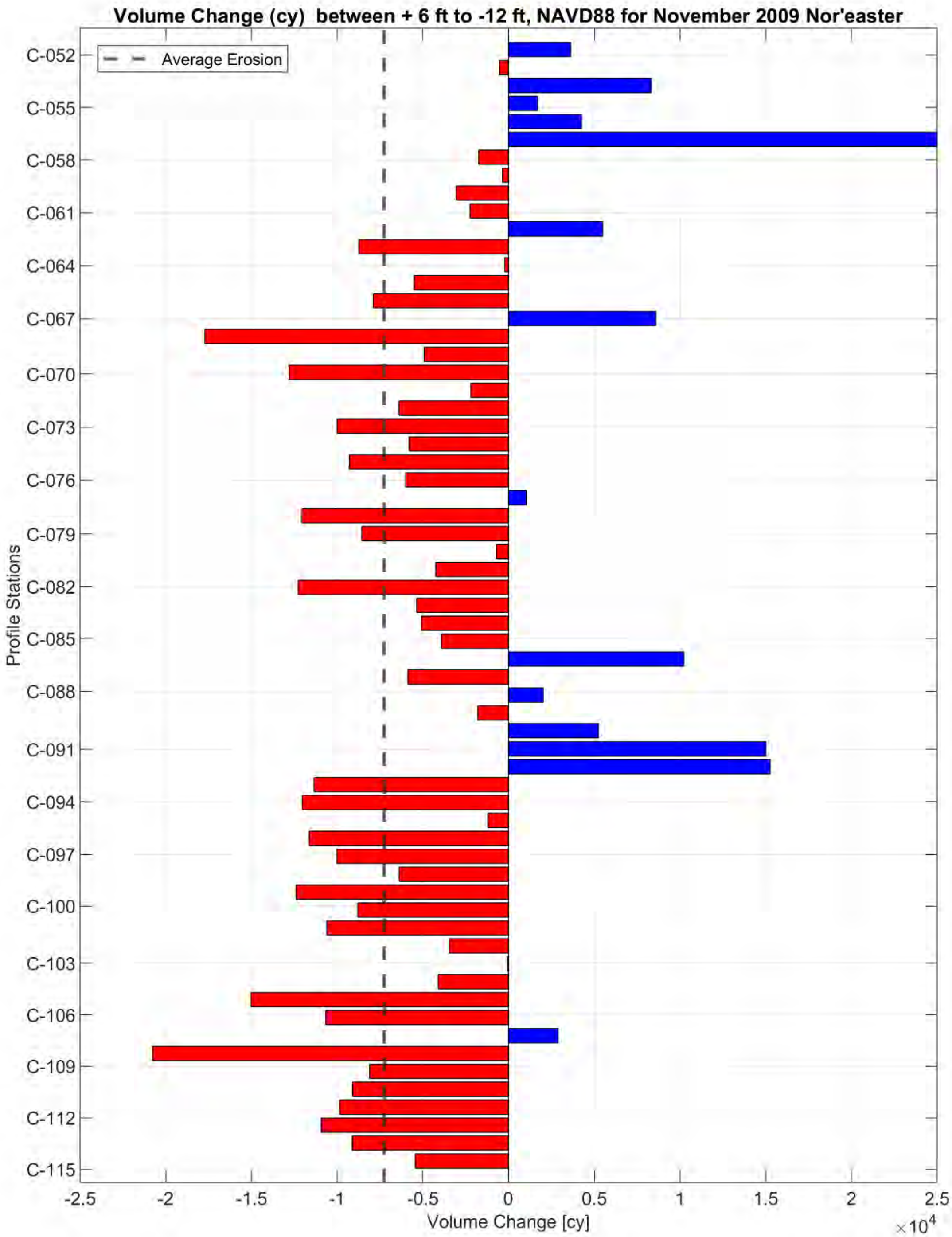


Figure 44. Volume change model results (in cy) between +6 ft to -12 ft, NAVD88 for November 2009 Nor’easter. The dashed black line represents the average erosion associated with the event.

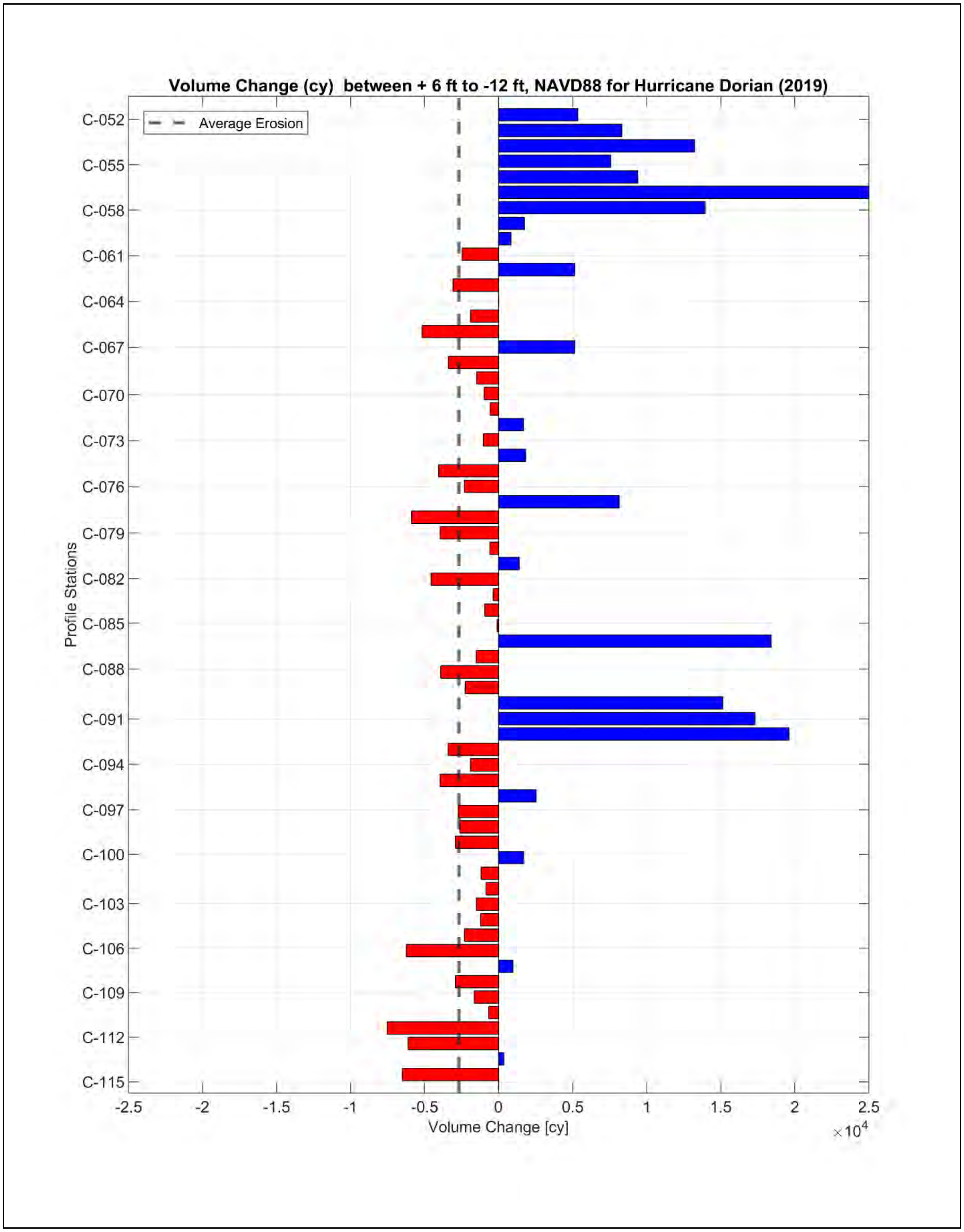


Figure 45. Volume change model results (in cy) between +6 ft to -12 ft, NAVD88 for Hurricane Dorian. The dashed black line represents the average erosion associated with the event.

Table 6. Volume change model results (in cy) between +6 ft to -12 ft NAVD88 for Hurricane Isabel, November 2009 Nor'easter and Hurricane Dorian.

Profile Stations	Volume Change (cy) Hurricane Isabel (2003)	Volume Change (cy) November 2009 Nor'easter	Volume Change (cy) Hurricane Dorian (2019)	Profile Stations	Volume Change (cy) Hurricane Isabel (2003)	Volume Change (cy) November 2009 Nor'easter	Volume Change (cy) Hurricane Dorian (2019)
C-052	21669	3613	5351	C-091	5263	15016	17316
C-053	4852	-543	8338	C-092	13522	15270	19623
C-054	1940	8338	13230	C-093	-8756	-11342	-3418
C-055	5866	1690	7561	C-094	-9379	-12033	-1909
C-056	-5470	4248	9379	C-095	5967	-1198	-3957
C-057	37808	31084	30311	C-096	-208	-11634	2526
C-058	510	-1747	13952	C-097	-12937	-10018	-2737
C-059	2114	-360	1757	C-098	-3960	-6378	-2627
C-060	4453	-3049	846	C-099	-1016	-12402	-2924
C-061	-3166	-2253	-2469	C-100	7688	-8801	1686
C-062	8467	5500	5129	C-101	767	-10608	-1191
C-063	-3552	-8729	-3085	C-102	-7372	-3477	-856
C-064	2941	-219	-13	C-103	-3429	-69	-1510
C-065	-4399	-5512	-1899	C-104	-7229	-4115	-1222
C-066	-10929	-7892	-5169	C-105	-6843	-15026	-2314
C-067	13924	8589	5143	C-106	-13958	-10663	-6237
C-068	-4449	-17726	-3398	C-107	5619	2899	960
C-069	-826	-4924	-1476	C-108	-5623	-20775	-2922
C-070	-5560	-12808	-985	C-109	-9108	-8104	-1650
C-071	4531	-2206	-589	C-110	-8514	-9111	-669
C-072	6142	-6383	1666	C-111	-19654	-9852	-7534
C-073	-103	-10004	-1036	C-112	-9201	-10929	-6112
C-074	-4386	-5801	1813	C-113	-4974	-9122	355
C-075	-5638	-9287	-4055	C-114	-23161	-5448	-6504
C-076	-6200	-6002	-2314				
C-077	9101	1049	8152				
C-078	-11989	-12062	-5901				
C-079	-3752	-8566	-3951				
C-080	-7656	-718	-598				
C-081	6622	-4246	1398				
C-082	-11273	-12281	-4568				
C-083	1115	-5350	-374				
C-084	-216	-5093	-938				
C-085	2156	-3917	-97				
C-086	19938	10234	18405				
C-087	-2071	-5885	-1526				
C-088	-3906	2016	-3913				
C-089	-13087	-1791	-2265				
C-090	-3181	5241	15127				

2.1.4 2026 XBeach Storm Vulnerability Analysis

Whereas the Delft3D analysis (Section 2.1.3) focused on identifying erosion hot spots across the active beach profile from the dry beach to the offshore bar, XBeach was applied to evaluate dune vulnerability, specifically the response of the dry beach and dune system to extreme storm events. XBeach is an open-source, process-based coastal model developed by TU Delft in collaboration with UNESCO-IHE that simulates nearshore hydrodynamics and morphology response under storm conditions. The model resolves key processes including short-wave transformation, long-wave (infragravity wave) generation and propagation, wave-induced setup, currents, sediment transport, and the resulting beach and dune erosion, overwash, and breaching/inundation.

One of the key features that makes XBeach particularly well-suited for simulating vulnerability to extreme storms is its ability to incorporate long-waves (infragravity waves) within its suite of coastal processes. During extreme events, swash motions and wave runup that cause dune erosion and dune overwash are primarily driven by infragravity waves. These motions represent the effects of wave "sets" or “surf beat” on water levels and wave runup. With periods of 1 minute or longer, infragravity waves are not dissipated by shallow bathymetry and can generate energetic hydrodynamic conditions capable of driving significant dune erosion and overwash. This phenomenon is crucial for assessing beach and dune erosion, dune overtopping, and storm-surge-induced flooding. Additional details of the model can be found at:
https://xbeach.readthedocs.io/en/latest/#.

XBeach was implemented using both one-dimensional (1D) and two-dimensional horizontal (2D) configurations. The 1D model was applied along the 1,000 ft. spaced monitoring profiles south of the Horse Gate to evaluate storm response and identify alongshore trends in erosion and overtopping potential. Based on the results of the 1D analysis, a 2D model was developed to further investigate selected areas in the Corolla and Pine Island Sections for elevated vulnerability, particularly with respect to dune breaching, overtopping, and inundation. This allowed for improved representation of alongshore variability and nearshore processes.

2.1.4.1 XBeach 1D

The following sections describe the 1D XBeach model setup, calibration, and application to selected storm scenarios to evaluate beach and dune vulnerability.

Computational Grids

A one-dimensional cross-shore grid was developed at each of the 58 surveyed profiles south of the Horse Gate, between Stations C-063 and C-120, corresponding to approximately 1,000-foot alongshore spacing across the Corolla and Pine Island Sections. These locations were selected based on the availability of pre-Hurricane Matthew (2016) topobathymetric data and to provide sufficient spatial coverage of the area.

Each grid extended from the onshore station benchmark to an offshore wave forcing boundary at approximately 80 ft. depth. Grid resolution varied with depth to balance computational efficiency with accurate resolution of nearshore and dune processes; the applied spacing zones are summarized in Table 7. An example cross-shore grid for the beach profile at Station C-063 is shown in Figure 46.

Table 7. XBeach 1D model cross-shore grid resolution.

Depth Zone	Depth Range (ft)	Grid Spacing (ft)
Offshore	>32	66
Transition	16 to 32	66 to 6 (graded)
Nearshore	<16	6

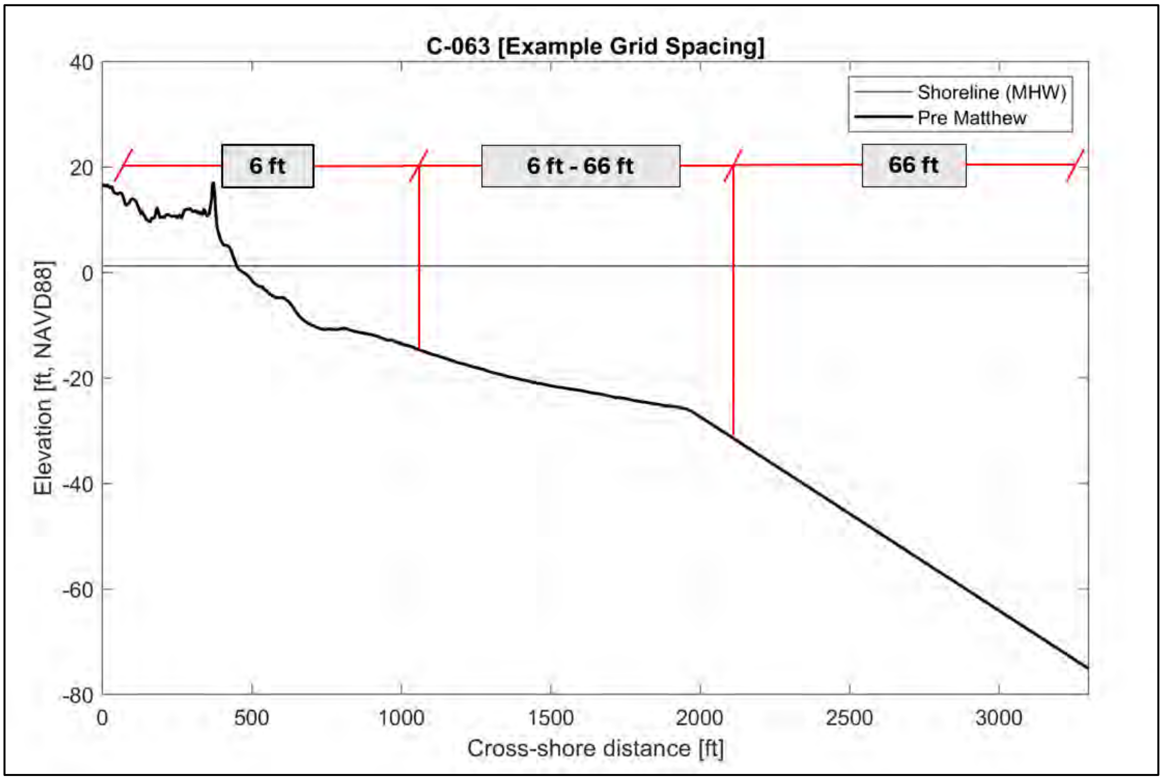


Figure 46. XBeach 1D model cross-shore grid resolution.

This refined nearshore and subaerial resolution is critical for accurately representing dune morphology and beach slope transitions, while the coarser offshore resolution improves computational efficiency without significantly affecting nearshore hydrodynamics.

Topography and Bathymetry

The topographic and bathymetric input for the 1D and 2D models was developed from various combinations of beach profile surveys, high-resolution LiDAR, and regionally compiled elevation datasets. The datasets used are summarized in Table 8.

Table 8. Topographic and bathymetric datasets used for XBeach 1D and 2D model grid development.

Date	Source	Type	Location	Resolution (ft)
June 2025	CPE	Beach Profiles	Currituck County Stations C-059 to C-120	N/A
June 2019	USACE NCMP	Topobathymetric LiDAR	Currituck County Stations C-059 to C-120	10
November 2016 (Post-Matthew)	USACE	Topographic LiDAR	Currituck County Stations C-059 to C-120	10
July 2016 (Pre-Matthew)	USACE NCMP	Topobathymetric LiDAR	Currituck County Stations C-063 to C-120	10
Multiple	NOAA NCEI	1/3 Arc-Second Continuously Updated DEM (CUDEM)	Atlantic Coast of North Carolina	35

For the 1D calibration, the July 2016 pre-Hurricane Matthew USACE NCMP topobathymetric LiDAR served as the primary dataset for model calibration, providing continuous nearshore coverage. To extend the bathymetric data from the nearshore LiDAR to the offshore wave forcing boundary, a 1:50 artificial slope was applied, consistent with Deltares guidance and selected to balance model physics with computational efficiency. The NOAA NCEI Continuously Updated Digital Elevation Model (CUDEM) was used to supplement areas landward of the LiDAR extents. An example of the resulting composite cross-shore profile is shown in Figure 46.

Boundary Conditions and Forcings

Model forcing conditions for waves, water levels, and wind fields were derived from publicly available datasets consistent with those used in the Delft3D analysis (Section 2.1.3.1) to maintain continuity between modeling approaches.

Model Calibration Parameter Selection

The XBeach model was calibrated using pre- and post-Hurricane Matthew (2016) LiDAR surveys to reproduce observed beach and dune response under storm conditions. Calibration focused on the dry beach and dune system due to the limited availability of post-storm bathymetric data.

The model was implemented in surfbeat (instationary) mode, which resolves both short-wave processes and long-wave (infragravity) motions. A morphological acceleration factor of 1 was used, such that morphological evolution was simulated without temporal scaling. Sediment transport was represented using a single sediment fraction with a median grain size (D50) of 0.19

mm and a D90 of 0.81 mm, based on sediment data from the 2020 Currituck County Beach Monitoring and Stability Assessment (CPE, 2020). A spatially uniform grain size was applied as a simplifying assumption for the calibration simulations.

Simulations were conducted over a three-day period from October 8 to October 11, 2016, as shown in Figure 47 and Figure 48. Lateral boundary conditions were specified as Neumann boundaries, assuming zero alongshore gradients.

Several model parameters were tested during calibration, and those that showed the most significant influence on model performance are summarized in Table 9.

Table 9. XBeach 1D model parameters adjusted during calibration of Hurricane Matthew.

Parameter	Description	Default	Selected
bedfriccoef	Bed friction coefficient	0.01	0.04
wbcevarreduce	Reduction factor of short-wave group variance	1	0.25
gamma	Wave breaker parameter	0.46	0.40
alpha	Wave dissipation coefficient	1.38	1.68

Model Calibration Results

Model performance was evaluated using both qualitative and quantitative comparisons between measured and simulated post-storm profiles.

The qualitative assessment focused on the model's ability to reproduce key morphological features, including dune erosion, berm lowering, and the general shape of the post-storm profile. Figure 49 illustrates representative comparisons between measured and modeled profiles, including identification of the 1-foot vertical recession point. The cross-shore profile plots for Hurricane Matthew (2016) for Stations C-063 to C-120 can be found in Appendix A.

The quantitative analysis was based on the cross-shore location of the 1-foot vertical recession point, defined as the most landward point at which the post-storm profile elevation was at least 1 foot lower than the pre-storm profile. This metric is similar to the vulnerability threshold applied in the 2022 SBEACH beach vulnerability analysis and identifies structures that could be impacted due to storm induced beach erosion caused by a storm having similar characteristics to the design storm. Table 10 shows the average difference between modeled and measured recession locations.

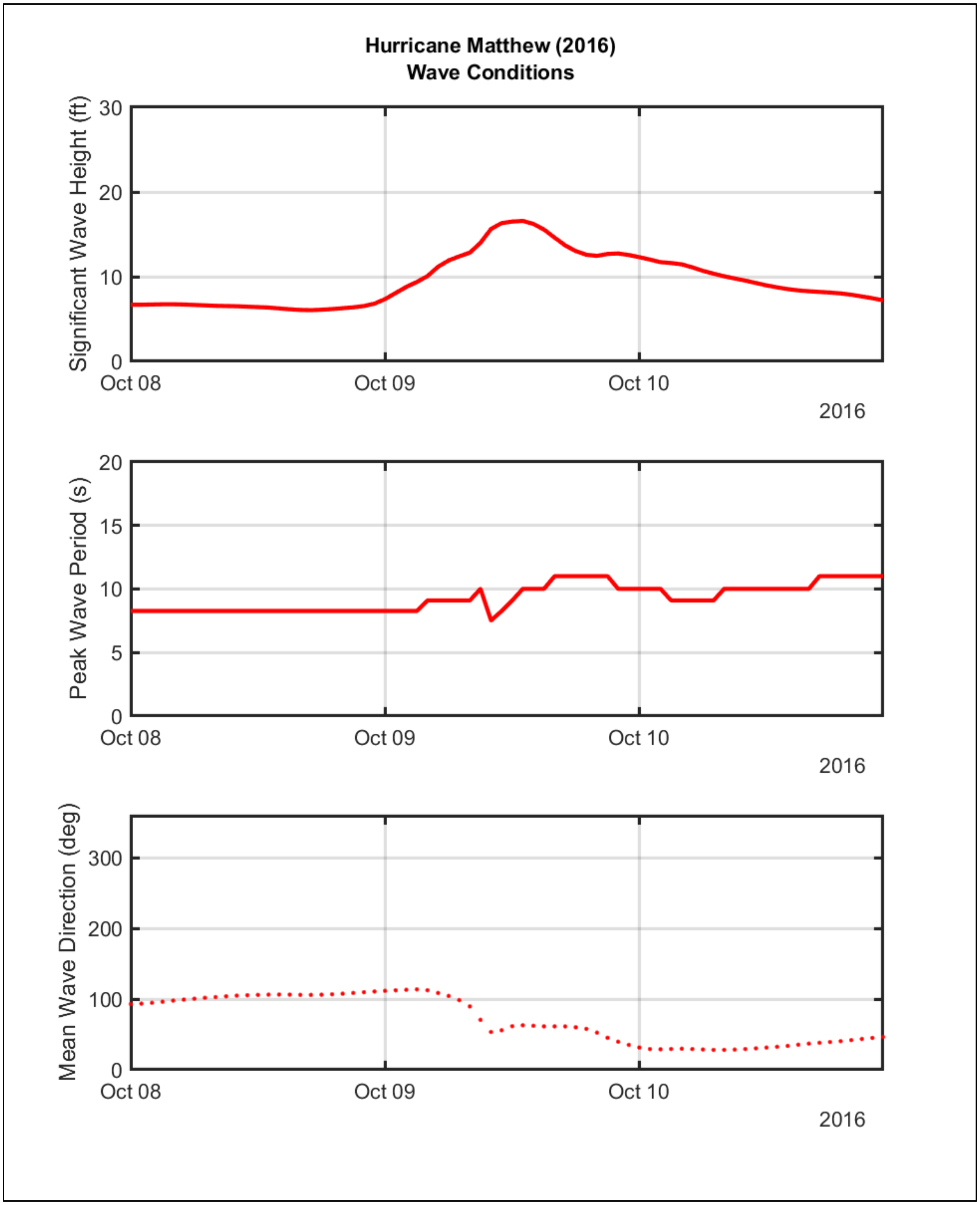


Figure 47. Hindcast forcing conditions used for XBeach model calibration during Hurricane Matthew (October 8–11, 2016): (top) significant wave height (ft), (middle) peak wave period (s), and (bottom) mean wave direction (degrees).

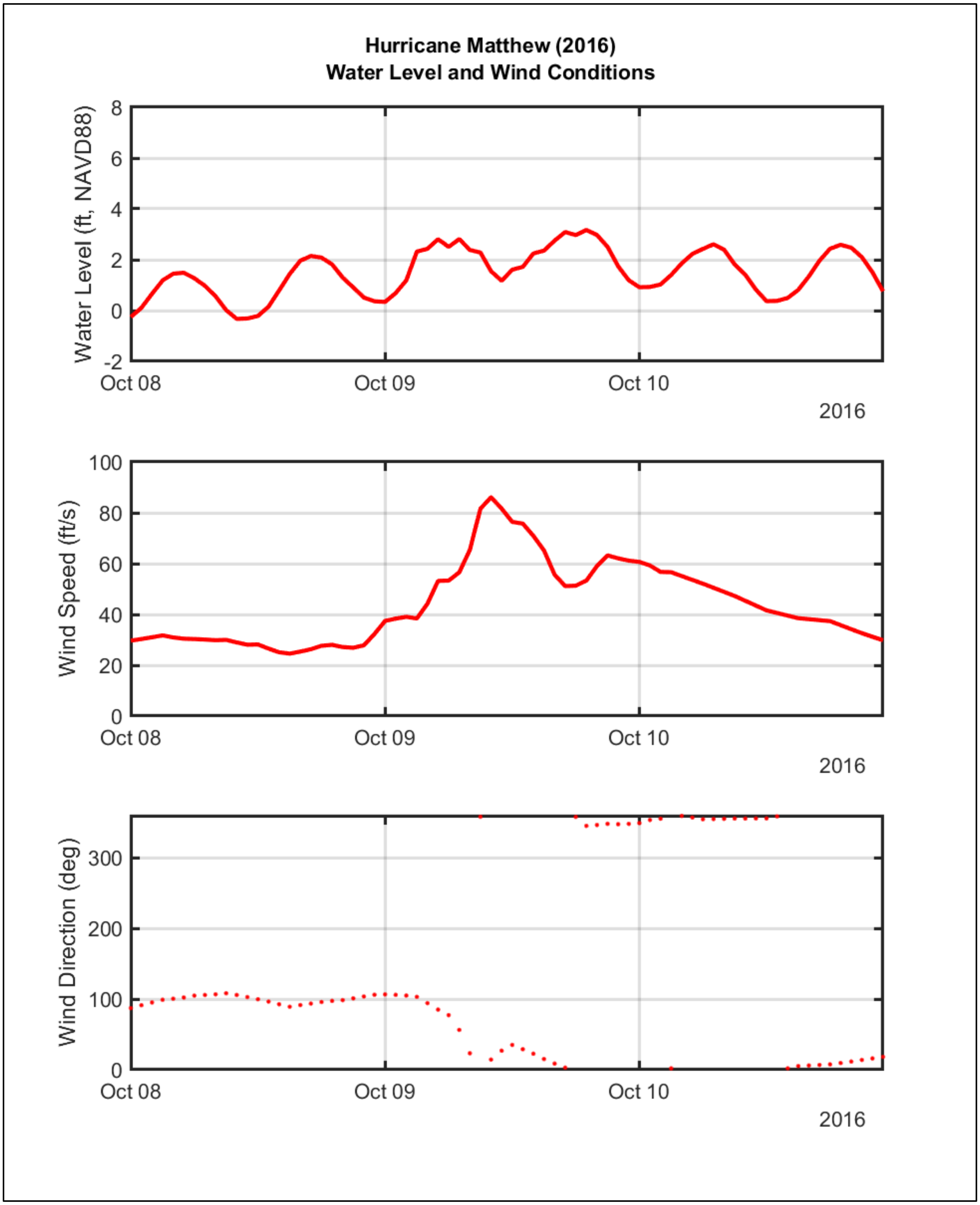


Figure 48. Hindcast meteorological and observed water level conditions used for XBeach model calibration during Hurricane Matthew (October 8–11, 2016): (top) water level (ft, NAVD88) at NOAA Station 8651370 (Duck, NC), (middle) wind speed (ft/s), and (bottom) wind direction (degrees).

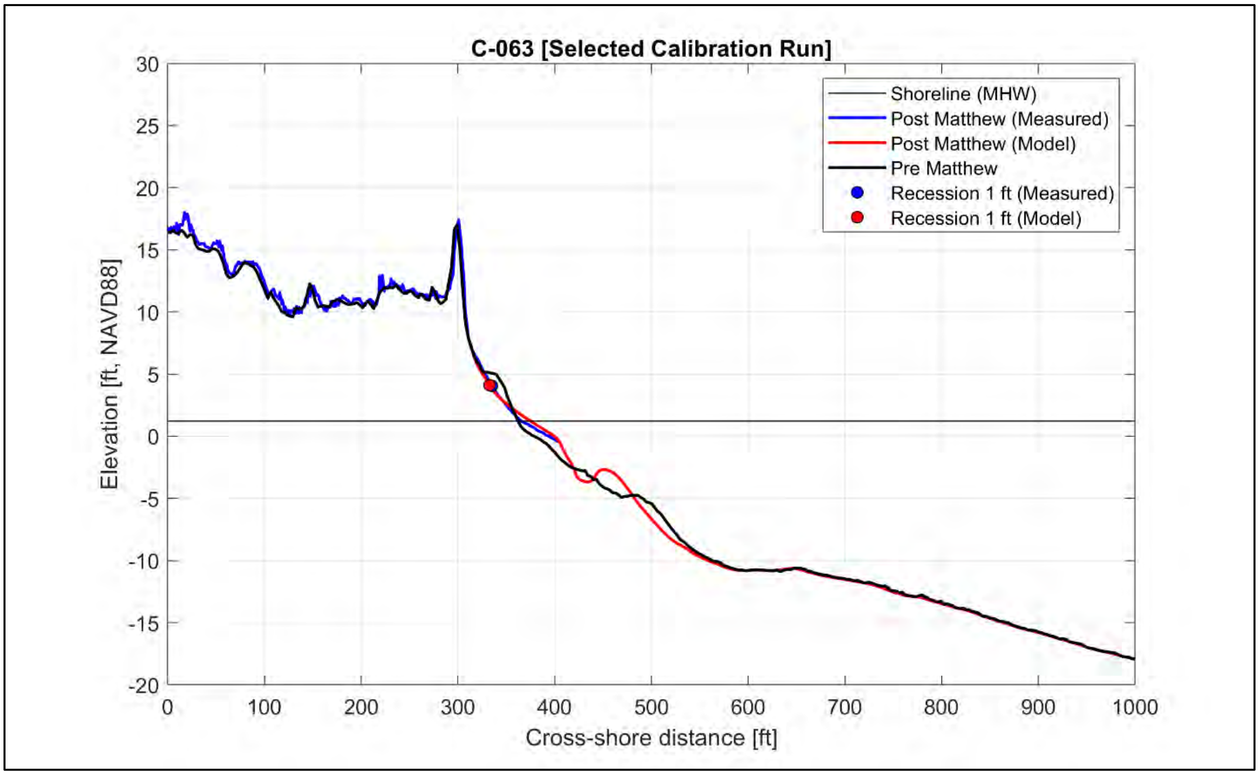


Figure 49. Comparison of measured and modeled cross-shore profiles for Hurricane Matthew, including identified 1-foot vertical recession points.

Table 10. Measured and modeled 1-foot vertical recession point locations (ft, NAVD88) for XBeach calibration profiles during Hurricane Matthew.

Profile Station	Recession Location (ft) Measured	Recession Location (ft) Modeled	Difference Between Measured and Modeled Recession Location (ft)
C-063	335.1	332.6	-2.5
C-064	344.6	343.8	-0.8
C-065	340.6	338.2	-2.5
C-066	342.8	341.7	-1.1
C-067	341.7	325.3	-16.4
C-068	370.3	338.0	-32.2
C-069	346.1	342.4	-3.7
C-070	338.1	328.2	-9.8
C-071	330.1	316.9	-13.2
C-072	351.9	321.4	-30.4
C-073	322.0	312.2	-9.7
C-074	337.9	340.2	2.4
C-075	340.3	340.3	0.0
C-076	NA	338.3	NA
C-077	NA	344.7	NA

Profile Station	Recession Location (ft) Measured	Recession Location (ft) Modeled	Difference Between Measured and Modeled Recession Location (ft)
C-078	350.9	337.9	-13.0
C-079	357.7	358.1	0.3
C-080	445.0	450.2	5.2
C-081	439.2	444.0	4.8
C-082	441.8	447.4	5.6
C-083	430.5	430.5	0.0
C-084	444.2	444.6	0.4
C-085	442.3	403.2	-39.1
C-086	455.8	480.0	24.2
C-087	468.5	NA	NA
C-088	479.3	464.4	-14.8
C-089	474.6	454.3	-20.3
C-090	481.9	462.3	-19.5
C-091	NA	490.9	NA
C-092	540.7	476.1	-64.6
C-093	538.9	590.7	51.7
C-094	553.9	539.0	-14.9
C-095	551.3	549.2	-2.1
C-096	586.3	546.0	-40.2
C-097	637.0	629.7	-7.3
C-098	614.8	596.9	-17.9
C-099	NA	567.9	NA
C-100	605.9	554.4	-51.5
C-101	544.1	515.4	-28.8
C-102	519.7	514.9	-4.8
C-103	556.5	508.3	-48.2
C-104	517.7	506.7	-10.9
C-105	NA	488.3	NA
C-106	NA	467.5	NA
C-107	475.5	470.7	-4.7
C-108	473.7	463.2	-10.5
C-109	NA	424.3	NA
C-110	445.4	424.2	-21.3
C-111	432.2	405.2	-27.0
C-112	465.3	401.4	-63.9
C-113	NA	392.6	NA
C-114	419.6	386.8	-32.8
C-115	437.8	393.9	-43.9
C-116	NA	398.5	NA
C-117	444.4	441.0	-3.4

Profile Station	Recession Location (ft) Measured	Recession Location (ft) Modeled	Difference Between Measured and Modeled Recession Location (ft)
C-118	473.5	458.8	-14.7
C-119	NA	432.9	NA
C-120	484.7	454.8	-29.9
Average	**447.3**	**432.8**	**-14.4**

***Note: NA indicates the vertical recession threshold was not reached along the measured or modeled profile during the storm event.**

As shown in Table 10, across Stations C-063 to C-120, the average difference between modeled and measured recession point locations was -14.4 feet, indicating the model tends to overestimate recession on average. An absolute average difference of 18.5 feet, computed using the absolute value of each profile error, was also calculated to better represent the typical magnitude of model error regardless of direction. The results reflect a combination of both under- and over-prediction across individual profiles, with negative values indicating a landward bias and positive values indicating a seaward bias. These results indicate that the model generally captures the order of magnitude and spatial variability of storm-induced erosion, with some discrepancies likely attributable to uncertainties in the post-storm LiDAR data and profile alignment. Profile-to-profile variability in model performance is expected given the limitations of 1D modeling in capturing three-dimensional processes.

Overall, the model demonstrates a reasonable ability to reproduce observed dune and beach response and is considered suitable for application to storm vulnerability analysis.

Production Runs Configuration

Following calibration, the 1D XBeach model was applied to selected storm scenarios to evaluate beach and dune vulnerability under present-day conditions.

Based on the extreme event analysis and Delft3D results, Hurricane Isabel (2003) and the November 2009 Nor'easter were selected for simulation. Hurricane Dorian (2019) was not included. Although selected for simulation based on the Delft3D results, initial XBeach testing indicated that it did not produce sufficient water levels or wave conditions to induce significant dune erosion, overtopping, or breaching/inundation.

To account for changes in relative sea level between the time of each storm and present-day (2025) conditions, a sea-level adjustment was applied to each event. These adjustments were derived from long-term water level trends at NOAA Station 8651370. Mean sea levels, with the seasonal cycle removed, were used to compute a least-squares linear trend over the period between each storm and 2025. This rate was then multiplied by the elapsed time to estimate the relative sea-level difference for each event. The resulting sea-level adjustments are summarized in Table 11.

Table 11. Sea-level adjustments applied to historical storm simulations.

Storm	Elapsed Time (yr)	Trend Rate (ft/yr)	Sea-Level Adjustment (ft)
Hurricane Isabel (2003)	22	0.020	0.448
November 2009 Nor'easter	16	0.018	0.290

In addition to the historical storms, a synthetic storm was developed to represent a 25-year return period event based on the frequency analysis presented in Section 2.1.2, using data from WIS Station ST63217 and NOAA Tides and Water Level Station 8651370. Hindcast peak significant wave heights from 1980 to 2024 at WIS ST63217 were used to scale Hurricane Isabel conditions to a 25-year storm. Waves, winds, and water levels were scaled independently based on separate frequency analyses, as each forcing parameter has a distinct return period relationship. This was achieved by applying a 15% reduction factor to the entire wave height and period time series.

Using the same approach, peak wind speeds during Hurricane Isabel were found to be below the 25-year return period and were therefore increased by 10%. Water levels from NOAA Station 8651370, with records spanning from the 1970s to present, were similarly adjusted, resulting in a 13% reduction applied during the peak tidal cycle of the storm.

All production runs used the same model setup as the calibration runs described in previous sections. The initial model bathymetry and topography were updated using June 2025 as the primary dataset, and grid points outside the survey extent were supplemented with the NOAA NCEI CUDEM (see Table 8). Wave, water level, and wind forcing were updated using the same data sources used during the Hurricane Matthew calibration.

Three storms were simulated using the forcing conditions and sea-level adjustments described above: the November 2009 Nor'easter over a 6-day period from November 11–17, 2009; Hurricane Isabel over a 3-day period from September 17–20, 2003; and a synthetic 25-year storm based on scaled Hurricane Isabel conditions over the same 3-day period. The forcing conditions applied at the model boundaries for each simulation are shown in Figure 50 through Figure 53.

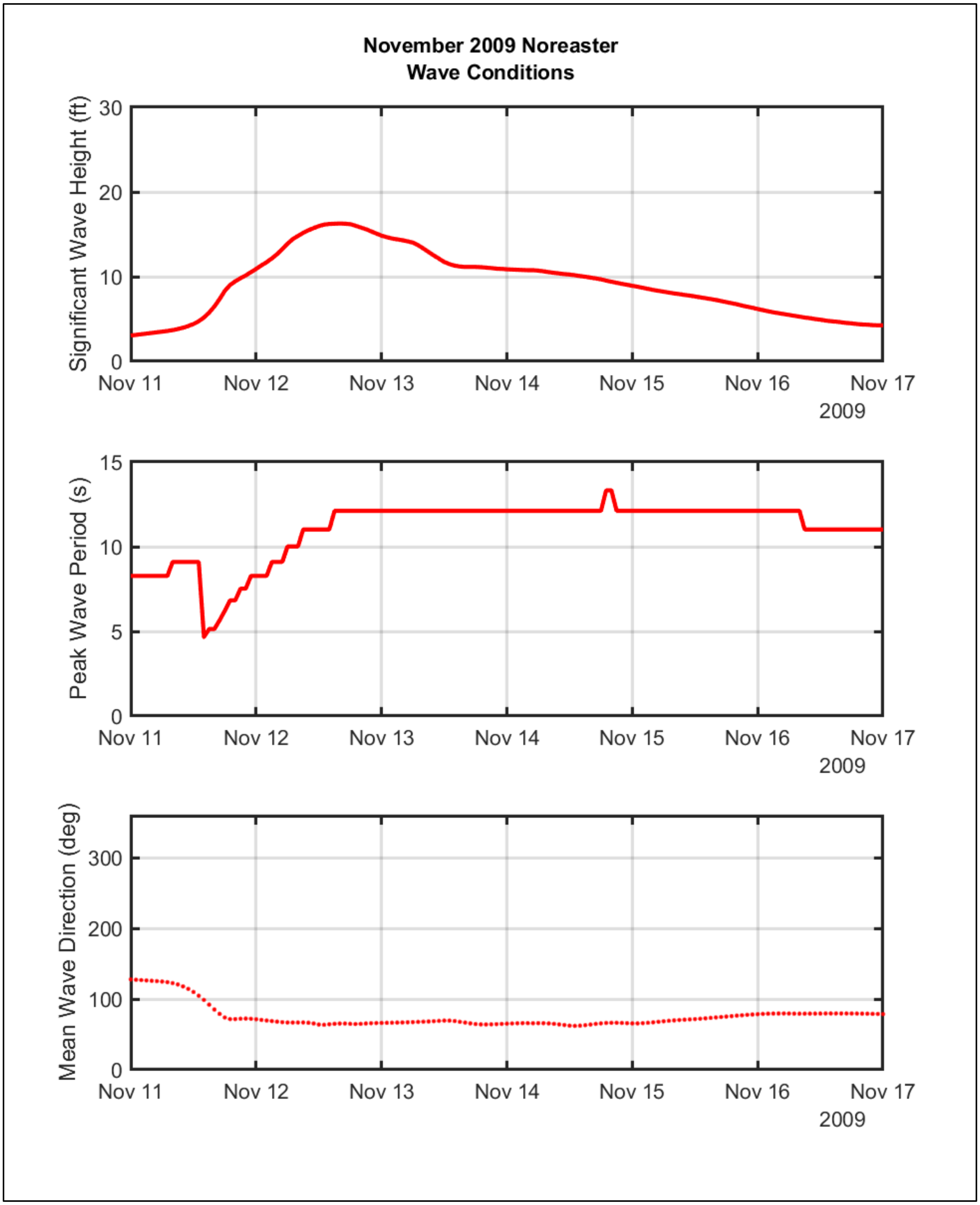


Figure 50. Hindcast forcing conditions used for the November 2009 Nor'easter XBeach simulation (November 11–17, 2009): (top) significant wave height (ft), (middle) peak wave period (s), (bottom) wave direction (deg).

