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moffatt & nichol

MULTI-DECADAL BEACH NOURISHMENT MASTER PLAN

Town of Nags Head, NC

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MULTI-DECADAL BEACH NOURISHMENT MASTER PLAN

Prepared for:

TOWN OF NAGS HEAD

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Prepared by:

moffatt & nichol

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EXECUTIVE SUMMARY

The Town of Nags Head has demonstrated its commitment to maintaining a healthy beach environment for storm protection, habitat preservation, and recreational use. Ongoing beach monitoring has informed the Town of the state of the beach, and beach nourishment projects have been completed as needed to enhance and protect the shoreline. This Multi-Decadal Beach Nourishment Master Plan has been completed to assist the Town in establishing a long-term strategy to permit, schedule, and finance ongoing beach nourishment efforts. The framework developed here allows for proactive planning and execution of sustainable beach management over the 50-year planning horizon.

The key aspects of this plan include statistical analysis of historical data to establish rates of volumetric sand loss due to long-term erosion as well as storm impacts, numerical modeling of storm impacts to determine equivalent Levels of Protection (LoP) for each area of the town's shoreline, and evaluation of alternatives to meet the town's beach management needs. In addition, a complete analysis of the offshore borrow area to be used as a long-term sediment source has been completed. Regulatory pathways and project timelines for both ongoing beach maintenance projects and post-storm emergency restoration projects have been completed to assist the Town in implementing the master plan. Figure ES-1 shows the Nags Head vicinity along with the reach designations that have been developed to facilitate the long-term monitoring and beach nourishment design process.

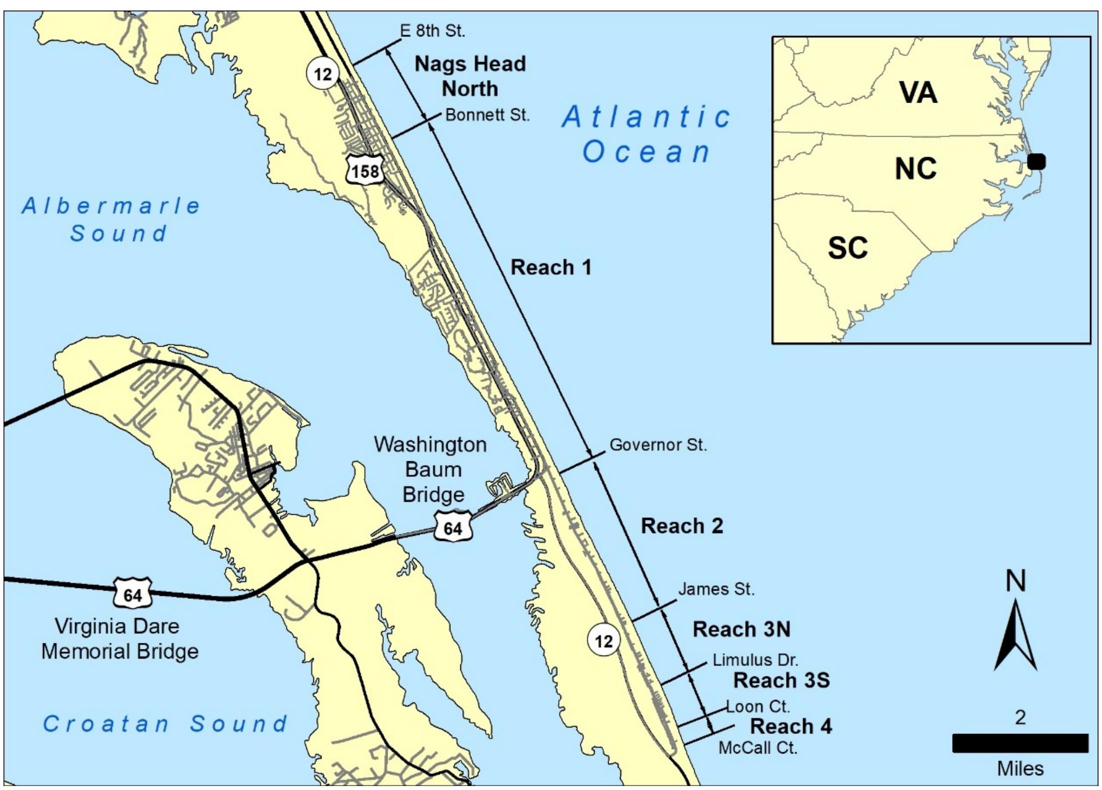


Figure ES-1: Nags Head Vicinity Map with Reaches

All of the long-term monitoring beach profile data was used to perform a statistical analysis of the sediment volume needs for each reach. Volume changes measured since 2011 were used along with the Crystal Ball software package to perform a Monte Carlo simulation and determine volume needs for long-term annual background erosion, as well as additional potential storm impacts, as presented in Table ES-1. Results showed an overall background volume loss along the Nags Head shoreline of approximately 450,000 cy/year at the 50% non-exceedance probability (i.e., there is a 50% likelihood that this volume will be exceeded). In order to estimate sediment need over the 50-year planning timeframe, potential impacts of additional storms were considered at the 75% non-exceedance probability (i.e., there is a 25% likelihood that this volume will be exceeded, as a conservative approach). An annualized total need of approximately 430,000 cy/year was estimated, considering 16 storms impacting the Town over the 50 years. These annual needs were summed and multiplied by 50 to estimate the 50-year need presented in Table ES-1.

Table ES-1: Nags Head Long-Term Nourishment Need from Background Erosion and Additional Storms

Category	Volume Above -19 ft, NAVD88 (cy)
Annual Background Volume Change (50% non-exceedance probability)	-451,218
Annualized* Storm Volume Change (75% non-exceedance probability)	-431,893
Annual Total Volume Change	-833,111
50-yr Material Need	44,155,550

**16 storms in 50-years*

Numerical modeling was performed to develop a preferred beach and dune profile design to achieve adequate LoP for habitable structures and infrastructure, along with appropriate trigger conditions for renourishment actions. Representative profiles were established along the Nags Head shoreline, based on the May 2018 profile survey data. These profiles are considered to demonstrate a quasi-natural state of the beach, being surveyed immediately prior to the 2019 beach nourishment project. The 25-year storm was selected as the most appropriate target for adequate LoP. Simulations were performed with the CSHORE 1D profile evolution model using the representative profiles and the 25-year storm conditions to evaluate the quasi-natural LoP of the beach state. Figure ES-1 shows the results of this analysis. In summary, the May 2018 pre-nourishment existing conditions of the beach and dune system are considered to provide a sufficient LoP along the northern and middle portions of Nags Head for up to a 25-year return period design storm event. Before the nourishment event, the representative profiles at Reaches 3 South and 4 do not have sufficient material available to protect the structures.