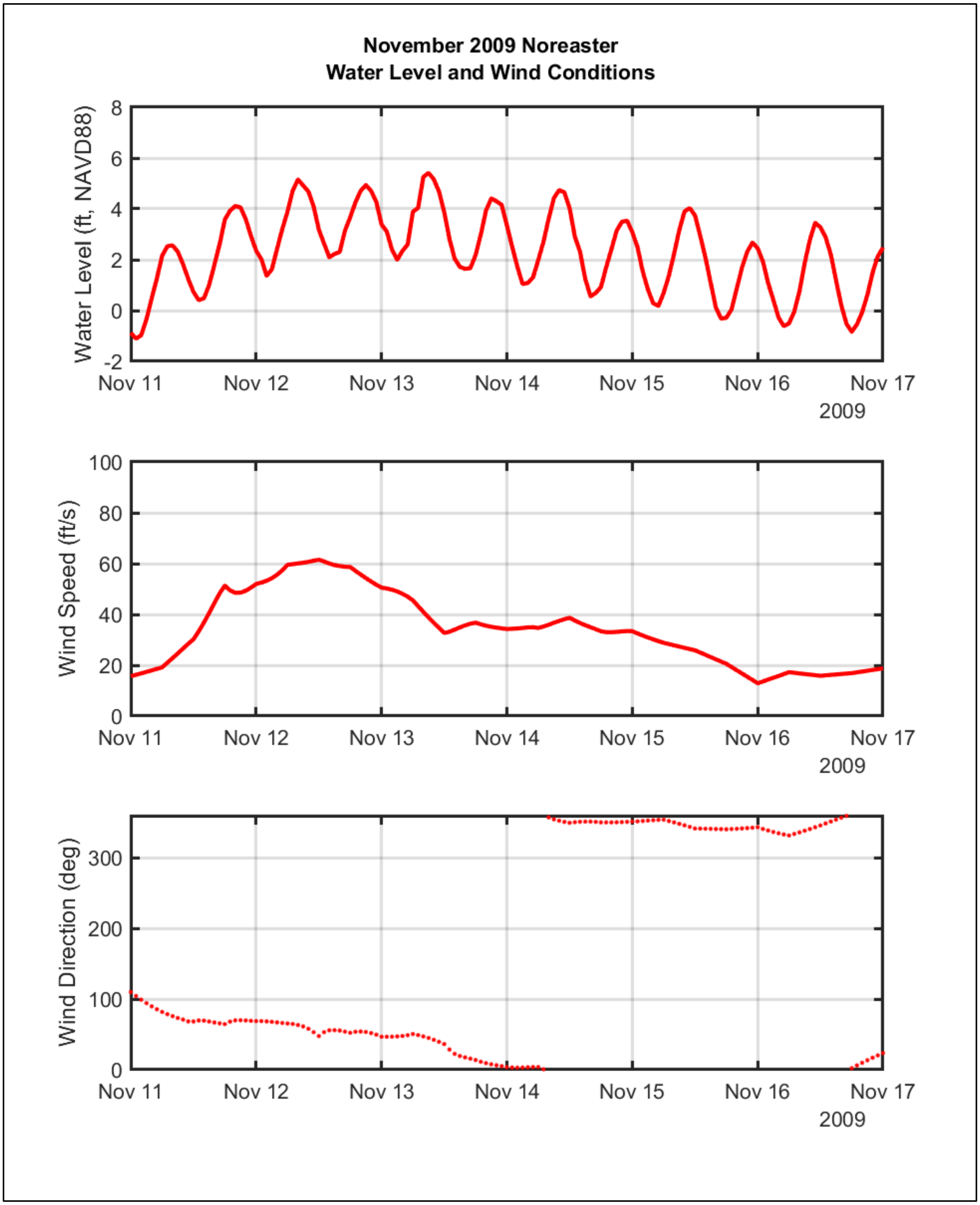


Figure 51. Hindcast meteorological and observed water level conditions used for XBeach during November 2009 Nor'easter XBeach simulation (November 11–17, 2009): (top) water level (ft, NAVD88) at NOAA Station 8651370 (Duck, NC), (middle) wind speed (ft/s), and (bottom) wind direction (degrees).

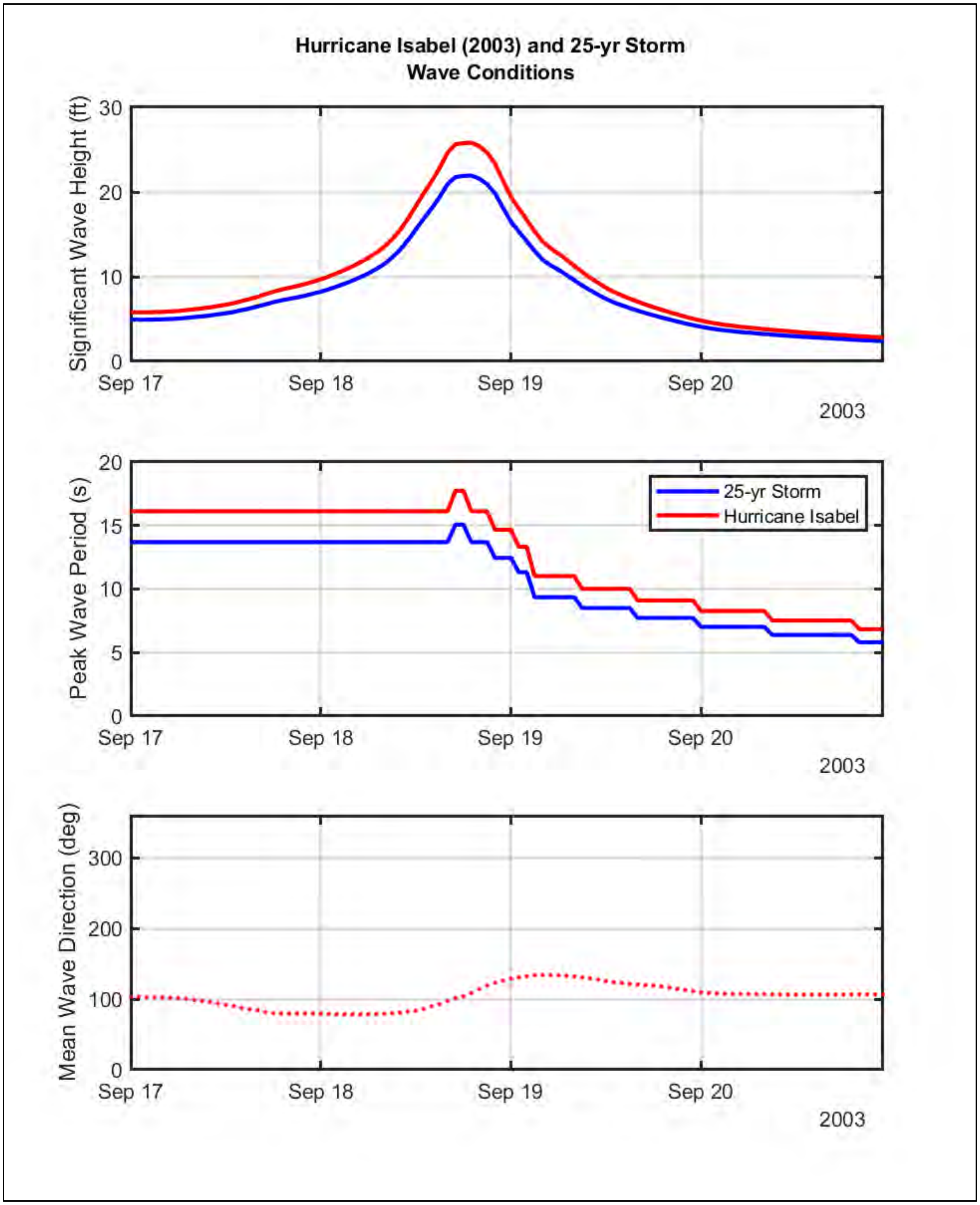


Figure 52. Hindcast forcing conditions used for the Hurricane Isabel (2003) and 25-yr Storm XBeach simulation (September 17–20, 2003): (top) significant wave height (ft), (middle) peak wave period (s), (bottom) wave direction (deg).

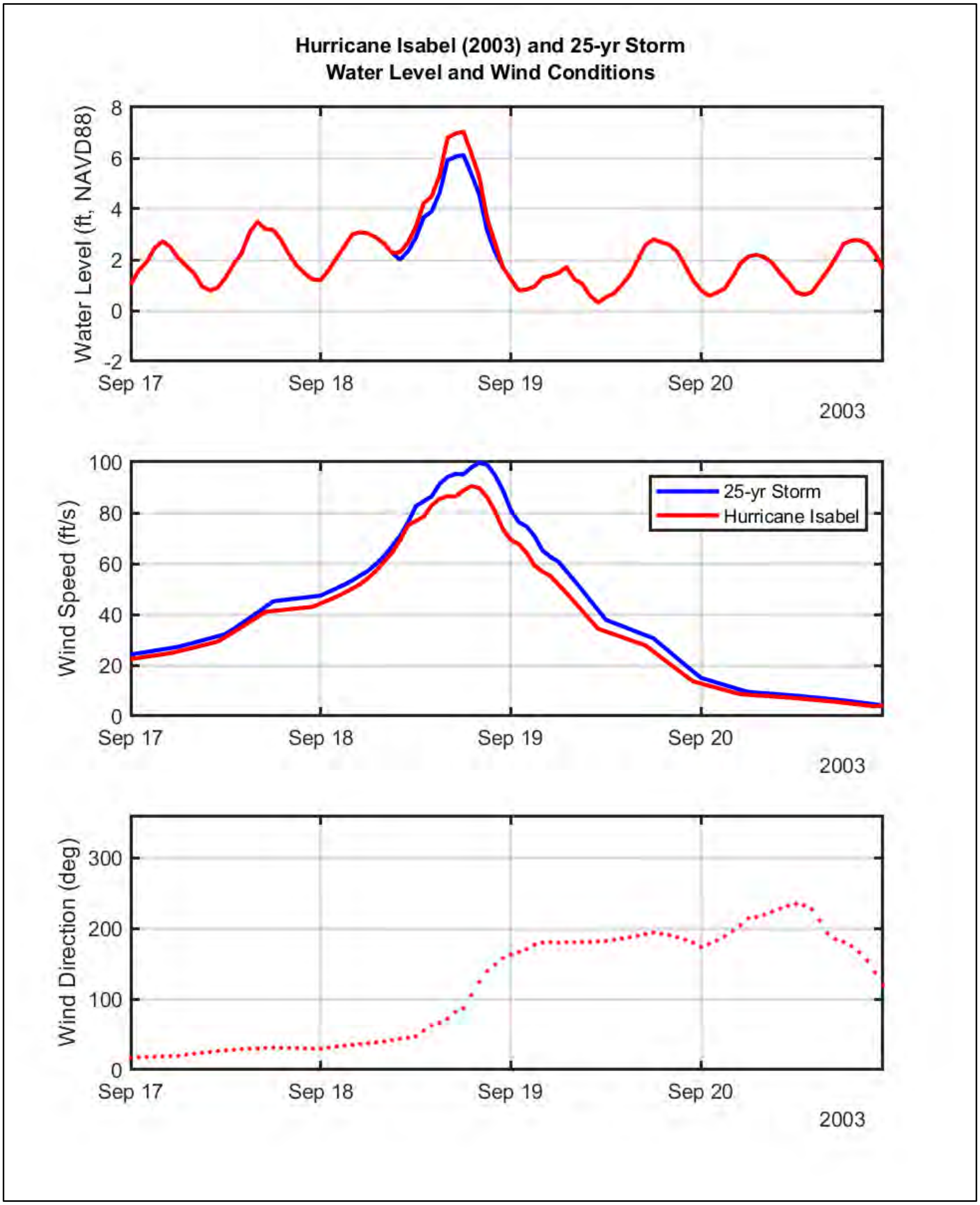


Figure 53. Hindcast meteorological and observed water level conditions used for XBeach during Hurricane Isabel (2003) and 25-yr Storm XBeach simulation (September 17–20, 2003): (top) water level (ft, NAVD88) at NOAA Station 8651370 (Duck, NC), (middle) wind speed (ft/s), and (bottom) wind direction (degrees).

Storm Simulation Results

Model results from the simulated storm scenarios were used to identify the 1-foot vertical recession point at each cross-shore profile. Recession point locations are reported relative to the dune crest, where positive values indicate the recession point remains seaward of the crest and negative values indicate landward penetration beyond the crest. Results for all profiles, south of the Horse Gate (C-059 to C-120), across the three storm scenarios are summarized in Table 12, and a representative post-storm profile response is shown in Figure 54.

Table 12. 1-foot vertical recession point locations relative to the pre-storm dune crest location for XBeach 1D Production Runs for the Hurricane Isabel, November 2009 Nor'easter, and the synthetic 25-year return interval storms.

Profile Station	Hurricane Isabel Recession Location (ft)	Nor'easter 2009 Recession Location (ft)	25-yr Storm Recession Location (ft)
C-059	-14.0	-4.4	-5.4
C-060	-16.4	-2.4	-4.9
C-061	1.8	16.0	12.3
C-062	-18.0	-4.9	-7.6
C-063	-28.6	-5.2	-6.8
C-064	-72.6	-4.9	-7.6
C-065	-13.9	-3.7	-7.4
C-066	-14.3	-2.1	-7.3
C-067	-10.7	-2.1	-4.9
C-068	-9.1	0.9	-1.5
C-069	-5.2	3.4	0.9
C-070	-11.0	-3.4	-5.2
C-071	-7.4	2.2	-1.5
C-072	-7.3	0.7	-1.3
C-073	-2.4	6.8	1.4
C-074	-7.8	0.3	-2.0
C-075	-4.0	2.2	0.9
C-076	6.8	18.4	14.7
C-077	-5.4	5.8	1.0
C-078	3.4	13.3	9.9
C-079	-4.4	4.1	1.0
C-080	-10.0	2.6	-2.6
C-081	-9.8	0.4	-3.1
C-082	-6.2	9.0	4.3
C-083	-2.8	7.5	3.9
C-084	-16.0	0.4	-3.1
C-085	-10.2	3.0	-2.5
C-086	-10.5	2.3	-2.7
C-087	-6.7	4.3	-2.0

Profile Station	Hurricane Isabel Recession Location (ft)	Nor'easter 2009 Recession Location (ft)	25-yr Storm Recession Location (ft)
C-088	-6.7	2.0	0.8
C-089	-3.1	5.5	4.3
C-090	-6.7	4.3	1.2
C-091	-2.7	5.9	4.3
C-092	-9.4	2.0	-2.3
C-093	-10.6	-2.4	-3.5
C-094	-6.6	4.7	-1.6
C-095	-2.7	9.4	2.7
C-096	-2.9	11.6	5.8
C-097	-5.9	10.9	7.7
C-098	-3.4	14.1	9.2
C-099	5.0	18.0	14.9
C-100	-7.2	3.1	-1.8
C-101	-10.3	0.9	-1.8
C-102	-20.3	-1.8	-7.2
C-103	-11.0	5.3	-0.9
C-104	-6.2	6.2	1.3
C-105	-3.5	10.5	5.3
C-106	-2.7	12.8	6.6
C-107	1.7	21.9	15.5
C-108	1.3	18.6	11.7
C-109	-3.4	11.2	6.4
C-110	11.0	30.4	26.0
C-111	-6.9	5.2	0.9
C-112	-11.5	0.9	-2.7
C-113	-7.3	5.6	2.1
C-114	-15.3	-3.0	-6.9
C-115	-23.7	-5.9	-11.4
C-116	-14.3	1.6	-2.6
C-117	-4.8	12.2	9.0
C-118	-1.6	19.5	14.1
C-119	-3.1	13.6	6.3
C-120	2.6	22.3	14.1
Average	**-8.1**	**5.6**	**1.6**

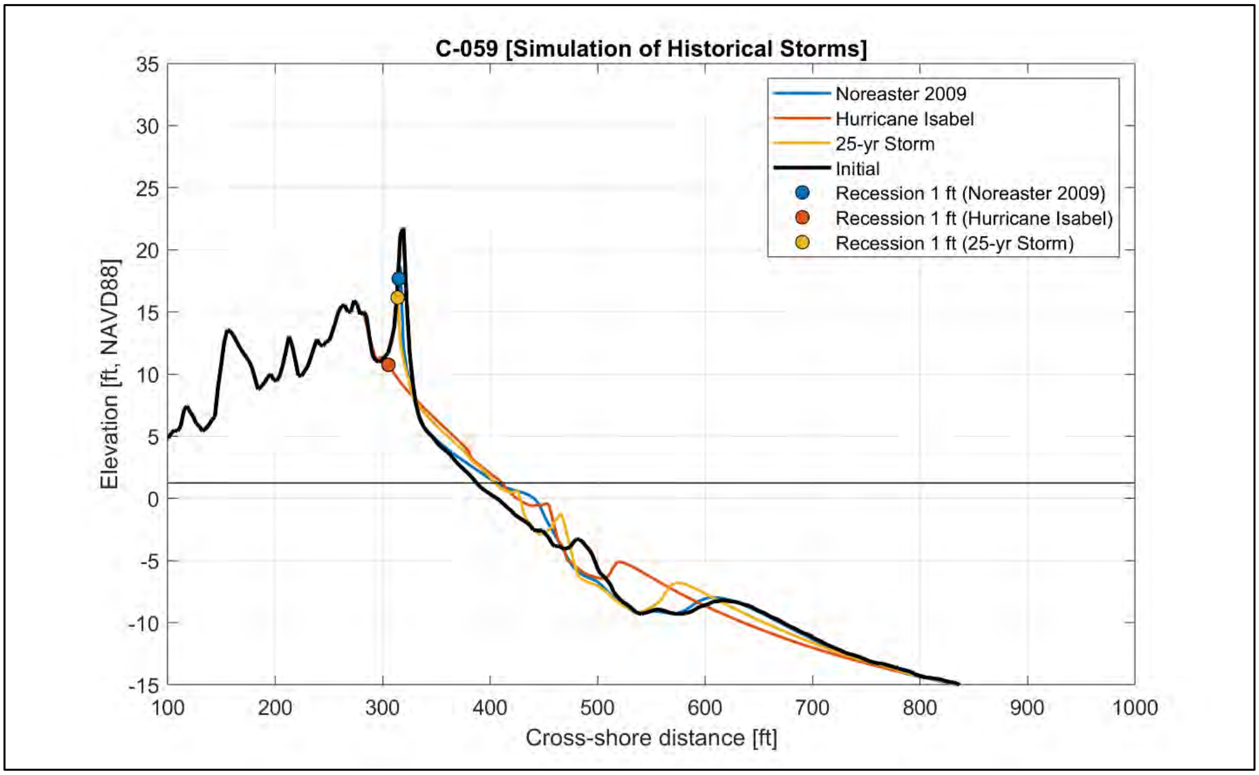


Figure 54. Example modeled post-storm profile response for selected storm scenarios, including identification of the 1-foot vertical recession point

The simulation of Hurricane Isabel under June 2025 conditions produced the most severe and spatially consistent landward recession across the study area, with an average recession point location of -8.1 ft. relative to the dune crest and nearly all profiles recording negative (landward of the dune crest) recession point location values. Several profiles in the northern reach recorded recession point locations exceeding -15 ft., indicating extensive dune erosion and increased overwash potential under extreme storm conditions. The 25-year synthetic storm yielded intermediate results, with an average recession point location of 1.6 ft. seaward of the dune crest and a combination of seaward and landward recession values reflecting spatially variable morphologic response. The November 2009 Nor'easter produced the least landward recession overall, with an average recession point location of 5.6 ft. seaward of the dune crest, although localized negative recession point values and a consecutive pattern of negative recession points across Stations C-059 through C-067 indicate that certain areas remain vulnerable even under lower-energy storm conditions.

The beach profiles at Stations C-060 through C-066 consistently exhibit significant landward recession across all three storms, suggesting beach vulnerability independent of storm severity. This vulnerability commonly corresponds with low dune crest elevations, narrow foredune widths, and narrow berm widths, which collectively reduce the morphologic buffer available to absorb wave runup and storm surge. The beach profile at Station C-064 is a notable outlier under Hurricane Isabel conditions, with a recession point location of -72.6 ft. landward of the dune crest indicative of likely full dune erosion and overwash penetration well into the backshore. Beyond

C-064, seven additional profiles recorded Hurricane Isabel recession point locations exceeding -15 ft. (C-060, C-062, C-063, C-084, C-102, C-114, and C-115), indicating that severe dune erosion and overwash potential were not isolated to a single location but distributed across multiple reaches of the study area.

The 1-foot vertical recession point locations were connected to generate a continuous vulnerability impact line for each storm scenario. Maps showing these impact lines along the Corolla and Pine Island Sections are provided in Appendix B and an example is shown in Figure 55. This spatial representation helps to visualize areas with the greatest potential for storm vulnerability and may be an indication of locations that are more vulnerable to overwash and breaching. These are the primary processes of concern of the XBeach analysis and lead into the 2D XBeach Analysis discussed in Section 2.1.4.2. The vulnerability impact lines also provide additional context to the recession point locations relative to existing infrastructure, offering greater insight than recession location magnitudes alone. Full profile and recession point plots for all profiles are provided in Appendix C.

Figure 55. Vulnerability impact lines interpolated from 1-foot vertical recession points for simulated storm scenarios.

After overlaying the vulnerability impact lines onto aerial imagery, the proximity of recession extents to existing infrastructure was evaluated to identify areas with the greatest potential threat to developed spans of the barrier island. These impact lines were used in the development of the vulnerability matrices described in Section 2.4 (Vulnerability Matrix). While some profiles exhibited only moderate recession magnitudes, the limited setback distance between the dune and developed infrastructure increases the potential consequences of overwash and breaching in this region.

2.1.4.2 XBeach 2D

The following sections describe the model setup, calibration, and application of the two-dimensional horizontal (2D) XBeach model used to evaluate beach and dune vulnerability under extreme storm conditions.

The 2D model built upon the 1D analysis by resolving alongshore variability in hydrodynamics and morphology, allowing for improved assessment of localized erosion, overwash, and breaching processes. The Delft3D analysis and the 1D Xbeach analysis, as well as past monitoring studies conducted along the Currituck County oceanfront, have consistently identified the section of beach spanning Stations C-060 to C-084 as the most vulnerable. This portion of the oceanfront includes the Ocean Hills and Whalehead Beach communities. Therefore, the 2D model domain was centered on the region spanning profiles C-060 to C-084.

Computational Grids

A two-dimensional computational grid was developed to encompass the targeted region , with sufficient buffer zones on either side to minimize boundary effects. The model domain extends alongshore from Station C-048 to C-096, providing approximately a 10-station buffer beyond the primary analysis reach (Station C-060 to C-084) and reducing artificial shadow zone effects associated with the lateral boundary conditions (Figure 56). The computational grid was developed using the Deltares program QUICKIN with a rectilinear grid configuration.

In the cross-shore direction, the grid extends from an offshore depth of approximately 79 feet to the Currituck Sound, encompassing the full barrier island cross-section. This extent is necessary to capture potential overwash and breaching processes that could transport sediment and floodwaters through the barrier and into the sound, while also ensuring that the relevant nearshore and offshore processes governing wave transformation are fully represented within the model domain.

Grid resolution was selected to balance computational efficiency with the need to accurately resolve nearshore hydrodynamics and dune morphology. The alongshore grid spacing was set to a uniform 82 feet. In the cross-shore direction, grid spacing varied from approximately 8 feet in the nearshore and subaerial regions to 131 feet near the offshore boundary. This variable resolution resulted in a total of approximately 382,000 computational cells.

The refined resolution across the nearshore and dune system is critical for resolving steep beach slopes, dune faces, and overwash pathways, while the coarser offshore resolution allows for efficient simulation without compromising nearshore accuracy.

Figure 56. XBeach 2D computational grid showing the model domain extent from Station C-048 to C-096.

Topography and Bathymetry

The topographic and bathymetric input for the 2D model was developed using the same datasets and methodology applied in the 1D analysis to maintain consistency between modeling approaches. The datasets were combined and interpolated onto each 2D computational grid to generate a continuous topobathymetric surface representative of pre-storm conditions. The resulting elevation surface used in the model is presented in Figure 57.

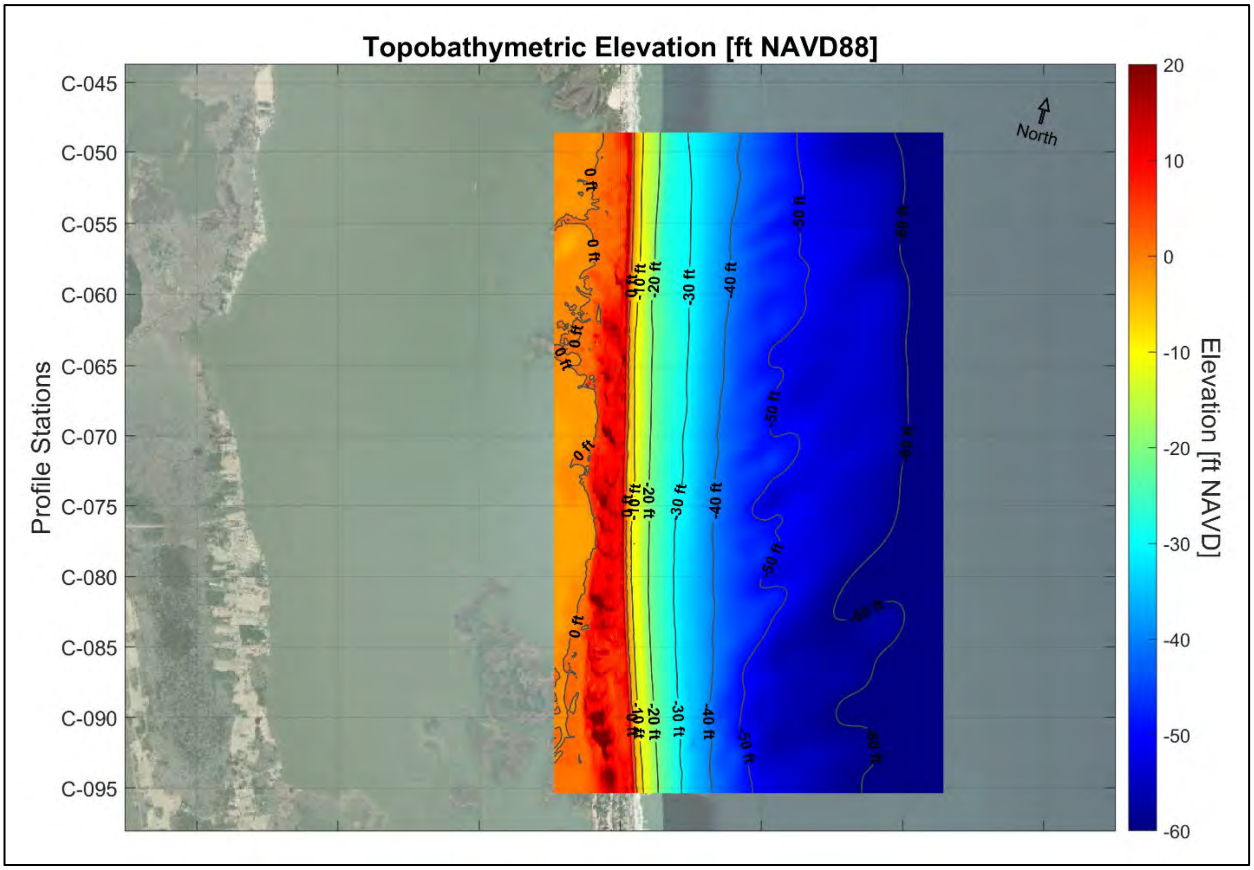


Figure 57. Interpolated pre-Hurricane Matthew (2016) topobathymetric surface used for the XBeach 2D calibration model.

Boundary Conditions and Forcings

Boundary conditions and forcing data for the 2D model were derived from publicly available datasets consistent with those used in the Delft3D and XBeach 1D analyses, ensuring continuity across modeling efforts (Section 2.1.3.1).

Model Calibration Parameter Selection

The 2D XBeach model was calibrated using Hurricane Matthew (2016) to reproduce observed morphological response under storm conditions. As with the 1D model, calibration focused primarily on the dry beach and dune system due to the limited availability of post-storm bathymetric data.

The model was implemented in *surfbeat* (instationary) mode, which resolves both short-wave processes and long-wave (infragravity) motions. A morphological acceleration factor of 1 was applied, such that morphological evolution was simulated without temporal scaling. Sediment transport was represented using a single sediment fraction with a median grain size (D50) of 0.19 mm and a D90 of 0.81 mm, based on sediment data from the 2020 Currituck County Beach

Monitoring and Stability Assessment. A spatially uniform grain size was applied as a simplifying assumption for the calibration simulations.

Simulations were conducted over a three-day period from October 8 to October 11, 2016, as shown in Figure 47 and Figure 48. Lateral boundary conditions were specified as Neumann boundaries, assuming zero alongshore gradients. The model was run using parallel processing (20 CPU-cores), with additional serial simulations performed to verify consistent model behavior.

Calibration involved adjustment of several model parameters to improve agreement with observed morphological change. Many parameters were consistent with the 1D calibration; however, some modifications were required to account for differences in two-dimensional process representation. The *wbcevarreduce* parameter was not applied in the 2D model, as short-wave group variability is inherently resolved in two dimensions. The *bedfriccoef* was reduced relative to the 1D value to increase sediment transport, and the *facua* parameter (wave skewness and asymmetry) was adjusted to improve model performance.

The final calibrated parameter set is summarized in Table 13.

Table 13. XBeach 2D model parameters adjusted during calibration of Hurricane Matthew.

Parameter	Description	Default	Selected
bedfriccoef	Bed friction coefficient	0.01	0.03
facua	Wave skewness and asymmetry parameter	0.175	0.165
gamma	Wave breaker parameter	0.46	0.40
alpha	Wave dissipation coefficient	1.38	1.68

Model Calibration Results

Model performance was evaluated through both qualitative and quantitative comparisons of measured and modeled morphological change.

The qualitative assessment focused on spatial patterns of erosion and sedimentation. Measured elevation change associated with Hurricane Matthew was computed by subtracting the pre-storm LiDAR surface (Figure 58) from the post-storm LiDAR surface (Figure 59). The elevation change from the two datasets is presented in Figure 60, and is the qualitative calibration target. Negative values (depicted by red colors) indicate erosion, and positive values (depicted by green colors) indicate sedimentation. The domain was subdivided into North (C-059 to C-071), Central (C-072 to C-084), and South (C-085 to C-095) regions to facilitate comparison of spatial variability, with region boundaries defined by the black dashed lines.

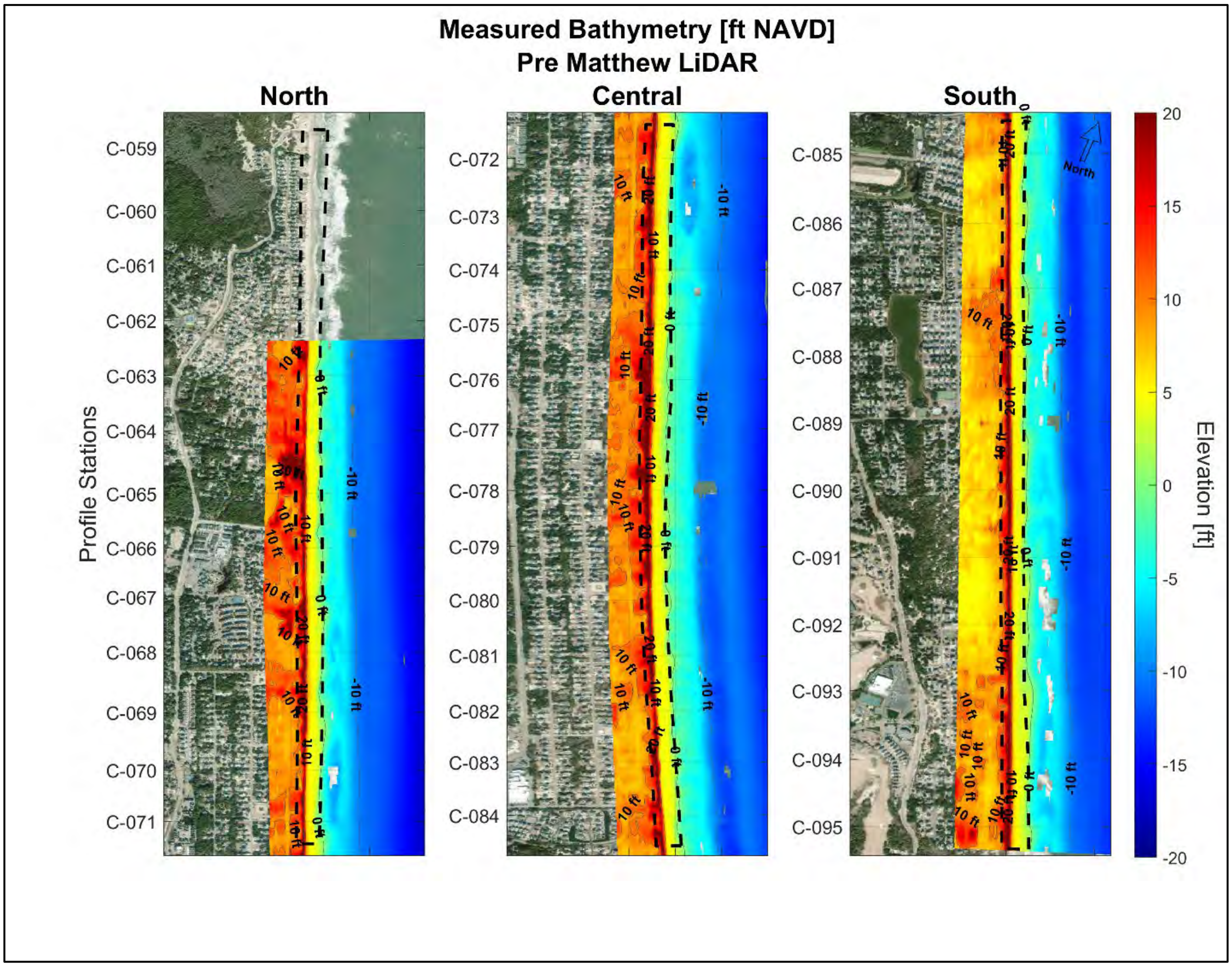


Figure 58. Pre-storm LiDAR surface elevation (ft, NAVD88) across the 2D model domain prior to Hurricane Matthew.

Modeled erosion and sedimentation patterns are shown in Figure 61. Overall, the model reproduces the observed distribution of erosional hotspots and depositional areas, including the general magnitude and spatial extent of change. Concentrated berm and dune face erosion landward of the MHW line is well captured across all three regions.

The North region is consistently erosional in both the measured and modeled results; however, the specific locations of peak erosion magnitude differ slightly, with the measured data showing the highest erosion concentrated in the upper half of the region and the model producing the highest erosion in the lower half. The Central region captures the erosion trends well relative to the measured data. A highly erosional zone spans an area located approximately between Stations C-072 to C-075 (1027 Lighthouse Dr. to 969 Lighthouse Dr.), transitioning to minimal erosion before intensifying again from Stations C-078 to C-084 (911 Lighthouse Dr. to 200 feet south of Albacore St.). Erosion magnitude in the measured data is slightly higher and more spatially concentrated than in the model, though the overall pattern is well established. The South region exhibits the most spatially variable erosion, with localized hotspots separated by low-change zones. The model captures the general location of these hotspots but smooths their spatial extent and underpredicts their magnitude, while correctly resolving the low-erosion intervals between them.

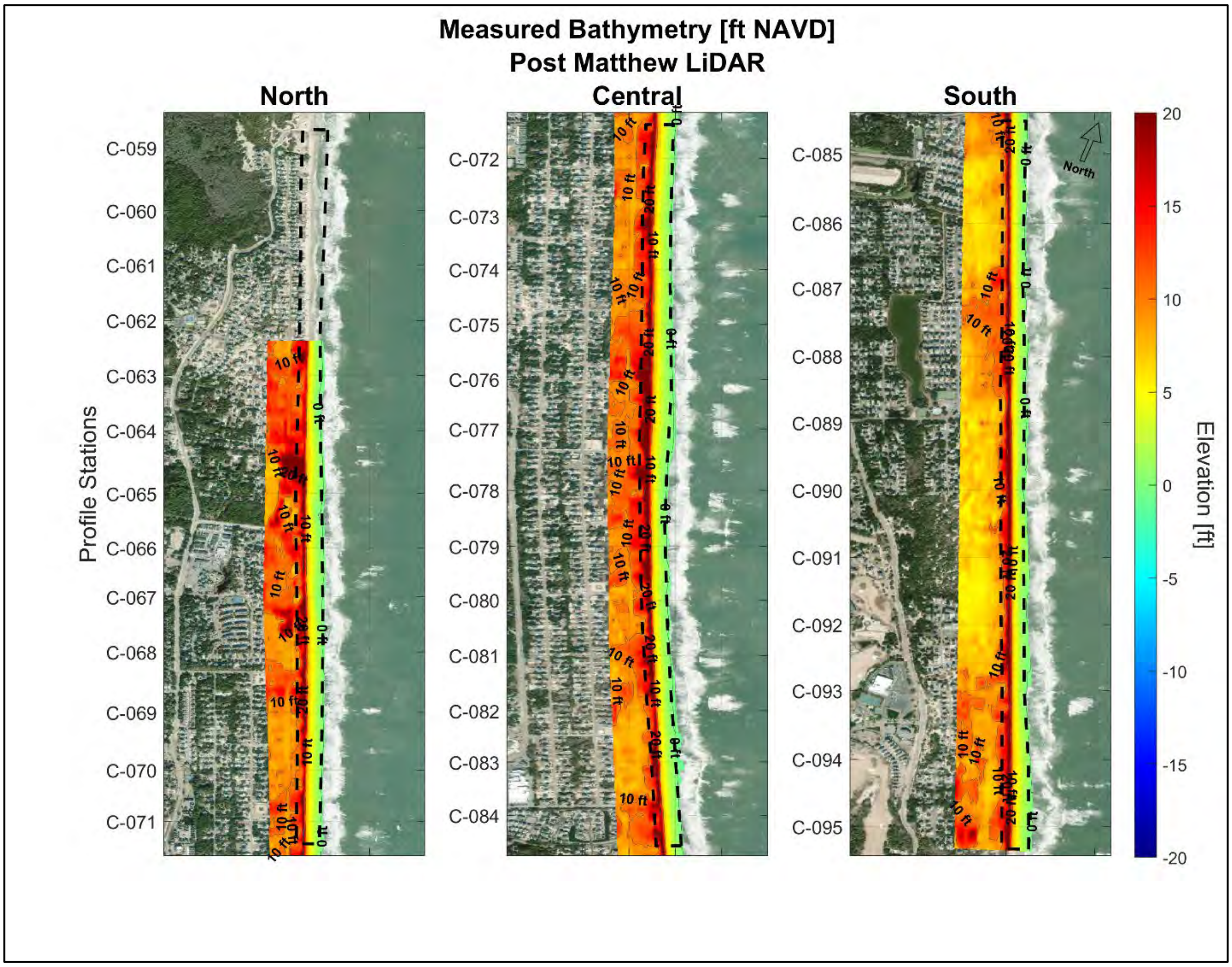


Figure 59. Post-storm LiDAR surface elevation (ft, NAVD88) across the 2D model domain following Hurricane Matthew.

Overall, the majority of erosion and sedimentation patterns are reproduced in the simulation; however, model performance has limitations. The modeled erosion bands are generally spatially smoother and less intense compared to the more localized, higher-magnitude signals in the measured LiDAR data. This is likely attributable to the model's alongshore grid resolution of approximately 82 ft., which is considerably coarser than the LiDAR survey resolution.

The quantitative analysis evaluated volumetric changes within each region. Figure 62 compares measured and modeled gross sedimentation, gross erosion, and net volume change for the North, Central, and South regions. The model shows reasonable agreement in gross erosion volumes across all three regions, with the closest agreement in the South region. Sedimentation volumes are generally underpredicted, particularly in the Central and South regions. Despite these differences in gross volumes, net volume changes are in good agreement, indicating that the model captures the bulk morphodynamic response of the system.

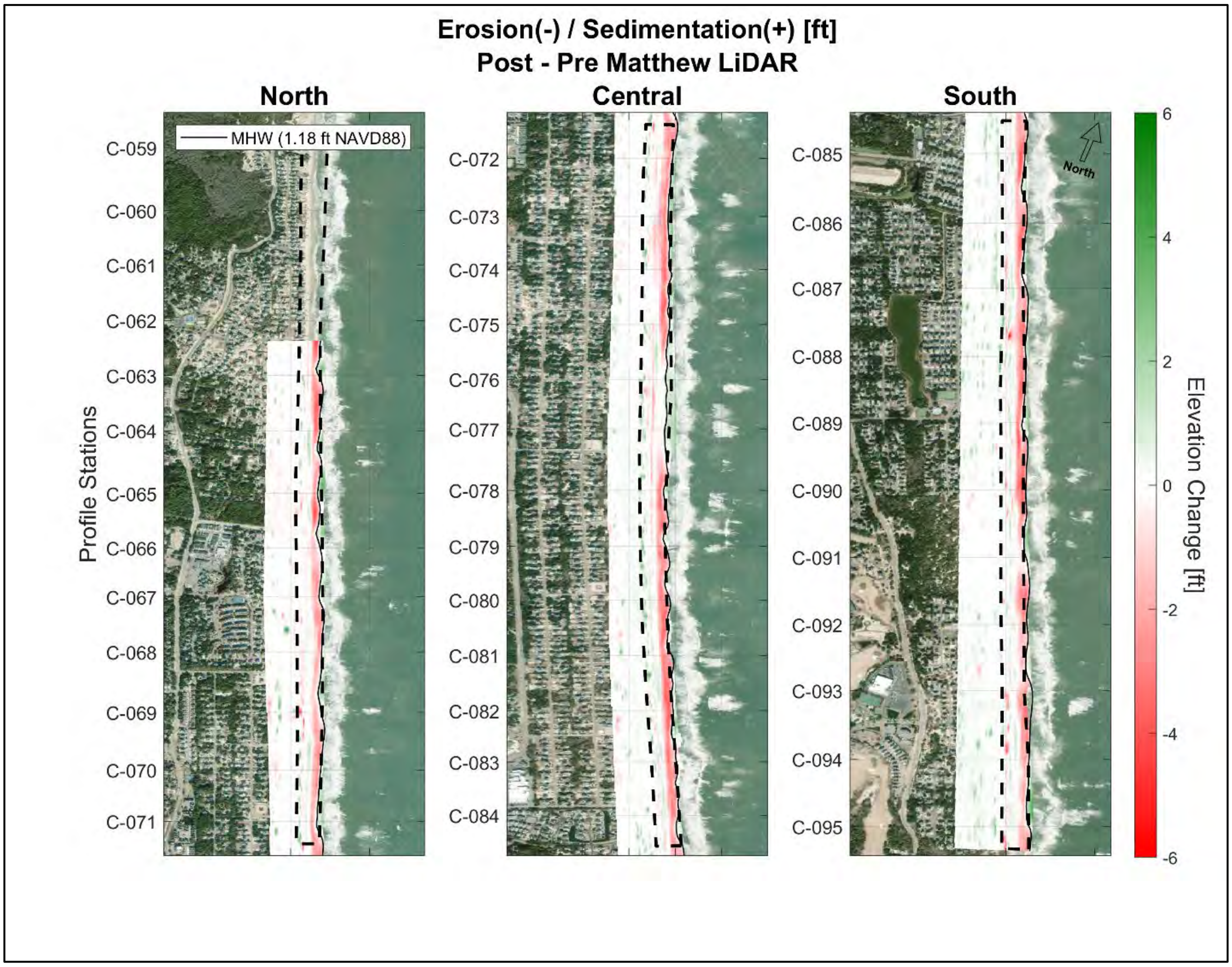


Figure 60. Measured elevation change associated with Hurricane Matthew, calculated as post-storm minus pre-storm LiDAR. Negative values indicate erosion and positive values indicate sedimentation.

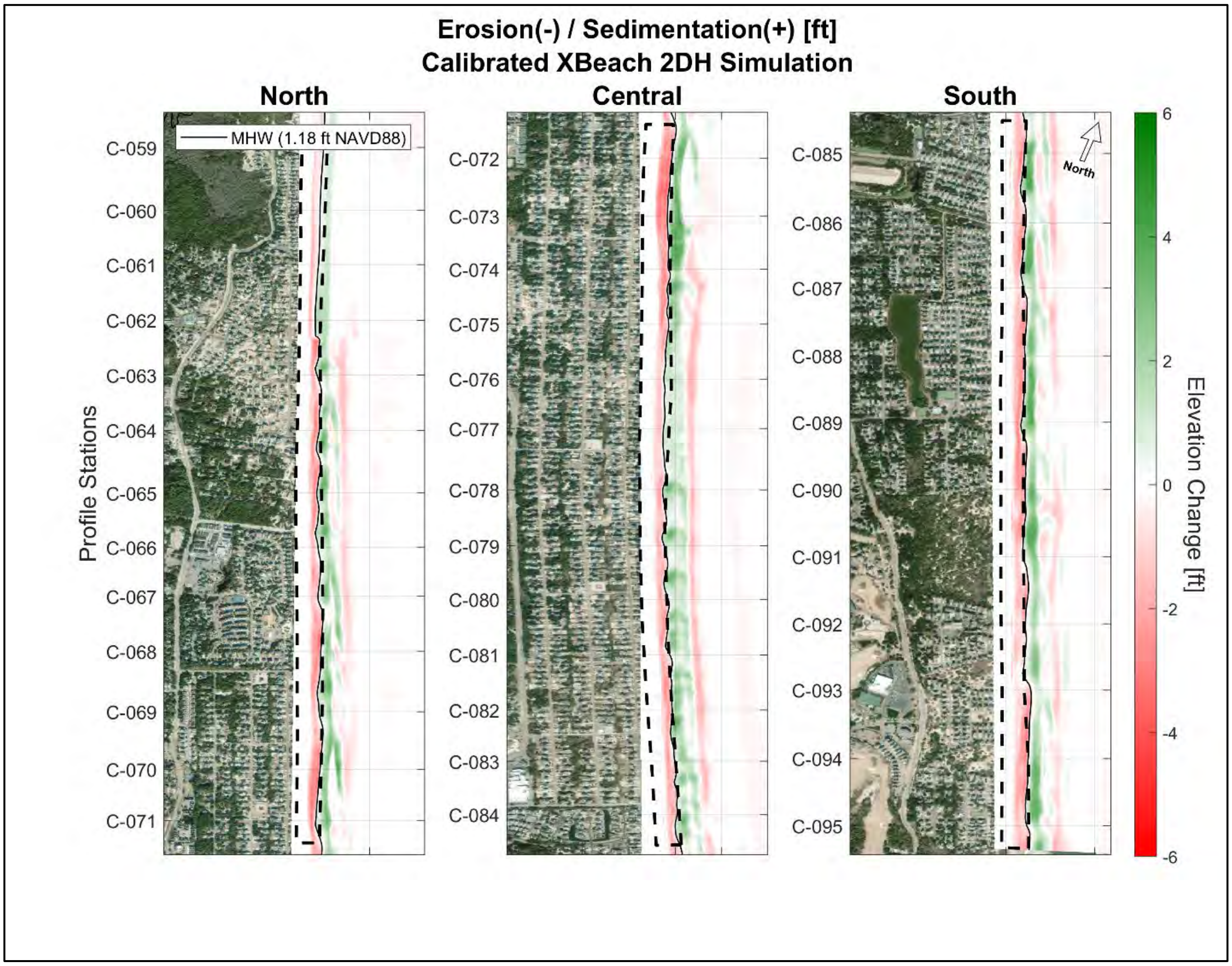


Figure 61. Modeled elevation change for Hurricane Matthew (2016) from the calibrated XBeach 2D simulation. Negative values indicate erosion and positive values indicate sedimentation. Dashed lines delineate the North, Central, and South regions used for quantitative analysis.

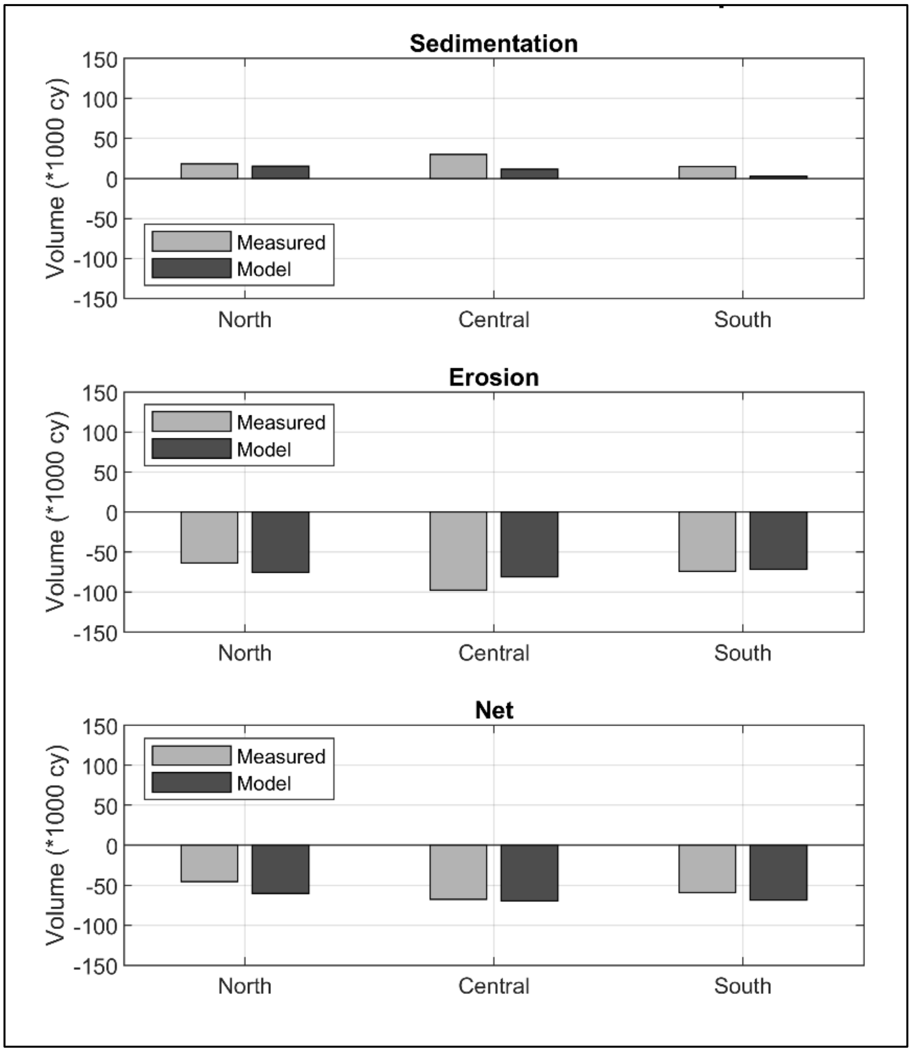


Figure 62. Comparison of measured and modeled volumetric changes (Hurricane Matthew, 2016) within the North, Central, and South regions.

A detailed assessment of alongshore variability is presented in Figure 63, which shows volume change per unit length of shoreline (cy/ft) at each alongshore grid column. These results were obtained by integrating cross-shore volume change within each column between the regional boundaries. The model successfully captures the spatial variability in erosion magnitude and reproduces the observed alongshore trends. Agreement is strongest in the Central region (Stations C-074 to C-086), while some divergence between measured and modeled values is observed in the northern portion of the domain near Stations C-068 to C-072. Overall, these results indicate that key processes controlling morphodynamic change are reasonably well represented.

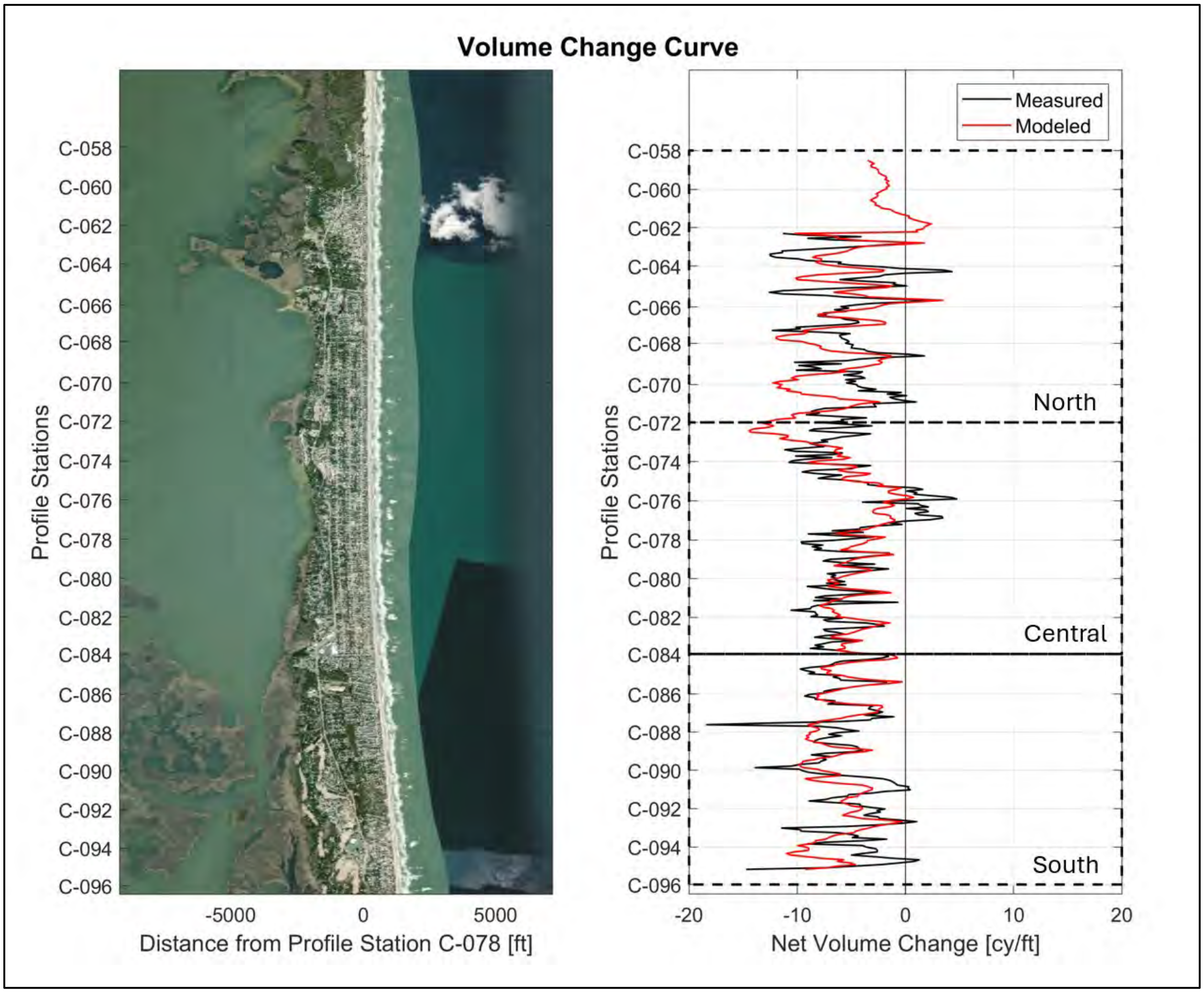


Figure 63. Alongshore distribution of net volume change (cy/ft) for measured and modeled conditions.

Production Runs Configuration

Following calibration, the 2D model was applied to selected storm scenarios to evaluate beach and dune vulnerability under more recent conditions for which data were available.

Based on the combined results of the extreme event analysis, Delft3D simulations, and XBeach 1D modeling, Hurricane Isabel (2003) and the synthetic 25-year storm were selected for simulation. Hurricane Dorian (2019) and the November 2009 Nor'easter were excluded, as preliminary testing indicated that these events did not generate sufficient water levels or wave conditions to produce significant dune erosion, overwash, or breaching within the model domain.

Sea-level adjustments and synthetic storm development followed the same methodology described in Section 2.1.4.1 and are summarized in Table 11.

All production run simulations were conducted using the calibrated model setup. Initial conditions for the 2D production runs used the 2019 USACE NCMP Topobathy LiDAR dataset, whereas the 1D production run simulations utilized the June 2025 beach profile survey data. For the 2D production runs, the simulations focused on overwash and breaching processes, where the higher-resolution LiDAR dataset was considered more appropriate because subtle topographic variations strongly influence flow pathways and localized erosion patterns. In contrast, the annual monitoring survey beach profile data, collected at 1,000-foot intervals, did not provide sufficient spatial resolution for these applications. The 2019 LiDAR dataset was determined to be the most recent high resolution data set available and was supplemented with NOAA NCEI CUDEM data in areas outside the LiDAR coverage to ensure complete representation of the model domain (Table 8). Forcing conditions were applied consistently with those used during the calibration simulations.

The two storms were simulated using the forcing conditions and sea-level adjustments described previously: Hurricane Isabel over a 3-day period from September 17–20, 2003 and the synthetic 25-year storm based on scaled Hurricane Isabel conditions over the same 3-day period. The forcing conditions applied at the model boundaries for each simulation are shown in Figure 50 through Figure 53.

Storm Simulation Results

Model results were analyzed using multiple metrics to characterize morphological response and identify areas susceptible to overwash and breaching.

Results for each storm scenario are presented in a series of three-panel figures (Figure 64 through Figure 67). Figure 64 and Figure 65 present results for Hurricane Isabel (2003), and Figure 66 and Figure 67 present results for the synthetic 25-year storm. The top subplot for Figure 64 and Figure 66 displays the full-domain erosion and sedimentation (ft), allowing for assessment of overall spatial patterns of morphological change. For Figure 65 and Figure 67, the top subplot is modified to display erosion only, constrained between 0 ft. and -10 ft. and discretized into 2-ft intervals, to improve visualization of erosion magnitude and allow for more direct comparison of severity across the domain. The second and third subplots present initial and post-storm maximum dune crest elevations (ft, NAVD88), and the corresponding change in dune crest elevation (ft), respectively. These outputs provide a quantitative measure of dune lowering and help identify locations where the protective capacity of the dune system is reduced. Initial and final topobathymetric surfaces used to generate the erosion and sedimentation plots for each storm scenario are provided in Appendix D for reference.

Appendix E presents zoomed plots of each storm scenario subdivided into six alongshore sub-domains, providing more detailed visualization of localized erosion patterns and spatial variability across the domain.

Key findings of the 2D model simulations are summarized below:

Hurricane Isabel

- Hurricane Isabel produced the most severe morphological response of the two storms simulated, consistent with the 1D results.
- Erosion was concentrated along the beach face and dune toe across the entire domain, with localized sedimentation observed in the nearshore.
- The 2D results showed dune crest elevations were lowered below the +10 ft. NAVD88 contour along several reaches, with the most severe reduction observed between Stations C-080 and C-088, where dune crest elevations were below the +10 ft. NAVD88 contour in several locations.
- Erosion above MHW was consistent and widespread across the entire domain (Figure 65), indicating that wave runup regularly exceeded the dune toe elevation throughout the study area.

25-Year Synthetic Storm

- The 25-year storm produced more moderate impacts compared to Hurricane Isabel, with post-storm dune crest elevations remaining above the +10 ft NAVD88 contour across the domain.
- The 2D results showed the dune crest elevation changes were generally less than 4 ft, with final dune crest elevations tracking closely with initial conditions across most of the domain.
- Erosion above MHW was more limited and spatially variable (Figure 67), suggesting that wave runup only intermittently exceeded the dune toe elevation under these conditions.

Areas of Highest Vulnerability

- The highest vulnerability to overwash and breaching under both storm scenarios was identified near Station C-064 (south end of Atlantic Ave.) and Station C-086 (between Crown Point and Ocean Sands communities).
- These areas are characterized by relatively low pre-storm dune elevations combined with elevated wave runup, resulting in pronounced erosional scarping and landward sediment transport indicative of overwash and localized breaching.
- These findings are consistent with the spatial vulnerability patterns identified in the 1D analysis.

Overall Assessment

- Based on 2019 conditions reflected by the Lidar data, the study area exhibited moderate resilience to more frequent storm events such as the 25-year synthetic storm.
- More extreme events comparable to Hurricane Isabel have the potential to significantly compromise dune integrity and create conditions conducive to widespread overwash and breaching.
- These processes have direct implications for infrastructure located landward of the dune system, where reduced dune elevations and breaching can increase exposure to wave attack, flooding, and structural damage.
- Given observed losses to the dunes along portions of Currituck County’s oceanfront since the annual monitoring surveys began in 2020, collection and analysis of Lidar data reflective of current conditions would provide a more current assessment of vulnerability.

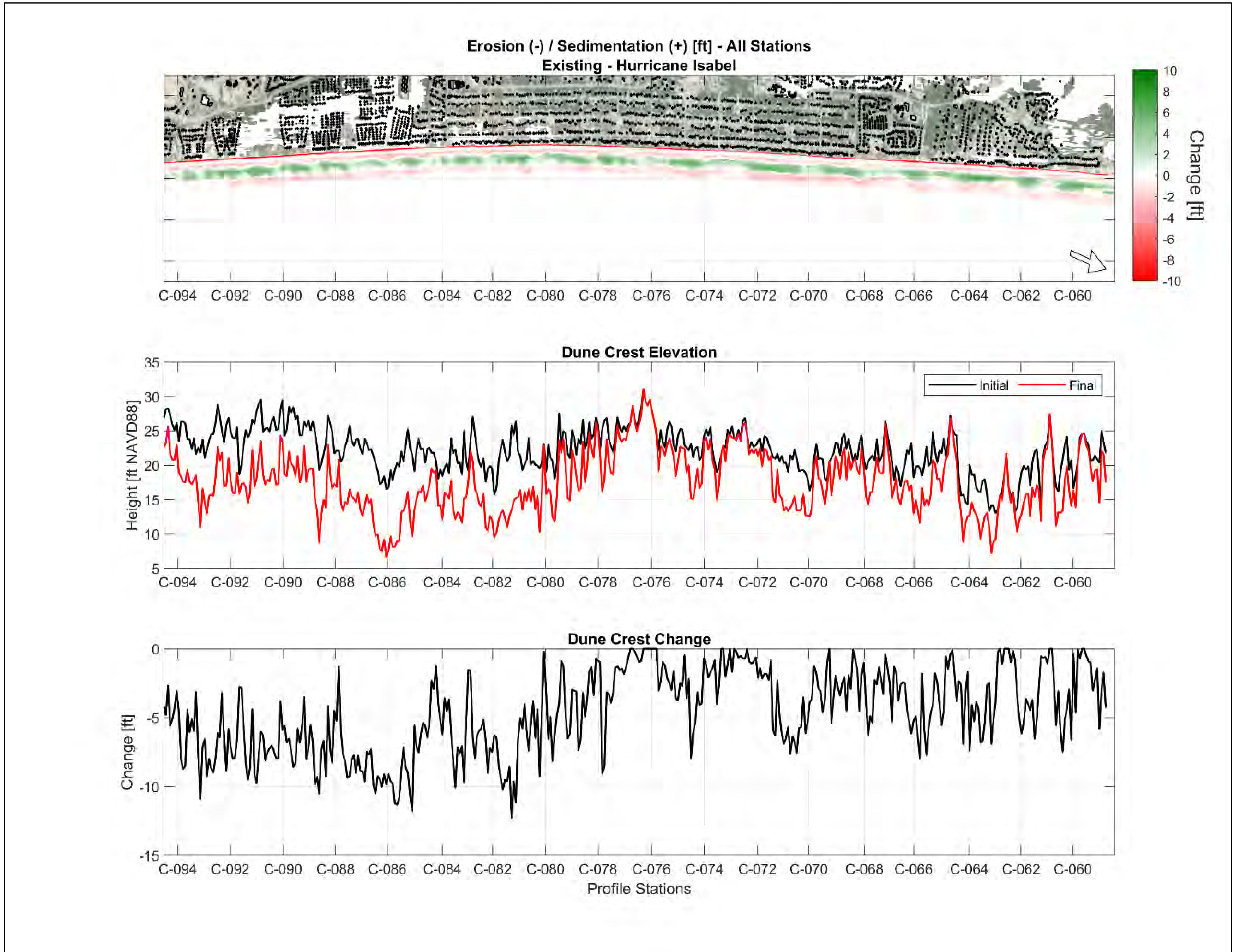


Figure 64. Modeled response to Hurricane Isabel (2003) across the full domain. Top panel: erosion and sedimentation (ft). Middle panel: initial and post-storm maximum dune crest elevations (ft NAVD88). Bottom panel: change in dune crest elevation (ft).

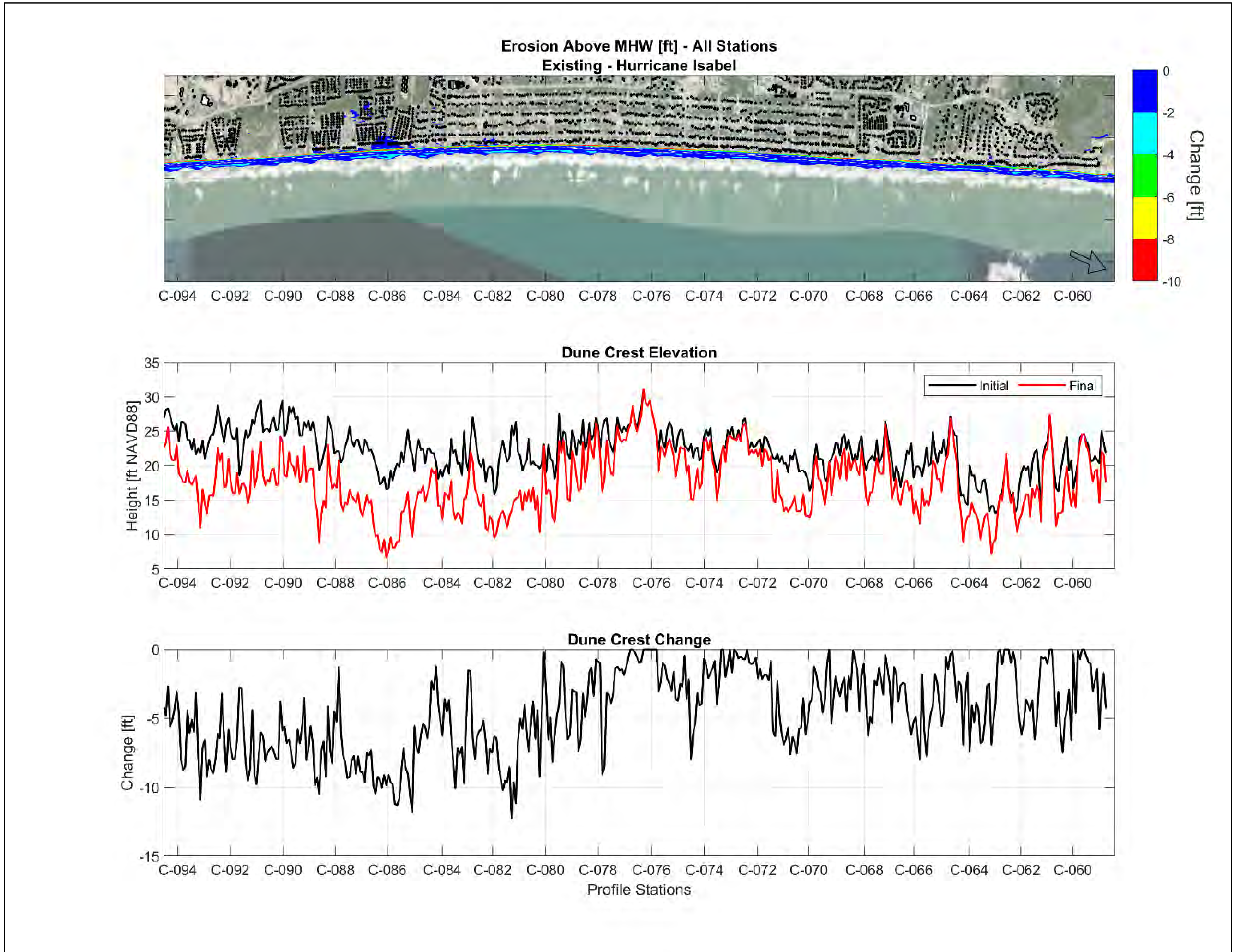


Figure 65. Discretized erosion view of modeled response to Hurricane Isabel (2003) across the full domain. Top panel: erosion above MHW (ft). Middle panel: initial and post-storm maximum dune crest elevations (ft NAVD88). Bottom panel: change in dune crest elevation (ft).

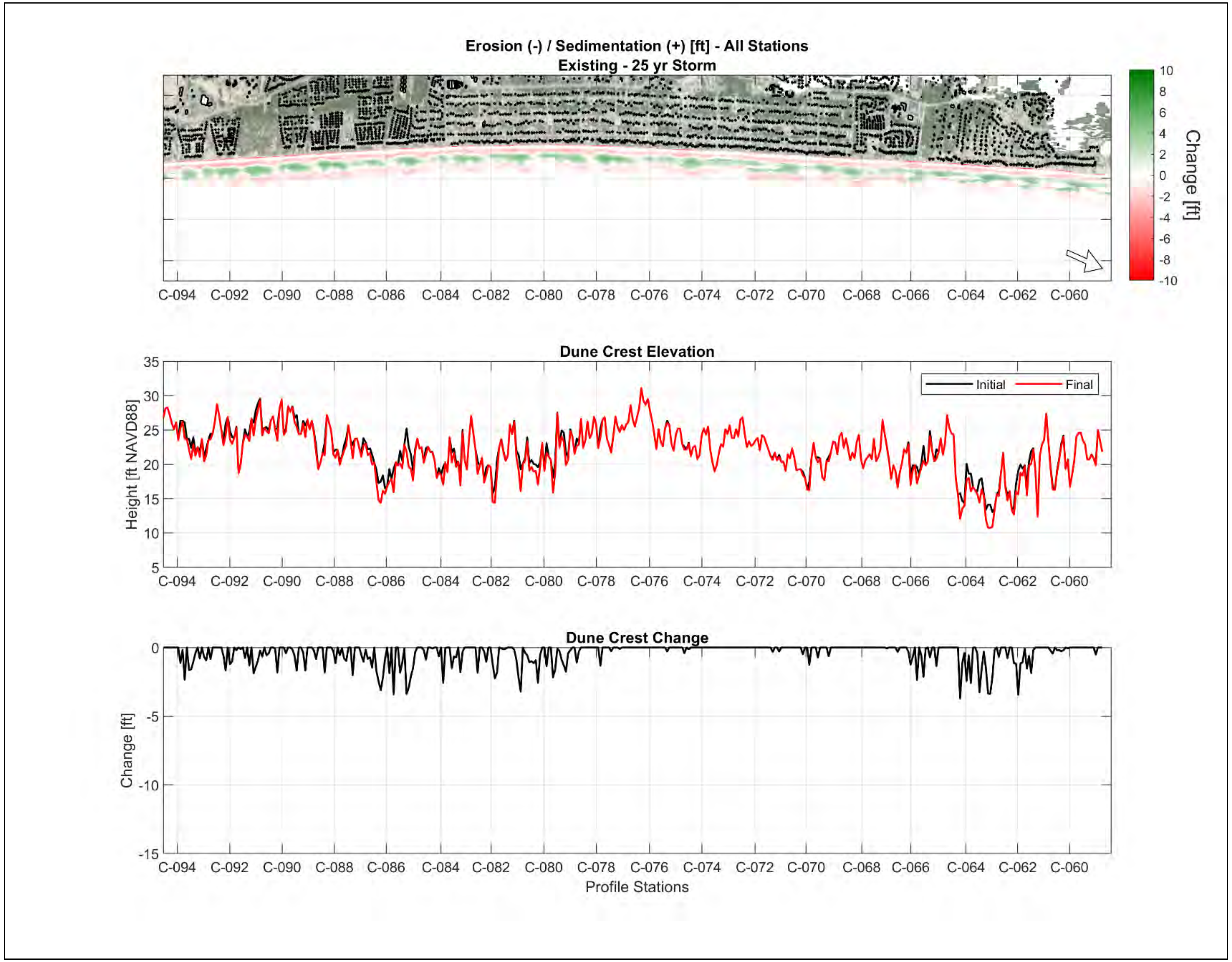


Figure 66. Modeled response to synthetic 25-year storm across the full domain. Top panel: erosion and sedimentation (ft). Middle panel: initial and post-storm maximum dune crest elevations (ft NAVD88). Bottom panel: change in dune crest elevation (ft).

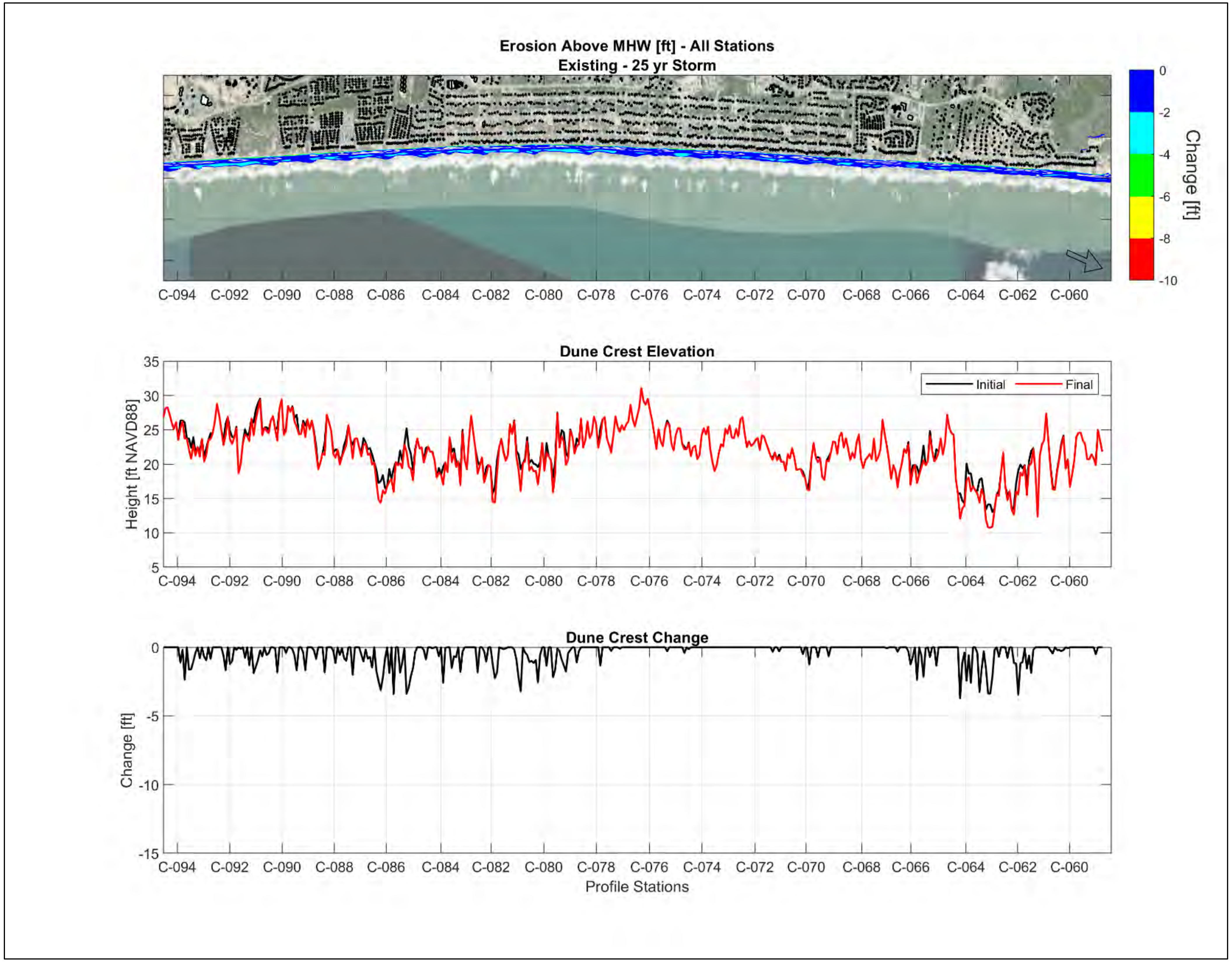


Figure 67. Discretized erosion view of modeled response to synthetic 25-year storm across the full domain. Top panel: erosion above MHW (ft). Middle panel: initial and post-storm maximum dune crest elevations (ft NAVD88). Bottom panel: change in dune crest elevation (ft).

2.2 Long Term Erosion

Oceanfront beaches are susceptible to a number of factors that can result in erosion. Coastal storms that produce large waves and storm surge can cause episodic erosion events. Regional sediment supply from rivers and inlets can have a profound impact on erosion along a particular oceanfront. In this regard, a location that has a large influx of regional sediment being input into a coastal area from large rivers or updrift movement of sediment may keep up with the erosion that occurs from episodic events like coastal storms. Changes in the gradient of alongshore currents due to nearshore coastal processes can also cause significant changes in localized erosion trends. Furthermore, coastal structures may impact erosional and accretional trends.

Erosion is often measured in terms of two metrics; shoreline change and volumetric change. Shoreline change is essentially a measured distance either landward or seaward in which the shoreline moves over time. A shoreline can be defined in several ways. At times shorelines are defined based on the location of the wet/dry line observed in ortho-rectified aerial photos. Other times shorelines are established based on a given elevation contour. In this regard, the location of the pre-determined elevation contour is identified through surveys and that position is compared to the location of that same elevation contour at various times. Shoreline change is often easier to determine due to the amount of publicly available aerial photos and lidar data available along beaches. However, shoreline change should be considered a proxy for erosion and not an actual evaluation of the change in the amount of sand along the beach.

Volumetric change is measured by comparing two surveys covering the same location from different time periods. Along beaches, these surveys are typically collected either at regularly spaced shore perpendicular transects along the beach or with the use of topo/bathy lidar systems. When computing volumetric changes measured along a beach, an important aspect of the process to be considered is the offshore extent to which volumetric changes are computed. Often, engineers will use what is referred to as a depth of closure as the offshore limit of these measurements. The concept of depth closure is used in coastal engineering applications to define a theoretical depth along a beach profile where sediment transport is very small or non-existent, dependent on wave characteristics and sediment grain size.

When considering erosion along a beach, the timescale for which the erosion is evaluated is important to consider. While episodic events like hurricanes or nor'easters may remove sand from a beach or transport the sand from one part of the beach to another, the beach may recover from these temporary impacts over period of months or weeks following an event depending on sea conditions following the storm. For this reason, evaluating long-term (multi-year) trends is important to understand how best to manage the beach.

Beginning in 2020, Currituck County initiated a Beach Monitoring and Beach Stability Assessment to evaluate long-term and short-term shoreline and volumetric changes occurring along Currituck's oceanfront beaches. In 2020, 120 beach profile transects were established along the entire length of the County's oceanfront. These transects are shown in Figure 2 through Figure 9. All 120 profiles were surveyed in May 2020, June 2021, and May 2022. In 2022, the County's monitoring program was adjusted so that only in even number years, is the entire County oceanfront surveyed and in the odd number years, monitoring would be conducted south of the Horse Gate only (C-059 to C-120). This pattern began in June 2023 and has continued through 2025.

The following sections provide information on long-term erosion based on the results of the County's monitoring program.

2.2.1 Shoreline Change

Data collected between May 2020 and June 2025 as part of the County's monitoring program, was combined with four (4) historical lidar data sets collected by the U.S. Army Corps of Engineers (USACE) between June 2009 and June 2019 to evaluate historical shoreline change rates. Individual rates for each of the 120 transects were calculated using a linear regression method (CPE, 2026). Average shoreline change rates for each of the four (4) Sections were computed and are listed in Table 14. Given the County's monitoring program only surveys the Carova and Reserve/Refuge Sections every other year on even years, Table 14 shows the historical rates for Carova and the Reserve/Refuge Section between August 2009 through June 2024; whereas the rates shown for the Corolla and Pine Island Sections reflect data between August 2009 and June 2025.

Table 14. Average Historical Shoreline Change Rates by Monitoring Sections

Section	Historical Rate (ft./yr.)
Carova (C-001 to C-027)	-0.9 (August 2009 to June 2024)
Reserve/Refuge (C-027 to C-059)	-3.6 (August 2009 to June 2024)
Corolla (C-059 to C-102)	-3.9 (August 2009 to June 2025)
Pine Island (C-102 to C-120)	-1.0 (August 2009 to June 2025)

The assessment of historical shoreline change rates conducted as part of the County's beach monitoring program, also included the development of shoreline change model to project shoreline change over a 10-, 20-, and 30- year period. The model uses the location of the +4.0 ft. NAVD88 contour at any given beach profile transect and projects shoreline change for the periods of 10-, 20-, and 30-years based on the historical shoreline change rates calculated between August 2009 and the most recent survey date. The first analysis was run using data between August 2009 and May 2020. The analysis has been updated annually since 2020 to include each subsequent data set and to initiate the projections from the most current shoreline position (+4.0 ft. NAVD88 contour). The analyses identify a house as "impacted" if any part of the footprint of the structure, as shown in the Currituck County GIS, was seaward of the 10-, 20-, or 30-year projected shorelines. The analyses do not include specific evaluations of damages to individual houses due to direct flooding, wave impacts, or wind impacts, nor do they quantify the economic impacts resulting from the damage or loss of such structures.

The nature of sand movement in response to wave and water level conditions makes shoreline position highly variable temporally. The response of a beach due to storm conditions typically results in a steepening of the beach slope near the water line and the movement of sand in the seaward direction forming offshore sand bars. During calmer wave periods, the beach often recovers as sand moves landward. The dynamic nature of the beach contours results in variation in the projected shoreline positions. While the overall rates used for the projections are based on multiple data sets dating back to 2009, and do not vary considerably from year to year, the position of the initial shoreline (+4.0 ft. NAVD88 contour) can vary considerably from year to year.

Table 15, Table 16, and Table 17 show the varying number of houses indicated as impacted over the 30-year, 20-year, and 10-year horizon based on the annual shoreline projection analyses conducted along Currituck County dating back to May 2020.

Table 15. Number of houses shown to be impacted over the 30-year shoreline projection conducted annually along Currituck County since May 2020.

Year	Total	Carova (C-001 to C-027)	Reserve/Refuge (C-027 to C-059)	Corolla (C-059 to C-102)	Pine Island (C-102 to C-120)
2020	**82**	5	5	68	4
2021	**75**	4	3	68	0
2022	**163**	0	5	158	0
2023	**158**	N/A	N/A	154	4
2024	**59**	0	3	56	0
2025	**43**	N/A	N/A	43	0

Table 16. Number of houses shown to be impacted over the 20-year shoreline projection conducted annually along Currituck County since May 2020.

Year	Total	Carova (C-001 to C-027)	Reserve/Refuge (C-027 to C-059)	Corolla (C-059 to C-102)	Pine Island (C-102 to C-120)
2020	**33**	0	3	27	3
2021	**19**	0	1	18	0
2022	**70**	0	4	66	0
2023	**45**	N/A	N/A	43	2
2024	**11**	0	1	10	0
2025	**19**	N/A	N/A	19	0

The results of the shoreline projection analyses demonstrate substantial year-to-year variability in the number of houses projected to be impacted, reflecting both the dynamic nature of shoreline position and changes in the initial shoreline condition used for each annual analysis. Across the six annual analyses conducted between 2020 and 2025, a general downward trend in the number of projected impacts is evident despite a pronounced spike in 2022. Over the 30-year projection horizon, the number of potentially impacted houses increased from 75 structures in 2021 to 163 structures in 2022 before declining steadily to 43 structures by 2025. A similar pattern was observed for the 20-year projections, which increased from 19 structures in 2021 to 70 structures in 2022, then declined to between 11 and 19 structures during 2024 and 2025. The 10-year projections identified substantially fewer impacts overall, ranging from zero to 14 structures, with no structures projected to be impacted in 2021, 2024, or 2025.

Table 17. Number of houses shown to be impacted over the 10-year shoreline projection conducted annually along Currituck County since May 2020.

Year	Total	Carova (C-001 to C-027)	Reserve/Refuge (C-027 to C-059)	Corolla (C-059 to C-102)	Pine Island (C-102 to C-120)
2020	**6**	0	2	4	0
2021	**0**	0	0	0	0
2022	**14**	0	3	11	0
2023	**2**	N/A	N/A	2	0
2024	**0**	0	0	0	0
2025	**0**	N/A	N/A	0	0

In nearly all projection periods, the Corolla Section accounted for the majority of projected impacts, whereas the Carova and Pine Island Sections generally exhibited minimal projected vulnerability to being impacted. The temporary increase in projected impacts observed in 2022 likely reflects short-term shoreline position variability rather than a significant change in long-term erosion rates, as the shoreline projection analyses are highly sensitive to the location of the initial +4.0 ft. NAVD88 shoreline contour used in each annual assessment. Overall, the more recent analyses from 2024 and 2025 indicate fewer projected impacts than earlier years, suggesting a short-term reduction in projected vulnerability to structural impacts relative to the peak conditions observed in 2022.

2.2.2 Volumetric Change

Data collected since May 2020 as part of the County's monitoring program, was also used to evaluate volumetric changes along the County's beaches. These measurements encompassed changes measured from the landward side of the primary dune seaward to the -19 ft. NAVD88 depth contour, which was established as the "Depth of Closure" (CPE, 2020). Given the County's monitoring protocol includes surveys south of the Horse Gate every year, but north of the Horse Gate in even year intervals only, the most up to date information on volume change is based on June 2025 data; whereas, the most up to date information on volume change north of the Horse Gate is based on June 2024 data.

Due to variability in data collection between the regions north and south of the Horse Gate, rates are based on the most recent datasets for each of the respective regions. The average volumetric change rate measured along the oceanfront north of Horse Gate between May 2020 and June 2024 was +1.1 cy/ft./yr. This translates to a total volumetric gain of approximately 269,900 cubic yards or approximately 66,103 cy/yr. Table 18 shows the volumetric change rates and total volume changes north of the Horse Gate along the Carova and Reserve/Refuge Sections. Carova experienced an average positive volumetric change rate of +3.1 cy/ft./yr over the approximate 4-year time period. In contrast, the Reserve/Refuge Section experienced a negative volumetric change of -0.5 cy/ft./yr. (CPE, 2025b).

Table 18. Summary of Average Volumetric Change Rates and Total Volume Changes North of the Horse Gate Above -19 ft. NAVD88

Section	Average Volumetric Change Rate (cy/ft./yr.)			Total Volume Change (cy)		
	May 2020 to June 2024	May 2020 to May 2022	May 2022 to June 2024	May 2020 to June 2024	May 2020 to May 2022	May 2022 to June 2024
Carova	3.1	12.4	-5.3	337,000	624,800	-287,800
Reserve/Refuge	-0.5	8.8	-9.3	-67,100	551,200	-620,500
North of the Horse Gate (C-001 to C-058)	**1.1**	**10.2**	**-7.5**	**269,900**	**1,176,000**	**-908,300**

South of the Horse Gate, the average volumetric change rate measured along the oceanfront between May 2020 and June 2025 was +1.8 cy/ft./yr. This translates to a total volumetric gain of approximately 549,700 cubic yards, which is equivalent to an annualized rate of 108,100 cy/yr. As shown in Table 19, the volumetric change rates and total volume change differ along the two (2) Sections. The Corolla and Pine Island Sections experienced average positive volumetric change rates at +1.4 and +2.7 cy/ft./yr, respectively, over the approximate 5-year time period.

Table 19: Summary of Average Volumetric Change Rates and Total Volume Changes South of the Horse Gate Above -19 ft. NAVD88

Section	Average Volumetric Change Rate (cy/ft./yr.)			Total Volume Change (cy)		
	May 2020 to June 2025	May 2020 to June 2023	June 2023 to June 2025	May 2020 to June 2025	May 2020 to June 2023	June 2023 to June 2025
Corolla	1.4	5.6	-5.1	305,800	740,300	-435,900
Pine Island	2.7	8.1	-5.7	243,900	448,600	-204,700
South of the Horse Gate (C-059 to C-120)	**1.8**	**6.3**	**-5.2**	**549,700**	**1,189,000**	**-640,600**

The positive volumetric change observed along the County's oceanfront beaches since May 2020 is somewhat anomalous compared to observed long-term erosion trends observed north and south of Currituck County. Coastal communities both north and south of the Currituck County have constructed beach nourishment projects as a result of long-term erosional trends and vulnerability of oceanfront development and infrastructure to storms. North of the Assessment Area, in Sandbridge, Virginia, a beach nourishment project was constructed in 1998. This project was re-nourished in 2003, 2007, 2013, and 2020. South of the Assessment Area, erosional trends and storm vulnerability prompted the Northern Dare County Towns of Duck, Southern Shores, Kitty Hawk, Kill Devil Hills, and Nags Head to implement beach nourishment programs. Initial construction of the beach nourishment project at Nags Head was constructed in 2011, while the projects at Duck, Kitty Hawk, and Kill Devil Hills were initially constructed in 2017. The Nags Head project has since been re-nourished twice, while the Kitty Hawk and Kill Devil Hills projects were re-nourished in 2022 at the same time as the initial construction of the project in the Town of Southern Shores. The Duck project was re-nourished in 2023.