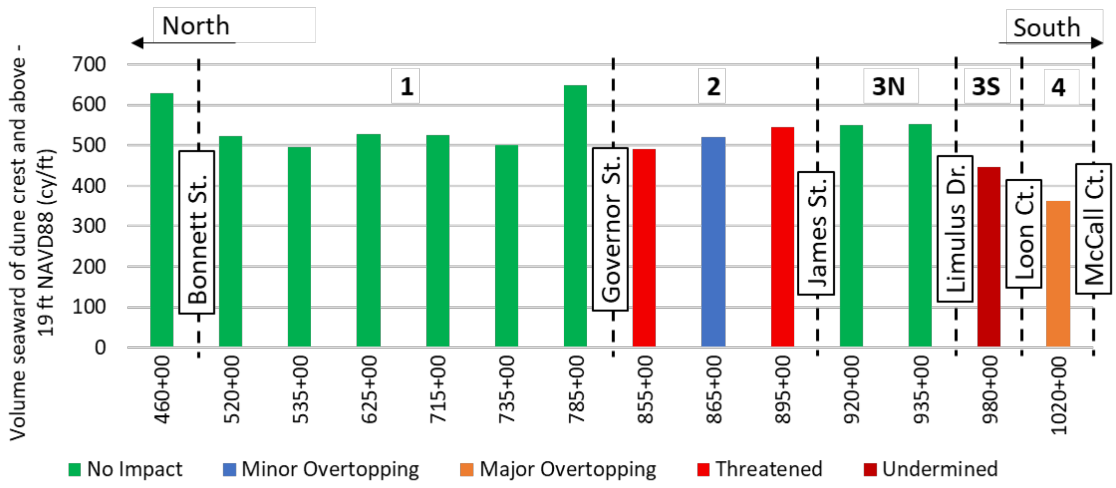


Figure ES-1: Pre-Nourishment Condition CSHORE Pre-Storm Profile Volumes Coded for 25-year Return Period LoP

The CSHORE model was then used along with the representative profiles to adjust the beach profile design to achieve an acceptable LoP along the Town's oceanfront in the design storm event. For cases where the profiles already provided adequate LoP, (e.g., Nags Head North, Reach 1, Reach 3N) dune and berm volume was removed to determine the threshold volume to meet the minimum LoP. The profiles at Reaches 2, 3 South, and 4 indicated severe impacts, so those were modified by adding dune and berm volumes to provide adequate protection. The volumes required to provide a 25-year LoP at each representative profile and within each reach are presented in Table ES-2. The May 2018 condition at each representative profile is also presented. It is noted that due to the condition of the profiles in Reaches 2, 3 South, and 4 at the time of the May 2018 survey, an estimated 0.6 Mcy would be required to be added to provide the minimum LoP. These triggers provide a basis for comparison with the annual beach monitoring profile surveys. When conditions arise such that the profile volumes are nearing the LoP triggers, the Town can begin planning the next maintenance project.

Table ES-2: Trigger Volumes Above -19 ft NAVD88 for 25-yr Event

Reach	Length (ft)	Rep. Profile	25-yr Trigger Volume (cy/ ft)	Reach Trigger for 25-yr event (cy/ft) (Weighted)	May 2018 Volume Above -19 ft (cy/ ft)
North	6,250	460+00	355	355	578
Reach 1	4,500	520+00	503	470	509
	5,500	535+00	451		472
	7,000	625+00	478		506
	5,500	715+00	479		501
	6,000	735+00	443		490
	2,500	785+00	604		610
Reach 2	5,500	855+00	491	502	446
	2,500	865+00	471		499
	2,500	895+00	526		485
	2,500	920+00	463		504
Reach 3 - North	4,500	935+00	464	446	464
Reach 3 - South	2,000	980+00	461		407
Reach 4	2,750	1020+00	401		373
TOTAL	59,500			464	

The implications of relative sea level change should also be considered when determining future beach nourishment needs. The dune crest and berm elevations would need to rise by approximately the same amount as relative sea level to maintain an equivalent LoP. An evaluation of the amount of sand volume that would be required to accommodate this required increase in dune crest and berm height and maintain the shoreline position has been performed using the Bruun Rule. Three sea level rise scenarios developed by NOAA for the Duck, NC tide gauge location were used to obtain a range of volume estimates, from 2.6 Mcy to 4.7 Mcy, to meet these needs.

The sea level rise volume need estimates were combined with the background erosion rate need, the additional storm erosion need, and the initial Level of Protection placement need analysis to develop a long-term sediment volume need, presented in Table ES-3. A relatively high estimate of potential volumetric losses during dredging was also computed. This volume estimate is considered to be conservative and can be compared with sand volumes available from identified borrow sources to provide assurance that the beach nourishment master plan can be executed successfully.

Table ES-3: Long-Term (50-Year) Sediment Volume Need

Crystal Ball	**Background Erosion 50 years (50%)**	22.5 Mcy		
	Additional Storms (16 storms) (75%)	21.5 Mcy		
LoP (25 year) Design		0.6 Mcy		
Relative Sea Level Rise (NOAA, 2022)		**Intermediate Low**	**Intermediate**	**Intermediate High**
		2.6 Mcy	3.4 Mcy	4.7 Mcy
TOTAL		**46.7 Mcy**	**47.5 Mcy**	**48.8 Mcy**
Assumed 20% losses during dredging		*56.0 Mcy*	*57.0 Mcy*	*58.6 Mcy*

A shoreline change model (GenCade) was calibrated and validated using historical data to enable assessment of longshore transport and long-term shoreline evolution along the Nags Head shoreline. The model shows that there is a reversal of sediment transport within the town where the net sediment transport is to the north along the northern reaches of the town, but the overall net sediment transport is towards the south. The exact location of the reversal varies according to the wave climate but is generally within Reach 1 or Reach 2. This reversal may be one of the reasons for the relative stability of Nags Head – North and Reach 1.

A series of engineering alternatives were evaluated to provide options for the Town to meet their goals to maintain a healthy beach over the next 50 years. These alternatives included discontinuing beach nourishment, varying cycles of beach nourishment, phased beach nourishment, and beach nourishment with structures.

To evaluate implications of discontinuing beach nourishment, a shoreline position forecast was made with the GenCade model, considering past wave conditions repeated consecutively to reach the 50-year timeframe. The resulting modeled shoreline was compared with structure footprints and parcels in a GIS framework. Structures, and their associated parcels, were considered impacted if the modeled 50-year shoreline came within 20 ft of the main structure footprint. Based on this analysis, approximately 1330 parcels were impacted, containing a total value of $805 million (2023 dollars). In addition to the potential property losses, potential losses to annual property tax could reach $3.9 million (2023 dollars). There are also significant potential economic implications for tourism if the beach is not maintained.