Analysis conducted as part of the 2024 and 2025 Beach Assessments (CPE, 2025b and CPE, 2026), indicated that there may be an inflexion point at which point the volumetric trend has shifted from a positive change to negative change. This inflection point can best be illustrated by plotting the cumulative volume change over time. Figure 68 shows the cumulative change in volume along the entirety of Currituck County between May 2020 and June 2024 (purple curve). Figure 68 also shows the cumulative change in volume along the portion of the County oceanfront North (green curve) and South (blue curve) of the Horse Gate. These data show the inflexion point in the trend north of the Horse Gate being May 2022 and south of the Horse Gate being June 2023.

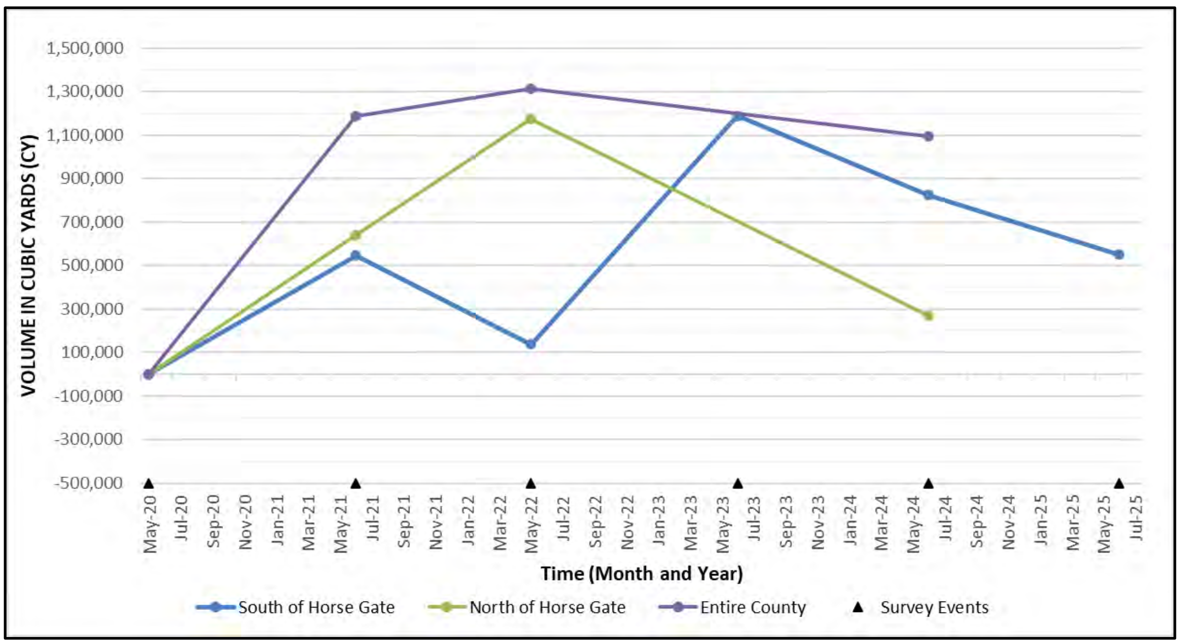


Figure 68. Graph showing cumulative volume change along Currituck County since May 2020.

Given these inflexion points in the trends north and south of the Horse Gate, Table 18 and Table 19 include rates and volumetric changes measured prior to and since the identified inflexion points. North of the Horse Gate, Table 18 provides rates for the Carova Section, the Reserve/Refuge Section, and the overall rates and changes north of the Horse Gate for the period from May 2020 to May 2022 during which the trend was positive, and between May 2022 and June 2024 during which the trend was negative. This shift reflects a reversal from a recovery state to an erosional state. Similarly, Table 19 provides rates for the Corolla Section, the Pine Island Section, and the overall rates and changes south of the Horse Gate for the period from May 2020 to June 2023 during which the trend was positive, and between June 2023 and June 2025 during which the trend was negative.

Various sediment transport mechanisms were considered to explain the observed positive trends in volumetric change observed over various periods. One hypothesis considered was whether beach nourishment projects in Sandbridge, Virginia, or in Duck, North Carolina, could be adding sediment to the system along the Currituck County Beaches. Approximately 7.4 million cubic yards have been placed along Sandbridge, VA since 1998 across five nourishment events. The Sandbridge beach nourishment project occurs approximately 10 miles north of Currituck County's northern border. The Duck, NC project has placed approximately 1.84 million cubic yards since 2017 across two nourishment events. The Duck, NC project occurs approximately 1.8 miles south of Currituck County's southern border.

The primary hypothesis discussed in the County's beach monitoring reports suggests that the multi-year positive volumetric trend observed may be the result of landward cross-shore sediment transport (sand moving from deeper water to shallower water) (CPE, 2023a and CPE, 2023b). This effect has been documented and sometimes referred to as "recovery" following a previous period of storm induced seaward cross-shore sediment transport (sand moving from shallower water to deeper depths). More information can be found in the 2022 Beach Monitoring and Beach Stability Assessment (CPE, 2023a).

A review of wave data over the past several years supports this hypothesis. Monitoring reports (CPE, 2024, 2025, and 2026) suggested that observed periods of volumetric recovery could be temporary and followed by a return to negative volume change trends. The inflexion points and changes in the trend from positive to negative illustrated in Figure 68 may therefore indicate that Currituck County beaches are reverting to an erosional volumetric trend.

Wave data representative of conditions offshore Currituck County were qualitatively reviewed, comparing wave climate conditions prior to the study period (January 2017 to January 2020), during the period of greatest measured volumetric gains (May 2020 to May 2022), and during the subsequent 25-month period from May 2022 to June 2025. Significant wave height measurements from a waverider buoy located in approximately 26 m of water offshore of the USACE Duck Field Research Facility pier were reviewed and are presented in Figure 69.

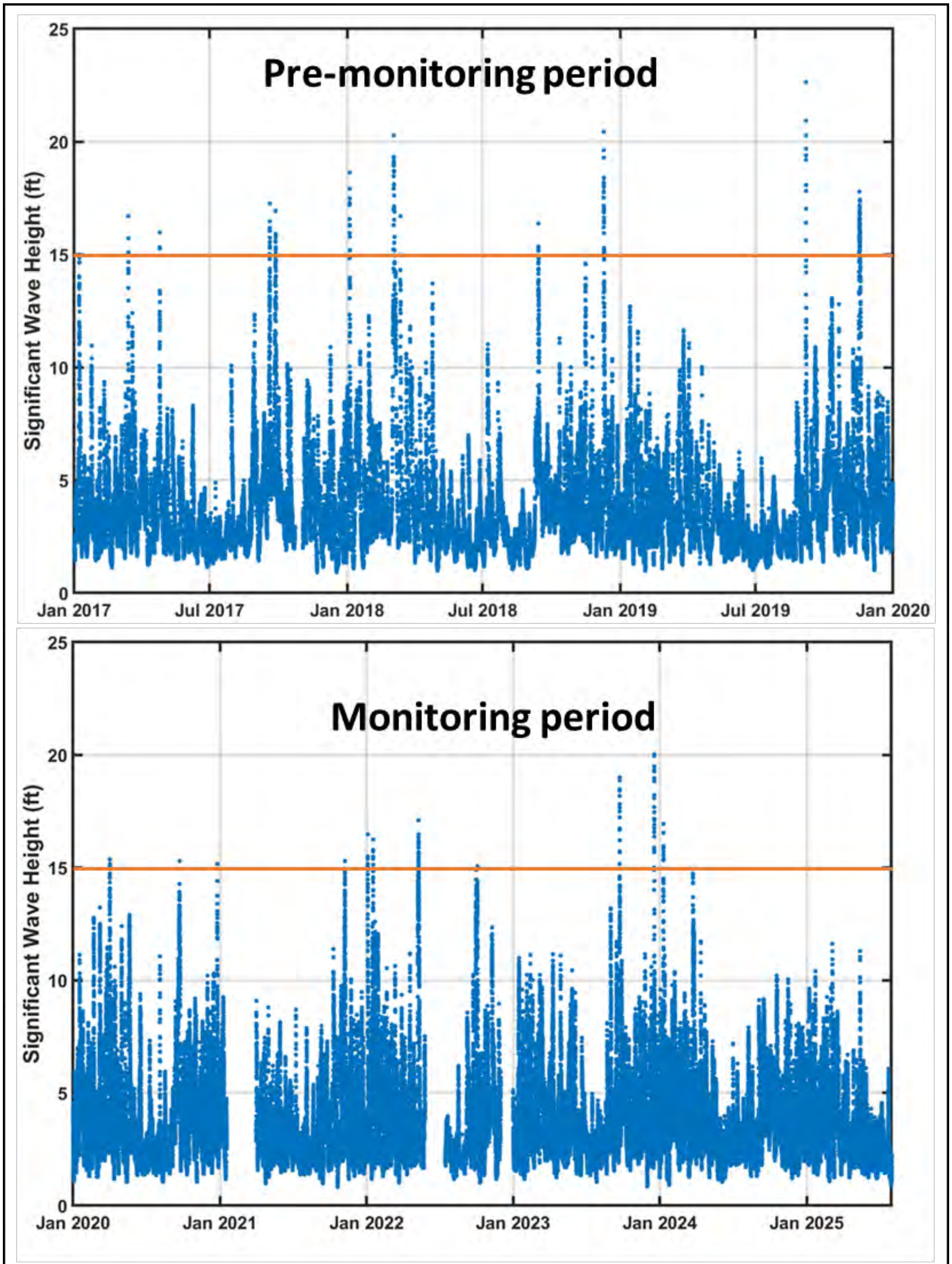


Figure 69. Significant Wave Height data prior to and during the monitoring period from waverider buoy located in 26 m of water offshore Duck, NC (Station 44100).

The upper panel in Figure 69 shows the wave data for the three-year period prior to the commencement of the Currituck County Beach Monitoring and Beach Stability Assessment (January 2017 to January 2020). The lower panel shows the wave data for the 5.5-year period from January 2020 to June 2025. These wave data indicate that the pre-monitoring period (January 2017 to January 2020) was more active in terms of wave events that produced significant wave heights greater than 15 feet. Specifically, there were three storm events during this three-year period where significant wave heights exceeded 20 ft. The first was a nor'easter in March 2018. This event was an extratropical cold front that brought strong winds, heavy snow, and tremendous coastal flooding to communities from the Mid-Atlantic to northern Maine. The second event with significant wave heights in excess of 20 ft. occurred in December 2018. The third event with significant wave heights in excess of 20 ft. was Hurricane Dorian, which occurred in September 2019. This storm caused significant impacts to the beach fill projects at Duck, Kill Devil Hills, Nags Head, and Buxton. Approximately two (2) months following the impacts of Hurricane Dorian, a major Nor'easter impacted the Outer Banks in mid-November of 2019 that produced significant wave heights at the same buoy of nearly 18 ft. A significant storm surge was also experienced during the November 2019 event.

An examination of the wave data shown in the lower panel of Figure 69, indicates that between January 2020 and July 2023, there were no wave events in which significant wave heights exceeded 20 ft. and fewer wave events in which significant wave heights exceeded 15 ft. Effectively, during this period the Currituck County oceanfront generally experienced an overall wave climate that was calmer than the preceding three years (January 2017 to January 2020). This correlates with the period in which positive volumetric changes were observed. However, between July 2023 and June 2024, two wave events occurred in which significant wave heights exceeded 20 ft. The first event was Tropical Storm Ophelia which affected the Assessment Area from September 22nd to 24th, 2023. The second event was a nor'easter that impacted the Assessment Area between December 17th and 20th, 2023. This storm caused ocean overwash along portion of highway NC-12 near Hatteras, NC. The period in which larger storms were observed generally correlates with negative volumetric changes being observed. Although the data indicates that the erosional conditions continued between June 2024 and June 2025, Figure 69 indicates no wave events in which significant wave heights exceeded 15 ft. at the buoy. This may indicate that erosion losses between June 2024 and June 2025 are more influenced by longshore sediment transport than cross-shore sediment transport.

While most of the discussion in this section focuses on average trends along the entire County oceanfront and the four (4) Sections of Carova, Reserve/Refuge, Corolla, and Pine Island, variations in volumetric changes were measured from transect to transect. Figure 70 and Figure 71 graphically illustrate these variations in volumetric change rates measured along each beach profile transect. The figures show both initial years of monitoring during which time a positive volumetric trend was observed and the more recent periods where negative volumetric change was observed. Figure 70 shows the data north of the Horse Gate in the Carova and Reserve/Refuge Sections. Rates are shown for both the period between May 2020 and May 2022, during which time the average volumetric change rates were positive, and between May 2022 and June 2024, during which time the average volumetric change rates were negative. Figure 71 shows the data south of the Horse Gate in the Corolla and Pine Island Sections. Rates are shown for both the period between May 2020 and June 2023, during which time the average volumetric change rates were positive, and between June 2023 and June 2025, during which time the average volumetric change rates were negative.

2.3 Sufficient Recreational Beach Width

The County expressed concerns with the overall condition of the beach in areas that did not have sufficient recreational beach width to meet the recreational and environmental goals established by the County as stated in Goal No. 5. In order to evaluate the beach in terms of sufficient recreational beach width, the "recreational beach width" was first defined and then measured. Subsequently, a determination of "sufficient" was made to align with the overall recreational and environmental goals of the County.

County staff were asked about any known portions of the beach that are considered "Insufficient" as a proxy in order to define a "Sufficient" beach. No specific locations were provided. The County did provide some locations where higher crowds have been observed, but the number of visitors present in those locations were more likely due to the convenience of parking and not necessarily directly tied to recreational beach width.

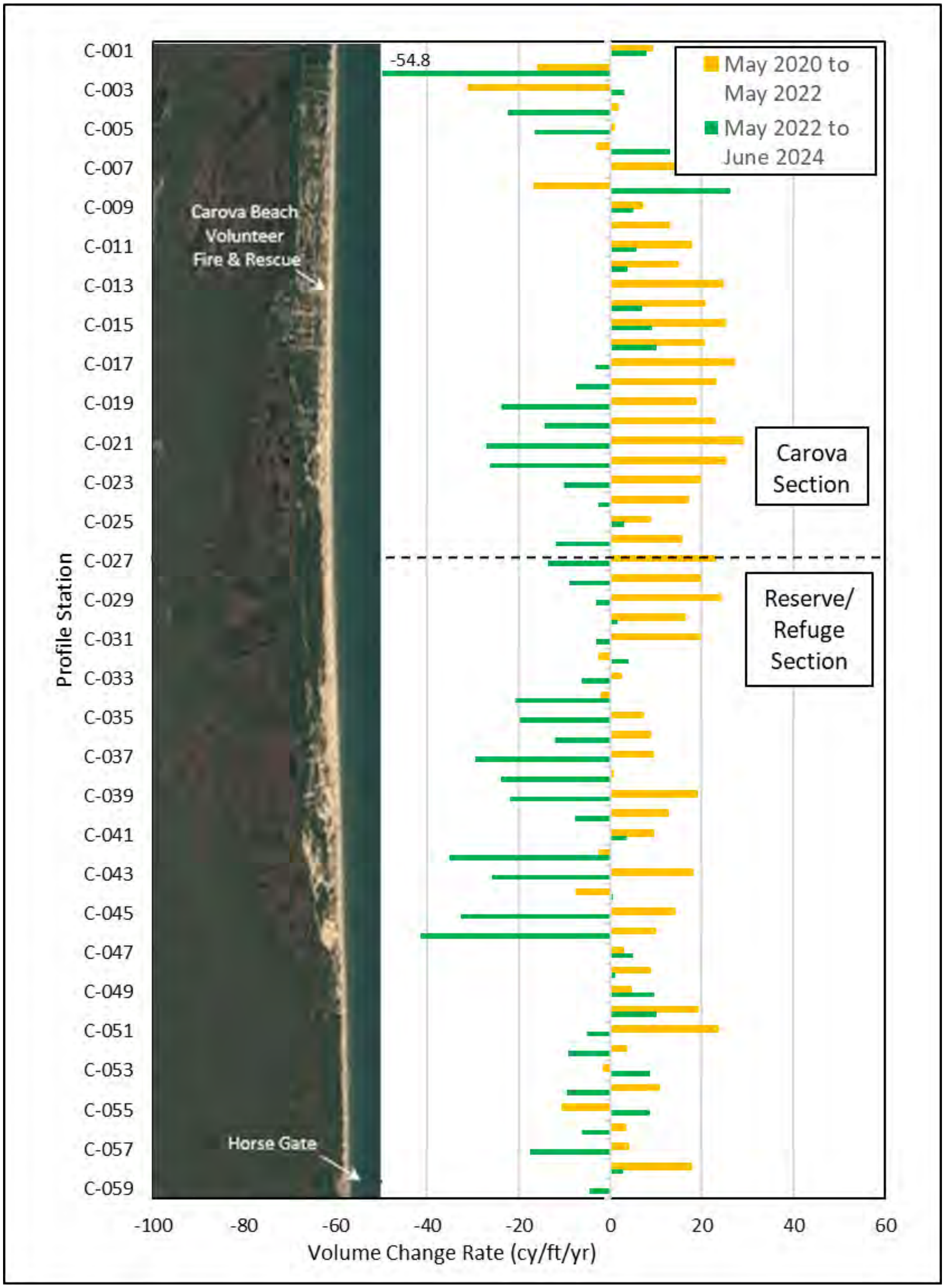


Figure 70. Volume Change Rate Above -19 ft. NAVD88 - north of the Horse Gate May 2020 to May 2022 and May 2022 to June 2024.

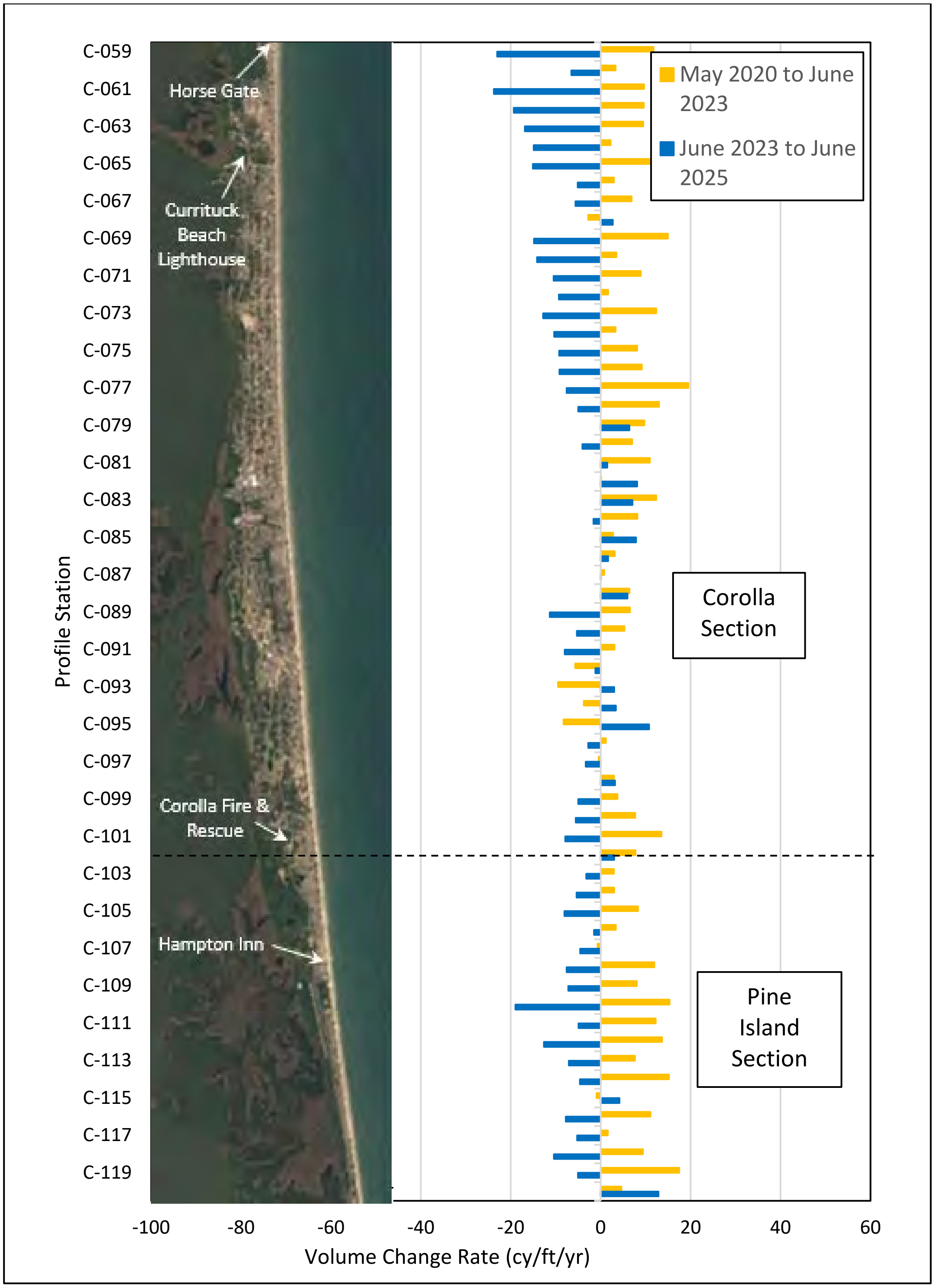


Figure 71. Volume Change Rate Above -19 ft. NAVD88 - south of Horse Gate May 2020 to June 2023 and June 2023 to June 2025

During the 2025 beach profile surveys, a coastal engineer was onsite to evaluate beach width and beach usage. Figure 72, Figure 73, Figure 74, and Figure 75 show various examples of the recreational beach as observed in June 2025. Each photograph includes a hand digitized indicator (solid black line) of the approximate seaward limit of the recreational beach. Figure 72 shows the beach near Station C-076 (approximately 1,200 feet south of Perch Street), which was measured to have a recreational beach width of 73 feet in June 2025. Figure 73 shows the beach near Station C-086 (just south of Crown Point Circle), which was measured to have a recreational beach width of 94 feet in June 2025. Figure 74 shows the beach near Station C-098 (North end of Breaker Arch), which was measured to have a recreational beach width of 57 feet in June 2025. Figure 75 shows the beach near Station C-102 (Spindrift Community), which was measured to have a recreational beach width of 58 feet in June 2025.

Figure 72. Photograph of the beach near Station C-076 (approximately 1,200 feet south of Perch Street) taken in June 2025 (CPE) illustrating the dry sand beach width.

Based on observations from the June 2025 site visit and initial consultation with County Staff, an initial establishment of 65 feet was made to represent "Sufficient Recreational Beach Width". This value is admittedly subjective and should be further evaluated through public input. Furthermore, an evaluation of the protective value of a minimum width of recreational beach, could provide further justification for a particular width to represent the "Sufficient Recreational Beach Width".

With that said, in order to measure the recreational beach width, profile plots containing the May 2020, June 2023, and June 2024 surveys were evaluated to determine representative elevation contours that would represent the recreational beach width or dry sand beach. The dry sand beach is typically considered when referring to the recreational beach and is also considered in terms of habitat for nesting sea turtles and shore birds. Based on this examination, the +8 ft. NAVD88 contour was used as the landward limit (approximate toe of dune location) of the recreational beach width, while the +4 ft. NAVD88 contour was used as the seaward limit. Figure

76 illustrates the portion of the profile that represents the recreational beach width as surveyed at Station C-080 near Sailfish Street in June 2025.

Figure 73. Photograph of the beach near Station C-086 (just south of Crown Point Circle) taken in June 2025 (CPE) illustrating the dry sand beach width.

Figure 74. Photograph of the beach near Station C-098 (North end of Breaker Arch) taken in June 2025 (CPE) illustrating the dry sand beach width.

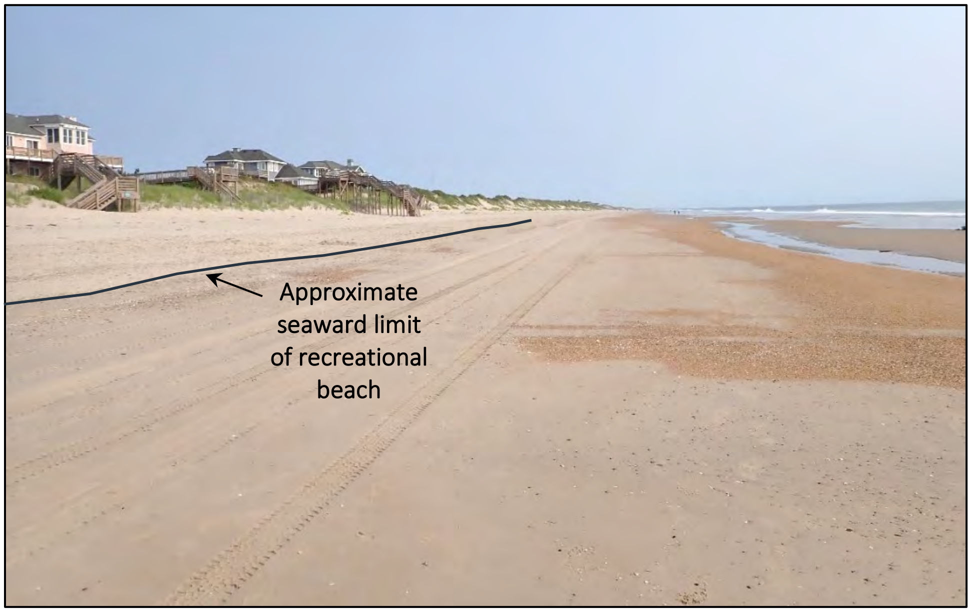


Figure 75. Photograph of the beach near Station C-102 (Spindrift Community) taken in June 2025 (CPE) illustrating the dry sand beach width.

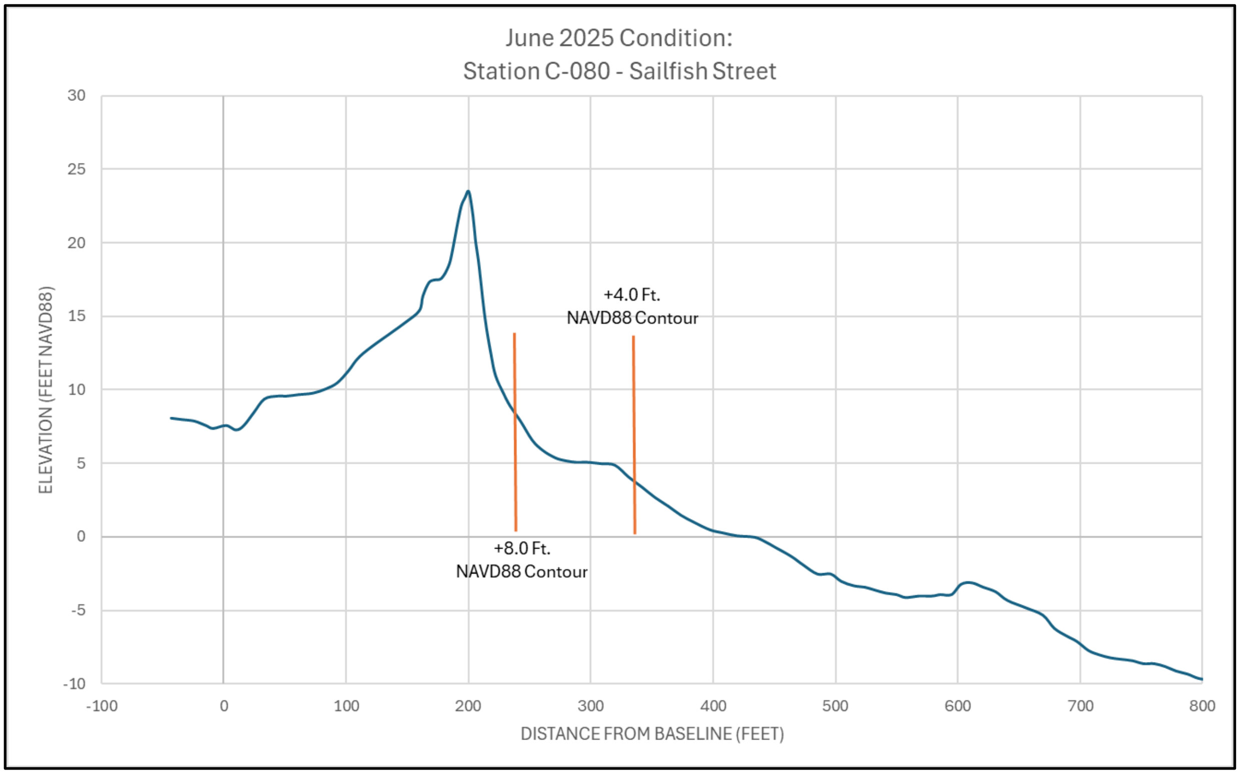


Figure 76. Cross section plot illustrating the extent of the dry sand beach used in the Recreational Beach Width analysis.

Once the contours used to delineate the landward and seaward extents of the recreational beach were determined, the distance between these two contours were measured along each of the 120 beach profiles for each data set available. As previously stated, the location of a particular beach contours is highly dynamic. Figure 77 illustrates this variability north of the Horse Gate by displaying the measured recreation beach width along each profile for the 3 most recent surveys. Similarly, Figure 78 illustrates the variability south of the Horse Gate by showing the measured recreational beach width along each profile at the time of the most recent 3 surveys.

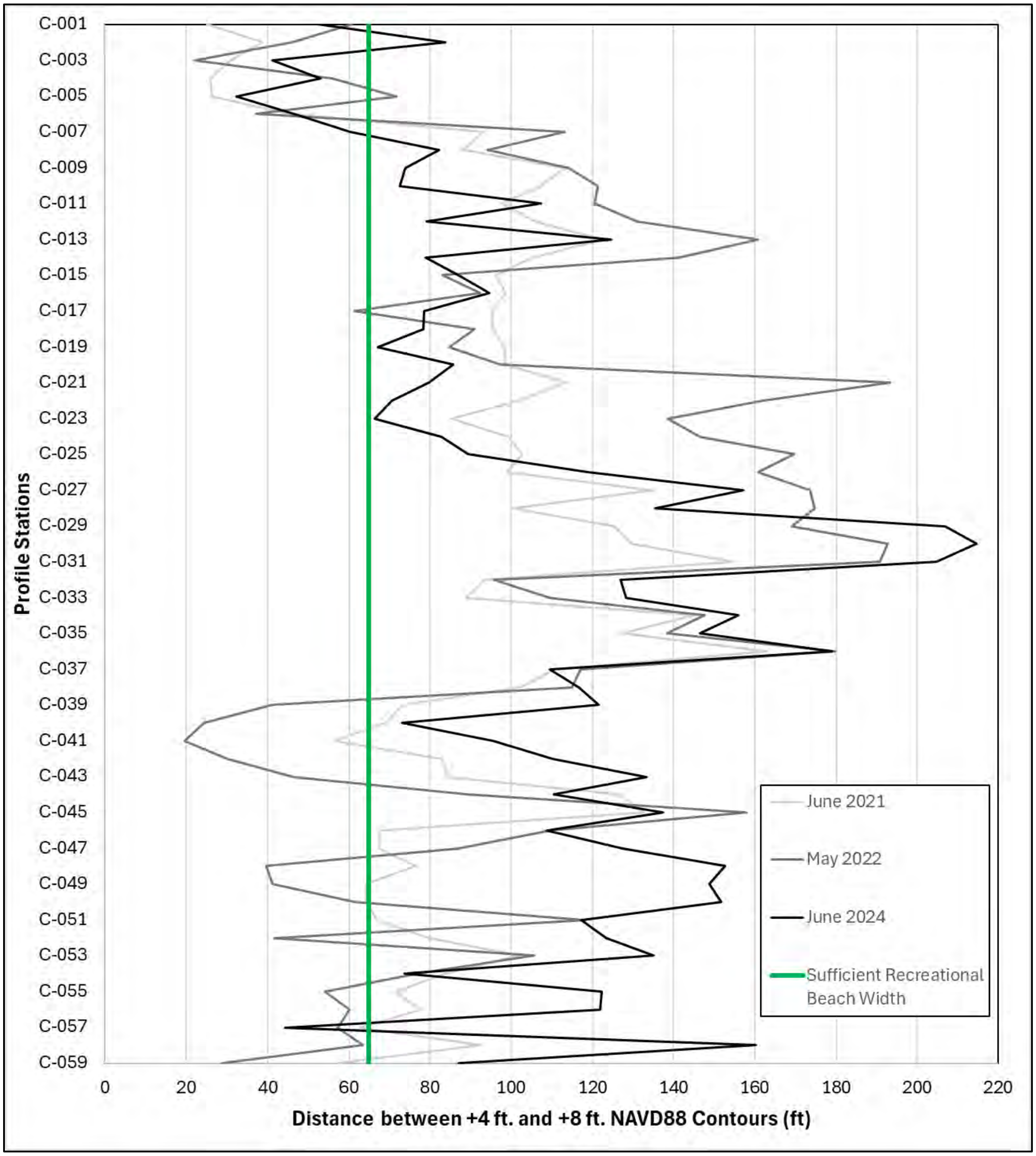


Figure 77. Recreational Beach Width north of the Horse Gate.

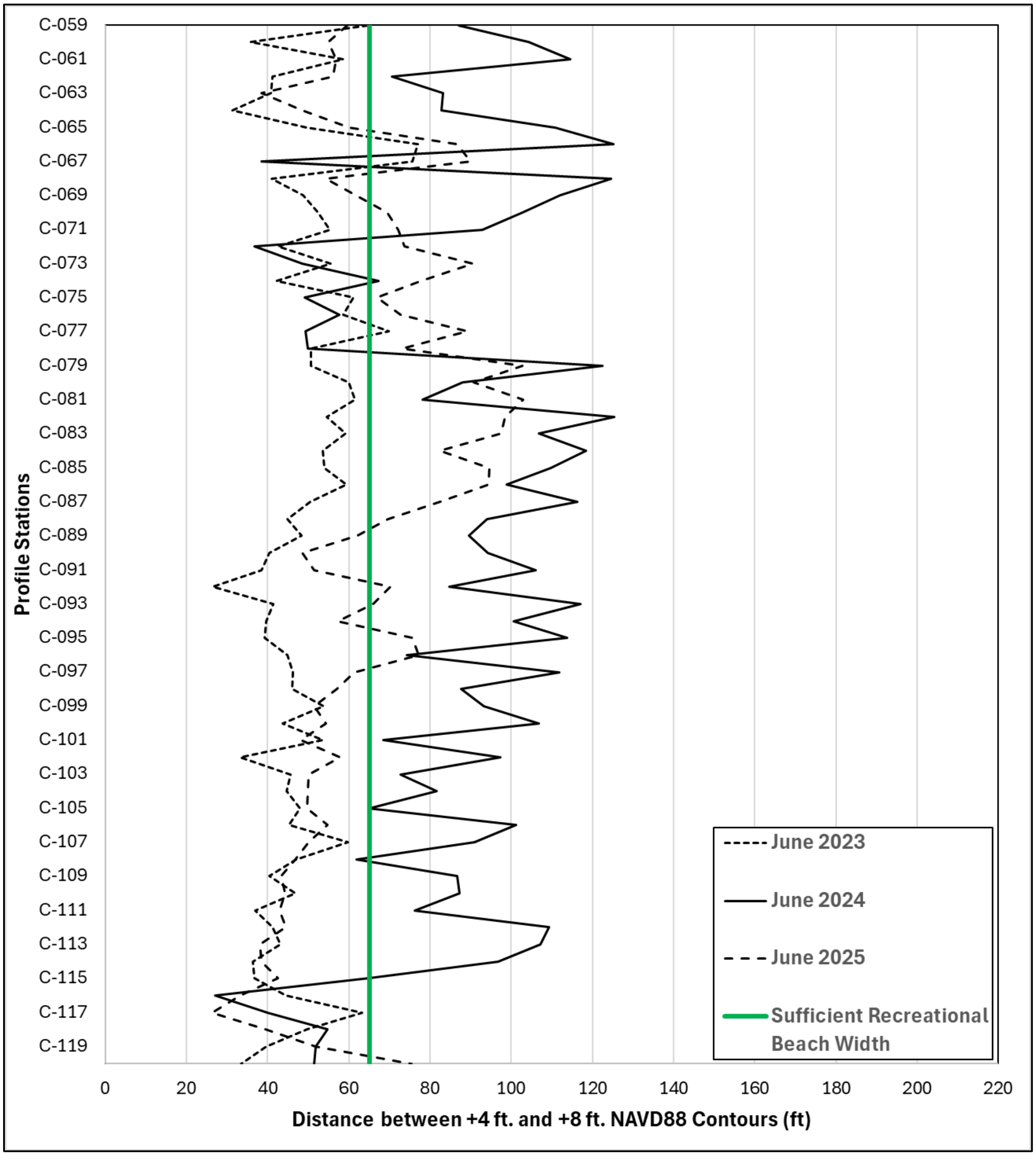


Figure 78. Recreational Beach Width south of the Horse Gate.

The results presented in Figure 77 and Figure 78 demonstrate that the recreational beach width varies substantially both spatially along the shoreline and temporally between survey periods. The vertical green line shown on the figures represents the initial 65-foot threshold, which was established based on observations made during the June 2025 site visit and initial consultation with County staff. North of the Horse Gate, Figure 77 shows that some profile locations consistently maintain recreational beach widths greater than the 65-foot initial threshold for "Sufficient Recreational Beach Width," while other areas periodically fall below this value. The variability observed between surveys reflects the dynamic nature of shoreline conditions and the continual redistribution of sediment along the beach system.

Figure 78 illustrates the recreational beach width changes south of the Horse Gate for the three most recent surveys. The results indicate that several portions of the southern shoreline maintain widths exceeding the 65-foot threshold, particularly in 2024, while other segments fall below the criterion as seen shown in the 2023 survey. Comparison of the survey results demonstrates that beach width conditions can change significantly over relatively short timeframes due to coastal processes, storm impacts, and subsequent recovery. The inclusion of the 65-foot threshold provides a consistent benchmark for identifying areas that may not satisfy the preliminary definition of "Sufficient Recreational Beach Width."

Overall, the results highlight the highly dynamic character of the dry sand beach and demonstrate the importance of evaluating recreational beach width over multiple surveys when assessing whether shoreline conditions meet the recreational and environmental objectives established by the County.

2.4 Vulnerability Matrix

Section 2 of this Plan evaluated various coastal hazards and vulnerabilities of the Currituck County beach. This included vulnerability to coastal storms, to long-term erosion, and issues associated with the recreational beach width. These various hazard and vulnerability analyses demonstrate significant variation along the County beaches depending on the specific type of hazard or vulnerability being assessed.

In order to visualize these variations and to determine areas that may require active beach management, vulnerability matrices were developed. A total of three (3) vulnerability matrices were generated, corresponding to the three (3) coastal storms evaluated in the vulnerability analyses. Each vulnerability matrix includes spatial information on five different vulnerability factors, namely: Storm Vulnerability, Breaching/Inundation, Shoreline Change, Erosion Rates, and Beach Width. The data used to determine spatial distribution of vulnerability for these five (5) factors are described in the following paragraphs.

Storm Vulnerability

The matrices incorporate Storm Vulnerability based on the results of the XBeach 1D storm vulnerability analysis described in Section 2.1.4.1. The storms evaluated for the matrices included Hurricane Isabel, a synthetic "25-year return interval storm", and the 2009 Nor'easter. For each storm, the impact line generated based on results of the XBeach simulations were evaluated to determine the number of impacted structures between the various beach profile stations along the County shoreline. It should be noted that this analysis was only conducted south the Horse Gate (Station C-059 to C-120) along the Corolla and Pine Island sections, due to scope limitations of the storm vulnerability analysis.

This analysis was conducted in an ESRI ArcGIS platform and utilized 2024 orthoimagery available through NC OneMap. Oceanfront structures were considered impacted by the storm if the impact lines crossed either the oceanfront structure itself, or the deck of an oceanfront pool located seaward of an oceanfront structure, whichever was more seaward. The reason for using oceanfront pools as an indicator of vulnerability is that these pools are generally located landward of the primary frontal dune. If the storm simulation indicated the pool would be impacted, meaning that a drop in elevation of at least one foot was shown, the inference can be made that the primary frontal dune, which would have been located seaward of this impact point, would have been degraded to a point that the oceanfront structure itself would be vulnerable.

In the matrices, areas along the County oceanfront shown to be impacted by "Storm Vulnerability" are those locations where at least two oceanfront structures were determined to be impacted by the XBeach 1D Storm Vulnerability Analysis between any two adjacent beach profile stations. Figure 79 shows the Vulnerability Matrix developed for the Isabel Storm, Figure 80 shows the Vulnerability Matrix developed for the synthetic "25-year return interval storm", and Figure 81 shows the Vulnerability Matrix developed for the 2009 Nor'easter storm.

Breaching/Inundation

The matrices incorporate Breaching/Inundation based on the results of the XBeach 2D Dune Breaching and Overtopping Analysis described in Section 2.1.4.2. The storms evaluated for the matrices included Hurricane Isabel and the synthetic 25-year return interval storm which were selected based on the combined results of the extreme event analysis, Delft3D simulations, and XBeach 1D modeling. Hurricane Dorian and the November 2009 Nor'easter were excluded from the analysis, as preliminary testing indicated that these events did not generate sufficient water levels or wave conditions to produce significant dune erosion, overwash, or breaching within the model domain. The XBeach 2D analysis was centered on the areas identified in the Delft3D, 1D storm vulnerability analysis, and previous monitoring analyses as having the greatest potential vulnerability to dune erosion, overwash, and breaching. For each storm, post-storm dune elevations generated by the XBeach simulations were evaluated to identify areas where significant dune degradation and overtopping occurred.

This analysis was conducted using the calibrated XBeach 2D numerical model and incorporated topographic and bathymetric datasets derived from 2019 USACE NCMP topo/bathymetric LiDAR, NOAA NCEI Digital Elevation Models (DEMs), and publicly available wave, water level, and wind data from WIS Station ST63217 and NOAA Station 8651370 at Duck, NC. The 2D model domain extended from profile Station C-048 to C-096 and encompassed the full barrier island cross-section from the Atlantic Ocean to the Currituck Sound in order to capture overwash and breaching processes. Post-storm dune crest elevations generated by the simulations were evaluated spatially to identify locations where the frontal dune system was substantially degraded during each storm event.