Varying cycles of beach nourishment along Reaches 1 to 4 were evaluated using estimated volume requirements and costs. An 8-year nourishment cycle had the lowest costs over the 50-year timeframe, because it minimized the number of projects and therefore lower mobilization and demobilization costs and lower costs per cubic yard for sand placement. However, a 6-year planning cycle allows for less expensive individual projects and more frequent ability to adapt to changes in the volumetric erosion rate. The nourishment interval is also flexible in that if volumetric triggers are not reached, the time period between projects can be extended, or the spatial limits of the project can be customized. Some general advantages of nourishing all of the reaches in each project are that this practice reduces the number of projects required over the 50-year planning horizon, minimizing mobilization/demobilization costs as well as the number of times the permitting process is required. Additionally, it may be perceived as equitable by residents and property owners as all of the reaches are nourished each time. However, in this case all of the reaches are affected by the disruptions and potential environmental impacts associated with the nourishment project every time.

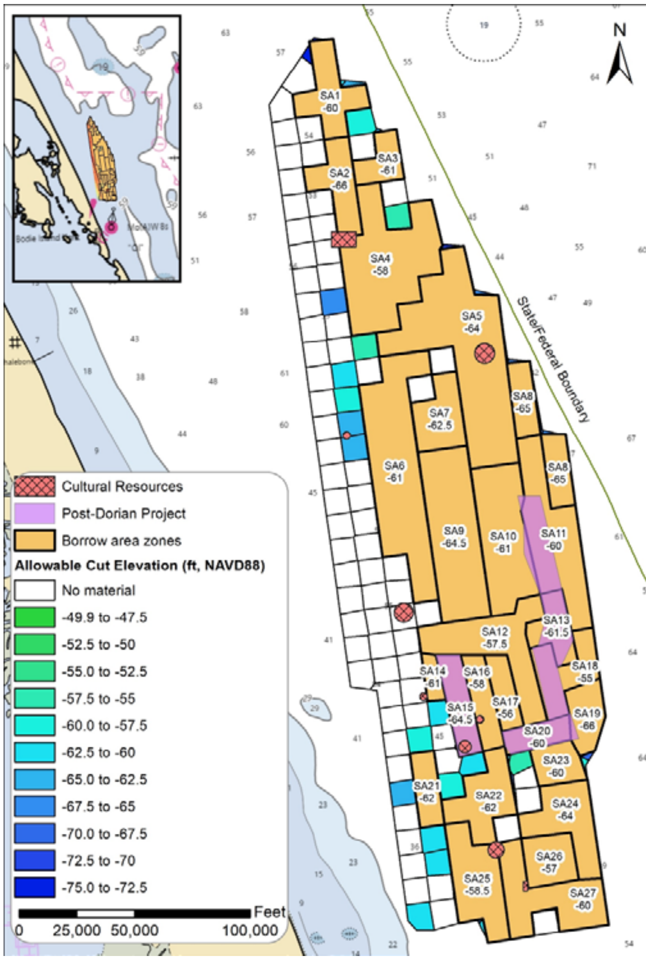
A phased approach was also considered where the interval between placement events would differ between Reach 1 and Reaches 2 to 4. Because the volumetric erosion rate in Reach 1 is less than that of the other reaches, direct placement of sand in Reach 1 can have a longer nourishment interval than Reaches 2 to 4. The phased approach provides nourishment volumes that would allow for Reach 1 to be nourished every other time that Reaches 2 to 4 are nourished. For example, the nourishment interval for Reaches 2 to 4 could be 4 years, while Reach 1 can be nourished every 8 years (a 4/8 year cycle). Intervals of 4/8 year cycles and 5/10 year cycles were evaluated. The 5/10 year cycles are the less expensive option over the 50-year master plan timeframe. The phased approach results in lower costs per cubic yard for Reach 1, because there is higher fill density for each project. In addition, the Reach 1 portion of the Town's shoreline is not subject to the disturbances and environmental impacts associated with project construction as often. Phasing also alternates between a lower-cost and a higher-cost project, which may have financing advantages for the Town. However, because there are more frequent projects in the phased approach than in the 6-year cycle or 8-year cycle where all of the reaches are nourished, overall mobilization and demobilization costs for the 50-year master plan timeframe are higher. Additionally, more frequent projects increase the number of times the environmental permitting process is required.

Structural alternatives to reduce erosion rates in South Nags Head (Reach 3S and Reach 4) were also considered in the alternatives analysis. Nearshore breakwaters added significant costs because the reduction in erosion provided by the breakwaters is not enough to substantially reduce the nourishment requirements. A groin alternative is shown to significantly reduce the erosion rates in Reaches 3S and 4, however, adverse downdrift effects are modeled within the Cape Hatteras National Seashore. These downdrift effects would likely add costs for required mitigation/downdrift sand placement. It is noted that oceanfront erosion control structures are currently not allowed under North Carolina G.S. § 113A-115.1, with the exception of terminal groins constructed at the terminus of an island or on the side of an inlet. Because the town is not immediately adjacent to Oregon Inlet, the groin approach would not fall within this exception.

Additional considerations for beach nourishment project design were reviewed, including project funding sources, feasibility of construction, and tourism and recreation. These factors can influence design and construction and can be evaluated on a project-by-project basis. Funding considerations may constrain a beach nourishment project in terms of the volume that is able to be placed with the available funds, as well as the timing of projects if funding sources take time to secure or favorable bids are not received from contractors. For beach nourishment project construction, there is generally a minimum fill volume density that is economically feasible for a contractor to construct. This volume density may vary depending upon the borrow source characteristics, dredging and placement methodology, and desired template. The engineering design and permitting of each nourishment event should include analysis to determine whether higher volumes with lower unit costs or lower volumes with higher unit costs will be more advantageous for the Town in terms of overall project cost. Finally, in addition to beach nourishment providing protection for the Town’s infrastructure, there are also recreational benefits to consider. The Town may choose to increase the volume of a planned beach nourishment to provide additional recreational beach width.

Maintenance of established dunes through best management practices is an important part of preserving and growing a healthy dune system. Dune planting along with installation of sand fencing is a proven method of stabilizing dunes and capturing sand, contributing towards dune growth. In order to create a robust vegetation system, it is recommended to participate in seasonal inspections and planting so as to allow for planting of multiple species of dune vegetation throughout the year.

A comprehensive evaluation of the previously identified borrow area S1 located offshore of Nags Head was performed, including collection of detailed geophysical and geological data to characterize and quantify the beach-compatible sand available. Sub-zones were delineated as shown in Figure ES-2, with allowable dredge cut elevation and available beach-compatible sand also presented. Based on this analysis of borrow area S1, approximately 67.9 Mcy of beach compatible material is made available. This quantity is considered sufficient to accommodate the estimated placement requirement of approximately 49 Mcy for the town's beach management efforts over the next 50 years.