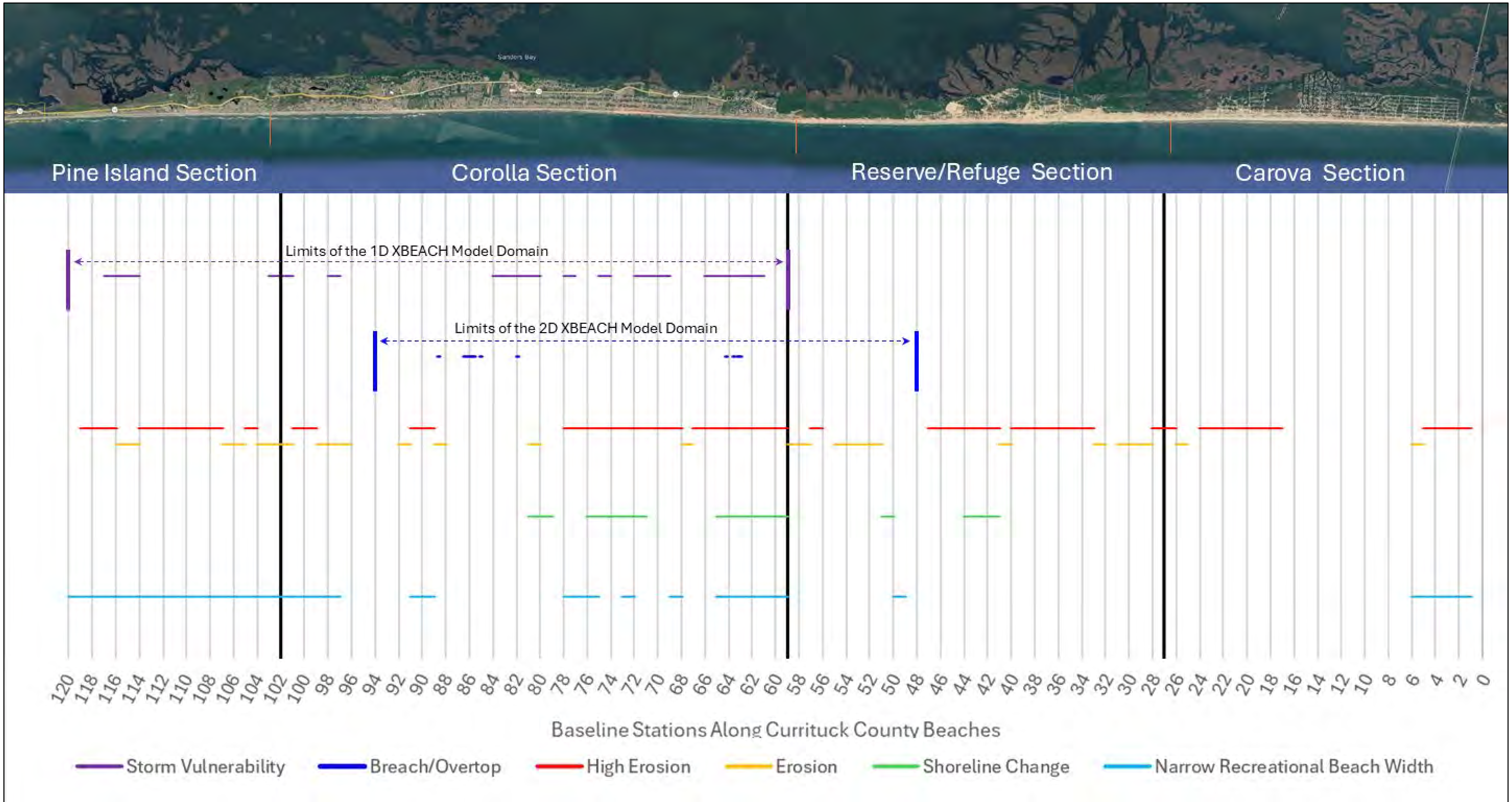


Figure 79. Vulnerability matrix reflective of storm impacts from a design storm comparable to Hurricane Isabel.

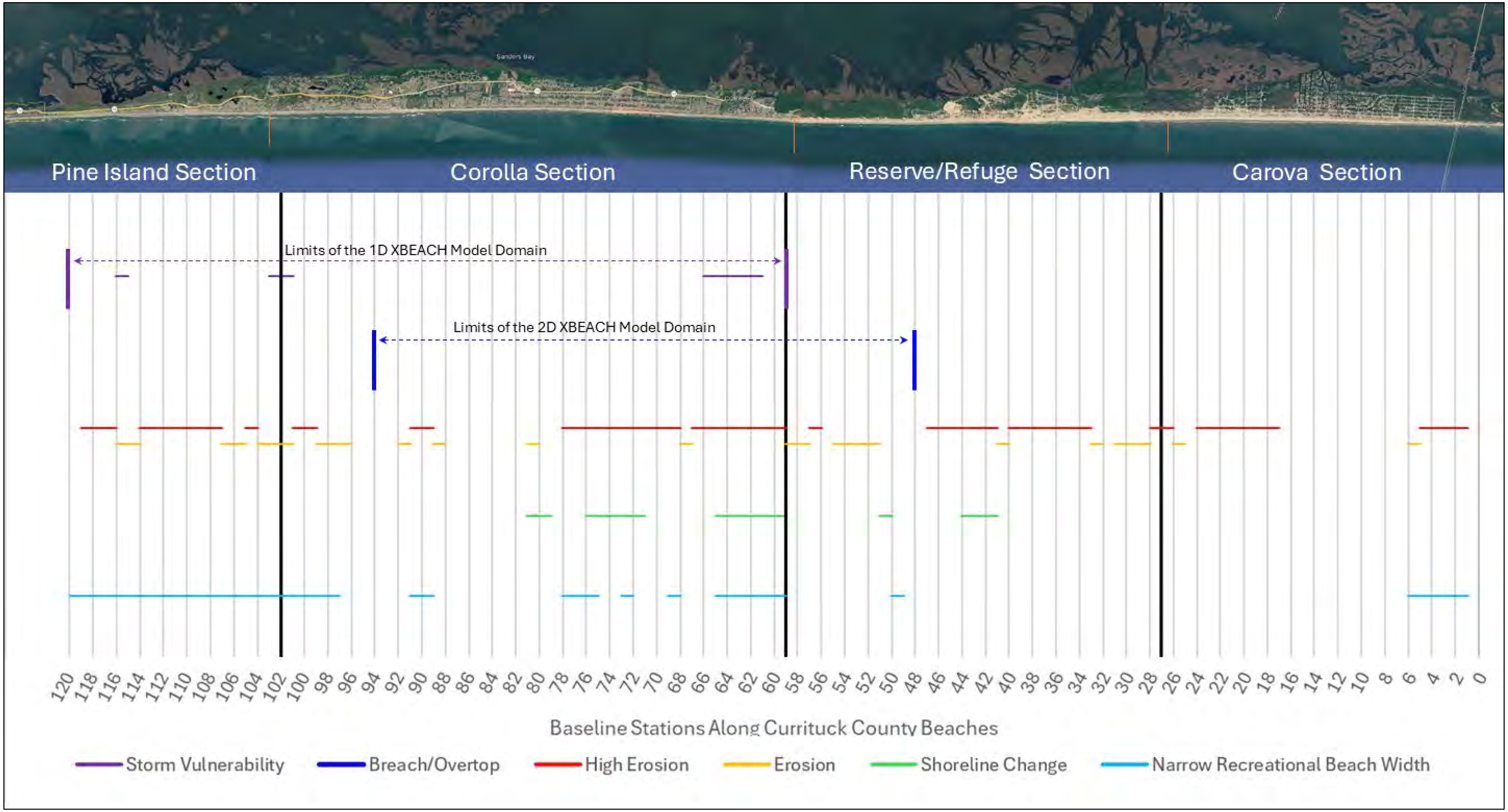
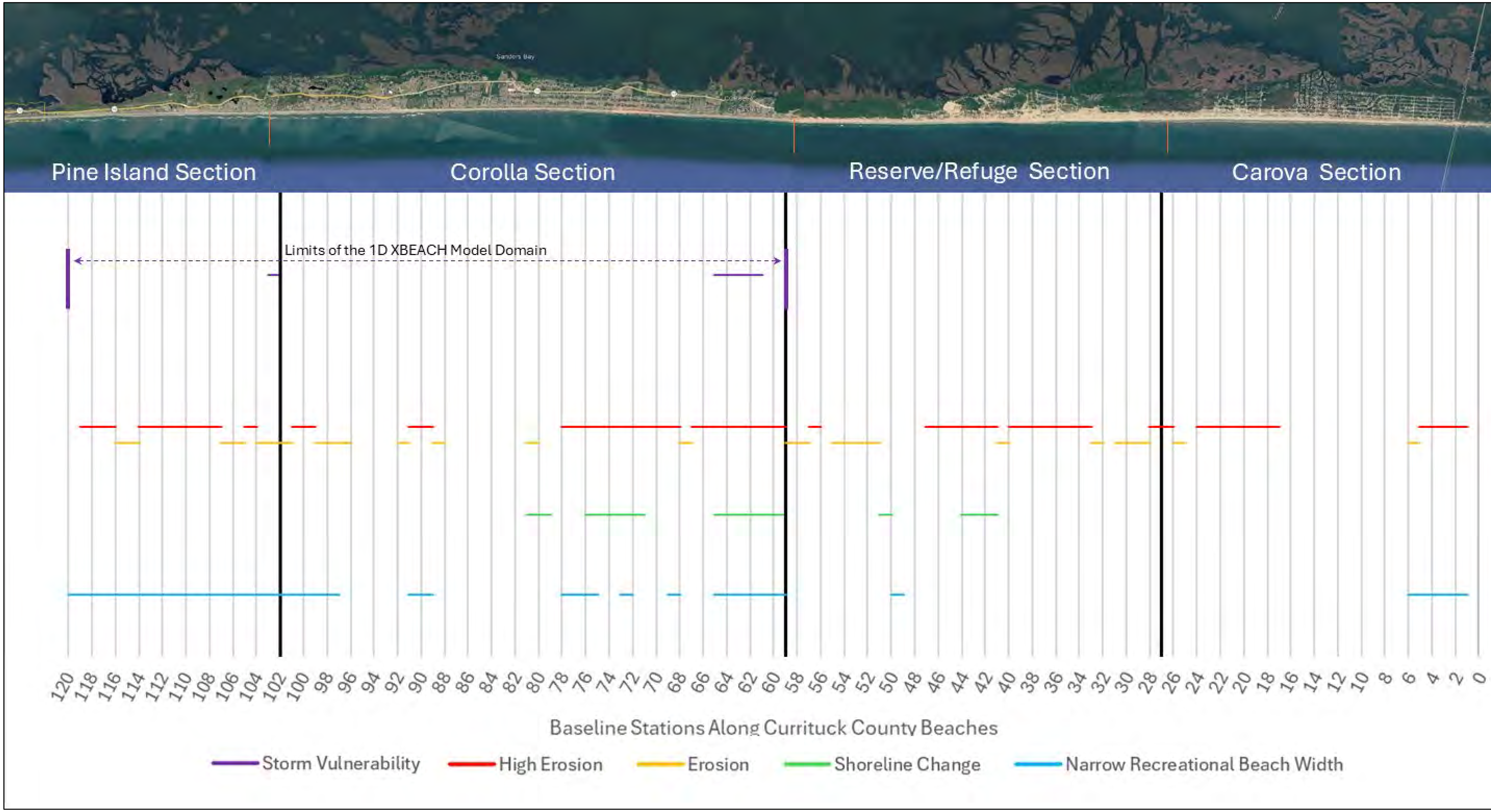


Figure 80. Vulnerability matrix reflective of storm impacts from a design storm comparable to the 25-year return period synthetic storm.



NOTE: The 2009 Nor'easter was not simulated using the XBeach 2D Model given the 25-year synthetic storm did not indicate vulnerability to breaching and overtopping as defined herein.

Figure 81. Vulnerability matrix reflective of storm impacts from a design storm comparable to the 2009 Nor'easter.

In the matrices, areas along the County oceanfront shown to be impacted by "Breaching/Inundation" are those locations where modeled overwash, dune breaching, or inundation conditions reduced dune crest elevations to below +10 ft. NAVD88. These areas were determined to create vulnerability to oceanfront infrastructure in the discrete areas where post-storm dune crest elevations fell below +10 ft. NAVD88. Figure 79 shows the Vulnerability Matrix developed for Hurricane Isabel, and Figure 80 shows the Vulnerability Matrix developed for the synthetic 25-year return interval storm.

Shoreline Change

The matrices incorporate Shoreline Change based on the shoreline projection analysis described in Section 2.2.1. Shoreline projections developed annually were evaluated for trends to account for the variable nature of these projections. The natural sand movement in response to wave and water level conditions makes shoreline position highly variable spatially and temporally. The dynamic nature of the beach contours can result in variation in the actual location of the shoreline position at any given time when surveys are conducted and therefore impacts the location of the projected shoreline positions.

With this natural variability in mind, the 30-year projection lines were used as a proxy to identify portions of the County oceanfront that are more susceptible to long-term shoreline change rates. The 30-year projection lines were reviewed from past reports to determine locations where the projected shoreline intersected oceanfront structures (CPE, 2021a, 2023a, 2023b, 2025, and 2026). The aerial imagery used to evaluate the shoreline projection lines varied by analysis year: the 2021 analysis used January 2018 imagery, the 2022 and 2023 analyses used February/March 2020 imagery, the 2024 analysis used August 2020 imagery, and the 2025 analysis used January/March 2024 imagery. In the matrices provided in Figure 79, Figure 80, and Figure 81, locations along the County oceanfront shown to be impacted by "Shoreline Change" are an indication of oceanfront structures/roads impacted between beach profile stations, and the frequency of impacts over multiple years. Consideration was given to the availability of datasets both north and south of the Horse Gate, as well as the role of the beach as the primary access corridor for residents and visitors traveling to beaches and homes within the Reserve/Refuge and Carova Sections north of the Horse Gate.

Because beach access is critical north of the Horse Gate, the threshold used to identify an impacted shoreline segment in the Reserve/Refuge and Carova Sections was one (1) impacted house between adjacent beach profile stations. South of the Horse Gate, the threshold was defined as two (2) or more impacted houses, or any roadway impact, between adjacent beach profile stations.

For each Section, the three (3) most recent available datasets were evaluated to determine recurring impacts. A shoreline segment between adjacent beach profile stations was classified as impacted if structures and/or roads were identified as impacted in two (2) or more of the three (3) most recent datasets. North of the Horse Gate, the most recent three (3) data sets were the

2024, 2022, and 2021 projections; whereas, south of the Horse Gate, the most recent three were the 2025, 2024, and 2023 projections.

Erosion Rates

The matrices incorporate erosion rates based on comparisons of the measured individual erosion rates at each beach profile station and the average volumetric change rates described in Section 2.2.2. As discussed previously, annual monitoring has indicated a shift in the volumetric trend from initially positive to more recently negative. North of the Horse Gate, the positive trend spans from May 2020 to May 2022; whereas south of the Horse Gate the positive trend spans from May 2020 to June 2023. The more recent trends, showing negative volumetric change trends, span from May 2022 to June 2024 north of the Horse Gate and from June 2023 to June 2025 south of the Horse Gate.

Table 18 shows the average volume change rates and total volume changes measured along the Carova and Reserve/Refuge Section (north of the Horse Gate). Within the table are the volume change rates for the period of negative volume change between May 2022 and June 2024. The average volumetric change rate for the Carova Section between May 2022 and June 2024 was -5.3 cy/ft./yr and the average volumetric change rate for the Reserve/Refuge Section during that same period was -9.3 cy/ft./yr. Table 19 shows the average volume change rates and total volume changes measured along the Corolla and Pine Island Section (south of the Horse Gate). Within the table are the volume change rates for the period of negative volume change between June 2023 and June 2025. The average volumetric change rate for the Corolla Section between June 2023 and June 2025 was -5.1 cy/ft./yr and the average volumetric change rate for the Pine Island Section during that same period was -5.7 cy/ft./yr.

In the matrices provided in Figure 79, Figure 80, and Figure 81, locations along the County oceanfront are indicated as “Erosion” where the volumetric change rate measured at beach profile stations were negative but less negative than the average negative volumetric change rate for the whole Section (May 2022 to June 2024 north of Horse Gate and June 2023 to June 2025 south of the Horse Gate). Locations along the County oceanfront indicated as “High Erosion” are where the volumetric change rates measured at beach profile stations were more negative than the average volumetric change rate for the whole Section.

Beach Width

The matrices incorporate Beach Width based on the results of the Sufficient Recreational Beach Width analysis described in Section 2.3. The values computed for the defined “recreational beach width” were evaluated for trends to account for the variable nature of the beach. In the same way consideration must be given to the natural sand movement on a beach when considering shoreline projections, this variability was also considered with respect to beach width.

In the matrices provided in Figure 79, Figure 80, and Figure 81, locations along the County oceanfront shown as having “Narrow Recreational Beach Width” are an indication of measured width relative to the 65-foot width threshold defined in Section 2.3 as representing "Sufficient" recreational beach width, and the frequency of observed beach width over past monitoring events that fall below this definition of "Sufficient". Specifically, the analysis reviewed the last 3 surveys conducted along each Section. In the Carova and Reserve/Refuge Sections where surveys have been conducted every other year in even years since 2022, the last three surveys available are 2024, 2022, and 2021. In the Corolla and Pine Island Sections where surveys have been conducted every year since 2020, the last three surveys available are 2025, 2024, and 2023. Using the three (3) most recent data sets for any given Section, a portion of oceanfront between adjacent beach profile stations was classified as having a "Narrow Recreational Beach Width" if the measured beach width was less than 65 ft. in two (2) or more of the last three (3) data sets.

3 BEACH MANAGEMENT CONCEPTS

Based on the County's beach management goals described in Section 1.2, and the identified hazards and vulnerabilities described in Section 2, various beach management concepts were considered to determine their applicability toward meeting the County goals. Generally speaking, all beach management concepts used by engineers, property owners, managers, and oceanfront communities may pursue one or a combination of the following approaches:

- Allow the beach to migrate landward naturally and remove/relocate threatened structures;
- Armor the coast with seawalls/revetments in an attempt to halt the landward retreat of the shoreline;
- Actively add sand to the system to bolster protection and keep up with the loss of sand due to long term erosion; and
- Attempt to slow the littoral transport of sand along the beaches and dunes (groins/breakwaters/sand fencing/dune vegetation/ beach bulldozing)

A seawall is a shore parallel structure designed and constructed to prevent further retreat of the shoreline and/or inundation or flooding (Kraus and McDougal, 1996). While some seawalls are built considerably landward of the active beach to serve as a "last line of defense" during times of extreme storm events, once seawalls are exposed to active wave runup, they can have significant adverse impacts to the beach. A comprehensive literature review on these impacts was published by Kraus and McDougal (1996). Given the potential for adverse impacts to the beach associated with seawalls and other permanent hardened structures, the North Carolina Coastal Resources Commission (NC CRC) enacted a rule in 1979, effectively prohibiting hardened structures. In 2003, the North Carolina General Assembly codified the ban on permanent hardened structures. Due to the potential adverse impacts to the beach and the NC General Assembly's ban on seawalls and revetments, these actions were not considered in this Plan.

Considering the other three (3) general options for beach management, this Plan considers the following beach management concepts:

- Relocation of vulnerable oceanfront structures;
- Small-scale beach nourishment projects utilizing truck hauling to increase the size of the dunes and/or widen the beach along shorter segments;
- Large-scale beach nourishment programs utilizing offshore dredging of sand;
- Incorporation of coastal structures into beach nourishment programs;
- Sand fencing and dune vegetation programs to increase the size of existing dunes; and
- Beach bulldozing program to temporarily increase the volume of sand in the dunes

The following sections of this plan describe each of the listed beach management concepts to provide the reader a general understanding of how these concepts work and when they are applicable. Section 4 of the Plan (Feasibility Analysis) considers various reaches of the County oceanfront that were identified through the use of the vulnerability matrices discussed in Section 2.4. For each of these reaches a series of alternatives were developed using the concepts discussed herein, and the feasibility of these alternatives were assessed.

3.1 Relocation of Vulnerable Oceanfront Structures

The U.S. Army Corps of Engineers (USACE) was provided broad authorization by Congress to support flood control projects through Public Law 86-645, often referred to as the 1960 Flood Control Act. In 1985, the USACE chartered what is referred to as the National Nonstructural Committee (NNC), to promote the use of "nonstructural measures" to reduce both loss of life and property damage associated with flooding. Before that period, federal flood policy focused more on structural measures (levees, dams, floodwalls, channelization, and diversion projects) designed to keep water away from people and property. The creation of the NNC in 1985 marked a deliberate effort to elevate an alternative philosophy: instead of trying to completely control floods, communities should also learn to live more safely with flooding.

The NNC lists the most common physical nonstructural measures as: acquisition/buyouts of properties, relocation of structures, elevating structures, wet and dry flood proofing, and basement removal/utility addition. While all of these options can be considered by property owners with properties at risk of flooding, when considering oceanfront beach management, typically the only one of these physical nonstructural measures considered are acquisition/buyouts and relocation.

For the purpose of this Plan, "buyouts" refer to a program whereby a government entity (Federal, State, or Local) purchases threatened oceanfront homes from the owner and then the threatened structure is permanently removed from the beach. "Relocation" refers to the movement of an oceanfront structure from its present location to a more landward, less flood prone portion, of the lot, or to a separate lot. This process may be funded by a property owner and/or funding provided by a government entity.

According to a white paper titled The Potential Cost/Benefits of Buyouts in Rodanthe, North Carolina (Program for the Study of Developed Shorelines, 2023), buyouts are rarely a first choice for beach management of coastal communities because property owners must be willing to sell and negotiating a fair market value can be difficult and complicated. Furthermore, in order for this strategy to be effective, multiple oceanfront property owners would likely need to agree to the program. Depending on the availability of sand, erosion rates, and the density of vulnerable development along a particular stretch of beach, solutions such as beach nourishment, may be more cost-effective options of beach management.

While buyouts and/or relocation may not be a viable solution along most portions of the County oceanfront, a number of structures have been identified along portions of the Reserve/Refuge Section where oceanfront structures are either currently threatened or vulnerability analyses suggest they could be threatened soon. The 2024 monitoring analysis (CPE, 2025b) as well as the 2022 Beach Vulnerability Analysis (CPE, 2023a), identified several oceanfront structures seaward of Sandfiddler Rd., between Canary Lane (Station C-040) and the south end of Sandfiddler Road (Station C-044). While the number of houses identified as threatened or vulnerable along this section of the County oceanfront is relatively small, the continued retreat of the shoreline has created pinch points for traffic transiting north and south through this area along the North Beach Access Road. The photos shown in Figure 82 illustrate the conditions in the vicinity of the "Laughing Gull" house, located between Stations C-043 and C-044 just south of Seagull Lane, between June 2020 and September 2024. The photo in the middle of the panel (B) shows that traffic had been re-routed around the west side of this structure during times of higher water levels. An example of those higher water levels can be seen in the bottom photo of the panel (C), which is from September 2024.

The concept of relocation of vulnerable oceanfront structures would involve the purchase and demolition of an oceanfront structure and/or the subsidizing of relocation of oceanfront structures that impede ingress/egress of vehicles from the entrance to the 4WD access just north of the Horse Gate, to points north along N. Beach Access Road. Individual properties or a smaller number of isolated properties north of the Horse Gate along portions of the Reserve/Refuge and/or Carova Sections of the County oceanfront may be the most likely targets for this type of beach management strategy. In addition to protecting public roads and emergency routes, this concept would also ensure these structures do not impede access to sufficient recreational beaches and would reduce the risk that these structures would be impacted by long-term erosion and coastal storms.

While implementation of this concept may not be feasible along longer stretches of oceanfront south of the Horse Gate where the density of development is much greater, there may be limited areas along those areas where this concept could be feasible. For instance, in areas where several oceanfront houses are more vulnerable than adjacent development and the construction of a relatively short beach fill section is cost prohibitive due to high diffusion losses, the targeted buyout and removal or relocation of a select number of structures may be feasible.

Figure 82. Photos of the same oceanfront home known as "Laughing Gull", located along Sandfiddler Road in the Reserve/Refuge Section: A) Photo taken June 2020 (courtesy CPE), B) Photo taken September 2023 (Courtesy Carova Volunteer Fire Dept.), C) Photo taken September 2024 (Courtesy Paula Penovi)

In order to implement this concept, a threshold or series of thresholds should be developed to determine when action should be taken by the County. This approach would be relatively novel, and legal councel will be needed to evaluate the County's authorities and rules to implement such a concept. This may include determining if the County has the legal authority to determine fair market value for properties that would be considered for removal. A financial model should also be developed to weigh the cost of implementing the concept based on the current number of structures that meet the threshold(s) and projected number of structures that may meet the threshold(s) over some period of time. The financial model should consider the likely cost to purchase the property, cost to demolish the structure, availability of grant funding to help support the program, and comparative cost of implementing other beach management concepts instead of relocation.

3.2 Small-scale Beach Nourishment Projects

Most successful beach management programs implemented along densely populated resort communities in the U.S., rely on the addition of sand to the active beach to reduce the risk of storm damage and/or to mitigate the effects of long-term erosion. The cost and ultimately the financial viability of these projects are heavily dependent on the cost to transport sufficient quantities of sediment to the project site to meet the goals of the project. Sources of sand may include commercial mines where sand is harvested and trucked to the beach, dredging projects that removed sand from navigation channels and beneficially place sand on beaches, and/or projects that dredge from either inland or offshore borrow sources.

The mobilization cost for dredges, particularly those that can work in the open ocean, are substantial, ranging in the millions of dollars per event. Furthermore, a major driver of the cost per cubic yard of sand placed is the distance between where the sand is being excavated and the recipient beach. In contrast, the mobilization cost associated with a truck haul project is considerably less than dredging, but typically, the cost per cubic yard considering the cost of the sand from the mine and the cost of transport to the recipient beach is considerably higher than the cost per cubic yard for dredging. Given these cost factors, smaller projects may be more economical to construct using truck hauled material; whereas larger scale projects, such as those discussed in Section 3.3, may be more economical to construct using dredging.

In an attempt to better identify the size of project for which truck haul operations may be more economical, cost estimates were developed based on recent and similar beach fill and truck haul projects constructed in the vicinity of Currituck County. Costs associated with truck haul projects were based on a project constructed in 2023 within the Spindrift community, located just north of the southern Currituck County beach access at Yaupon Lane. Costs associated with ocean dredging projects used a calibrated cost estimating spreadsheet that considers recent bids for various projects in Dare County. Table 20 summarizes estimated mobilization/demobilization costs for ocean dredging, along with estimated unit costs for both truck haul and dredge and fill projects in Currituck County. Cost estimates were adjusted based on distances from potential sand resources and recipient beaches.

Table 20. Information used to compare truck haul cost to ocean dredging costs.

Description	Cost	Units
Mobilization/Demobilization for Ocean Dredging	$8,779,000.00	Lump Sum
Unit Cost for Sand Placed from Ocean Dredging	$10.56	Cubic Yard
Unit Cost for Sand Placed for Truck Haul	$69.36	Cubic Yard[(2)]

Using the values provided in Table 20, the equivalent quantity at which both truck haul and dredge and fill projects would be relatively equal in price, is around 150,000 cubic yards. This value is provided as a planning tool to determine the scale of projects that may be cost effective to construct as truck haul projects in Currituck County. In general, projects requiring less than 150,000 cubic yards of fill may be more economically constructed using truck haul methods, while projects exceeding 150,000 cubic yards may be more cost-effective when completed through offshore dredging.

However, a number of variables may influence the relative cost-effectiveness of each construction method, including permitting costs, beach access, offshore transport distance between the borrow source and the recipient beach, and the ability to time dredge projects with other communities. Therefore, a detailed project-specific cost evaluation during the design phase is recommended to determine the most economical construction approach.

Given the fact that truck haul projects may only be economical for smaller scale projects along the Currituck County oceanfront, this concept may be limited to smaller sections of beach where supplemental sand is required to meet the County's beach management goals.

The concept of smaller scale truck haul projects would involve the design, permitting, and construction of projects focused on any number of the established County goals for beach management. The threshold of when to use this concept will primarily be based on the volume of sand needed to achieve the specific project goal; however additional thresholds could be considered as well. As stated previously, the cutoff point has been estimated to be in the range of 150,000 cubic yards. That said, factors controlling costs of construction should be evaluated from time to time to confirm this threshold value is still applicable.

A number of communities and private homeowners along the Currituck County oceanfront have taken the initiative to construct truck haul projects. If the County were to adopt truck haul projects as a concept to be implemented in a comprehensive beach management plan, specific thresholds should be established to determine whether County participation in the project is warranted. The truck haul concept should also consider how the County, as part of its beach management plan, would encourage, incentivize, and/or implement smaller scale truck haul projects.

3.3 Large-Scale Beach Nourishment

While the truck haul concept is a reasonable option for small scale beach nourishment projects, large-scale beach nourishment projects have provided multiple years of erosion protection and storm damage reduction throughout the world. More specifically, numerous successful large-scale beach nourishment projects have been implemented along portions of the Outer Banks. Beach nourishment is the periodic placement of sand along a beach to reduce storm damage, mitigate flooding and long-term erosion, and/or provide sufficient recreational beach. Beach nourishment transfers sand from borrow areas to the recipient beach by hydraulic dredging or truck haul (Dean, 2002). As discussed in Section 3.2, there may be volumetric limits at which truck haul projects along the Outer Banks may be less economically viable than beach nourishment using offshore sand sources and dredges. For this reason, Section 3.3 assumes that large-scale beach nourishment would utilize dredging and offshore sand sources as borrow areas.

Typically, a beach nourishment design consists of two primary components, a Design Section and Advanced Fill (NRC, 1995). The Design Section is the cross-section required to meet project objectives such as storm damage reduction, reduction of risk of dune breaching, and maintaining sufficient recreational beach. Advanced Fill is the sacrificial portion of the fill required to mitigate long-term erosion and protect the Design Section. Figure 83 illustrates these two components in cross section. The Design Section typically includes a designed beach berm with a defined width and elevation and may also include a dune with specified crest height, crest width, and dune slope. The volume of Advanced Fill required is determined based on background erosion rates, the number of years anticipated between renourishment cycles, and diffusion losses. Diffusion or spreading occurs with any sand placement activity as the nourished beach evolves into an equilibrium planform comparable to the adjacent shorelines (Dean, 2002). Diffusion losses are the result of the fill template spreading alongshore and occurs when the fill material spreads outside the fill placement or project area.

The concept of large-scale beach nourishment would involve the design, permitting, and construction of projects focused on any number of the established County goals for beach management. The threshold of when to use this concept will primarily be based on the volume of sand needed to achieve the specific project goals. As stated in Section 3.2, projects greater than 150,000 cubic yards may be more economically constructed using offshore sand sources and dredges. However, factors controlling costs of construction should be re-evaluated from time to time to confirm this threshold value is still applicable.

Submarine Sand Sources

The financial viability of a beach nourishment program is highly dependent on the availability of a sufficient quantity of beach compatible sand proximate to the recipient beach. Several sand investigations have been conducted offshore of the northern Outer Banks region to identify sand resources for beach nourishment projects. Early efforts included vibracore sampling by NCGS/MMS in 1996 (Hoffman, 1998), and extensive geophysical and geotechnical investigations by the USACE in the mid-1990s (USACE, 2000), which led to the identification of three potential borrow areas, including Borrow Area S1 offshore of Nags Head, North Carolina, that contained high-quality beach sand and was partially used by the Town of Nags Head for beach nourishment in 2011. Building on this work, the Towns of Duck, Kitty Hawk, and Kill Devil Hills commissioned a comprehensive sand search in 2013–2014 that included geophysical surveys, jet probes, and vibracores, resulting in the design and permitting of Borrow Areas A and C (CPE-NC, 2015), which were subsequently used for beach nourishment projects in 2017 and 2022/2023. A later investigation in 2020 explored areas south of Borrow Area C but was discontinued after sediments were found to be finer, darker, and less suitable than those in Borrow Area A. Figure 84 shows an overview map illustrating some of the historical geotechnical data, investigation areas, and permitted borrow sites.

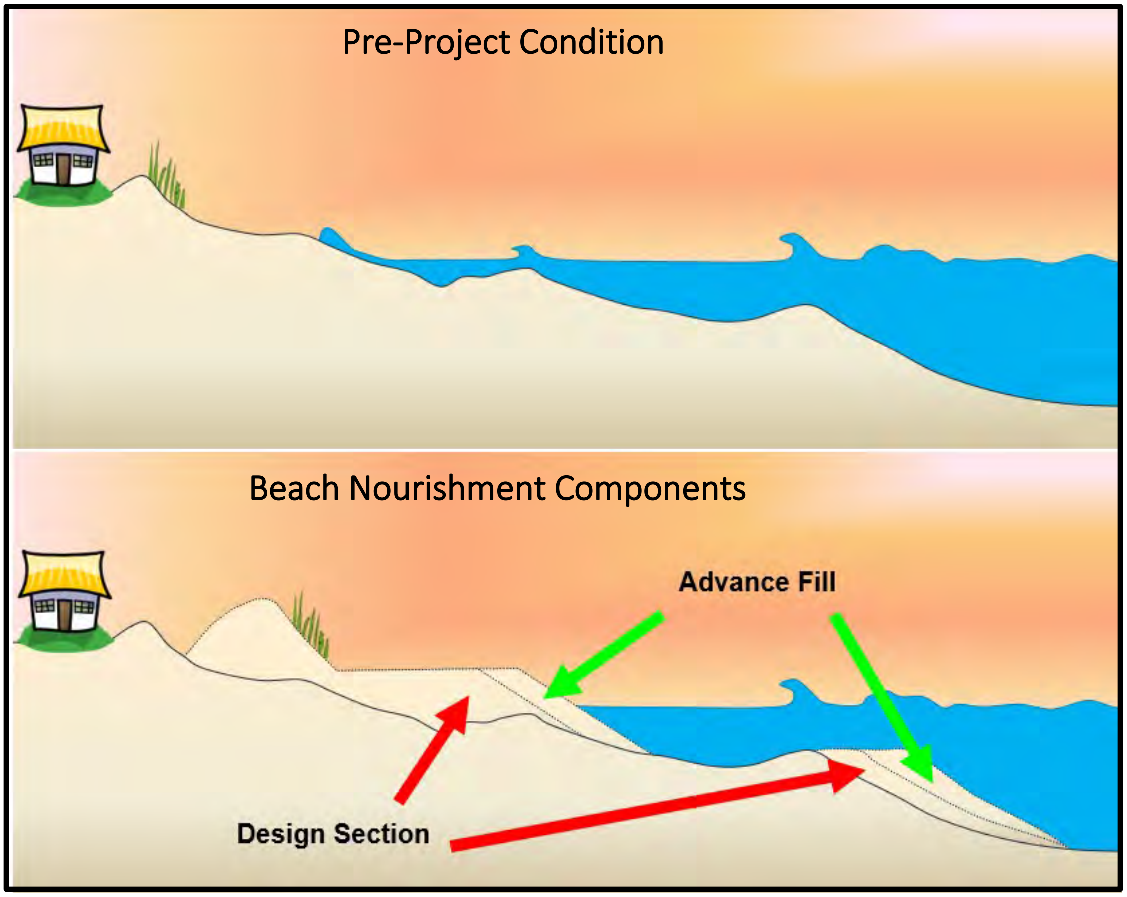


Figure 83. Illustration of the two beach nourishment design components, Design Section and Advanced Fill.

In 2022, Dare County received grant funding through the North Carolina Coastal Storm Damage Reduction Fund (CSDRF), for a 2-year regional sand resource investigation. The goals of the investigation were to 1) identify sand sources more proximate to various project sites, to decrease cost of future maintenance events; and 2) to provide assurances for planning that sufficient sand resources exist to sustain the projects over a long-term (30-year) planning horizon. During initial scoping of the project, Dare County coordinated with Currituck County staff. However, at the time, Currituck County did not have an immediate need to participate in the investigation.

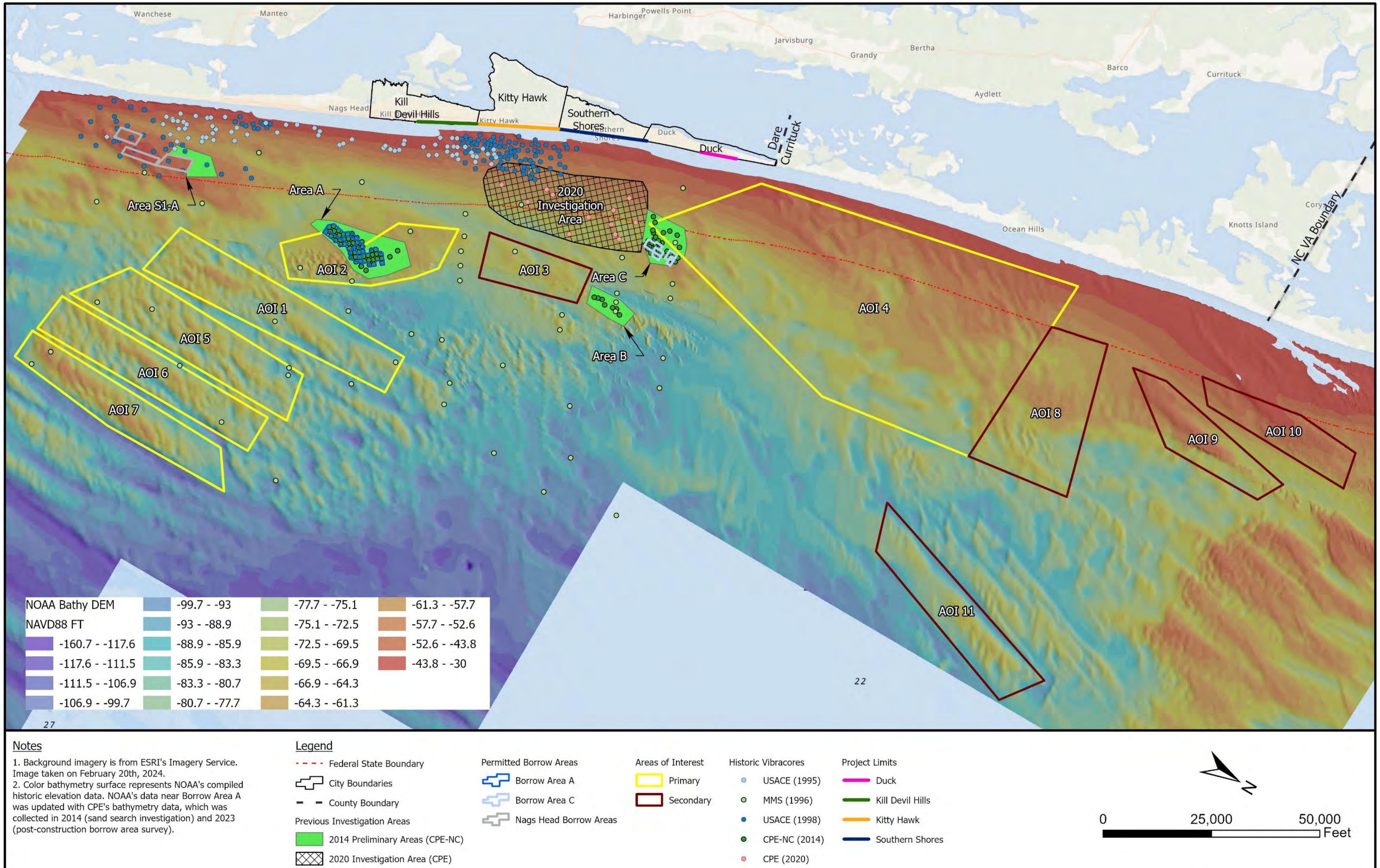


Figure 84. Historical data collection and borrow areas designed off of the Northern Outer Banks (CPE, 2024).

The regional sand resource investigation conducted by Dare County employed a systematic approach to marine sand searches developed over the years (e.g. Finkl, Andrews and Benedet, 2003; and Finkl, Andrews, Willson, and Andrews, 2005). This methodology typically divides the investigation into three (3) sequential phases, which can be modified to meet the scope of the investigation and accommodate the level of work previously performed. Phase I included a desktop analysis of available data and identification of Areas Of Interest (AOI), Phase II included reconnaissance geophysical and geotechnical investigations, and Phase III included design level geophysical and geotechnical investigations and the design of proposed borrow areas.

Phase I of the investigation identified eleven (11) Areas Of Interest (AOI), which are shown in Figure 84. Of these eleven (11) AOI's, six (6) of them were targeted during Phase II of the investigation for reconnaissance analysis. AOI 3 was not selected for further analysis due to its proximity and similarity to two previous AOI investigated in 2014 (CPE-NC, 2015) and 2020 (CPE, 2021). These investigations found that material in this region was finer and darker than the recipient beaches. AOI 8, 9, 10, and 11 shown in Figure 84 were not targeted in the investigation due to the distances of the AOI's from the nourishment projects in Dare County.

During reconnaissance level geophysical and geotechnical investigations completed in 2023 (Phase II), seven (7) Potential Sand Resource Areas were identified. Three (3) of these areas were located within AOI4 off of Currituck County, namely Potential Sand Resource Areas E, I, and J. Figure 85 shows the location of these three Potential Sand Resource Areas as well as the geophysical data tracklines surveyed and vibracore samples collected in the vicinity. The following is a brief synopsis of potential sand resource for each Area based on the 2023 reconnaissance level investigations (CPE, 2025a):

- **Potential Sand Resource Area E** covers approximately 5,266 acres and is located between 0.7–4.0 nautical miles offshore of southern Currituck County. The area is estimated to contain up to 32.3 MCY of beach-compatible sand, with a mean grain size of 0.25 mm.
- **Potential Sand Resource Area I** covers approximately 1,842 acres and is located between 6.3 and 7.4 nautical miles offshore Corolla in Currituck County. The area is estimated to contain up to 1.5 MCY of beach-compatible sand, with a mean grain size of 0.20 mm.
- **Potential Sand Resource Area J** covers approximately 2,922 acres and is located between 1.5–4.0 nautical miles offshore of southern Currituck County. The area is estimated to contain up to 16.6 MCY of beach-compatible sand, with a mean grain size of 0.24 mm.

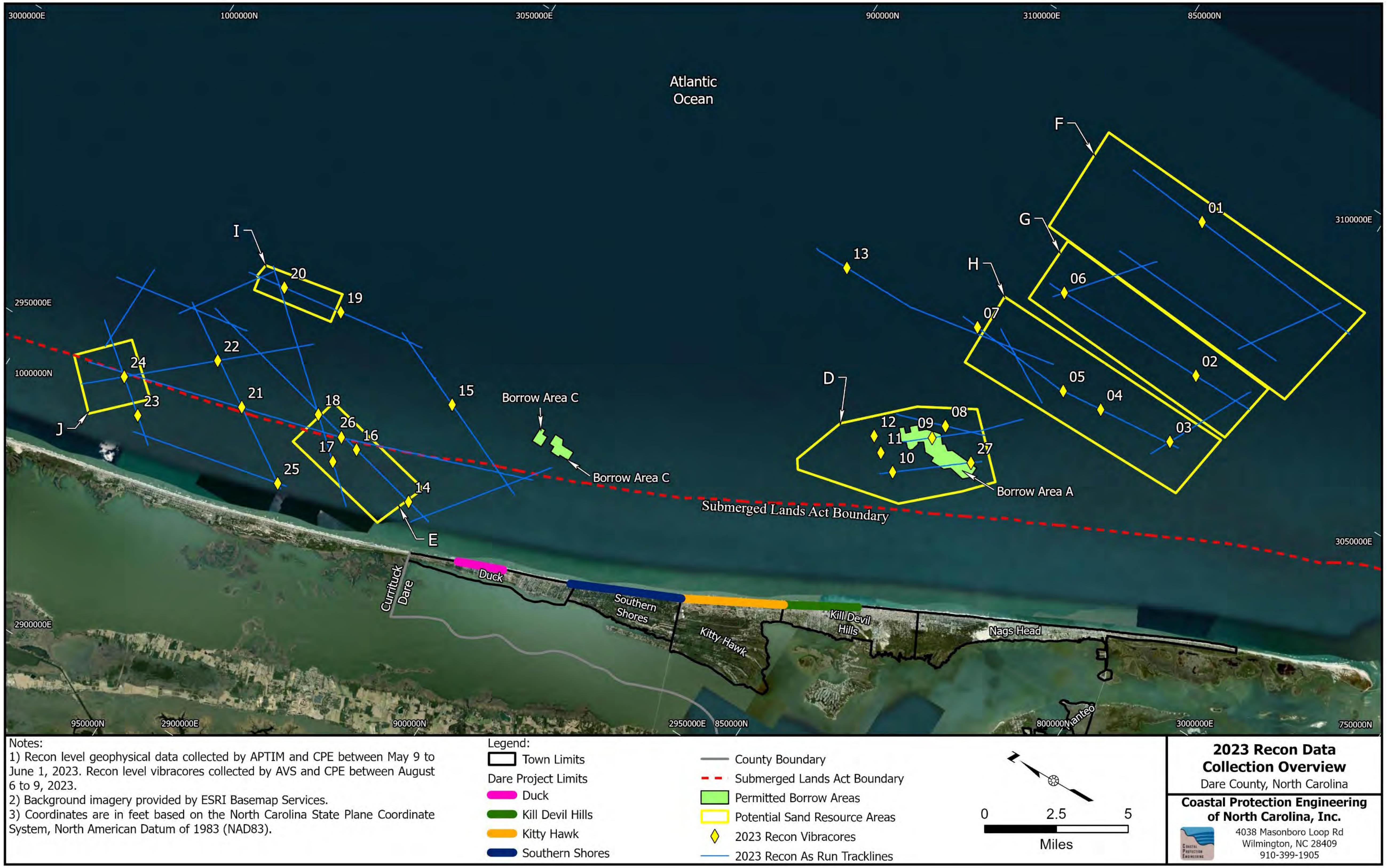


Figure 85. Reconnaissance level geophysical and geotechnical data collected offshore Currituck and Dare County in 2023 (CPE, 2025).