Zone	Allowable Cut Elevation (ft, NAVD88)	Available Sand to Cut Elevation (cy)
SA1	-60	236,947
SA2	-66	1,476,340
SA3	-61	423,663
SA4	-58	2,306,244
SA5	-64	10,013,758
SA6	-61	5,949,522
SA7	-62.5	2,308,713
SA8	-65	2,902,471
SA9	-64.5	8,501,582
SA10	-61	5,796,575
SA11	-60	3,917,228
SA12	-57.5	4,195,481
SA13	-61.5	420,665
SA14	-61	329,510
SA15	-64.5	111,967
SA16	-58	692,023
SA17	-56	473,870
SA18	-55	1,272,303
SA19	-66	1,320,016
SA20	-60	USED
SA21	-62	626,489
SA22	-62	2,474,583
SA23	-60	1,374,315
SA24	-64	3,308,557
SA25	-58.5	2,160,860
SA26	-57	1,867,713
SA27	-60	3,424,295
SUM		67,885,691

Figure ES-2: Borrow Area Sub-Zones and Corresponding Maximum Dredge Cut Elevations

The master plan approach is designed to make the regulatory process more streamlined and efficient by developing volumetric requirements and evaluating borrow sources in advance of an imminent project. The required permitting process for a beach nourishment project includes both CAMA and USACE permits and coordination with multiple state and federal agencies. Construction moratoriums and avoidance measures are required to minimize environmental impacts of each project. Because of the coordination required as well as the time needed for project engineering design, bidding, and financing the project, it generally takes on the order of two years to complete a project from initiation to construction start. The annual beach monitoring surveys along with the volumetric LoP triggers provide the tools for the Town to initiate this process well in advance of a needed maintenance project. If an emergency post-storm project is required, an application for FEMA post-disaster assistance is initiated along with the other project tasks. FEMA review can take on the order of six months, and depending on the storm occurrence timeline, it may be up to three years before a post-storm recovery project is constructed to replace the losses incurred during the storm event.

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LIST OF ACRONYMS

CSDM	Coastal Storm Damage Mitigation
CO-OPS	[NOAA] Center for Operational Oceanographic Products and Services
cy	Cubic yards
cy/lf	Cubic yards per linear foot
DEM	Digital Elevation Model
NC CGIA	North Carolina Center for Geographic Information and Analysis
NC CRC	State of North Carolina Coastal Resources Commission
NC DCM	North Carolina Division of Coastal Management
NC DEQ	North Carolina Department of Environmental Quality
NCDIT	North Carolina Department of Information
NCDOT	North Carolina Department of Transportation
NCEI	[NOAA] National Centers for Environmental Information
CSE	Coastal Science & Engineering, Inc.
FEMA	Federal Emergency Management Agency
FRF	Field Research Facility
H_s	Significant wave height
H_{m0}	Spectral significant wave height
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
T_p	Peak wave period
Mcy	Million cubic yards
MHW	Mean High Water
MHHW	Mean Higher High Water
MLW	Mean Low Water
MLLW	Mean Lower Low Water
MSD	Municipal Service District
MSL	Mean Sea Level
MMS	US Minerals Management Service
NAIP	[USDA] National Agriculture Imagery Program
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum of 1988
NGS	National Geodetic Survey
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Research Council
RSLC	Relative Sea Level Change
SLR	Sea Level Rise
SWEL	Still Water Elevation
UNC CSI	University of North Carolina Coastal Studies Institute
USACE	US Army Corps of Engineers
USDA	US Department of Agriculture
USGS	US Geological Survey

1.0 INTRODUCTION

The Town of Nags Head was the first community in Dare County to conduct a locally-funded beach nourishment project, with an initial project constructed in 2011 (Kana and Kaczkowski, 2012). This project has successfully provided storm protection and has increased the available beach and dune habitat within the town, including enabling dune growth of an average of 3 cubic yards per linear foot (cy/ft) for the first five years after project construction as documented by Kaczkowski *et al.* (2018). The town demonstrated its commitment to regular maintenance of its beach, as valuable infrastructure, by completing its first planned town-wide beach renourishment in the summer of 2019. The beach was then significantly eroded by Hurricane Dorian in September 2019, and in partnership with the Federal Emergency Management Agency (FEMA), the Town completed a post-Hurricane Dorian beach renourishment project in August 2022 to replace sand lost as a result of that storm.

Construction of these beach nourishment projects has been funded primarily by the Town through a combination of town-wide property taxes and revenues from its own Municipal Service Districts (MSDs). The Town has also received funding support from Dare County via the County’s Beach Nourishment Fund. In addition, FEMA post-disaster Public Assistance funding and a The Federal Emergency Management Agency (FEMA) and a North Carolina Department of Environmental Quality (NC DEQ), Division of Water Resources Coastal Storm Damage Mitigation (CSDM) grant provided the funds for the post-Hurricane Dorian restoration project in 2022 (Town of Nags Head, 2022).

The town is committed to maintaining a healthy beach and dune system to provide protection for upland properties, maintain habitat for many species of wildlife, and serve as a valuable recreational asset. In keeping with that commitment, the Town decided to pursue a more comprehensive, forward looking multi-decadal beach nourishment master plan. This report documents the initial version of that master plan. The report describes the history of beach nourishment, shoreline and volume changes observed from historical data, coastal engineering and modeling studies, and investigations and analysis of potential beach quality sand borrow areas available for present and future beach nourishments within the plan’s timeframe. This multi-decadal beach nourishment master plan provides the Town of Nags Head with a framework to plan and conduct beach maintenance and storm response projects over a 50-year time frame. With this framework in place, the town will be able to efficiently plan the permitting, financing, and construction of those future projects.

1.1 Study Area

The study area for the master plan is the Town of Nags Head’s approximately 11-mile Atlantic Ocean shoreline (Figure 1-1). Additional areas considered include the downdrift shoreline to the south within the Cape Hatteras National Seashore as well as the updrift communities within Dare County. Unless otherwise noted, all units in this report are in the US Customary system, and all elevations are referenced to the North American Vertical

Datum of 1988 (NAVD88). All horizontal coordinates are referenced to State Plane US Survey Feet, NAD 83 horizontal datum.

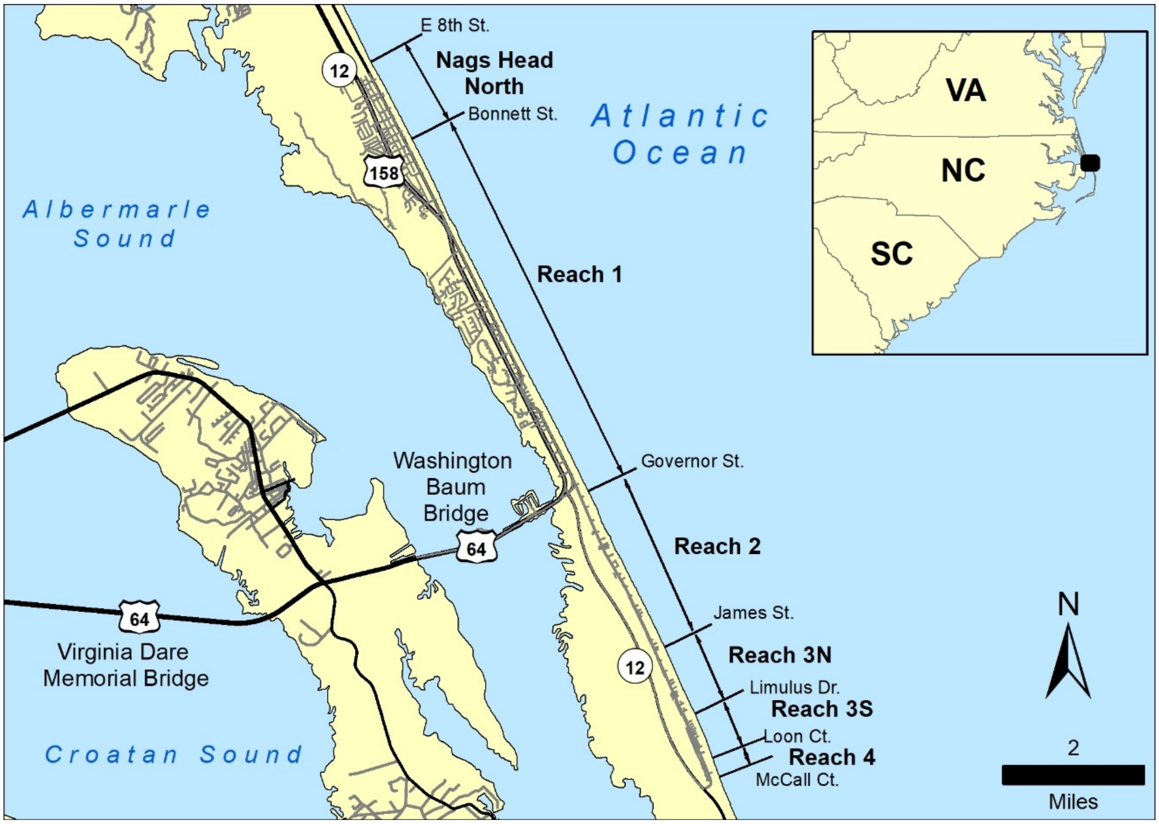


Figure 1-1: Study Area of Nags Head, Dare County, NC

Within the study area, a series of transects and reaches were developed when the Town initiated beach nourishment and monitoring in 2011 (Town of Nags Head, 2011). The reaches were later modified to divide Reach 3 into two sub-reaches (Reach 3 – North and Reach 3 – South). Table 1-1 presents the reach start and end points, corresponding transect stations, and reach lengths.

Table 1-1: Reach Start and End Points

Reach	Stations	Length (ft)	Start Point	End Point
Nags Head - North	430+00-495+00	6,750	E 8th Street	Bonnett Street
Reach 1	495+00-790+00	29,000	Bonnett Street	Governor Street
Reach 2	790+00-920+00	13,000	Governor Street	James Street
Reach 3 - North	920+00-975+00	5,500	James Street	Limulus Drive
Reach 3 - South	975+00-1010+00	3,500	Limulus Drive	Loon Court
Reach 4	1010+00-1025+00	2,000	Loon Court	McCall Court

2.0 PROJECT PURPOSE AND NEED

2.1 Project Purpose

The Nags Head Multi-Decadal Beach Nourishment Master Plan's purpose is to:

1) establish a programmatic plan to facilitate authorization and implementation of beach nourishment events (maintenance and storm response), including borrow source identification and analysis;

2) provide a project plan for the long-term maintenance of the dune, beach, and foreshore within the Town of Nags Head to:

- establish an equivalent level of storm protection to upland property and infrastructure within the town, protecting Nags Head residents' properties as well as protecting the associated local, state, and federal tax bases;
- ensure the viability of the Nags Head tourism industry;
- maintain natural resources and associated recreational uses while avoiding and minimizing adverse environmental impacts to the extent feasible;

3) provide an efficient framework to financially and logistically manage the Town of Nags Head's beaches in coordination with Dare County and surrounding communities.

2.2 Project Need

The Town of Nags Head has completed three beach nourishment projects over the past 12 years. Two of those projects were focused on beach maintenance and one on post-storm recovery. The town is dedicated to maintaining a healthy beach for storm protection and recreational use. A master plan approach will enable the town to establish a long-term strategy to permit, schedule, and finance ongoing beach nourishment efforts.

Having estimates of the long-term ongoing volumes needed for beach maintenance and storm response will enable the town to work with Dare County as well as state and federal sources to allocate adequate funding. These estimates, in conjunction with a comprehensive analysis of the identified offshore borrow area, provide assurance that enough beach-compatible sand is available to supply the estimated need for the 50-year plan time horizon. In addition, establishing project timelines based on volume triggers and storm occurrence allows for proactive planning of regulatory considerations and permitting requirements.

2.3 Scope of Study

This comprehensive report reviews present-day beach conditions, past beach nourishment projects, and ongoing monitoring data to develop a nourishment plan based on volumetric thresholds for the town. In addition, the regulatory requirements are reviewed and permitting timelines established to facilitate timely project implementation. The planning horizon is 50 years to provide long-term stability to the town's beach nourishment program. The master plan examines alternatives including beach nourishment across all nourished reaches, beach nourishment with variable timing according to need, and beach nourishment in conjunction with structures (nearshore breakwaters or terminal groin).

The final master plan is intended to 1) establish the parameters (such as volumetric thresholds) for future beach nourishment and management, 2) provide a basis for the town to continue to qualify for FEMA reimbursement for replacement of sand lost during a federally-declared disaster, and 3) provide Town with proactive planning and execution of sustainable beach management for a 50-year planning horizon; including regulatory timelines, financial needs, and the tools to assess the Town's level of protection based on annual monitoring surveys.

The workflow for development of the master plan is shown in Figure 2-1. Initially, the technical work plan, including numerical modeling needs was developed. Next, existing data sets describing historical and existing conditions were assembled, including wave climate, water levels, beach topography and nearshore bathymetry, shoreline changes, and sediment resources. These data sets were used to perform analytical assessment of beach profile changes, localized hot spots, and sand sources. These were then employed to develop the beach nourishment volume needs and triggers. In parallel, a calibrated and validated numerical model of shoreline change was developed using historical data. The results of the analytical assessment were used to estimate beach nourishment needs over the 50-year planning timeframe.

With input from the town, alternative scenarios were developed for evaluation. The analytical and numerical modeling tools developed using historical beach behavior were used to evaluate the performance of each alternative. These results in conjunction with preliminary cost estimates and project timelines comprise the master plan.