In 2024, additional investigations were conducted within Potential Sand Resource Area E as part of Phase III of the same regional investigation. The investigation led to the development of three (3) proposed borrow areas within Area E, namely Borrow Areas E-1, E-2, and E-8, as shown in Figure 86 (CPE, 2025a). In total, approximately 4.4 MCY of beach compatible sand has been identified within these three proposed borrow areas. Proposed Borrow Area E-1 covers approximately 186 acres and contains an estimated 1.2 MCY of beach-compatible sand with a mean grain size of 0.22 mm. The material is moderately sorted and contains 1.69% fines passing the No. 230 sieve. Proposed Borrow Area E-2 covers approximately 240 acres and also contains an estimated 1.2 MCY of beach-compatible sand, with a mean grain size of 0.23 mm. The material is moderately sorted and contains 2.53% fines passing the No. 230 sieve. Proposed Borrow Area E-8 encompasses approximately 198 acres and contains an estimated 2.0 MCY of beach-compatible sand with a mean grain size of 0.27 mm. The material is moderately sorted and contains 1.59% fines passing the No. 230 sieve.

3.4 Beach Nourishment with Coastal Structures

As previously stated, most successful beach management programs implemented along densely populated resort communities in the U.S., rely on the addition of sand to the active beach. The addition of sand to the natural environment, sometimes referred to as “green” infrastructure, relies on the natural ability of systems to protect oceanfront development and infrastructure from storm impacts and long-term erosion while providing co-benefits such as recreational area, habitat, and the enhancement of ecosystem services (O’Donnell, 2017). It is generally preferred by state and federal resource agencies over hardened structures.

While “green” infrastructure is preferred to hard structures, some projects have benefited from the incorporation of coastal erosion control structures to the overall design of beach management programs. Coastal erosion control structures can generally be broken into two categories, shoreline hardening structures and sand retention structures. As previously discussed in Section 3, armoring the coast with shoreline hardening structures such as seawalls or revetments are not an ideal solution along retreating shorelines in oceanfront communities focused on beach tourism. However, sand retention structures that trap and retain sand, such as groins and breakwaters, have been successfully incorporated into beach nourishment projects.

Sand retention structures are typically designed and constructed to modify waves and currents that interact with the beach and drive sand transport, which results in varying erosion and accretion trends along a beach. Groins are shore-perpendicular structures that trap sand as it moves laterally along the beach. A terminal groin is a single groin structure constructed at the end of an island or littoral cell. Breakwaters are shore-parallel structures that create wave breaks that significantly reduce wave energy in the lee of the structures, which reduces sediment transport on the leeward side (or shadow) of the structures. Figure 87 and Figure 88 provide schematic illustrations of groins and breakwaters, respectively.

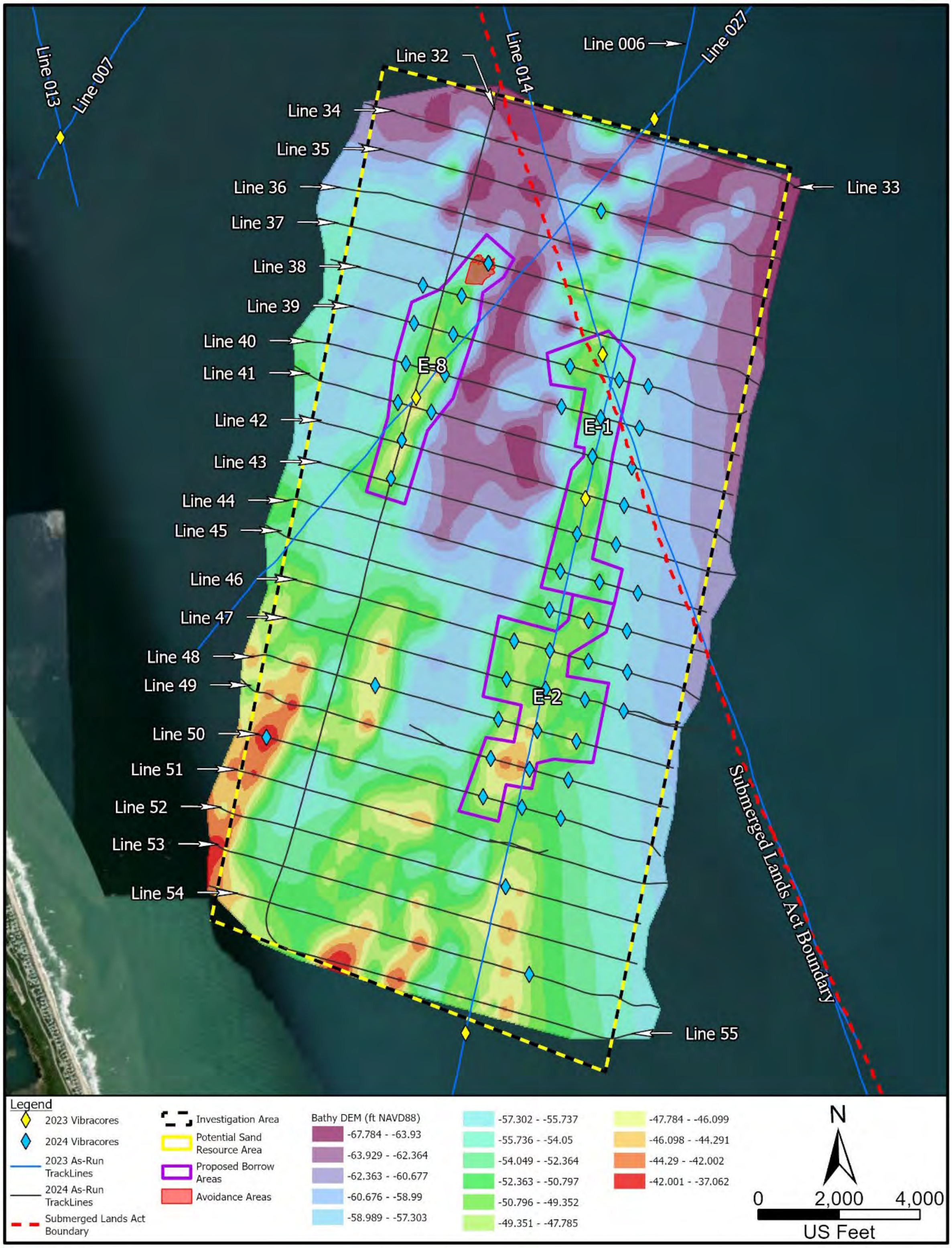


Figure 86. Locations of proposed Borrow Areas E-1, E-2, and E-8 within Potential Sand Resource Area E.

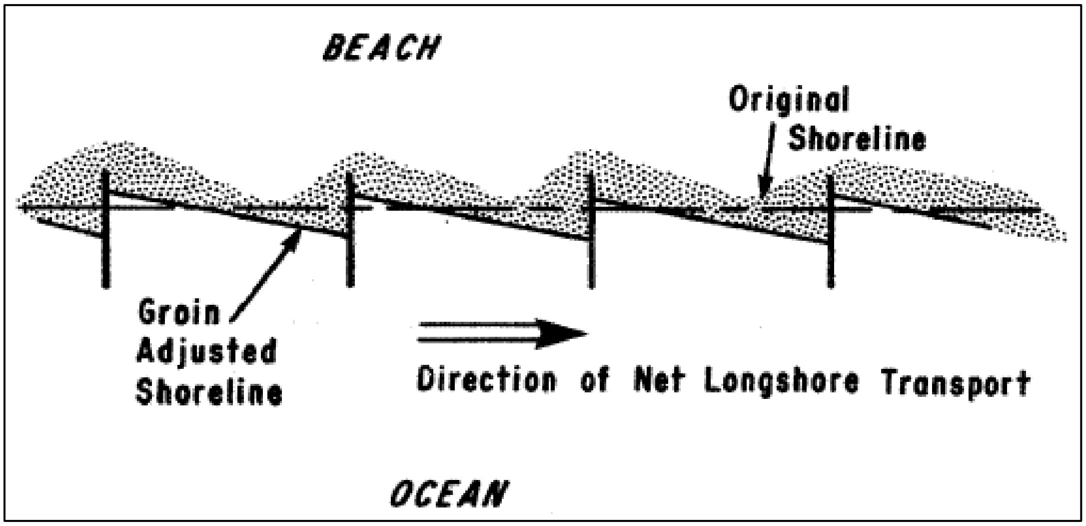


Figure 87. Schematic of groin field (Modified from USACE, 2008).

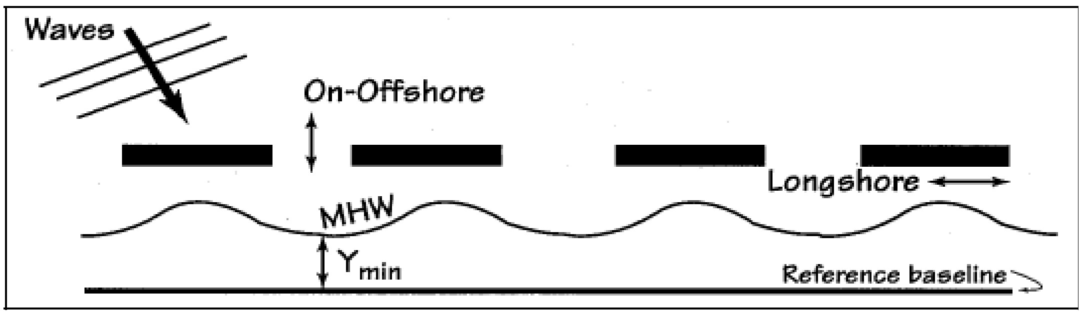


Figure 88. Schematic of breakwater field (Modified from USACE, 2008).

The incorporation of sand retention structures into coastal programs must consider that these structures do not add sand to the system that would increase coastal protection and/or mitigate erosion, they retain sand that is part of the littoral system. Therefore, if these structures are the only aspect of a coastal management strategy, the retention of sand in front of one section of beach is likely to result in adverse downdrift effects on an adjacent section of beach. For this reason, coastal engineers typically use these structures in conjunction with beach nourishment projects to reduce the rate of sediment loss along a specific section of beach, often referred to as a "hot spot." Figure 89 and Figure 90 show examples of groin fields and breakwater fields being incorporated into beach nourishment projects.

As previously discussed, the North Carolina Coastal Resources Commission (NC CRC) enacted a rule in 1979, effectively prohibiting hardened structures along the coast of North Carolina. In 2003, the North Carolina General Assembly codified the ban on permanent hardened structures. In 2011, after extensive study of the impact of terminal groins, the North Carolina General Assembly passed Senate Bill 110, which allowed for up to four pilot projects to construct terminal groins adjacent to inlets in North Carolina. In 2015, the North Carolina General Assembly passed legislation increasing the number of terminal groins that could be constructed within the state to six. To date, two of the allowed six terminal groins have been constructed since the initial change in the state law in 2011, those being at Bald Head Island and Ocean Isle Beach.

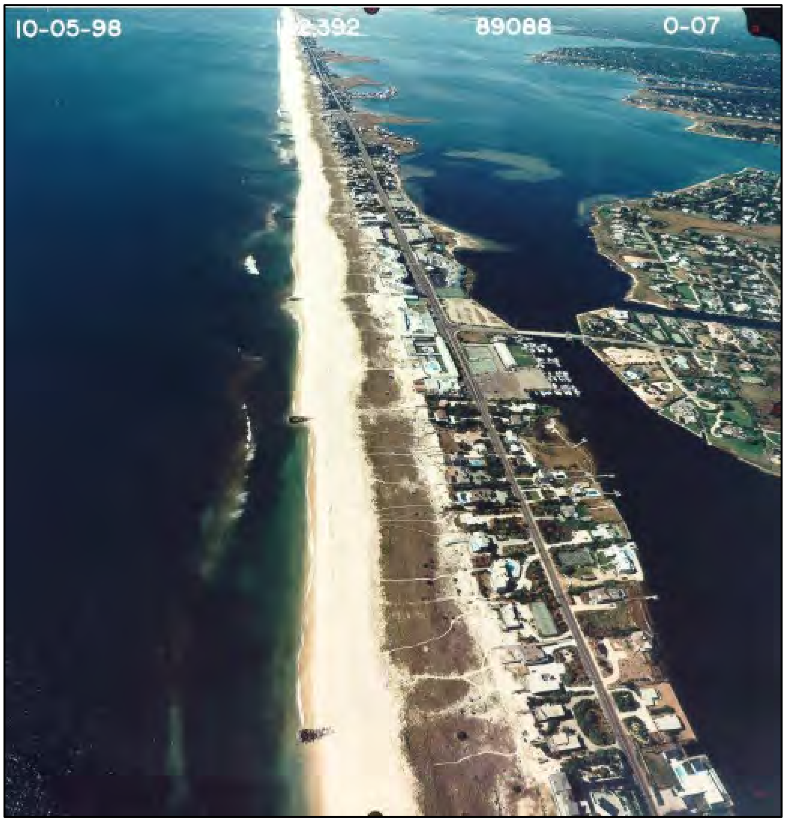


Figure 89. Example of groin field and renourished beach at Westhampton Beach, New York, 1998 (Courtesy USAED, New York).

Figure 90. Example of a breakwater field and a renourished beach at Holly Beach, Louisiana (Mann and Thomson, 2003)

The 2011 and 2015 legislations could be interpreted as the NC General Assembly's openness to allowing hardened structures as a part of beach management. However, these allowances have been very specific to locations adjacent to tidal inlets where erosion rates are considerably higher. In these instances, beach nourishment alone had been demonstrated to be insufficient to mitigate the high rates of loss. Given the fact that the current allowances for hardened structures are limited to areas in the vicinity of tidal inlets, additional changes to current state law would be required to allow for Currituck County to incorporate any hardened structures into its beach management plan. Furthermore, the 2011 legislation mandates that hardened structures only be constructed as part of a beach nourishment project (Senate Bill 110, 2011).

In Spring 2026, two bills were filed in the North Carolina Senate, which could change the status of hardened structures in North Carolin. SB 1009 aims to repeal the ban on hardened structures established by the NC General Assembly in 2003. SB 1008, which was introduced in early May 2026 aims to establish a pilot program to permit construction of shoreline stabilization projects under certain conditions. At the time of the completion of this report, it is uncertain whether these bills will be passed into law, but both bills could have impacts on what options are available for beach management in the future.

With the success of beach nourishment projects constructed in Dare County and north of Currituck County in Sandbridge, Virginia, and the relatively low average erosion rates measured along the County's oceanfront, beach nourishment alone may be a viable option to meet the goals of the County's beach management plan. Where specific hot spots are identified where erosion rates suggest that beach fill alone would not be sufficient to meet the County's goals and where the incorporation of sand retention structures in conjunction with beach fill is warranted, consideration of structures should be given.

3.5 Sand Fencing and Dune Vegetation

As previously described, most successful beach management programs rely on the addition of sand to the active beach to reduce the risk of storm damage and/or to mitigate the effects of long-term erosion. Typically, the creation or increase in width and height of sand dunes are incorporated into projects and programs where sand is being added to the beach. For decades, coastal engineers and scientists have understood that dunes protect developed coastal areas from both elevated water levels and wave erosion associated with coastal storms (Sallenger, 2000).

Sand dunes are essentially large coastal features that are typically formed when wind-blown sand is trapped and stabilized by vegetation (Elko et al., 2016). Coastal communities and property owners have also used sand fencing to trap wind-blown sand on or at the toe of existing dunes to increase the level of protection provided by the dune. A recent example of dune planting and sand fence installation along a beach nourishment project is shown in Figure 91. The construction and maintenance of dunes not only provides protection from wave runup and erosion, but functional dunes also provide ecosystem services. These include habitat for a variety of endangered species. Dunes also provide sites of higher tourism value, groundwater recharge zones, and more recently stormwater storage (Horstman, 2021).

Figure 91. A constructed dune in the Town of Kitty Hawk, NC where dune vegetation was planted along the seaward dune slope and crest and sand fence was installed along the crest (May, 2023).

While planting and maintaining vegetation and installing sand fencing is an effective way of trapping sand in the dune and increasing the protective capacity of a dune, a steady supply of wind blown sand is required for this approach to be successful. Typically, if the beach immediately seaward of the dune is low lying and frequently overtopped, planting and installing sand fencing will have limited effect due to a lack of supply of wind-blown sand. Furthermore, if a dune is actively being eroded by storm events, it is unlikely that the addition of vegetation or sand fence alone will be an effective way of enhancing or maintaining the dune.

The state of North Carolina does not have specific rules on dune planting. However, natural beach processes typically limit the proliferation of dune vegetation seaward out onto the beach. Between late fall and early spring, the Outer Banks and most of the east facing beaches of North Carolina are impacted by nor'easters. These relatively large and frequent weather systems temporarily erode the berm and reduce the width of the dry sand beach. The frequency of these events typically does not allow for significant beach recovery during this time of year. While dune grasses do naturally grow on the berm during the summer months, during the more stormy season between late fall and early spring, erosion typically reaches the vegetation and undermines the newer less established growth located on the berm (Rogers and Nash, 2003).

The installation of sand fencing is allowed under Coastal Resources Commission rules 15A NCAC 7K .0212. The installation of sand fencing can be permitted under a CAMA Minor Development Permit or may be exempt from the permit requirements if the installation meets the requirements set forth in NCAC 7K .0212.

Because the effectiveness of dune vegetation and sand fencing is highly dependent upon local beach morphology, dune condition, and the availability of wind-blown sand, the County could consider developing a proactive, data-driven coastal management initiative utilizing drone technology to evaluate the condition and performance of the oceanfront dune system and identify locations where these nature-based stabilization measures would provide the greatest benefit. One concept would involve periodic unmanned aerial system (UAS) flights of the beachfront to assess dune crest elevations, dune continuity, dry beach width, and sediment accumulation patterns in order to strategically target locations where sand fencing and dune vegetation could improve shoreline resiliency and storm protection.

This concept aligns with the County's recently expanded Sand Fence and Dune Vegetation Programs, which were modified by the Board of Commissioners to increase participation and encourage broader implementation of dune stabilization measures. On January 20, 2026, the Board of Commissioners approved a budget amendment increasing funding for both programs and converting them from traditional cost-sharing programs to reimbursement-based programs intended to incentivize dune protection efforts along the oceanfront.

3.6 Beach Bulldozing

"Beach bulldozing" is an action permitted by the State of North Carolina, that is defined as the "…process of moving natural beach material from any point seaward of the first line of stable vegetation to repair damage to frontal or primary dunes." In essence sand is mechanically scraped or harvested from the lower elevation portions of the beach and placed higher up on the profile to bolster the size of the protective dune.

Similar to dune planting and installation of sand fencing, beach bulldozing does not add sand to the beach system. This management practice moves sand from the lower portion of the beach to the dune in an attempt to bolster the protective nature of the dune. With the beach being in a constant state of change based on wave characteristics, water levels, and grain size variation of the sand, this management practice should be considered more temporary than the other management practices discussed in this plan. While the movement of sand from the wet sand portion of the beach to higher elevations close to or into the dune can provide temporary protection from a storm, typically these efforts do not last more than a few months depending on the number and size of the storms that impact the area immediately following the action.

Beach bulldozing is allowed under current Coastal Resources Commission rules 15A NCAC 07H .1800. When conducting beach bulldozing, no greater than one foot of material vertically can be removed from the lower beach and relocated landward. Material cannot be moved from any point seaward of the Mean Low Water (MLW) line. Beach bulldozing is typically conducted on a property-by-property basis and when permitted, the efforts cannot extend laterally outside of the permitted property to adjacent properties.

It may be possible to utilize beach bulldozing in specific locations to temporarily improve the width and height of a dune to increase the protection provided. Typically, this type of management option has been left to individual property owners to implement and is not implemented by beach municipalities. However, in some instances following significant impacts from coastal storms, some communities have taken steps to rebuild dunes temporarily using this concept. Likewise, municipalities have used beach bulldozing to close beach access locations during anticipated storm or high water conditions to minimize the risk of inundation of seawater through access points that tend to be lower in elevation.

4 FEASIBILITY ANALYSIS

The County has established the following goals for a Countywide beach management plan.

1. Reduce risk to oceanfront properties from coastal storms;
2. Mitigate risk to oceanfront properties from long-term erosion;
3. Reduce the risk of dune breaching which can cause considerable flooding of beachfront communities;
4. Maintain/Protect public roads/emergency evacuation corridors; and
5. Provide sufficient recreational beaches that promote and encourage tourism

The results of the coastal hazard and vulnerability analysis described in Section 2, indicate that the Countywide beach management plan must address several immediate issues to reduce existing risk. Furthermore, the beach management plan should also seek to establish a long-term program aimed at achieving the stated goals over a long-term planning horizon. This plan considers 30 years as its planning horizon. However, a successful beach management program requires adaptive management. Variables such as erosion rates, storm impacts, performance of implemented solutions, funding availability, changing environmental policy, and changes in technology have the potential of requiring considerable adaptations to an established plan. For that reason, this plan incorporates regular monitoring and review and update of the overall plan on a 5-year basis.

Given the differences in density of development, land use, and access restrictions north and south of the Horse Gate along the County's oceanfront, the feasibility analysis and beach management plan address these two areas separately.

4.1 North of the Horse Gate

4.1.1 Problem Statement and Objective

North of the Horse Gate, within the Carova and Reserve/Refuge Sections of the County's beaches, the coastal hazard and vulnerability analysis identified several shoreline segments where the shoreline change projections indicate oceanfront houses are vulnerable. Analyses conducted between 2020 and 2024 indicate that 1 to 4 oceanfront houses were vulnerable over the 20-year shoreline change projection and 0 to 3 were vulnerable over the 10-year projection. North of the

Horse Gate, access to private properties and the Reserve/Refuge Section is primarily along the oceanfront beach road. The structures that have been identified through shoreline change projections, particularly those located between Stations C-041 and C-044, are houses that are located on the open beach. These structures have the potential to impact the flow of traffic along the beach road (See Figure 82). The vulnerability matrices shown in Figure 79, Figure 80, and Figure 81, also indicate that the area between Stations C-041 and C-044 has experienced a higher than average erosion rate, which also suggests this section is not likely to correct itself.

It should be noted that the model domain used to indicate storm vulnerability and the potential for breaching or overtopping did not extend north of the Horse Gate, and therefore, that analysis was not performed along the Carova or Reserve/Refuge Sections. However, a previous SBEACH storm vulnerability analysis conducted in 2022 did indicate some of the same oceanfront structures located between Stations C-041 and C-044, would be vulnerable to a design storm consistent with Hurricane Isabel (CPE, 2023a).

In order to achieve the County goals for beach management, the alternatives evaluated for the portions of the County oceanfront north of the Horse Gate focused on reducing coastal storm risk to oceanfront properties, mitigating risk to long-term oceanfront erosion, and maintaining the public road that serves as the primary access corridor to and from points north of the Horse Gate. Most recreation areas north of the Horse Gate are accessed using 4-wheel drive vehicles. The alternatives considered for beach management north of the Horse Gate did not focus specifically on maintaining sufficient recreational beaches as most sections were indicated as having sufficient recreational beaches, which are easily accessible to 4-wheel drive vehicles.

4.1.2 Alternatives

Three alternatives were evaluated as part of the feasibility assessment for the Sections north of the Horse Gate: 1) the No Action Alternative; 2) Buyout and Removal of Threatened Oceanfront Structures; and 3) Beach Nourishment Program. These alternatives focus on the portion of shoreline located between Stations C-041 and C-044 shown in Figure 92 and is referred to as the Central Reserve/Refuge Reach.

Alternative 1 - No Action Alternative
The No Action Alternative involves no direct active management of the beach along the Central Reserve/Refuge Reach by Currituck County. As previously stated, there are oceanfront structures located along this Reach that have been identified as vulnerable to a design storm consistent with Hurricane Isabel. These structures are located along portions of the beach characterized by erosion rates greater than the average erosion rate observed between 2022 and 2024 in the Reserve/Refuge Section. Furthermore, these structures which are situated directly on the open beach, are impacting travel along the beach road that serves as the primary access corridor to and from points north of the Horse Gate.

Figure 92. Map showing the extent of the Central Reserve/Refuge Reach.

Implementation of this Alternative would not require a direct financial outlay by the County. However, given this alternative is not anticipated to achieve the County's goals for beach management, the County may experience a reduction in tax revenues from potential loss of oceanfront structures (ad valorem taxes). In addition, public perception of unsafe or undesirable beach conditions due to structures collapsing on the beach and concerns over access along the beach road could adversely impact the area's reputation as a tourist destination.

Alternative 2 - Buyout and Removal of Threatened Oceanfront Structures

Alternative 2 involves the buyout and removal of oceanfront structures that impede emergency access and evacuation routes north of the Horse Gate in the offroad section of the Reserve/Refuge and Carova Sections. Implementation of this alternative would first require the establishment of a County committee or policy framework to define criteria for identifying structures eligible for buyout and removal, determining fair market value for the buyout, and evaluating whether any future disclosure requirements should be developed to notify future buyers of the policy.

Once a structure has been identified for the buyout and removal program, the County would negotiate with the owners to obtain the property and remove the structure(s) from the property. This alternative assumes that by obtaining the property and removing the structure, the risk to the oceanfront structures identified as vulnerable to coastal storms would be eliminated. Furthermore, there would be no reason to mitigate for long-term erosion to the structure(s) that have been removed. In addition, removing structures located directly on the open beach, would help preserve and maintain the beach road which serves as a critical access route for emergency responders and public evacuation.

The cost associated with this alternative would primarily be driven by the cost to purchase structures, and fees paid to demolition contractors to remove the structures. This alternative assumes no additional life cycle costs for maintenance. Once the structures have been removed, no maintenance is anticipated for those previously threatened properties. The 30-year shoreline change projections are used to identify the number of potential targets for buyouts and removal of threatened oceanfront structures. Furthermore, the County may be able to reduce the need to buyout and remove the structures if alternative access can be established around these structures where emergency access and evacuation would not be impacted.

Alternative 3 – Beach Nourishment Program

Alternative 3 involves the construction of relatively small beach and dune truck haul projects along portions of the beach where oceanfront structures have been identified as vulnerable and where emergency access and evacuation is being impacted by the oceanfront structures located on the open beach. This alternative would require engineering design to determine the appropriate volume and beach fill configuration (width and height of dune and width and height of dry sand beach) to achieve the County goals. Depending on the final design configuration, permits may be required from both the North Carolina Division of Coastal Management and the U.S. Army Corps of Engineers.

Additional engineering design analysis is required to evaluate the volume of material needed under this alternative to achieve the County's beach management goals. While specific storm simulations have not been run for the areas north of the Horse Gate, analyses conducted for areas south of the Horse Gate were used to estimate the design volume required to achieve the County goals. While design volume estimates are provided for the estimated fill needed to achieve the risk reduction goals, the relatively short length of the projects may require a significant amount of additional fill to maintain such a design given the relatively short length of the anticipated truck haul projects.

This alternative assumes that by constructing a beach nourishment project, and maintaining it with periodic renourishment events, the risk to the oceanfront structures identified as vulnerable to coastal storms would be addressed. Through regular sand maintenance events, this alternative could mitigate for long-term erosion impacts on the threatened structures. With a sufficient protective dune and dry sand beach fronting the structures, the goal of maintaining and protecting access for emergency responders and an evacuation route would be achieved.

The cost associated with this alternative would initially include permitting, engineering design, and construction of the beach nourishment project. This alternative would also include considerable life cycle costs associated with the continued placement of maintenance sand to mitigate for long-term erosion. It should be noted that the Reserve/Refuge Section, where the identified vulnerable structures are located, has the highest erosion rate over the recently identified erosional trend at -9.3 cy/ft./yr between 2022 and 2024.

4.1.3 Feasibility Evaluation

In order to evaluate the feasibility of each alternative, a feasibility matrix was developed using a modified version of the TELOS method (Hall, 2012), which provides a structured framework for evaluating project alternatives across five core dimensions of feasibility. TELOS is an acronym that refers to the five (5) core dimensions, namely Technical, Economic/Financial, Legal/Regulatory/ Environmental, Operational, and Schedule. This modified method compares the three alternatives described in Section 4.1.2 against the goals stated in the problem statement and objectives in Section 4.1.1. A three-tier color-coded scoring system for each of the criterion was established using green as the highest scoring, yellow as intermediate scoring, and red as lowest scoring. The feasibility matrix is graphically represented in Figure 93.

Technical (T)

Technical feasibility assesses overall performance, reliability, and compatibility with existing protocols as it relates to accomplishing the goals set forth in the problem statement and objectives for beach management along the Central Reserve/Refuge Reach. The red tier indicates an alternative that does not satisfy any of the goals established in the problem statement and objectives. The yellow tier indicates an alternative that may satisfy some goals but is unlikely to satisfy all goals in an economic manner over the 30-year planning horizon. The green tier reflects alternatives likely to address all goals for the 30-year planning horizon.

BEACH MANAGEMENT PLAN – ALTERNATIVE FEASIBILITY ANALYSIS (ALTERNATE)

Evaluation Criteria	Alternative 1 No Action Alternative	Alternative 2 Buyouts and Removal of Threatened Structures	Alternative 3 Beach Nourishment	Description of Ranking Criteria
T - Technical Performance, reliability, compatibility with existing protocols	Low	High	Moderate	● Does not satisfy any of the goals in the Problem Statement. ● May satisfy some goals in the Problem Statement but does not satisfy all of the goals over a 30-year planning horizon. ● Likely to address all goals in the Problem Statement for the 30-year planning horizon.
E - Economic/Financial Initial and Life-Cycle Costs, benefits	Low	High	Low	● 30-year life cycle cost anticipated to exceed the benefits. ● 30-year life cycle benefits anticipated to exceed the costs.
L - Legal/Regulatory/ Environmental Legal challenges, environmental permitting, risk to public or ecosystem	Moderate	Low	Moderate	● Likely to face permitting or legal challenges and/or may have long-term adverse environmental impacts. ● Short-term environmental impacts but no long-term adverse environmental impacts anticipated. Not likely to face legal or permitting challenges. ● Minimal environmental or legal objections anticipated.
O - Operational Allows for normal operations, requirement for maintenance	Low	High	Moderate	● Likely to result in a loss of function of normal beach operations. ● Allows for normal beach operations other than temporary construction efforts. Requires long-term maintenance. ● Allows for normal beach operations other than temporary construction efforts. Does not require long-term maintenance.
S - Schedule Time to implement	High	High	Low	● Initial implementation expected to require more than 1 year. Requires long-term maintenance. ● Initial implementation expected to be completed in less than 1 year. Requires some long-term maintenance. ● Initial implementation expected to be completed in less than 1 year. Does not require long-term maintenance.

Figure 93. Feasibility Matrix used to assess alternatives for beach management along the Central Reserve/Refuge Reach.

The No Action Alternative (Alternative 1) scores poorly under the Technical criteria because it is unlikely to satisfy any of the goals established as the objectives for beach management along the Central Reserve/Refuge Reach. While Alternative 3 (Beach Nourishment) may satisfy some goals, the volume of sand required to satisfy all of the goals is expected to render the project economically unfeasible over the long-term 30-year planning horizon. Specifically, the fill density necessary to both maintain reliable passage seaward of the vulnerable structures and provide storm damage risk reduction to those isolated homes could exceed a fill density of 65 cubic yards per linear foot, based on storm vulnerability analyses conducted for portions of the County oceanfront located south of the Horse Gate. Furthermore, the volume of sand needed to keep up with long-term erosion would be relatively high in this location as the Reserve/Refuge Section has experienced the highest average erosion rates observed during the 2022 to 2024 monitoring period. In addition, because the shoreline segments requiring beach fill to protect the identified vulnerable oceanfront structures are relatively short, the volume needed to mitigate for the principle of diffusion or alongshore spreading may be two (2) to three (3) times greater than the volume required for the initial beach fill design configuration (Figure 83). With the volume required to mitigate for erosion and diffusion being so large for a relatively short project, the overall volume required to meet all the stated objectives may push what was intended to be a small-scale truck haul project into larger scale beach nourishment project.

The Buyout and Removal of Threatened Structures alternative is expected to address all of the goals established as the objectives for beach management along the Central Reserve/Refuge Reach. The removal of the identified vulnerable oceanfront structures would reduce all risk to those structures to future storms and long-term erosion. Furthermore, the removal of these structures located on the open beach would maintain and protect the beach road which serves as access for emergency responders and as an evacuation route.

Economic/Finance (E)

This dimension of feasibility evaluates initial and life-cycle costs and benefits. For this dimension, only a two tiered scoring system was employed. The red tier indicates alternatives for which the 30-year life cycle costs are anticipated to exceed the benefits of the alternative. The green tier indicates alternatives for which the 30-year life cycle benefits are anticipated to exceed the costs.

Overall, costs are anticipated to outweigh the benefits of Alternative 1. Alternative 1 would provide any measurable reduction to risk from storm damage or long-term erosion. While Alternative 1 has no direct cost associated with implementation, the County is expected to experience some loss of tax revenue. This would be due to the collapse of oceanfront structures along the Central Reserve/Refuge Reach and the public perception that comes from media coverage of these oceanfront collapses. The loss of an oceanfront house would also reduce considerably any ad-valorem taxes collected on those properties by the County. Furthermore, the County may experience losses in tax revenues from room occupancy and other tourism related taxes due to a loss of dependable transportation corridors along the beach road if threatened oceanfront homes impede normal travel, emergency access, and evacuation routes.

In addition to loss of tax revenues realized by Currituck County, individual homeowners are also likely to see losses. Direct loss of an oceanfront home comes with considerable financial loss. Furthermore, for those homes owned and operated as rentals, the degradation of property and/or outright loss of portions of or all of the facility would result in considerable loss of income. As real property is often held as an investment asset, significant decreases in property values due to the degradation of the oceanfront along the Central Reserve/Refuge Reach would have an adverse impact on property owners.

The benefits associated with Alternative 2 are anticipated to outweigh the cost of implementation. Alternative 2 is anticipated to meet the goals established for the Central Reserve/Refuge Reach. Therefore, the benefits of this Alternative include the elimination of the losses in tax revenues to the County and individual income and property value losses associated with Alternatives 1. The implementation of Alternative 2 would include legal costs, the cost to purchase the property, and the cost to demolish the property. The County would experience a complete loss of ad-valorem taxes on these several properties once ownership was transferred to the County. However, no long-term reduction in other tourism related tax revenues are anticipated. As the at risk properties would be purchased from the present owners, their financial losses would be minimized compared to losing the structure to collapse. No long-term maintenance costs are anticipated under Alternative 2.

As stated under the Technical criteria, in order for Alternative 3 to meet the objectives established for beach management along the Central Reserve/Refuge Reach, a considerable amount of sand would be required to protect relatively few at-risk homes. The initial cost alone of implementing this alternative is anticipated to far exceed the value of the structures for which the project would be designed.

Legal/Regulatory/Environmental (L)

This dimension of feasibility examines legal challenges, environmental permitting, and risk to the public or ecosystem. The red tier signals alternatives likely to face permitting or legal challenges and/or cause long-term adverse environmental impacts. The yellow tier indicates alternatives that may result in short-term environmental impacts but no long-term adverse impacts and not likely to face legal or permitting issues. The green tier indicates alternatives that are not anticipated to experience environmental or legal objections.

While none of the three alternatives are expected to face considerable environmental challenges through the permitting process, Alternative 2 has the highest likelihood of facing legal challenges. If the County and affected property owners can come to an agreement on a fair market buyout price, legal challenges may be avoided. However, determining fair market value is typically one of the greatest hurdles to buyouts. In the event the County adopted a policy that allowed it to take the property under imminent domain, the process could face legal challenges.

Both the Alternative 1 and 3 were scored with the intermediate tier of yellow. Both alternatives are likely to result in some short-term environmental impacts but neither area anticipated to face long-term adverse environmental impacts and are not likely to face permitting challenges. While neither are anticipated to face legal or permitting challenges, based on the pending case between the Corolla Civic Association and Currituck County, it is possible that with no action taken, the County could be exposed to some risk of litigation.

Operational (O)

Operational feasibility considers the ability to allow normal beach operations and the requirement for maintenance. The red tier denotes alternatives likely to result in a loss of function of normal beach operations. The yellow tier indicates alternatives that allow for normal beach operations with the exception of temporary construction efforts but are also anticipated to require long-term maintenance. The green tier denotes alternatives that support normal beach operations with the exception of temporary construction efforts and are not anticipated to require long-term maintenance.

Alternative 1 is anticipated to result in a loss of function of normal beach operations as it is expected to result in impediments to the beach road that serves as the primary transportation corridor along the County beaches north of the Horse Gate. It also serves as access for emergency responders and as an evacuation route. Both Alternative 2 and Alternative 3 would allow for normal beach operations other than temporary construction efforts. However, Alternative 3 would require long-term maintenance, which would cause additional temporary interruptions; whereas Alternative 2 would not require long-term maintenance and therefore is not expected to cause additional interruptions.

Schedule (S)

This dimension of feasibility focuses on time to implement. The red tier indicates alternatives for which initial implementation is expected to require more than one year and long-term maintenance would be required. The yellow tier denotes alternatives for which initial implementation is anticipated to be completed in less than one year but requires long-term maintenance. The green tier represents alternatives for which the initial implementation is expected to be completed in less than one year and does not require long-term maintenance.

Given the volume of fill required under Alternative 3 to achieve the beach management goals and objectives along the Central Reserve/Refuge Reach, initial implementation of this Alternative would likely require a Major CAMA Permit and a Dept. of the Army Permit. Furthermore, the size of the project will require formal bidding by the County. Due to the volume of sand required and the logistical challenges associated with transporting material north of the Horse Gate, implementation is expected to require more than 1 year to complete. Furthermore, Alternative 3 would require long-term maintenance.

Both Alternative 1 and 2 could reasonably be implemented in less than 1 year. This assumes that a fair market value could be negotiated as it relates to the implementation of Alternative 2. Neither Alternative 1 nor 2 is expected to require long-term maintenance.

4.1.4 Summary

Based on the assessment of the three alternatives using the five evaluation criteria, the recommended alternative for beach management along the Central Reserve/Refuge Reach is Alternative 2 – Buyouts and Removal of Threatened Structures. Alternative 2 is most likely to address all of the goals and objectives for beach management along the Central Reserve/Refuge Reach while also allowing for continued normal operations without the need for long-term maintenance. Although the No Action Alternative scores similarly or even better than Alternatives 2 and 3 based on the Economical/Financial, Legal/Regulatory/Environmental, and Schedule criterion, the No Action Alternative fails to meet the goals and objectives for beach management under the Technical criteria and is likely to result in the most disruptions in Operations. Alternative 3 is not the recommended alternative primarily because the initial construction costs, combined with the long-term maintenance requirements, likely exceeds the value of the structures the project would be designed to protect.

4.2 South of the Horse Gate

4.2.1 Problem Statement and Objective

South of the Horse Gate, within the Corolla and Pine Island Sections of the County's beaches, the coastal hazards and vulnerability analysis indicates several sections where storm vulnerabilities were identified based on the 1D XBeach analysis described in Section 2.1.4.1. The storm vulnerability analysis included simulations of three different design storms including a storm with characteristics comparable to Hurricane Isabel, a synthetic storm with characteristics consistent with a 25-year return frequency, and a storm with characteristics comparable to the Nor'easter that impacted the County beaches in 2009. All three of the storm simulations indicated storm vulnerability along the Ocean Hills Community and along the Spindrift Community at the dividing line between the Corolla Section and the Pine Island Section. The storm simulations for the synthetic 25-year storm indicated storm vulnerability along a slightly longer portion of Ocean Hills, all of the Spindrift Community, and along a short section south of the Hampton Inn in Pine Island along the south end of Hicks Bay Ln. The most extensive storm impacts were identified from storm simulations of a design storm comparable to Hurricane Isabel. Those simulations indicated vulnerabilities along most of Ocean Hills, various portions of the Whalehead Beach community, a short section within Ocean Sands South off of Conch Crescent, all of the Spindrift Community and a slightly larger stretch south of the Hampton Inn in Pine Island along Hicks Bay Ln and Cottage Cove Rd.

In addition to the storm vulnerability identified through the use of the 1D XBeach simulations, the 2D XBeach model was used to evaluate vulnerability to breaching and overtopping. It should be noted that the evaluation of vulnerability to breaching and overtopping that employed the 2D XBeach model, was limited to the area between Station C-049 in the Reserve/Refuge Section and Station C-096, located near Sandhill Lane in Ocean Sands. As described in Section 2.4, a proxy elevation was determined to indicate the vulnerability of dune breaching and overtopping. When the final dune crest elevation obtained through the 2D XBeach model simulations fell below this proxy elevation, those areas were identified as at risk for breaching and overtopping. The simulations of the storm comparable to Hurricane Isabel indicated a number of locations that were at risk to dune breaching and/or overtopping. Most of the areas identified as at risk overlapped with areas indicated as vulnerable form the 1D XBeach simulations (Ocean Hills and Whalehead Beach communities). However, several additional locations were identified between the south end of the Crown Point community and Seabird Way in Ocean Sands. The simulation of the 25-year storm did not indicate any sections of the beach within the model domain at risk to breaching or dune overtopping based on the evaluation criteria. The 2009 Nor'easter was not simulated with the 2D XBeach model as preliminary testing indicated that it did not generate sufficient water levels or wave conditions to produce significant dune erosion, overwash, or breaching within the model domain.

Shoreline change analysis also indicate oceanfront houses along both the Ocean Hills and Whalehead Beach communities are vulnerable to projected shoreline change. The vulnerability matrices shown in Figure 79, Figure 80, and Figure 81, specifically indicates that the area between Stations C-059 and C-065 in Ocean Hills and the oceanfront segments within Whalehead Beach between Stations C-071 and C-076 and Stations C-079 and C-081 were vulnerable to long-term shoreline change. As previously described, the vulnerability matrices represent the frequency with which areas were identified as vulnerable over the 30-year horizon during the three most recent analyses. Along the Ocean Hills community (Stations C-059 to C-065), analyses conducted between 2023 and 2025 indicated that between 40% and 100% of the oceanfront houses, along with portions of Atlantic Avenue, were vulnerable to the 30-year shoreline projections. Those same analyses further indicated that between 15% and 42% of the oceanfront houses were vulnerable over the 20-year horizon. The 2023 analysis indicated two (2) oceanfront structures that were vulnerable over the 10-year horizon, and in 2022 the same analysis identified 14 oceanfront structures as vulnerable over the 10-year horizon. The 2023 analysis also indicated that approximately 25% of the oceanfront structures along the southern 1.1 mile of the Whalehead Beach community were vulnerable over the 20-year horizon.