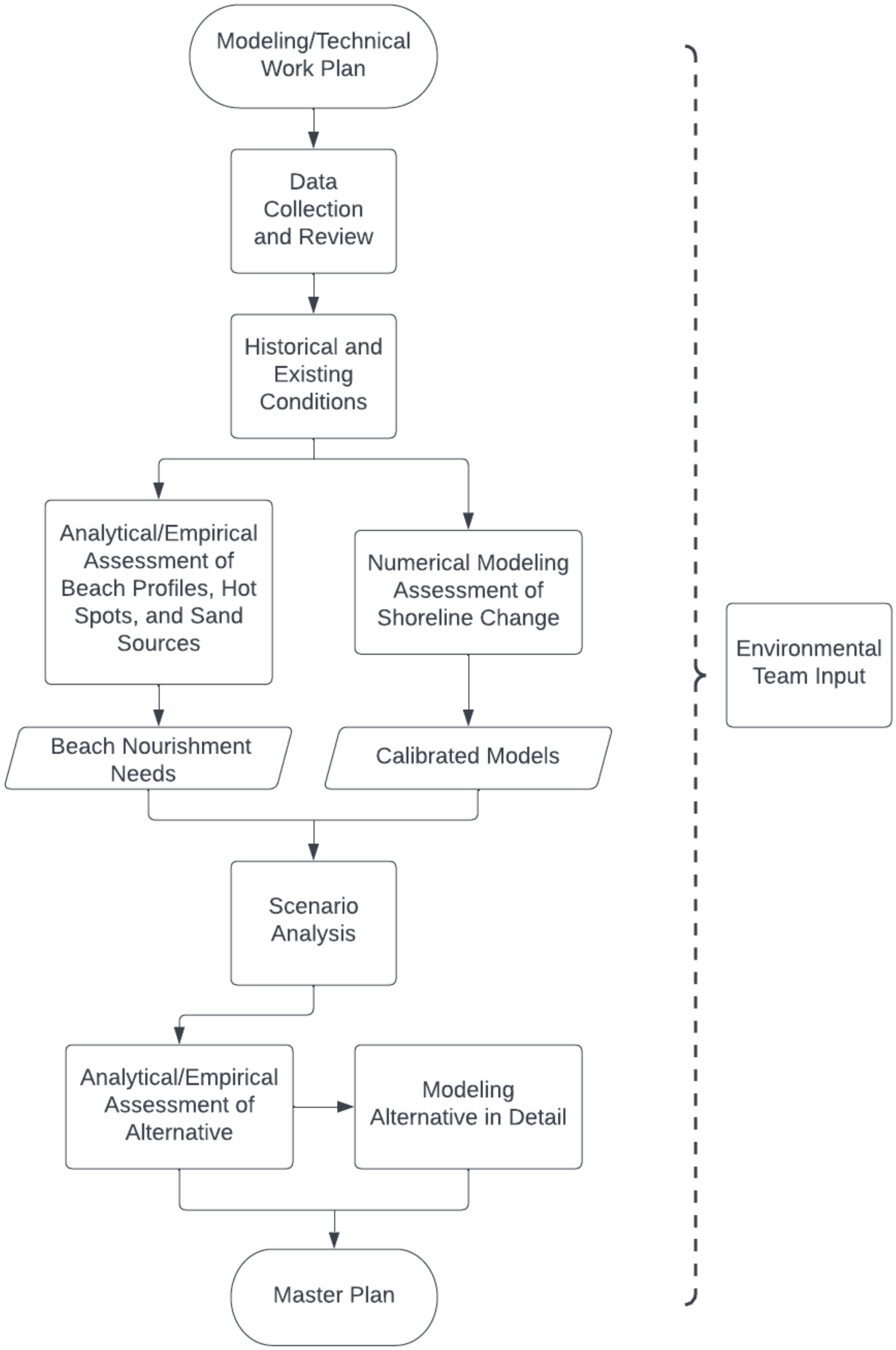


Figure 2-1: Workflow for development of Beach Nourishment Master Plan

3.0 REVIEW OF AVAILABLE DATA

Data from various sources including public (federal, state, and local entities) and private sources, such as previous studies by others, were compiled during the course of this study. The primary types of data include historical measured water levels; historical measured and hindcast wave conditions; historical shoreline positions, beach profiles and nearshore bathymetry; aerial photography; sediment characteristics both on the Nags Head beaches and within potential borrow areas; logs and records of historical coastal engineering works along Nags Head; and a collection of previous studies by others relative to coastal processes in the project area. This chapter documents the most significant data utilized for the coastal engineering analysis of this study.

3.1 Wave Climate

The primary mechanism of sediment movement along an open ocean coast is the action of waves and the associated currents. In order to understand the magnitude and direction of sediment movement, it is necessary to properly characterize the wave climate. The shape of the nearshore bathymetry and the angle at which waves approach the coastline influence the shoreline changes. Wave characteristics have short-term (seasonal) and long-term impacts on cross-shore and along-shore sediment transport. Drastic changes in beach width and elevation can occur during large storm events (hurricanes) with elevated wave conditions, but it is the more frequent storms and wave events that generally drive the overall shoreline position. The wave climate is a driver for the modeling of sediment movement and shoreline evolution pre- and post-nourishment projects.

Relevant wave data in the study area consist of three directional wave buoys that have been operated at various times by the UNC Coastal Studies Institute and the U.S. Army Corps of Engineers (USACE). The wave measurements at these stations include wave height, period, and direction in varying intervals and over varying time periods, as described below. The publicly available historical water level and wave data sources considered in this study are shown in Figure 3-1.

This section of the report provides a brief summary of the offshore wave data sources relevant to determining the wave climate at Nags Head. Appendix A provides a more detailed presentation and discussion of the offshore wave data sources and wave transformation model simulations to generate nearshore wave climates for various components of this master plan.