The vulnerability matrices also indicate that the areas indicated as vulnerable to storms, breaching/overtopping, and long-term shoreline projection coincide with areas indicated as having erosion trends or higher than average erosion trends, and that have narrow recreational beach widths. This suggests these areas are not likely to correct themselves.

In order to achieve the County goals for beach management, the alternatives evaluated for portions of the County oceanfront south of the Horse Gate focused on reducing the risk to oceanfront properties from coastal storms, reducing the risk of dune breaching/overtopping, and mitigating risk to oceanfront erosion. While some of the 30-year shoreline change projections have indicated that parts of Atlantic Avenue in Ocean Hills could be vulnerable to the 30-year shoreline projections, this was not a primary focus of the alternatives. The assumption made is that if alternatives are implemented that address the storm vulnerability and mitigate for erosion in these areas, the road will be far less vulnerable to long-term shoreline change. Similarly, the alternatives considered for beach management south of the Horse Gate did not focus specifically on maintaining sufficient recreational beach width. If alternatives are implemented that address the storm vulnerability and mitigate for erosion, many of the areas indicated as having narrow recreational beach widths are likely to be corrected. Once those alternatives have been implemented, monitoring data can be used to further evaluate if additional beach management to address narrow recreational beach width is warranted.

With these goals for beach management south of the Horse Gate established, three sub-sections of this portion of the County oceanfront were identified for consideration. These areas are generally referred to as 1) the North Corolla Reach; 2) the Spindrift Reach; and 3) the South Pine Island Reach. In the following sections, each of these three sub-sections are evaluated by considering multiple alternatives for each sub-section and evaluating the feasibility of these alternatives using the TELOS method previously described.

Furthermore, it should be noted that the storm vulnerability analysis used in this study was based on three different design storms (Hurricane Isabel, 25-year return interval synthetic storm, and 2009 Nor'easter). Federal shore protection projects undergo a rigorous benefit to cost analysis focused on maximizing the benefit to cost ratio based on extensive risk modeling of 100s of coastal storms to develop probabilistic curves. However, non-federal programs typically employ a simpler approach whereby the level of storm protection that can be achieved is more dependent on the non-federal sponsors ability to pay. Given no decision has been made as to overall project budget, the following feasibility analyses evaluated the level of effort for beach management alternatives under each of these three storm scenarios.

4.2.2 North Corolla Reach

The North Corolla Reach, shown in Figure 94, includes the northern 5.7 miles of the Corolla Section from the northern boundary of the Ocean Hills community near the Horse Gate south to Seabird Way, which is just south of Ocean Lake within the Ocean Sands community (stations C-059 through C-089). The extent of any future beach management strategy to be implemented along this Reach would ultimately depend on which design storm is considered, beach conditions at the time the project is authorized for implementation, additional detailed engineering and environmental assessments, and other factors. The alternatives provided herein are not final project limits. They are based on the available data used to evaluate the feasibility of various management alternatives along the Reach.

4.2.2.1 Alternatives

Three alternatives were evaluated as part of the feasibility assessment for the North Corolla Reach: 1) No Action; 2) Sand Fencing and Dune Vegetation Program; and 3) Beach Nourishment Program.

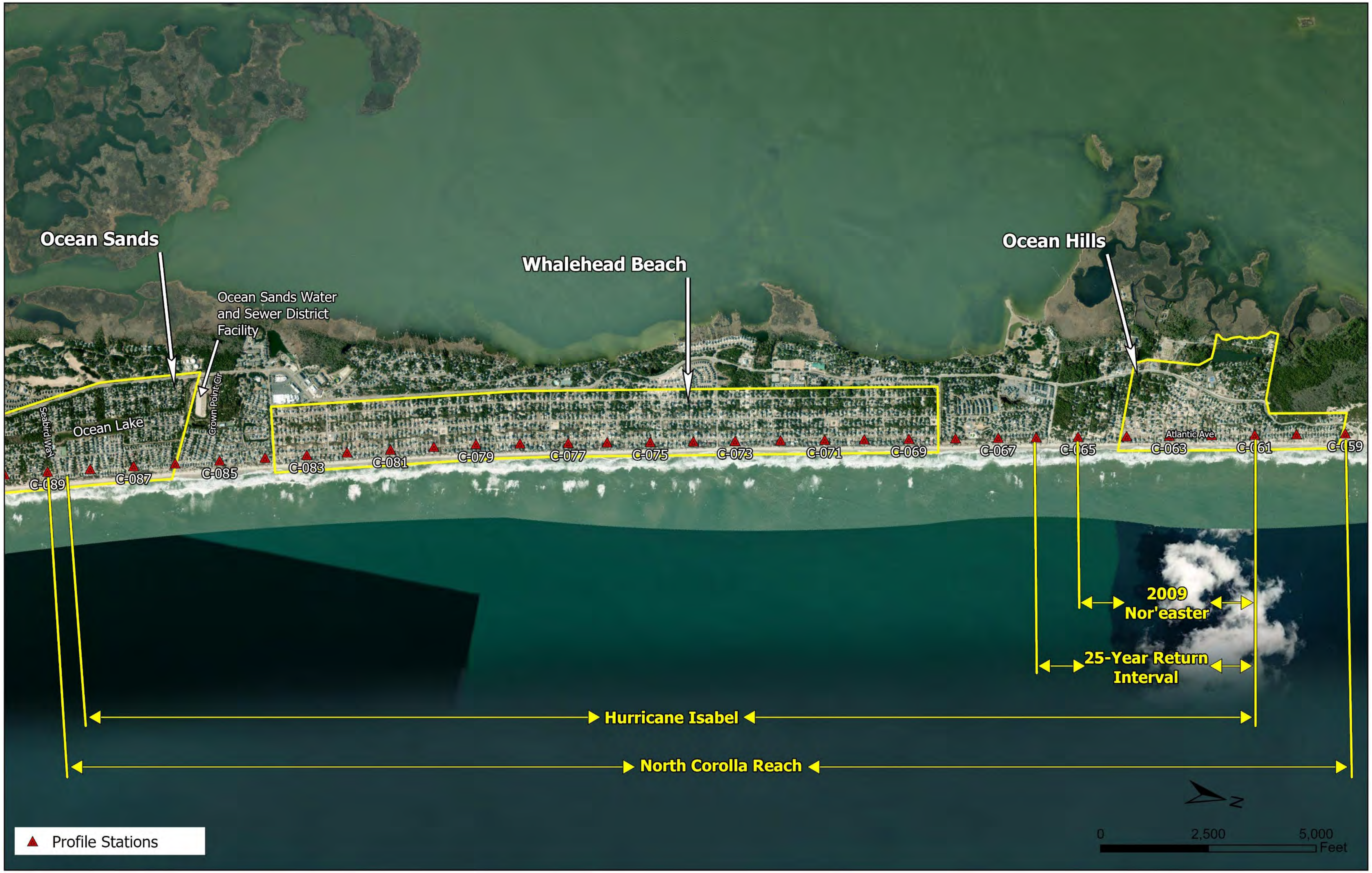


Figure 94. Map showing the extent of the North Corolla Reach.

Alternative 1 - No Action Alternative

The No Action alternative involves no direct active management of the beach along the North Corolla Reach. As previously stated, various portions of the North Corolla Reach have been identified as vulnerable to storms. Vulnerability was assessed based on three different simulated storms of varying return frequency. Most of these portions of the oceanfront beach identified as vulnerable have also exhibited erosion trends over recent years.

The implementation of Alternative 1 would not require a direct outlay by the County. However, given this alternative is not anticipated to achieve the County's goals for beach management, the County would be expected to experience a reduction in tax revenues from potential loss of structures (ad valorem taxes and room occupancy taxes), and a decrease in tourism caused by the public perception of dangerous or undesirable beach conditions due to structures collapsing on the beach. Furthermore, the breaching/overtopping analysis suggests numerous locations along the North Corolla Reach could be breached resulting in inundation to properties and roads landward of the oceanfront line of development. Two of the most susceptible areas are within the Ocean Hills community and the areas between the Crown Point community and Ocean Sands in the vicinity of Ocean Lake and the Ocean Sands Water and Sewer District facility south of Crown Point Circle.

Alternative 2 – Sand Fencing and Dune Vegetation Program

The Sand Fencing and Dune Vegetation Program Alternative involves installation of sand fencing and dune vegetation to the upper limits established by the County's current Sand Fence and Dune Vegetation program. This program provides cost reimbursement of up to $500 per 100 feet of linear oceanfront for sand fencing and $400 per 100 feet of linear oceanfront for American Beach grass. These programs are directed by the Currituck County Planning and Inspections Department.

As previously mentioned, the storm vulnerability analyses evaluated vulnerability based on three different design storms (Hurricane Isabel, 25-year return interval synthetic storm, and 2009 Nor'easter). The linear extent of the implementation of Alternative 2 for these three storms are provided in Table 21. Furthermore, based on the upper limit for reimbursement for sand fencing and dune vegetation based on the County's existing program, estimated costs for each of these scenarios have been provided in the table. Given the fact that the County Program requires applicants to adhere to Coastal Area Management Act (CAMA) requirements, no additional cost for permitting or design is anticipated.

Table 21. Linear extent of Alternative 2 for North Corolla Reach under various design storms.

Design Storm	Linear Extent (Ft.)	Baseline Stationing	Estimated Cost
Hurricane Isabel	23,935	Stations C-061 through C-088.5	$215,400
25-year Return Interval	5,070	Stations C-061 through C-066	$45,600
2009 Nor'easter	4,097	Stations C-061 through C-065	$36,900

The cost associated with this alternative would primarily be driven by the cost to reimburse HOAs, POAs, and/or individual property owners for the cost of installation of sand fencing and dune planting. The costs shown in Table 21 reflect a one-time cost to install sand fencing and dune vegetation. Depending on whether the sand fencing was completely buried or whether sand fencing installed and/or vegetation planted was washed out by storms, it may be necessary to re-install sand fencing and/or dune vegetation. Life cycle costs should assume repeated installation of both sand fencing and dune vegetation based on the likelihood of sand fencing being covered and/or sand fencing and dune vegetation being washed out by storms.

While sand dunes are an important aspect of a beach's ability to provide protection from storms impacts, the dune is just one part of the protective beach system. The dry sand beach or berm situated seaward of the foreshore slope and offshore bars all play a part in absorbing the wave energy produced by coastal storms. If sufficient sand is not available throughout the overall beach system, dunes alone cannot provide sufficient coastal protection. The authors of *The Dune Book* stated that "Sand dunes are very poor protection from long-term erosion, inlet changes and even seasonal fluctuations in the beach." (Rogers and Nash, 2003). This is due to the fact that the sand volume in the dune is relatively small compared to the overall sand volume contained in the berm and nearshore area (foreshore slope and sand bars). As these other features are eroded away, a reduction in the height or width of the dune may not be observed. In fact, there may be times where an increase in the volume of sand in the dune could be observed if sand fencing and/or dune vegetation are being actively promoted. However, once the berm, foreshore slope, and bars are sufficiently reduced in volume, even a small-scale nor'easter could do significant damage to a dune.

Based on the overall vulnerability analysis which considers shoreline change, volume change, and overall width of the recreational beach, the portions of the Currituck oceanfront identified as vulnerable lack the volume of sand within not only the dune, but the berm, foreshore slope, and sand bars to provide sufficient risk reduction to coastal storms. Without the addition of sand to the beach profile along areas identified as vulnerable, sand fencing and dune vegetation alone are not anticipated to provide sufficient risk reduction.

While the implementation of Alternative 2 would require a relatively low initial cost of implementation, and life cycle costs for repeated sand fencing and dune vegetation would also be relatively low compared to the costs of alternatives such as beach nourishment, the implementation of Alternative 2 is not anticipated to achieve the County's goals for beach management. Therefore, the County would be expected to experience a reduction in tax revenues from potential loss of structures (ad valorem taxes and room occupancy taxes), and a decrease in tourism caused by the public perception of dangerous or undesirable beach conditions due to structures collapsing on the beach. Furthermore, the breaching/overtopping analysis suggests numerous locations along the North Corolla Reach could be breached resulting in inundation to properties and roads landward of the oceanfront line of development. Two of the most susceptible areas are within the Ocean Hills Community and the areas between the Crown Point community and Ocean Sands in the vicinity of Ocean Lake and the Ocean Sands Water and Sewer District facility south of Crown Point Circle.

Alternative 3 – Beach Nourishment Program

Alternative 3 considers the construction of a beach nourishment projects along the extent of the North Corolla Reach where oceanfront structures have been identified as vulnerable and/or where the risk of breaching/overwash has been identified. Ultimately, to implement a beach nourishment project along this Reach, detailed engineering design and permitting efforts would be required. Based on available data, initial analysis were performed as part of this study in order to provide preliminary estimates of volume.

The beach fill design considered under Alternative 3 includes a dune with varying crest height ranging between +15.0 ft. and +18.0 ft. NAVD88 and crest width of 20 feet. The design considered also includes a variable width beach berm constructed seaward of the dune, at an elevation of 6.0 ft. NAVD88. The design berm width varied from 40 feet to 60 feet from the toe of the dune. In addition to the design fill, a beach nourishment project also typically includes advanced fill, which is the sacrificial portion of the fill required to mitigate long-term erosion and protect the design section. This concept was discussed in detail in Section 3.3. Based on observed erosion rates along the North Corolla Reach, estimates were made of the advanced fill required for a project designed with a 5-year maintenance interval. Further analysis would be required to refine the design including the evaluation of potential spreading losses which is dependent on the fill density and length of the overall project.

As previously mentioned, the storm vulnerability analyses evaluated vulnerability based on three different design storms (Hurricane Isabel, 25-year return interval synthetic storm, and 2009 Nor'easter). The linear extent of beach nourishment projects considered under Alternative 3 are shown in Figure 94. These various linear extents correspond to the limits identified based on assessments of vulnerability and hazards, specifically as it relates to storm vulnerability. The volume estimated for each of these possible beach nourishment configurations under Alternative 3 are provided in Table 22.

Table 22. Linear extent and estimated volumetric needs of Alternative 3 for North Corolla Reach under various design storms.

Design Storm	Linear Extent (Ft.)	Baseline Stationing	Estimated Volume
Hurricane Isabel	23,935	Station C-061 through C-088.5	1,963,000
25-year Return Interval	5,070	Station C-061 through C-066	642,000
2009 Nor'easter	4,097	Station C-061 through C-065	542,000

Given the estimated volume requirements under these three scenarios, it is likely that the most cost-effective method for constructing projects of this size would involve dredging sand from offshore borrow areas as opposed to truck haul projects. As described in Section 3.3, the financial viability of a beach nourishment program is highly dependent on the availability of a sufficient quantity of beach compatible sand proximate to the recipient beach.

During reconnaissance level investigations completed in 2023 by Dare County, three (3) Potential Sand Resource Areas were identified offshore of Currituck County, namely Potential Sand

Resource Areas E, I, and J. Figure 85 shows the location of these three Potential Sand Resource Areas. Geophysical and geotechnical data collected indicate that both Potential Sand Resource Areas E and J have sufficient beach compatible sand to support initial construction of the projects based on the volumes included in Table 22. Furthermore, the initial desktop studies conducted by Dare County suggest there may be additional areas north of these three Potential Sand Resource Areas offshore of Currituck County.

Implementation of Alternative 3 may require additional design level investigations to permit offshore borrow areas for beach nourishment. However, in 2024, design level investigations were conducted within Potential Sand Resource Area E by Dare County. The investigation led to the development of three (3) proposed borrow areas within Area E, namely Borrow Areas E-1, E-2, and E-8, as shown in Figure 86. In total, approximately 4.4 MCY of beach compatible sand has been identified within these three proposed borrow areas. That said, implementation of Alternative 3 may require additional design level investigations to permit offshore borrow areas and confirm compatibility requirements for the recipient beach.

Alternative 3 assumes that by constructing a beach fill project and maintaining it with regular maintenance events, the risk to the oceanfront structures identified as vulnerable to coastal storms and the risk of dune breaching/overtopping would be addressed. Through regular sand maintenance events, this alternative could mitigate long-term erosion to the threatened structures.

The cost associated with this alternative would initially be the cost to permit, design, and construct the beach nourishment project. This alternative would also include life cycle costs associated with the renourishment of maintenance sand to mitigate for long-term erosion. Due to the nature of beach nourishment projects, the initial construction is significantly more expensive than subsequent renourishment events because the initial construction requires the placement of additional sand to construct the design fill. Maintenance events are typically only replacing the advanced fill volume.

4.2.2.2 Feasibility Evaluation

In order to evaluate the feasibility of each alternative, a feasibility matrix was developed using a similar version of the TELOS method used for the feasibility analysis of areas north of the Horse Gate. The method provides a structured framework for evaluating project alternatives based on the evaluation of Technical, Economic/Financial, Legal/Regulatory/Environmental, Operational, and Schedule aspects of the alternatives. The method compares the alternatives described in Section 4.2.2.1 against the goals stated in the problem statement and objectives in Section 4.2.1. A three-tier color-coded scoring system for each of the criterion was established using green as the highest scoring, yellow as intermediate scoring, and red as lowest scoring. The feasibility matrix is graphically represented in Figure 95.

BEACH MANAGEMENT PLAN – ALTERNATIVE FEASIBILITY ANALYSIS

Evaluation Criteria	Alternative 1 No Action Alternative	Alternative 2 Sand Fencing and Dune Vegetation Program	Alternative 3 Beach Nourishment	Description of Ranking Criteria
T - Technical Performance, reliability, compatibility with existing protocols	Low	Low	High	• Does not satisfy any of the goals in the Problem Statement. • May satisfy some goals in the Problem Statement but does not satisfy all of the goals over a 30-year planning horizon. • Likely to address all goals in the Problem Statement for the 30-year planning horizon.
E - Economic/Financial Initial and Life-Cycle Costs, benefits	Low	Low	High	• 30-year life cycle cost anticipated to exceed the benefits. • 30-year life cycle benefits anticipated to exceed the costs.
L - Legal/Regulatory/ Environmental Legal challenges, environmental permitting, risk to public or ecosystem	Moderate	Moderate	Moderate	• Likely to face permitting or legal challenges and/or may have long-term adverse environmental impacts. • Short-term environmental impacts but no long-term adverse environmental impacts anticipated. Not likely to face legal or permitting challenges. • Minimal environmental or legal objections anticipated.
O - Operational Allows for normal operations, requirement for maintenance	Low	Low	Moderate	• Likely to result in a loss of function of normal beach operations. • Allows for normal beach operations other than temporary construction efforts. Requires long-term maintenance. • Allows for normal beach operations other than temporary construction efforts. Does not require long-term maintenance.
S - Schedule Time to implement	High	Moderate	Low	• Initial implementation expected to require more than 1 year. Requires long-term maintenance. • Initial implementation expected to be completed in less than 1 year. Requires some long-term maintenance. • Initial implementation expected to be completed in less than 1 year. Does not require long-term maintenance.

Figure 95. Feasibility Matrix used to assess alternatives for beach management along the North Corolla Reach.

Technical (T)

Technical feasibility assesses overall performance, reliability, and compatibility with existing protocols as it relates to accomplishing the goals set forth in the problem statement and objectives for beach management along the North Corolla Reach. The red tier indicates an alternative that does not satisfy any of the goals established in the problem statement and objectives. The yellow tier indicates an alternative that may satisfy some goals but does not satisfy all of the goals over a 30-year planning horizon. The green tier reflects alternatives likely to address all goals for the 30-year planning horizon.

Both the No Action Alternative (Alternative 1) and the Sand Fencing and Dune Vegetation Program (Alternative 2) score poorly under the Technical criteria because neither are likely to satisfy any of the goals established as the objectives for beach management in the North Corolla Reach. Alternative 2 may provide some increased protection provided by the dune portion of the beach system, however, storm simulations indicate that the overall volume of sand in the beach system is not sufficient to provide the design level of risk reduction. Furthermore, given the recent erosional trends observed and long-term shoreline change trends, the level of protection provided under Alternative 1 and 2 over the 30-year planning horizon is expected to decrease with time rendering oceanfront development even more susceptible to storm impacts.

Alternative 3 is the only alternative expected to address all of the goals established as the objectives for beach management along the North Corolla Reach. Initial storm simulations suggest that a beach nourishment program that places volumes indicated in Table 22 and maintains the program through renourishment of the advanced fill volumes to maintain the design fill, would provide sufficient storm risk reduction. Initial storm simulations also indicate that these initial fill volumes would provide adequate risk reduction to breaching/overtopping along the North Corolla Reach.

Economic/Finance (E)

This dimension of feasibility evaluates initial and life-cycle costs and benefits. For this dimension, only a two-tiered scoring system was employed. The red tier indicates alternatives for which the 30-year life cycle costs are anticipated to exceed the benefits of the alternative. The green tier indicates alternatives for which the 30-year life cycle benefits are anticipated to exceed the costs.

Alternative 1 would not provide any benefit as it would not provide any risk reduction to storm damage or long-term erosion. While Alternative 1 has no direct cost associated with implementation, the county is expected to experience considerable loss of tax revenue. This loss would be a combination of actual lost ad valorem taxes caused by the decrease in value of oceanfront properties as lots become unbuildable. Furthermore, as oceanfront structures are lost, the ad valorem taxes on those parcels would go to nearly zero as would any room occupancy taxes that had previously been generated from those properties. It is also reasonable to assume that decreases in room occupancy would be experienced as oceanfront structures fall into disrepair and renters consider other areas to rent. While some of these renters may still rent in other parts of Currituck County, it is likely that some decrease in revenue from room occupancy would be realized. Furthermore, with reductions in the number of rentals and public perception that comes from media coverage of oceanfront collapses, tourism spending is also anticipated to decrease which would result in a reduction in sales tax revenues.

While all of the expenses listed in the previous paragraph focus on costs to the County, consideration should also be given to individual homeowners. Direct loss of an oceanfront pool or oceanfront home comes with considerable financial loss. Furthermore, for those homes owned and operated as rentals, the degradation of property and/or outright loss of portions of or all of the facility would result in considerable loss of income. As real property is often held as an investment asset, significant decreases in property values due to the degradation of the oceanfront within the North Corolla Reach would have an adverse impact on property owners.

Alternative 2 may provide some temporary and limited benefits. However, as has been stated previously, without a considerable addition of sand to the beach system, the goal of providing sufficient design level risk reduction would not be met. Therefore, the benefits of Alternative 2 are considered minimal.

Alternative 2 has modest initial cost to be considered. However, similar to Alternative 1, the County is expected to experience considerable loss of tax revenue given Alternative 2 is not expected to meet the goals of reducing risk to coastal storms or mitigating long-term erosion. Similar to what was stated for Alternative 1, this loss of tax revenue would be a combination of actual lost ad valorem tax, room occupancy tax, and sales tax. Furthermore, there would be a similar level of cost to the property owner as was described for Alternative 1.

Given Alternative 3 is specifically formulated to achieve the risk reduction goals and erosion mitigation goals for the three storm scenarios, the benefits of this Alternative are the elimination of the losses in taxes and individual income and property value described under Alternatives 1 and 2.

Alternative 3 would include a considerable upfront cost associated with the initial construction of the beach nourishment project. Depending on numerous factors including the design level storm chosen the extent of the project, and the location of the sand source, initial costs to implement the project could range between $20 Million and $35 Million. While the costs are dependent on the volume of sand being placed, a number of the costs associated with the overall project implementation are relatively fixed such as permitting and design services, borrow area investigation services, and construction mobilization/demobilization. Therefore, cost escalation is not linear in relation to the volume of the overall project.

A more rigorous analysis of cost associated with these three options may be required to determine an optimal beach fill configuration. While the overall cost increases as the project length is extended and the volume is increased, the performance of beach nourishment projects are generally proportional to the length of project (i.e. the longer the project the better the project performs). This has the potential of reducing the overall maintenance volume required. Furthermore, when considering how to pay for these projects, the longer the project, the greater the number of property owners that would directly benefit from the project which is a consideration if a municipal service district is used to pay for a portion of the project.

At this point in the development of the Alternatives, an accurate assessment of the 30-year life cycle cost of the project has not been conducted. Such an assessment will require additional engineering design outside the scope of this study. This would include further analysis of erosion rates and an analysis of whether the nourishment interval could be extended beyond what is currently assumed to be 5 years. For example, in Dare County, the Towns of Duck, Southern Shores, Kitty Hawk, and Kill Devil Hills are currently evaluating the potential to plan future projects for a 6- or 7-year nourishment interval rather than a 5-year interval which is how the projects have been designed in the past. Furthermore, consideration should be given to the potential to partner with neighboring communities on future nourishment events to save costs on various aspects of the design, permitting, and construction, most notably the mobilization/demobilization costs.

While additional analysis is required to accurately quantify the benefit to cost ratio associated with Alternative 3, based on similar assessments, the 30-year life cycle benefits are anticipated to outweigh the 30-year life cycle costs.

Legal/Regulatory/Environmental (L)

This dimensions of feasibility examines legal challenges, environmental permitting, and risk to the public or ecosystem. The red tier signals alternatives likely to face permitting or legal challenges and/or cause long-term adverse environmental impacts. The yellow tier indicates alternatives that may result in short-term environmental impacts but no long-term adverse impacts and is not likely to face legal or permitting issues. The green tier indicates alternatives that are not anticipated to experience environmental or legal objections.

All three of the Alternatives were ranked the same with respect to this dimension of feasibility. Each alternative is anticipated to result in short-term environmental impacts but no long-term adverse environmental impacts and are not likely to face legal or permitting challenges. Alternatives 1 and 2 were ranked in this tier due to the expectation that continued erosion and storm impacts will eventually result in structures being lost along the North Corolla Reach. If not demolished in an organized fashion prior to collapse, the collapse of the structures during storm events can cause considerable debris fields which pose risk to swimming and beach dwelling organisms including humans. However, these impacts are typically short-term as debris is picked up or disperses. Alternative 3 was ranked in this tier due to the understanding the beach nourishment projects have the potential to induce short-term environmental impacts on benthic organisms and may temporarily impact nesting sea turtles and shorebirds but with proper avoidance and minimization measures are not anticipated to result in long-term adverse environmental impacts.

While none of the Alternatives are anticipated to face legal challenges, based on the pending case between the Corolla Civic Association and Currituck County, it is possible that with no action taken, the County could face some risk of litigation. With respect to permitting challenges, the only Alternative that would require permits is Alternative 3 and based on the number of beach nourishment projects permitted throughout North Carolina, it is assumed that Alternative 3 would not face permitting challenges.

Operational (O)

Operational feasibility considers the ability to allow normal beach operations and the requirement for maintenance. The red tier denotes alternatives likely to result in a loss of function of normal beach operations. The yellow tier indicates alternatives that allow for normal beach operations with the exception of temporary construction efforts but is also anticipated to require long-term maintenance. The green tier denotes alternatives that support normal beach operations with the exception of temporary construction efforts and is not anticipated to require long-term maintenance.

Alternative 1 and 2 are anticipated to result in a loss of function of normal beach operations. This is based on the assumption that with no effective measures to reduce risk to storms or to mitigate long-term erosion, the beach would fail to serve these normal functions. Furthermore, as the beach continues to erode and oceanfront houses are eventually situated on the open beach, these structures would eventually become an impediment to beach users.

Alternative 3 would allow for normal beach operations other than temporary construction efforts. Alternative 3 was ranked in the yellow tier due to the fact that the alternative would require long-term maintenance which would introduce temporary interruptions to beach operations during those maintenance events.

Schedule (S)

This dimension of feasibility focuses on time to implement. The red tier indicates alternatives for which initial implementation is expected to require more than one year and requires long-term maintenance. The yellow tier denotes alternatives for which initial implementation is anticipated to be completed in less than one year but requires long-term maintenance. The green tier represents alternatives for which the initial implementation is expected to be completed in less than one year and does not require long-term maintenance.

Given no active beach management effort is required for Alternative 1, the implementation of this alternative could be done in less than 1 year and does not require any long-term maintenance. Alternative 2 does not require any permits and could be implemented in less than 1 year. However, due to the likelihood of sand fencing being covered or sand fencing and/or vegetation being washed out by storm events, it is expected that Alternative 2 would require regular maintenance. Alternative 3 is likely to require over 1 year to implement. Based on similar projects constructed along the northern Outer Banks, the time required from initiating permitting and design efforts to construction is likely to require between 1.5 to 2.5 years. Furthermore, as previously discussed, Alternative 3 would require maintenance to maintain the design level of risk reduction and to mitigate long-term erosion.

4.2.2.3 Summary

Based on the assessment of the three alternatives using the five evaluation criteria, the recommended alternative for beach management along the North Corolla Reach is Alternative 3 – Beach Nourishment. Alternative 3 is most likely to address all of the goals and objectives for beach management along the North Corolla Reach and is likely the only alternative that has a positive benefit to cost ratio. Furthermore, Alternative 3 allows for normal operations other than temporary construction efforts during initial construction and maintenance. The Legal/ Regulatory/Environmental criterion was not a distinguishing factor between the three Alternatives as all were ranked the same. While Alternatives 1 and 2 both scored better than Alternatives 3 based on the Schedule criterion, neither of the other two Alternatives met the goals and objectives for beach management under the Technical criteria.

4.2.3 Spindrift Reach

The Spindrift Reach, which is shown in Figure 96, includes the oceanfront portion of the Spindrift community along Land Fall Ct, located just north of the Public Beach Access at Yaupon Lane. This reach only extends approximately 1,200 feet from the northern boundary of Lot 9 to the south side of the County owned Parcel just south of the Spindrift community. This reach spans the boundary between the Corolla Section and the Pine Island Section. Depending on the design storm considered, the volume of sand required to achieve the design level of risk reduction varies. Regardless of the design storm considered, the linear extent of the area where active management would be required remained the same under each of the three storm scenarios. Differences relative to the design storms considered are described below where applicable.

4.2.3.1 Alternatives

Four alternatives were evaluated as part of the feasibility assessment for the Spindrift Reach: 1) No Action; 2) Buyout and Removal of Threatened Homes; 3) Beach Nourishment Program; and 4) Beach Nourishment with Coastal Structures.

Alternative 1 - No Action Alternative

The No Action alternative involves no direct active management of the beach along the Spindrift Reach. Depending on which storm scenario is considered anywhere from six (6) to all nine (9) of the oceanfront homes along the Spindrift Reach are vulnerable to storm impacts. The Spindrift Reach is outside of the area evaluated for breaching/overtopping therefore it is unknown whether this area is vulnerable to the same breaching/overtopping identified within the North Corolla Reach.

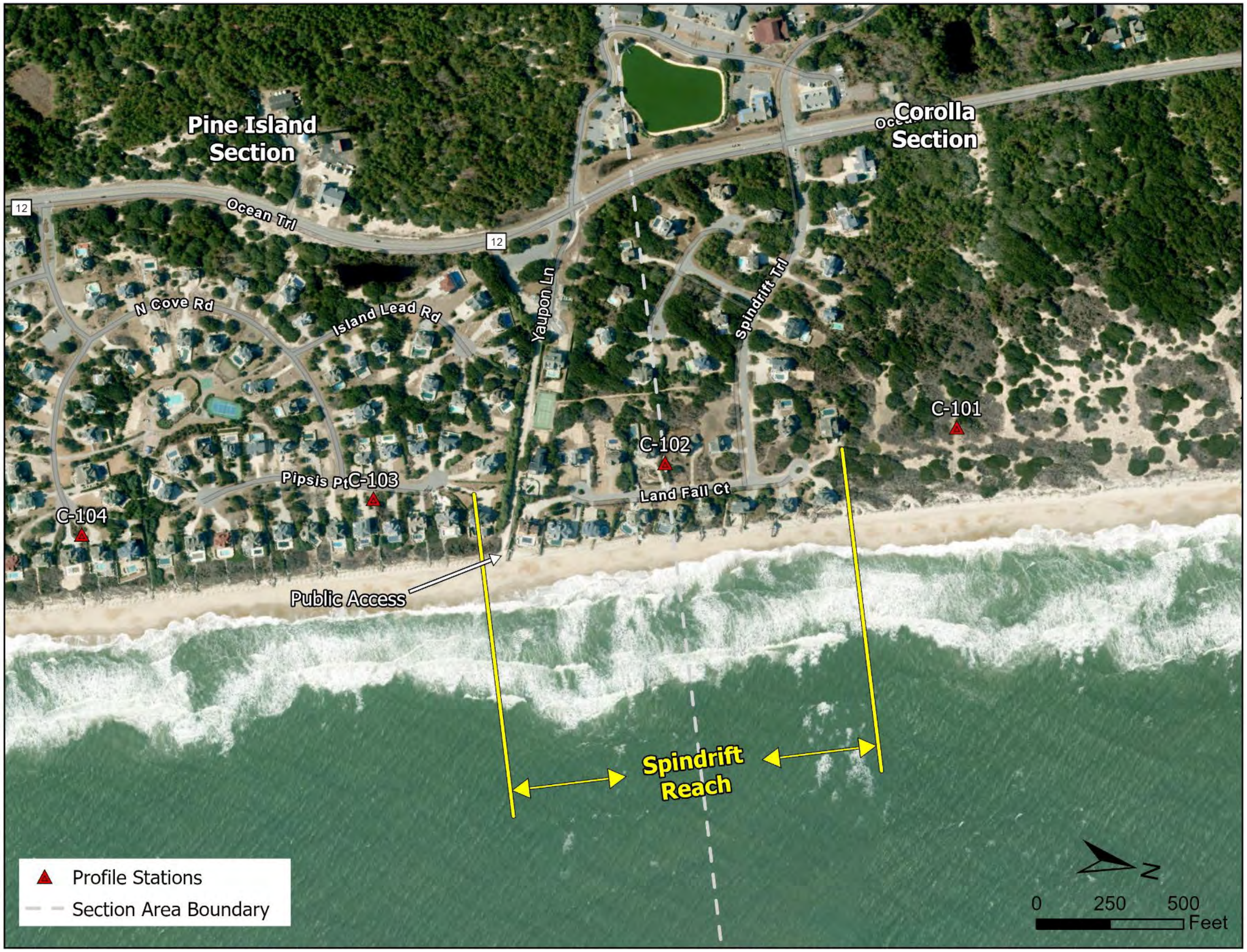


Figure 96. Map showing the extent of the Spindrift Reach.

The implementation of Alternative 1 would not require a direct financial expenditure by the County. However, given this alternative is not anticipated to achieve the County's goals for beach management, the County would be expected to experience a reduction in tax revenues from potential loss of structures (ad valorem taxes and room occupancy taxes), and a decrease in tourism caused by the public perception of dangerous or undesirable beach conditions due to structures collapsing on the beach.

Alternative 2 - Buyout and Removal of Threatened Oceanfront Structures

Alternative 2 involves the buyout and removal of threatened oceanfront structures as they become at risk of imminent collapse and/or restrict emergency response operations on the beach. This alternative would first require a committee to establish a County policy on how to identify targeted structures for buyout and removal, how to establish fair market value for the buyout, and whether any future policies should be developed to notify future buyers of the policy.

Once a structure has been identified for the buyout and removal program, the County would negotiate with the owners to obtain the property and remove the structure(s) from the property. This alternative assumes that by obtaining the property and removing the structure, the risk to the oceanfront structures identified as vulnerable to coastal storms would be eliminated. Furthermore, there would be no reason to mitigate for long-term erosion to the structure(s) that have been removed. At the time this report was published, breaching/overtopping analysis was not conducted along the Spindrift Reach. The 2026 annual monitoring surveys are anticipated to collect additional data that may allow for a breaching/overtopping analysis to be conducted. This analysis would better inform the risk to breaching/overtopping and potential inundation in the event that erosion continued under Alternative 2.

The cost associated with this alternative would primarily be driven by the cost to purchase structures, and fees paid to demolition contractors to remove the structures. This alternative assumes no additional life cycle costs for maintenance. Once the structures have been removed, no maintenance is anticipated for those previously threatened properties. While storm simulations or 30-year shoreline change projections have not indicated impacts to any of the structures west of Land Fall Ct or the road itself, future impacts are possible. If the oceanfront structures were removed and erosion continues to persist, at some point Land Fall Ct. and/or structures west of it could be at risk. That said, these risks are not anticipated over the 30-year planning horizon.

Alternative 3 – Beach Nourishment Program

Alternative 3 would involve the construction of a beach nourishment project along the extent of the Spindrift Reach where oceanfront structures have been identified as vulnerable. This alternative would require detailed engineering design and permitting efforts to implement. While additional design efforts would be required to determine the design specifics for such a project, initial analysis were performed as part of this study to estimate anticipated volumes.

As previously mentioned, the storm vulnerability analyses evaluated vulnerability based on three different design storms (Hurricane Isabel, 25-year return interval synthetic storm, and 2009

Nor'easter). The beach fill design considered under Alternative 3 for the Hurricane Isabel design storm, includes a dune with a crest height of +15.0 ft. NAVD88 and crest width of 20 feet fronted by a 60 foot wide beach berm constructed at an elevation of 6.0 ft. NAVD88. The beach fill design considered under Alternative 3 for the 25-year return interval synthetic storm and the 2009 Nor'easter design storm, included a dune with a crest height of +15.0 ft. NAVD88 and crest width of 20 feet fronted by a 40 foot wide beach berm constructed at an elevation of 6.0 ft. NAVD88.

In addition to the design fill, a beach nourishment project also typically includes advanced fill, which is the sacrificial portion of the fill required to mitigate long-term erosion and protect the design section. This concept is discussed in detail in Section 3.3. Based on observed erosion rates along the Spindrift Reach, estimates were made of the advanced fill required for a project designed with a 5-year maintenance interval. Preliminary estimates of volumetric requirements for Alternative 3 for each storm scenario are provided in Table 23. The volumes in the table only represent the design volume and advanced fill volume.

Table 23. Linear extent of Alternative 3 and estimated design fill and advanced fill volumetric requirements for the Spindrift Reach under various design storms.

Design Storm	Linear Extent (Ft.)	Estimated Volume
Hurricane Isabel	1,200	210,000
25-year Return Interval	1,200	175,000
2009 Nor'easter	1,200	175,000

Further analysis would be required to refine the design including the evaluation of potential spreading losses or diffusion which is dependent on the fill density and length of the overall project. As described previously under Alternative 3 for the Central Reserve/Refuge Reach, beach nourishment is difficult to implement along short segments. Given the relatively short segment covered by the Spindrift Reach, the volume needed to mitigate for the principle of diffusion or alongshore spreading may be two (2) to three (3) times greater than the fill volume listed in Table 23.

With the volume required to mitigate for erosion and diffusion being so large for a relatively short project, the overall volume required to meet all the stated objectives may be more cost effective to obtain through offshore dredging. Furthermore, if this project was conducted in conjunction with a beach nourishment project for the North Corolla Reach, the use of offshore sand would be expected to be far more cost effective than a truck haul.

As previously described under Alternative 3 for the North Corolla Reach, Potential Sand Resource Areas have been identified offshore of Currituck County. Geophysical and geotechnical data collected indicate these Potential Sand Resource Areas have sufficient beach compatible sand to implement Alternative 3 for the Spindrift Reach. Furthermore, the initial desktop studies conducted by Dare County suggest there may be additional areas north of these three Potential Sand Resource Areas offshore of Currituck County.

Implementation of Alternative 3 may require additional design level investigations to permit offshore borrow areas for beach nourishment and confirm compatibility requirements for the recipient beach. However, in 2024, design level investigations were conducted within Potential Sand Resource Area E by Dare County. The investigation led to the development of three (3) proposed borrow areas within Area E, namely Borrow Areas E-1, E-2, and E-8, as shown in Figure 86. In total, approximately 4.4 MCY of beach compatible sand has been identified within these three proposed borrow areas.

Alternative 3 assumes that by constructing a beach nourishment project and maintaining it with regular maintenance events, the risk to the oceanfront structures identified as vulnerable to coastal storms would be addressed. Through regular sand maintenance events, this alternative could mitigate long-term erosion to the threatened structures.

The cost associated with this alternative would initially be the cost to permit, design, and construct the beach nourishment project. This alternative would also include life cycle costs associated with the renourishment of maintenance sand to mitigate for long-term erosion. While typically renourishment or maintenance events require considerably less volume than the initial construction, the relatively short length of the Spindrift Reach project and the relatively high diffusion losses expected suggest that maintenance intervals may not require much less volume than the initial construction.

Alternative 4 – Beach Nourishment with Coastal Structures

Alternative 4 would involve the construction of a similar design fill as described under Alternative 3. However, in Alternative 4, diffusion losses and background erosion losses would be reduced through the use of one or more shore-perpendicular coastal structures. The initial concept would be to construct a relatively short groin on the south end of the Spindrift Reach. It may also be necessary to construct a groin on the north end of the Reach.

This alternative would require detailed engineering design and permitting efforts to implement. The design analysis would include sophisticated numerical modeling to determine the optimal position, orientation, and size of the groin(s).

The use of groin(s) are intended to reduce the volume of sand required for both the initial construction and for maintenance events, specifically the volume needed to account for high diffusion losses. Even with the use of groin(s) to decrease the fill required, if Alternative 4 is constructed in conjunction with beach nourishment along the North Corolla Reach, the most cost-effective source of sand is likely to be dredging of sand from offshore borrow areas as described under Alternative 3. Similarly, Alternative 4 may require additional design level investigations to permit offshore borrow areas for beach nourishment.

Alternative 4 assumes that by constructing a beach nourishment project, constructing groin(s) to reduce diffusion losses, and maintaining the design level beach fill through regular maintenance events, the risk to the oceanfront structures identified as vulnerable to coastal storms would be addressed. Through regular sand maintenance events, this alternative could also mitigate long-term erosion to the threatened structures.

The cost associated with this alternative would initially be the cost to permit, design, and construct the beach nourishment project and groin(s). This alternative would also include life cycle costs associated with the renourishment of maintenance sand to mitigate for long-term erosion.

4.2.3.2 Feasibility Evaluation

In order to evaluate the feasibility of each alternative, a feasibility matrix was developed using a similar version of the TELOS method used for the feasibility analysis of areas north of the Horse Gate and the North Corolla Reach. The method provides a structured framework for evaluating project alternatives based on the evaluation of Technical, Economic/Financial, Legal/Regulatory/Environmental, Operational, and Schedule aspects of the alternatives. The method compares the alternatives described in Section 4.2.3.1 against the goals stated in the problem statement and objective in Section 4.2.1. A three-tier color-coded scoring system for each of the criterion was established using green as the highest scoring, yellow as intermediate scoring, and red as lowest scoring. The feasibility matrix is graphically represented in Figure 97.

Technical (T)

Technical feasibility assesses overall performance, reliability, and compatibility with existing protocols as it relates to accomplishing the goals set forth in the problem statement and objectives for beach management along the Spindrift Reach. The red tier indicates an alternative that does not satisfy any of the goals established in the problem statement and objectives. The yellow tier indicates an alternative that may satisfy some goals but does not satisfy all of the goals over a 30-year planning horizon. The green tier reflects alternatives likely to address all goals for the 30-year planning horizon.