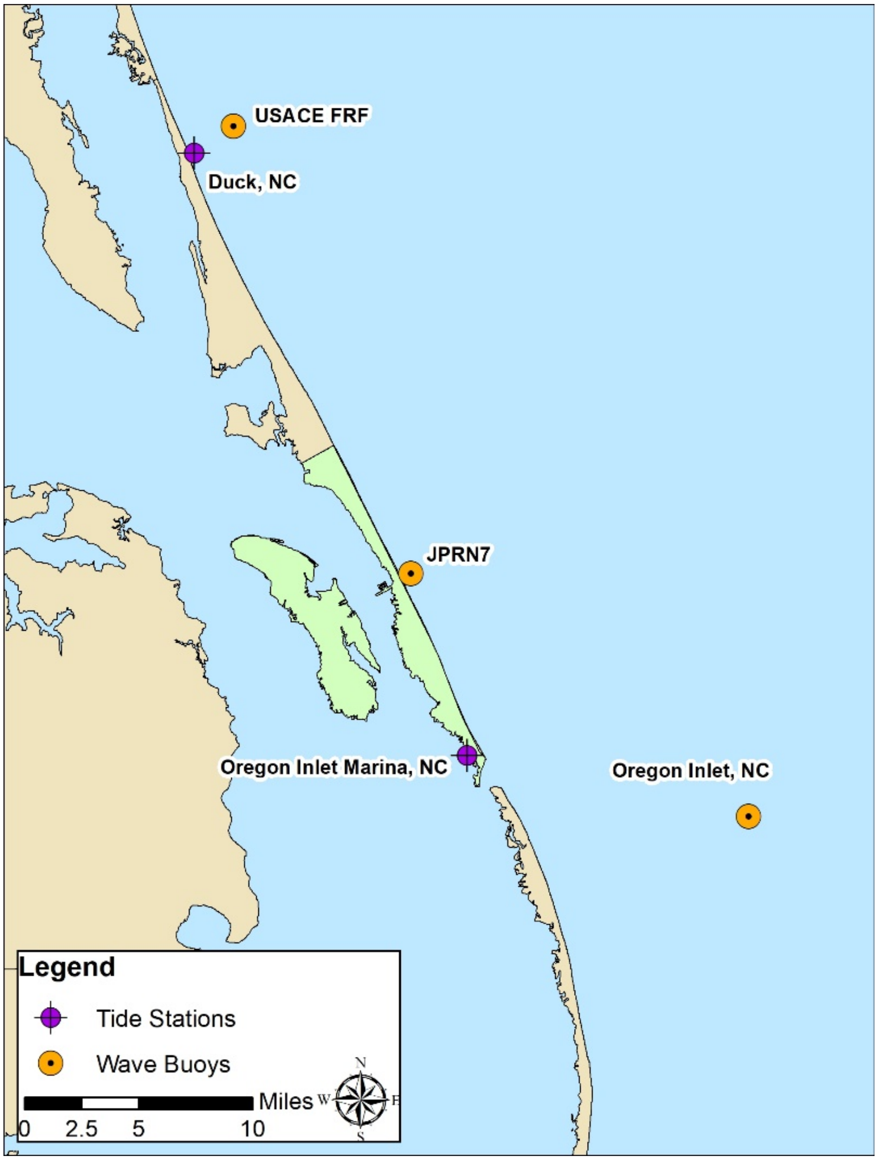
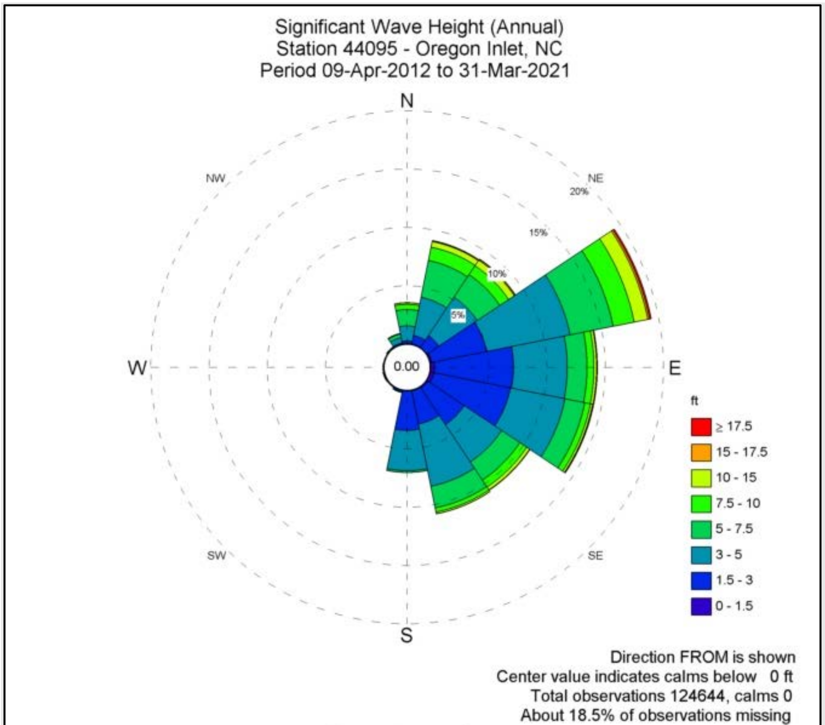


Figure 3-1: Wave and Water Level Data Locations

3.1.1 UNC Coastal Studies Institute Oregon Inlet Station, NDBC 44095

UNC buoy #44095 (Oregon Inlet) is located approximately 18.3 miles southeast of Nags Head and in a water depth of approximately 69 ft. The data record spans April 2012 – May 2021, with significant gaps in coverage, including May 13 to July 16, 2013; February 2 to April 24, 2015; December 5, 2016 to April 23, 2017; and February 3 to June 8, 2020. Figure 3-4 shows a rose plot of wave heights by direction at this location. The rose indicates that, offshore of Oregon Inlet, waves are predominantly from the east-northeast through the east-southeast sectors, with measured significant wave heights predominantly between 1.5 ft and 7.5 ft. Measured significant wave heights exceed 9.4 ft approximately 5.0% of the time, and they exceed 14.0 ft approximately 1.0% of the time.



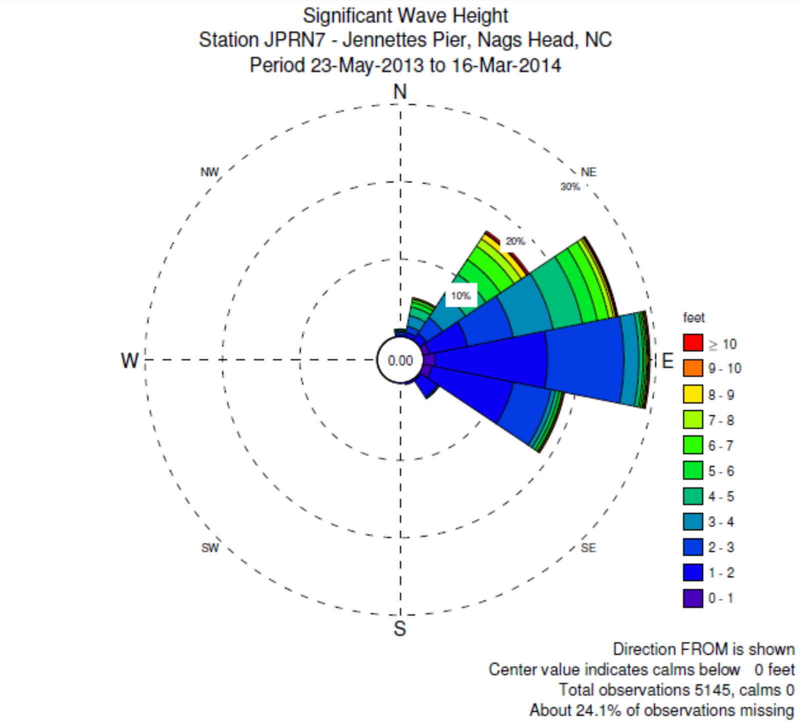
Percentage of Occurrence

Significant Wave Height, ft	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	3.55	9.09	9.18	19.36	14.32	14.32	10.68	10.82	7.02	0.22		0.12			0.13	0.97	100.00
≥ 17.5				0.14													0.30
15 - 17.5				0.15													0.44
10 - 15	0.13	0.49	0.57	1.20	0.23	0.19	0.29	0.15									3.26
7.5 - 10	0.46	1.17	0.92	1.84	0.59	0.50	0.71	0.37									6.63
5 - 7.5	1.40	3.22	2.33	3.77	1.70	1.73	1.87	1.89	0.16							0.31	18.44
3 - 5	1.29	3.33	3.95	7.30	4.61	4.78	3.86	5.44	3.45							0.45	38.70
1.5 - 3	0.26	0.79	1.26	4.80	6.78	6.70	3.77	2.91	3.39	0.14						0.14	31.18
0 - 1.5				0.16	0.35	0.34	0.13										1.06

Figure 3-2: Station 44095 Offshore Significant Wave Height Rose from April 2012 – March 2021

3.1.2 USACE Station JPRN7 – Jennette's Pier

A nearshore station data source USACE buoy JPRN7 (Jennette's Pier) was used in wave model calibration efforts to validate the MIKE 21 Spectral Waves model described in Appendix A. The data record at this gauge spans May 2013 – March 2014. JPRN7 was a bottom mounted acoustic Doppler current profiler (ADCP) located approximately 0.35 miles offshore of the Jennette's Pier in a water depth of approximately 37.1 ft. At the station, waves are predominantly from the northeast through the east-southeast (Figure 3-3).