The No Action Alternative (Alternative 1) scores poorly under the Technical criteria because it is not likely to satisfy any of the goals established as the objectives for beach management in the Spindrift Reach. In contrast, Alternatives 2, 3, and 4 are all expected to address all of the goals established as the objectives for beach management along the Spindrift Reach. While buyout and removal of threatened oceanfront structure would reduce the risk to those structures in the future and mitigate for long-term erosion that might impact the homes, initial storm simulations suggest that establishment and maintenance of a beach fill design consistent with those described under Alternatives 3 and 4, would provide sufficient storm risk reduction. The maintenance through renourishment is meant to mitigate the effects of long-term erosion.

BEACH MANAGEMENT PLAN – ALTERNATIVE FEASIBILITY ANALYSIS

Evaluation Criteria	Alternative 1 No Action Alternative	Alternative 2 Buyouts and Removal of Threatened Oceanfront	Alternative 3 Beach Nourishment	Alternative 4 Beach Nourishment with Coastal Structures	Description of Ranking Criteria
T - Technical Performance, reliability, compatibility with existing protocols	Low	High	High	High	● (red) Does not satisfy any of the goals in the Problem Statement. ● (yellow) May satisfy some goals in the Problem Statement but does not satisfy all of the goals over a 30-year planning horizon. ● (green) Likely to address all goals in the Problem Statement for the 30-year planning horizon.
E - Economic/Financial Initial and Life-Cycle Costs, benefits	Low	Low	Low	Low	● (red) 30-year life cycle cost anticipated to exceed the benefits. ● (green) 30-year life cycle benefits anticipated to exceed the costs.
L - Legal/Regulatory/ Environmental Legal challenges, environmental permitting, risk to public or ecosystem	Moderate	Low	Moderate	Low	● (red) Likely to face permitting or legal challenges and/or may have long-term adverse environmental impacts. ● (yellow) Short-term environmental impacts but no long-term adverse environmental impacts anticipated. Not likely to face legal or permitting challenges. ● (green) Minimal environmental or legal objections anticipated.
O - Operational Allows for normal operations, requirement for maintenance	Low	High	Moderate	Moderate	● (red) Likely to result in a loss of function of normal beach operations. ● (yellow) Allows for normal beach operations other than temporary construction efforts. Requires long-term maintenance. ● (green) Allows for normal beach operations other than temporary construction efforts. Does not require long-term maintenance.
S - Schedule Time to implement	High	High	Low	Low	● (red) Initial implementation expected to require more than 1 year. Requires long-term maintenance. ● (yellow) Initial implementation expected to be completed in less than 1 year. Requires some long-term maintenance. ● (green) Initial implementation expected to be completed in less than 1 year. Does not require long-term maintenance.

Figure 97. Feasibility Matrix used to assess alternatives for beach management along the Spindrift Reach.

At the time this report was published, breaching/overtopping analysis was not conducted along the Spindrift Reach. The 2026 annual monitoring surveys are anticipated to collect additional data that may allow for a breaching/overtopping analysis to be conducted. This analysis would better inform the risk reduction provided by Alternative 3 and 4 to breaching/overtopping and potential inundation. Based on the results of the 1D and 2D XBeach analysis conducted in the North Corolla Reach, the assumption was made that Alternatives 3 and 4 would provide sufficient risk reduction to breaching/overtopping.

Economic/Finance (E)

This dimension of feasibility evaluates initial and life-cycle costs and benefits. For this dimension, only a two-tiered scoring system was employed. The red tier indicates alternatives for which the 30-year life cycle costs are anticipated to exceed the benefits of the alternative. The green tier indicates alternatives for which the 30-year life cycle benefits are anticipated to exceed the costs.

Based on the data available, the evaluation of economic feasibility of the four Alternatives suggests that all four Alternatives may have costs that outweigh the benefits. Alternative 1 would provide no benefit as it would not achieve any risk reduction to storm damage or long-term erosion. While Alternative 1 has no direct cost associated with implementation, the county is expected to experience loss of tax revenue. This loss would include the actual lost ad valorem taxes caused by the decrease in value of oceanfront properties as lots become unbuildable. Furthermore, as oceanfront structures are lost the ad valorem taxes on those parcels would go to nearly zero as would any room occupancy taxes that had previously been generated from those properties. It is also reasonable to assume that decreases in room occupancy would be experienced as oceanfront structures fall into disrepair and renters consider other areas to rent. While some of these renters may still rent in other parts of Currituck County, it is likely that some decrease in revenue from room occupancy would be realized. Furthermore, with reductions in the number of rentals and public perception that comes from media coverage of oceanfront collapses, tourism spending is also anticipated to decrease which would result in some reduction in sales tax revenues.

In addition to costs to the County, consideration should also be given to potential losses to homeowners. Direct loss of an oceanfront pool or oceanfront home comes with considerable financial loss. Furthermore, for those homes owned and operated as rentals, the degradation of property and/or outright loss of portions of or all of the facility would result in considerable loss of income. As real property is often held as an investment asset, significant decreases in property values due to the degradation of the oceanfront within the Spindrift Reach would have an adverse impact on property owners within the Spindrift community and may also have impacts to property owners in the surrounding areas.

Alternative 2 is anticipated to meet the goals established for the area south of the Horse Gate. Therefore, the benefits of this Alternative are the elimination of the losses in tax revenues to the County and individual income and property value losses associated with Alternatives 1. The implementation of Alternative 2 would include legal costs, the cost to purchase the property, and the cost to demolish the property. The County would experience a complete loss of ad-valorem taxes on these several properties once ownership was transferred to the County. However, no long-term reduction in other tourism related tax revenues are anticipated. As the at risk properties would be purchased from the present owners, their financial losses would be minimized compared to losing the structure to collapse. They would also lose any revenue being generated from rentals once the property was sold. No long-term maintenance costs are anticipated under Alternative 2.

Alternative 3 is anticipated to meet the goals established for the area south of the Horse Gate. Therefore, the benefits are the elimination of the losses in tax revenues to the County and individual income and property value losses associated with Alternatives 1. As stated in the description of Alternative 3, in order for Alternative 3 to achieve the risk reduction intended and to mitigate for long-term erosion, a considerable amount of sand would be required to protect relatively few at-risk homes. Alternative 3 would include a considerable upfront cost associated with the initial construction of the beach nourishment project. Depending on numerous factors including the design level storm chosen, the extent of the project, and the location of the sand source, initial costs to implement Alternative 3 could range between $2.2 Million and $3.4 Million. These costs are based on beach placement volumes as listed in Table 23, and assume that the project is combined with beach nourishment along the North Corolla Reach. These costs also include anticipated additional costs associated with design, permitting, and additional efforts to design offshore borrow areas.

The costs listed here do not include the cost associated with diffusion losses. As described under the description for Alternative 3, further analysis would be required to refine the design including the evaluation of potential spreading losses or diffusion which is dependent on the fill density and length of the overall project. Given the relatively short segment covered by the Spindrift Reach, the volume needed to mitigate for diffusion may be two (2) to three (3) times greater than the fill volume listed in Table 23.

While the initial cost to construct Alternative 3 may be less than the overall value of the structures it aims to protect, the high volume of sand required for each subsequent maintenance project is likely to exceed the value of these properties over time, even if the projects are combined with other beach nourishment projects within the region.

Alternative 4 is also anticipated to meet the goals established for the area south of the Horse Gate and therefore, the benefits are the same as those mentioned for Alternatives 2 and 3. In order for Alternative 4 to achieve the risk reduction intended and to mitigate for long-term erosion, the volumes anticipated for the initial construction of the project are as shown in Table 23. Instead of the considerable amount of sand required to account for the diffusion losses, Alternative 4 attempts to minimize spreading losses and reduce erosion through the use of shore perpendicular coastal structures or groins. Alternative 4 would include all the initial costs previously listed for Alternative 3 as well as additional costs associated with the design, permitting, and construction of the coastal structures.

While the initial cost to construct Alternative 4 may be slightly more than the initial construction for Alternative 3, given the significant reduction in the overall maintenance requirements under

Alternative 4, the 30-year life cycle cost of Alternative 4 is anticipated to be less than Alternative 3. Additional design analysis would be required to confirm these assertions. Even with a lower overall 30-year life cycle cost than Alternative 3, Alternative 4 is still assumed to have costs over the 30-year life cycle greater than the benefits.

Legal/Regulatory/Environmental (L)

This dimensions of feasibility examines legal challenges, environmental permitting, and risk to the public or ecosystem. The red tier signals alternatives likely to face permitting or legal challenges and/or cause long-term adverse environmental impacts. The yellow tier indicates alternatives that may result in short-term environmental impacts but no long-term adverse impacts and not likely to face legal or permitting issues. The green tier indicates alternatives that are not anticipated to experience environmental or legal objections.

Alternatives 1 and 3 are anticipated to result in short-term environmental impacts but no long-term adverse environmental impacts and are not likely to face legal or permitting challenges. Alternative 1 was ranked in this tier due to the expectation that continued erosion and storm impacts will eventually result in structures being lost along the Spindrift Reach. If not demolished in an organized fashion prior to collapse, the collapse of the structures during storm events can cause considerable debris fields which pose risk to swimming and beach dwelling organisms including humans. However, these impacts are typically short-term as debris is picked up or disperses. Given Alternative 1 requires no active beach management, this Alternative does not require any permits and therefore would not face permitting challenges. While Alternative 1 is not anticipated to face legal challenges, based on the pending case between the Corolla Civic Association and Currituck County, it is possible that with no action taken, the County could face some risk of litigation.

Alternative 3 was ranked in this tier due to the understanding the beach nourishment projects have the potential to induce short-term environmental impacts on benthic organisms and may temporarily impact nesting sea turtles and shorebirds but with proper avoidance and minimization measures are not anticipated to result in long-term adverse environmental impacts. Furthermore, based on the number of beach nourishment projects permitted throughout North Carolina, it is assumed that Alternative 3 would not face permitting challenges.

While Alternatives 2 and 4 are not expected to result in long-term adverse environmental impacts, both Alternatives are likely to face permitting or legal challenges. Alternative 2 is considered likely to face legal challenges based on past experiences with buyout programs and the ability to come to agreeable terms on purchase price. Determining fair market value is typically one of the greatest hurdles to buyouts. If the County were to adopt a policy that allowed it to take the property under imminent domain, the process could face legal challenges.

At present hardened structures such as those proposed as part of Alternative 4 are banned by State Law. Recently, legislation was introduced to both repeal the ban and to allow pilot projects. Without changes to current legislation, Alternative 4 would be deemed illegal. Even with additional legislation, it is possible that the permitting of Alternative 4 could face legal challenges.

Operational (O)

Operational feasibility considers the ability to allow normal beach operations and the requirement for maintenance. The red tier denotes alternatives likely to result in a loss of function of normal beach operations. The yellow tier indicates alternatives that allow for normal beach operations with the exception of temporary construction efforts but is also anticipated to require long-term maintenance. The green tier denotes alternatives that support normal beach operations with the exception of temporary construction efforts and is not anticipated to require long-term maintenance.

Alternative 1 is anticipated to result in a loss of function of normal beach operations. This is based on the assumption that with no effective measures to reduce risk to storms or to mitigate long-term erosion, the beach would fail to serve these normal functions. Furthermore, if the beach continues to erode due to both long-term erosion and storms, oceanfront houses may eventually be situated on the open beach. At that point, these structures could become an impediment to beach users.

Alternative 2 would allow for normal beach operations other than temporary construction efforts during periods where houses that had been purchased by the County were removed. Once the structure was removed, no long-term maintenance would be required; however, it is acknowledged that it is unlikely that all houses would be purchased and removed at the same time.

Alternatives 3 and 4 would allow for normal beach operations other than temporary construction efforts. Both Alternatives were ranked in the intermediate or yellow tier due to the fact that the Alternatives would require long-term maintenance which would introduce temporary interruptions to beach operations during those maintenance events.

Schedule (S)

This dimension of feasibility focuses on time to implement. The red tier indicates alternatives for which initial implementation is expected to require more than one year and requires long-term maintenance. The yellow tier denotes alternatives for which initial implementation is anticipated to be completed in less than one year but requires long-term maintenance. The green tier represents alternatives for which the initial implementation is expected to be completed in less than one year and does not require long-term maintenance.

Given no active beach management effort is required for Alternative 1, the implementation of this alternative could be done in less than 1 year and does not require any long-term maintenance. Furthermore, Alternative 2 is also anticipated to be implemented in less than 1 year. Alternative 2 is not anticipated to require CAMA permits or Dept. of the Army Permits to implement. The anticipated timing to implement Alternative 2 assumes that a fair market value could be negotiated as it relates to the implementation of Alternative 2. Once the house is purchased and removed, Alternative 2 does not anticipate long-term maintenance.

Both Alternatives 3 and 4 are expected to require more than 1 year to implement and will require long-term maintenance. Based on similar projects constructed along the northern Outer Banks, the time required from initiating permitting and design efforts to construction of Alternative 3 is likely to require between 1.5 to 2.5 years. Given the uncertainty of the legality of Alternative 4, the potential for more extensive environmental review and consultation, and the potential for legal challenges if the current hardened structures ban is repealed, Alternative 4 is likely to require more than 2.5 years to implement. As previously discussed, both Alternatives 3 and 4 would require maintenance to maintain the design level of risk reduction and to mitigate long-term erosion.

4.2.3.3 Summary

The feasibility assessment of the four alternatives considered for the Spindrift Reach using the five evaluation criteria discussed herein did not result in a clear recommended alternative. While all four alternatives, other than the No Action Alternative, are anticipated to meet the functional and technical goals for beach management south of the Horse Gate, the cost of all of the alternatives may outweigh the benefits achieved. While Alternatives 2 and 4 may have lower 30-year life cycle costs than Alternative 3, both Alternative 2 and 4 may face permitting and legal challenges. Alternative 2 also scored better than Alternatives 3 and 4 in terms of operational disruptions and schedule to implement.

The Spindrift Reach may require additional analysis that focuses on a lesser level of storm damage risk reduction while allowing for continued monitoring of current practices that have used small-scale truck haul projects to provide temporary shore protection.

4.2.4 South Pine Island Reach

The South Pine Island Reach, which is shown in Figure 98, includes an approximately 3,000 foot long portion of the Pine Island Section, south of the Hampton Inn. The Reach covers the oceanfront from Station C-014 to C-017, east of Hicks Bay Lane and Cottage Cove Road. Of the three different design storms considered, the South Pine Island Reach was only identified as vulnerable to storm damage under the Hurricane Isabel design storm. The impacts observed through simulations of the 25-year return interval and 2009 Nor'easter design storms did not rise to the level that warranted active beach management.

4.2.4.1 Alternatives

Four alternatives were evaluated as part of the feasibility assessment for the South Pine Island Reach: 1) No Action; 2) Sand Fencing and Dune Vegetation Program; 3) Beach Nourishment Program; and 4) Beach Nourishment with Coastal Structures.

Figure 98. Map showing the extent of the South Pine Island Reach

Alternative 1 - No Action Alternative

The No Action Alternative involves no direct active management of the beach along the South Pine Island Reach. As previously stated, Alternatives were only developed for the South Pine Island Reach under the Hurricane Isabel design storm scenario. The other storm scenarios evaluated did not indicate a level of risk to warrant the development of Alternatives at this time. The South Pine Island Reach is outside of the area evaluated for breaching/overtopping therefore it is unknown whether this area is vulnerable to the same breaching/overtopping identified within the North Corolla Reach.

The implementation of Alternative 1 would not require a direct financial outlay by the County. However, given this alternative is not anticipated to achieve the County's goals for beach management, the County would be expected to experience a reduction in tax revenues from potential loss of structures (ad valorem taxes and room occupancy taxes), and a decrease in tourism caused by the public perception of dangerous or undesirable beach conditions due to structures collapsing on the beach.

Alternative 2 – Sand Fencing and Dune Vegetation Program

The Sand Fencing and Dune Vegetation Program Alternative involves installation of sand fencing and dune vegetation to the maximum limits currently authorized under the County's Sand Fence and Dune Vegetation program. Under this program, the County provides cost reimbursement of up to $500 per 100 feet of linear oceanfront for sand fencing and $400 per 100 feet of linear oceanfront for planting American Beach grass. These programs are directed by the Currituck County Planning and Inspections Department.

The linear extent of the implementation of Alternative 2 is 3,000 feet. Based on the upper limit for reimbursement for the installation of sand fencing and dune vegetation in accordance with the County's existing program, estimated costs for Alternative 2 would be approximately $27,000. Given the fact that the County Program requires applicants to adhere to Coastal Area Management Act (CAMA) requirements, no additional cost for permitting or design is anticipated.

The cost associated with this alternative would primarily be driven by the cost to reimburse HOAs, POAs, and/or individual property owners for the cost of installation of sand fencing and dune planting. The cost of $27,000 reflect a onetime cost to install sand fencing and dune vegetation. Depending on whether the sand fencing was completely buried or whether sand fencing installed and/or vegetation planted was washed out by storms, it may be necessary to re-install sand fencing and/or dune vegetation. Life cycle costs should assume repeated installation of both sand fencing and dune vegetation based on the likelihood of sand fencing being covered and/or sand fencing and dune vegetation being washed out by storms.

While sand dunes are an important aspect of a beach's ability to provide protection from storm impacts, the dune is just one part of the protective beach system. The dry sand beach or berm situated seaward of the dune, the foreshore slope, and offshore bars all play a part in absorbing the wave energy produced by coastal storms. If sufficient sand is not available throughout the overall beach system, dunes alone cannot provide sufficient coastal protection. The authors of

The Dune Book stated that "Sand dunes are very poor protection from long-term erosion, inlet changes and even seasonal fluctuations in the beach." (Rogers and Nash, 2003). This is due to the fact that the volume of sand in the dune is relatively small compared to the overall sand volume contained in the berm and nearshore area (foreshore slope and sand bars). As these portions of the overall beach system are eroded, a reduction in the height or width of the dune may not be observed. In fact, there may be times where an increase in the volume of sand in the dune could be observed if sand fencing and/or dune vegetation are being actively promoted. However, once the berm, foreshore slope, and bars are sufficiently reduced in volume, even a small-scale nor'easter could do significant damage to a dune.

The vulnerability matrix indicates that the South Pine Island Reach is experiencing an erosional trend and, in some portions, experiencing higher than average erosion rates compared to the overall average of the Pine Island Section. Furthermore, the vulnerability matrix indicates that the South Pine Island Reach is also characterized as having a relatively narrow recreational beach. Both of these factors indicate that the volume of sand within the beach system may not promote continued dune growth with the installation of sand fencing and dune vegetation and the supply would continue to diminish if the current erosional trends persist. Without the addition of sand to the beach profile along the South Pine Island Reach, sand fencing and dune vegetation alone are not anticipated to provide sufficient risk reduction to meet the County's established beach management goals.

While the implementation of Alternative 2 would require a relatively low initial cost of implementation, and life cycle costs for repeated sand fencing and dune vegetation would also be relatively low compared to the costs of alternatives such as beach nourishment, the implementation of Alternative 2 is not anticipated to achieve the County's goals for beach management. Therefore, the County would be expected to experience a reduction in tax revenues from potential loss of structures (ad valorem taxes and room occupancy taxes), and a decrease in tourism caused by the public perception of dangerous or undesirable beach conditions due to structures collapsing on the beach.

Alternative 3 – Beach Nourishment Program

Alternative 3 would involve the construction of a beach nourishment project along the extent of the South Pine Island Reach where oceanfront structures have been identified as vulnerable. This alternative would require detailed engineering design and permitting efforts to implement. While additional design efforts would be required to determine the design specifics for such a project, initial analysis were performed as part of this study to estimate anticipated volumes.

As previously mentioned, the storm vulnerability analyses determined that only under the Hurricane Isabel design storm scenario, would the South Pine Island Reach require active beach management to reduce risk. The beach fill design considered under Alternative 3 for the Hurricane Isabel design storm, includes a dune with a crest height of +15.0 ft. NAVD88 and crest width of 20 feet fronted by a variable width berm ranging from 40 to 55 feet wide and constructed at an elevation of 6.0 ft. NAVD88.

In addition to the design fill, a beach nourishment project also typically includes advanced fill, which is the sacrificial portion of the fill required to mitigate long-term erosion and protect the design section. This concept is discussed in detail in Section 3.3. Based on observed erosion rates along the South Pine Island Reach, estimates were made of the advanced fill required for a project designed with a 5-year maintenance interval. The preliminary estimate of volumetric requirements for Alternative 3 is 233,000 cubic yards. This volume represents the design volume and advanced fill volume and does not include diffusion losses.

Further analysis would be required to refine the design including the evaluation of potential diffusion or spreading losses. These losses of sand to a beach nourishment project are highly dependent on the fill density and length of the overall project and tend to be much higher on smaller nourishment projects. Given the relatively short segment covered by the South Pine Island Reach, the volume needed to mitigate for the principle of diffusion may be considerably greater than the 233,000 cubic yards stated above.

Given the volume of sand required for Alternative 3, and the fact that this project could be combined with beach nourishment Alternatives for other reaches, Alternative 3 assumes the project would be constructed with offshore sand and dredging. As previously described under beach nourishment alternatives for other reaches, Potential Sand Resource Areas have been identified offshore of Currituck County and design level work has been done to identify several borrow areas offshore of the Pine Island Section. That said, implementation of Alternative 3 may require additional design level investigations to permit offshore borrow areas and confirm compatibility requirements for the recipient beach.

Alternative 3 assumes that by constructing a beach nourishment project and maintaining it with regular maintenance events, the risk to the oceanfront structures identified as vulnerable to coastal storms would be addressed. Through regular sand maintenance events, this alternative could mitigate long-term erosion to the threatened structures.

The cost associated with this Alternative would initially be the cost to permit, design, and construct the beach fill project. Additional analysis would be required to accurately estimate the 30-year life cycle costs of the Alternative. While typically renourishment or maintenance events require considerably less volume than the initial construction, the relatively short length of the South Pine Island Reach and the relatively high diffusion losses expected suggest that maintenance intervals may require comparable volumes of sand as the initial construction. Further analysis is necessary to confirm these differentials.

Alternative 4 – Beach Nourishment with Coastal Structures

Alternative 4 would involve the construction of a similar design fill as described under Alternative 3. However, in Alternative 4, diffusion losses and background erosion losses would be reduced through the use of one or more coastal structures. The initial concept would be to construct a relatively short groin on the south end of the South Pine Island Reach. It may also be necessary to construct a groin on the north end of the Reach.

This alternative would require detailed engineering design and permitting efforts to implement. The design analysis would include sophisticated numerical modeling to determine the optimal position, orientation, and size of the groin(s).

The use of groin(s) are intended to reduce the volume of sand required for both the initial construction and for maintenance events, specifically the volume needed to account for high diffusion losses. The beach nourishment constructed in conjunction with groin(s) under Alternative 4 would use offshore sand sources and dredging. This is assumed to be the most cost-effective sand source based on the estimated volume and likelihood that the project could be combined with beach fill projects along other Reaches. As stated under Alternative 3, while sand resources have been identified offshore of the Pine Island Section, some additional design level investigations may be required to permit offshore borrow areas and confirm compatibility requirements for the recipient beach.

Alternative 4 assumes that by constructing a beach nourishment project and constructing groin(s) to reduce diffusion losses, the management goal of reducing sufficient storm risk to the oceanfront structures along the reach would be achieved. Furthermore, with regular sand maintenance events, this alternative could also mitigate long-term erosion to the threatened structures and achieve the storm risk reduction goals throughout the 30-year life cycle.

4.2.4.2 Feasibility Evaluation

In order to evaluate the feasibility of each alternative, a feasibility matrix was developed using a similar version of the TELOS method used for the feasibility analysis of the other oceanfront reaches discussed. The method provides a structured framework for evaluating project alternatives based on the evaluation of Technical, Economic/Financial, Legal/Regulatory/ Environmental, Operational, and Schedule aspects of the alternatives. The method compares the alternatives described in Section 4.2.4.1 against the goals stated in the problem statement and objective in Section 4.2.1. A three-tier color-coded scoring system for each of the criterion was established using green as the highest scoring, yellow as intermediate scoring, and red as lowest scoring. The feasibility matrix is graphically represented in Figure 99.

Technical (T)

Technical feasibility assesses overall performance, reliability, and compatibility with existing protocols as it relates to accomplishing the goals set forth in the problem statement and objectives for beach management along the South Pine Island Reach. The red tier indicates an alternative that does not satisfy any of the goals established in the problem statement and objectives. The yellow tier indicates an alternative that may satisfy some goals but does not satisfy all of the goals over a 30-year planning horizon. The green tier reflects alternatives likely to address all goals for the 30-year planning horizon.

BEACH MANAGEMENT PLAN – ALTERNATIVE FEASIBILITY ANALYSIS

Evaluation Criteria	Alternative 1 No Action Alternative	Alternative 2 Sand Fencing and Dune Vegetation Program	Alternative 3 Beach Nourishment	Alternative 4 Beach Nourishment with Coastal Structures	Description of Ranking Criteria
T - Technical Performance, reliability, compatibility with existing protocols	Low	Low	High	High	Red: Does not satisfy any of the goals in the Problem Statement. Yellow: May satisfy some goals in the Problem Statement but does not satisfy all of the goals over a 30-year planning horizon. Green: Likely to address all goals in the Problem Statement for the 30-year planning horizon.
E - Economic/Financial Initial and Life-Cycle Costs, benefits	Low	Low	Low	Low	Red: 30-year life cycle cost anticipated to exceed the benefits. Green: 30-year life cycle benefits anticipated to exceed the costs.
L - Legal/Regulatory/ Environmental Legal challenges, environmental permitting, risk to public or ecosystem	Moderate	Moderate	Moderate	Low	Red: Likely to face permitting or legal challenges and/or may have long-term adverse environmental impacts. Yellow: Short-term environmental impacts but no long-term adverse environmental impacts anticipated. Not likely to face legal or permitting challenges. Green: Minimal environmental or legal objections anticipated.
O - Operational Allows for normal operations, requirement for maintenance	Low	Low	Moderate	Moderate	Red: Likely to result in a loss of function of normal beach operations. Yellow: Allows for normal beach operations other than temporary construction efforts. Requires long-term maintenance. Green: Allows for normal beach operations other than temporary construction efforts. Does not require long-term maintenance.
S - Schedule Time to implement	High	Moderate	Low	Low	Red: Initial implementation expected to require more than 1 year. Requires long-term maintenance. Yellow: Initial implementation expected to be completed in less than 1 year. Requires some long-term maintenance. Green: Initial implementation expected to be completed in less than 1 year. Does not require long-term maintenance.

Figure 99. Feasibility Matrix used to assess alternatives for beach management along the South Pine Island Reach.

Both the No Action Alternative (Alternative 1) and the Sand Fencing and Dune Vegetation Program (Alternative 2) score poorly under the Technical criteria because neither are likely to satisfy any of the goals established as the objectives for beach management in the South Pine Island Reach. Alternative 2 may provide some increased protection provided by the dune portion of the beach system, however, storm simulations indicate that the overall volume of sand in the beach system is not sufficient to provide the design level of risk reduction. Furthermore, given the recent erosional trends observed and long-term shoreline change trends, the level of protection provided under Alternatives 1 and 2 over the 30-year planning horizon is expected to decrease with time rendering oceanfront development even more susceptible.

In contrast, Alternatives 3 and 4 are expected to address all of the goals established as the objectives for beach management along the South Pine Island Reach. Initial storm simulations suggest that establishment and maintenance of a beach fill design consistent with those described under Alternatives 3 and 4, would provide sufficient storm risk reduction. The maintenance through renourishment is meant to mitigate the effects of long-term erosion.

At the time this report was published, breaching/overtopping analysis was not conducted along the South Pine Island Reach. The 2026 annual monitoring surveys are anticipated to collect additional data that may allow for a breaching/overtopping analysis to be conducted along the Pine Island Section. This analysis would better inform the risk reduction provided by Alternatives 3 and 4 to breaching/overtopping and potential inundation. Based on the results of the 1D and 2D XBeach analysis conducted in the North Corolla Reach, the assumption was made that Alternatives 3 and 4 would provide sufficient risk reduction to breaching/overtopping along the South Pine Island Reach.

Economic/Finance (E)

This dimension of feasibility evaluates initial and life-cycle costs and benefits. For this dimension, only a two-tiered scoring system was employed. The red tier indicates alternatives for which the 30-year life cycle costs are anticipated to exceed the benefits of the alternative. The green tier indicates alternatives for which the 30-year life cycle benefits are anticipated to exceed the costs.

Based on the data available, the evaluation of economic feasibility suggests that all four Alternatives as described in Section 4.2.4.1, may have costs that outweigh the benefits. Alternative 1 would provide no benefit as it would not achieve any risk reduction to storm damage or long-term erosion. While Alternative 1 has no direct cost associated with implementation, the County is expected to experience loss of tax revenue. This loss would include the actual lost ad valorem taxes caused by the decrease in value of oceanfront properties as lots become unbuildable. Furthermore, as oceanfront structures are lost the ad valorem taxes on those parcels would go to nearly zero as would any room occupancy taxes that had previously been generated from those properties. It is also reasonable to assume that decreases in room occupancy would be experienced as oceanfront structures fall into disrepair and renters consider other areas to rent. While some of these renters may still rent in other parts of Currituck County, it is likely that some decrease in revenue from room occupancy would be realized. Furthermore, with reductions in the number of rentals and public perception that comes from media coverage of oceanfront collapses, tourism spending is also anticipated to decrease which would result in some reduction in sales tax revenues.

In addition to costs to the County, consideration should also be given to potential losses to homeowners. Direct loss of an oceanfront pool or oceanfront home comes with considerable financial loss to the homeowner. Furthermore, for those homes owned and operated as rentals, the degradation of property and/or outright loss of portions of or all of the facility would result in considerable loss of income. As real property is often held as an investment asset, significant decreases in property values due to the degradation of the oceanfront within the South Pine Island Reach would have an adverse impact on property owners along the Reach and may also have impacts to property owners in the surrounding areas.

Alternative 2 may provide some temporary and limited benefits. However, as has been stated previously, without a considerable addition of sand to the beach system, the goal of providing sufficient design level risk reduction would not be met. Therefore, the benefits of Alternative 2 are considered minimal.

Alternative 2 has modest initial cost to be considered. However, similar to Alternative 1, the County is expected to experience loss of tax revenue given Alternative 2 is not expected to meet the goals of reducing risk to coastal storms or mitigating long-term erosion. Similar to what was stated for Alternative 1, this loss of tax revenue would be a combination of actual lost ad valorem tax, room occupancy tax, and sales tax. Furthermore, there would be a similar level of cost to the property owner as was described for Alternative 1.

Alternative 3 is anticipated to meet the goals established for the South Pine Island Reach. Therefore, the benefits are the elimination of the losses in tax revenues to the County and individual income and property value losses associated with Alternatives 1. As stated in the description, in order for Alternative 3 to achieve the risk reduction intended and to mitigate for long-term erosion, a considerable amount of sand would be required to protect relatively few at-risk homes. Alternative 3 would include a considerable upfront cost associated with the initial construction of the beach nourishment project. Preliminary opinions of cost to implement Alternative 3 range between $2.9 Million and $3.8 Million. These costs are based on the placement of 233,000 cubic yards of sand to construct the design fill and account for background erosion rates. The preliminary opinion of cost also assumes that the project is combined with beach nourishment along other Reaches. These costs include costs associated with design, permitting, and additional efforts to design offshore borrow areas.

The costs listed here do not include the cost associated with diffusion losses. As described under the description for Alternative 3, further analysis would be required to refine the design including the evaluation of potential spreading losses or diffusion which is dependent on the fill density and length of the overall project. Given the relatively short segment covered by the South Pine Island Reach, the volume needed to mitigate for diffusion may be comparable to or greater than the fill volume of 233,000 cubic yards stated above.

While the initial cost to construct Alternative 3 may be less than the overall value of the structures it aims to protect, the high volume of sand required for each subsequent maintenance project is likely to exceed the value of these properties over time, even if the project is combined with other beach nourishment projects within the region. An updated assessment of the risk to breaching, overtopping, and inundation, may change this assumption, but based on available information, Alternative 3 is assumed to have greater cost than benefit.

Alternative 4 is also anticipated to meet the goals established for the South Pine Island Reach and therefore, the benefits are the same as those mentioned for Alternative 3. The base volume (design fill and advanced fill for background erosion) anticipated for Alternative 4 is the same as Alternative 3. Instead of the considerable amount of sand required to account for the diffusion losses, Alternative 4 attempts to minimize spreading losses and reduce erosion through the use of shore perpendicular coastal structures or groins. Alternative 4 would include all the initial costs previously listed for Alternative 3 as well as additional costs associated with the design, permitting, and construction of the coastal structures.

While the initial cost to construct Alternative 4 is assumed to be slightly more than the initial construction for Alternative 3, given the anticipated reduction in the overall maintenance requirements under Alternative 4, the 30-year life cycle cost of Alternative 4 is anticipated to be less than Alternative 3. Additional design analysis would be required to confirm these assertions. Even with a lower overall 30-year life cycle cost that Alternative 3, Alternative 4 is still assumed to have costs over the 30-year life cycle greater than the benefits. However, an updated assessment of the risk to breaching, overtopping, and inundation, may change this assumption.

Legal/Regulatory/Environmental (L)

This dimension of feasibility examines legal challenges, environmental permitting, and risk to the public or ecosystem. The red tier signals alternatives likely to face permitting or legal challenges and/or cause long-term adverse environmental impacts. The yellow tier indicates alternatives that may result in short-term environmental impacts but no long-term adverse impacts and is not likely to face legal or permitting issues. The green tier indicates alternatives that are not anticipated to experience environmental or legal objections.

Alternatives 1, 2, and 3 are anticipated to result in short-term environmental impacts but no long-term adverse environmental impacts. Furthermore, these Alternatives are not likely to face legal or permitting challenges. Alternatives 1 and 2 were ranked in this tier due to the expectation that continued erosion and storm impacts will eventually result in structures being lost along the South Pine Island Reach. If not demolished in an organized fashion prior to collapse, the collapse of the structures during storm events can cause considerable debris fields which pose risk to swimming and beach dwelling organisms including humans. However, these impacts are typically short-term as debris is picked up or disperses. Neither Alternative 1 or 2 require permits and therefore would not face permitting challenges. While Alternative 1 is not anticipated to face legal challenges, based on the pending case between the Corolla Civic Association and Currituck County, it is possible that with no action taken, the County could face some risk of litigation.

Alternative 3 was ranked in this tier due to the understanding that beach nourishment projects have the potential to induce short-term environmental impacts on benthic organisms and may temporarily impact nesting sea turtles and shorebirds. However, with proper avoidance and minimization measures Alternative 3 is not anticipated to result in long-term adverse environmental impacts. Furthermore, based on the number of beach nourishment projects permitted throughout North Carolina, it is assumed that Alternative 3 would not face permitting challenges.

While Alternative 4 is not expected to result in long-term adverse environmental impacts, it is likely to face permitting or legal challenges. At present hardened structures such as those proposed as part of Alternative 4 are banned by State Law. Recently, legislation was introduced to both repeal the ban and to allow pilot projects. Without changes to current legislation, Alternative 4 would be deemed illegal. Even with additional legislation, it is possible that the permitting of Alternative 4 could face legal challenges.

Operational (O)

Operational feasibility considers the ability to allow normal beach operations and the requirement for maintenance. The red tier denotes alternatives likely to result in a loss of function of normal beach operations. The yellow tier indicates alternatives that allow for normal beach operations except for temporary construction efforts but is also anticipated to require long-term maintenance. The green tier denotes alternatives that support normal beach operations with the exception of temporary construction efforts and is not anticipated to require long-term maintenance.

Alternatives 1 and 2 are anticipated to result in a loss of function of normal beach operations. This is based on the assumption that with no effective measures to reduce risk to storms or to mitigate long-term erosion, the beach would fail to serve these normal functions. Furthermore, if the beach continues to erode due to both long-term erosion and storms, oceanfront houses may eventually be situated on the open beach. At that point, these structures could become an impediment to beach users.

Alternatives 3 and 4 would allow for normal beach operations other than temporary construction efforts. Both Alternatives were ranked in the intermediate or yellow tier due to the fact that the Alternatives would require long-term maintenance which would introduce temporary interruptions to beach operations during those maintenance events.

Schedule (S)

This dimension of feasibility focuses on time to implement. The red tier indicates alternatives for which initial implementation is expected to require more than one year and requires long-term maintenance. The yellow tier denotes alternatives for which initial implementation is anticipated to be completed in less than one year but requires long-term maintenance. The green tier represents alternatives for which the initial implementation is expected to be completed in less than one year and does not require long-term maintenance.

Given no active beach management effort is required for Alternative 1, the implementation of this alternative could be done in less than 1 year and does not require any long-term maintenance. Alternative 2 does not require any permits and could be implemented in less than 1 year. However, due to the likelihood of sand fencing being covered or sand fencing and/or vegetation being washed out by storm events, it is expected that Alternative 2 would require regular maintenance.

Both Alternatives 3 and 4 are expected to require more than 1 year to implement and will require long-term maintenance. Based on similar projects constructed along the northern Outer Banks, the time required from initiating permitting and design efforts to construction of Alternative 3 is likely to require between 1.5 to 2.5 years. Given the uncertainty of the legality of Alternative 4, the potential for more extensive environmental review and consultation, and the potential for legal challenges if the current hardened structures ban is repealed, Alternative 4 is likely to require more than 2.5 years to implement. As previously discussed, both Alternatives 3 and 4 would require maintenance to maintain the design level of risk reduction and to mitigate long-term erosion.

4.2.4.3 Summary

The feasibility assessment of the four alternatives considered for the South Pine Island Reach using the five evaluation criteria discussed herein did not result in a clear recommended alternative. While Alternatives 3 and 4 are anticipated to meet the functional and technical goals for beach management south of the Horse Gate, the cost of all four alternatives may outweigh the benefits achieved. While Alternative 4 may have lower 30-year life cycle costs than Alternative 3, Alternative 4 may face permitting and legal challenges.

The South Pine Island Reach may require additional analyses focused on a lesser level of storm damage risk reduction while allowing for continued monitoring of current practices that have used small-scale truck haul projects, sand fencing, and dune planting to provide temporary shore protection. Given the fact that the vulnerability analysis indicated that the current beach configuration provided sufficient risk reduction to the 25-year return interval design storm, a management alternative focused on mitigating for long-term erosion by placing smaller volumes of sand than those called for under Alternatives 3 and 4 and the use of sand fencing and dune planting to increase the size of the protective dune over time, may see greater benefits than costs over the 30-year life cycle.

5 PROPOSED BEACH MANAGEMENT PLAN

At the time this draft document is being submitted to the County for consideration, the information in this section should be viewed as recommendations for consideration. These recommendations are based on 1) an understanding of the current goals of the County for beach management; 2) the results of the vulnerability analyses described in Section 2 of this draft document; and 3) the

feasibility assessment described in Section 4 of this draft document. Once the County has had the opportunity to review this information, solicit public input on the recommendations, and provide feedback to the authors, this section will be updated to provide final recommendations for the proposed Beach Maintenance Plan.

The following recommendations and considerations are provided to Currituck County elected officials, Currituck County staff, and the general public as they review the draft document and consider next steps towards finalizing the County's Beach Management Plan:

1. The XBeach 2D storm vulnerability analysis focused on overtopping added considerable value to the assessment of storm vulnerability. However, as described in Section 2.1.4.2, the analysis was limited by two factors. The first was the model domain, which was budget limited and focused mostly on the North Corolla Reach. The second was the availability of higher resolution topographic/bathymetric Lidar data of which the most recent dataset reflected conditions from 2019. An update of the XBeach 2D storm vulnerability analysis would provide additional value to the development of Alternatives and for the feasibility analyses. As part of the proposed 2026 Currituck County Monitoring scheduled for Spring 2026, Lidar data will be acquired along the entire oceanfront of Currituck County. The proposal includes costs for processing sub-sections of that data and re-running the XBeach 2D storm vulnerability assessment within the same limited model domain (C-048 to C-096). It is recommended that all of the data collected south of the Horse Gate be processed and that the XBeach 2D storm vulnerability model be re-run using the updated 2026 conditions.

2. As Currituck County elected officials and staff, as well as the general public, review this draft document, consideration should be given to the Alternatives evaluated in Section 4 for the various Reaches. Feedback is requested on whether other reasonable alternatives should be considered in the feasibility analyses of the four (4) reaches identified for active beach management.

3. Furthermore, as this draft document is reviewed by County elected officials and staff, and the general public, consideration should be given to the assumptions made in the Feasibility Analysis included in Section 4. While evaluation of technical aspects of the engineering and environmental impacts have been made based on considerable experience working on similar projects, general assumptions have been made using best judgment on potential monetary losses to the County and private property owners. If reviewers believe that additional considerations should be made in these assessments, comments submitted will be considered.

4. Spindrift Reach – While the Alternatives described in Section 4.2.3.1 of this draft document were assumed to have a 30-year life cycle cost greater than the benefits realized over the same period, further analysis of the cost and benefits of these alternatives are warranted. This additional analysis would focus on more accurately

quantifying the cost of losses under the No Action Alternative, and to further assess the 30-year life cycle cost of Alternative 2 (Buyout and Removal of threatened Oceanfront Structures), Alternative 3 (Beach Nourishment) and Alternative 4 (Beach Nourishment with Coastal Structures). Additional engineering analysis such as more detailed analysis of diffusion losses and the recommended updates for the XBeach 2D storm vulnerability model discussed in Item #1 above, are expected to provide a more accurate assessment of the benefit to cost ratio. Further consideration may also be warranted for the level of storm to which the Alternatives for the Spindrift Reach are designed. Designing to the Hurricane Isabel storm scenario may not result in an alternative for which benefits outweigh the costs of no action. However, designing to a less extreme storm may result in a positive benefit to cost ratio.

5. South Pine Island Reach – Similar to the Spindrift Reach, the Alternatives described in Section 4.2.4.1 of this draft document for the South Pine Island Reach, were assumed to have a 30-year life cycle cost greater than the benefits realized over the same period. For this Reach, further analysis of the cost and benefits of the alternatives considered are also warranted. This additional analysis would focus on more accurately quantifying the cost of losses under the No Action Alternative, and to further assess the 30-year life cycle cost of both Alternatives 3 (Beach Nourishment) and Alternative 4 (Beach Nourishment with Coastal Structures). Additional engineering analysis such as more detailed analysis of diffusion losses and the recommended updates for the XBeach 2D storm vulnerability model discussed in Item #1 above, are expected to provide a more accurate assessment of the benefit to cost ratio. Further consideration may also be warranted for the level of storm to which the Alternatives for the South Pine Island Reach are designed. Designing to the Hurricane Isabel storm scenario may not result in an alternative for which benefits outweigh the costs of no action. However, designing to a less extreme storm may result in a positive benefit to cost ratio.

6. The Beach Management Plan intended to establish thresholds for when beach management plans should be initiated. Based on the vulnerability analysis included in this draft document, depending on the storm scenario for which the County desires to design, the four Reaches defined in Section 4 require beach management actions now to achieve the stated goals of this plan. However, as indicated in the previous bullets, consideration is still being given to the appropriate design storm to consider. Once there is agreement on the design storm(s) to be considered, existing data from the storm vulnerability analyses and annual beach profile monitoring data can be used to establish thresholds and monitor the beach relative to those thresholds to track areas that may need active beach management in the future.

7. Once preferred alternatives have been finalized for each of the Reaches, cost estimates will be developed. Once these cost estimates have been developed, additional public engagement will be needed to evaluate the level of cost sharing required to implement

the preferred alternatives. Most successful beach management programs require a combination of funding streams including state funding, general funds from Counties/municipalities, room occupancy funds through Counties/municipalities, and funding paid by individual homeowners through either municipal service districts that levy a higher ad valorem tax for those that benefit from the projects or direct assessments. External funding sources can also be considered such as grants for coastal resilience and pre-disaster mitigation.

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