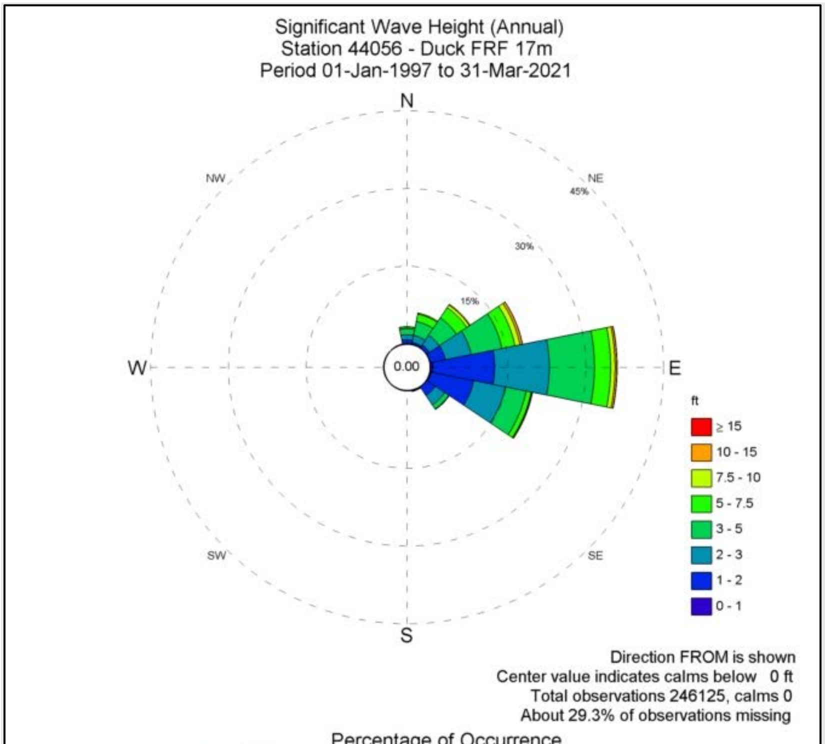
Percentage of Occurrence

Significant Wave Height, feet	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	0.97	5.17	17.01	25.66	29.23	18.60	3.05	0.29									100.00
>10			0.27	0.17													0.49
9–10			0.12	0.12													0.35
8–9			0.82	0.29													1.32
7–8		0.12	1.13	0.62	0.16												2.10
6–7		0.37	2.12	1.52	0.23	0.17											4.41
5–6		0.62	2.25	1.94	0.27	0.37											5.50
4–5	0.19	1.15	3.17	3.87	0.54	0.49											9.41
3–4	0.16	1.40	3.56	5.27	1.94	0.58											12.94
2–3	0.35	0.82	2.49	6.01	9.87	4.98	0.23										24.74
1–2	0.21	0.56	1.07	5.05	14.50	10.71	2.55	0.25									34.93
0–1				0.80	1.50	1.17	0.23										3.81

Figure 3-3: Station JPRN Offshore Significant Wave Height Rose from May 2013 – March 2014

3.1.3 USACE Field Research Facility (FRF) Station 44056

The USACE FRF buoy data was used to establish the overall wave climate offshore of Nags Head. The FRF buoy is located approximately 15 miles north of the Town in a water depth of approximately 58 ft. The data record at this gauge spans January 1997 – March 2021. The longer-term wave time series available from the FRF buoy was used to establish extreme wave heights for use in developing synthetic design storm data sets for cross-shore modeling described in Section 5.3. Figure 3-4 shows a rose plot of wave heights by direction at this location. At the FRF buoy the recorded waves are predominantly from the east direction. Waves from east-northeast and east-southeast are also observed frequently. Wave heights are predominantly between 1.0 and 5.0 ft. Measured significant wave heights exceed 7.5 ft approximately 4.1% of the time, and they exceed 10.0 ft approximately 1.0% of the time.



Percentage of Occurrence

Significant Wave Height, ft	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	3.33	6.19	10.14	18.23	36.05	20.19	5.31	0.26									100.00
≥ 15																	0.11
10–15			0.17	0.47	0.35												1.11
7.5–10		0.21	0.61	0.99	0.84	0.17											2.88
5–7.5	0.34	1.46	2.38	2.57	3.14	0.97	0.11										10.98
3–5	1.14	2.73	4.02	6.05	8.71	4.11	0.93										27.75
2–3	1.01	1.37	2.27	5.11	10.54	6.22	2.20	0.14									28.96
1–2	0.77	0.41	0.70	2.92	11.95	8.39	2.02	0.11									27.40
0–1					0.47	0.22											0.82

Figure 3-4: Station 44056 Offshore Significant Wave Height Rose from January 1997 – March 2021

3.2 Water Levels

Changes in water level are tidally influenced and driven by changes with climate, sea level rise, and subsidence. Along the open ocean coast this rise and fall dictates the typical range of water levels along the shore. Elevated water levels will increase the exposure of the coast to storm-driven surge and high waves, magnifying their impact on the coast. The most severe coastal impacts tend to occur when a storm surge coincides with high tides and/or during periods of anomalously high sea level.

The National Oceanic and Atmospheric Administration (NOAA) tides and currents website contains two active tide stations in the vicinity of Nags Head: Duck and Oregon Inlet Marina, NC. These tide stations' locations are shown in Figure 3-1**.**

3.2.1 NOAA Tide Station #8651370 Duck Station

The only open-coast NOAA tide gauge listed by NOAA's CO-OPS program in the immediate study area is located in the Town of Duck at the USACE FRF Pier (see Figure 3-1). Verified hourly and 6-minute water level measurements are readily available from NOAA's CO-OPS program website since June 1978 and October 1995, respectively.

The data recorded at this gauge were used in calibration and verification of the CSHORE model as described in Section 5.3.2 and for the extreme analysis to calculate the design storm peak water levels, which is explained further in Section 5.5.1. NOAA's published tidal datum sheet for the Duck station indicates a range of 3.69 ft between MHHW and MLLW, with a range of 3.23 ft between MHW and MLW. Figure 3-5 shows the relationships of tidal datums MHHW, MLLW, and MSL in feet relative to NAVD88 at the Duck tide station based on NOAA's 1983-2001 tidal epoch.

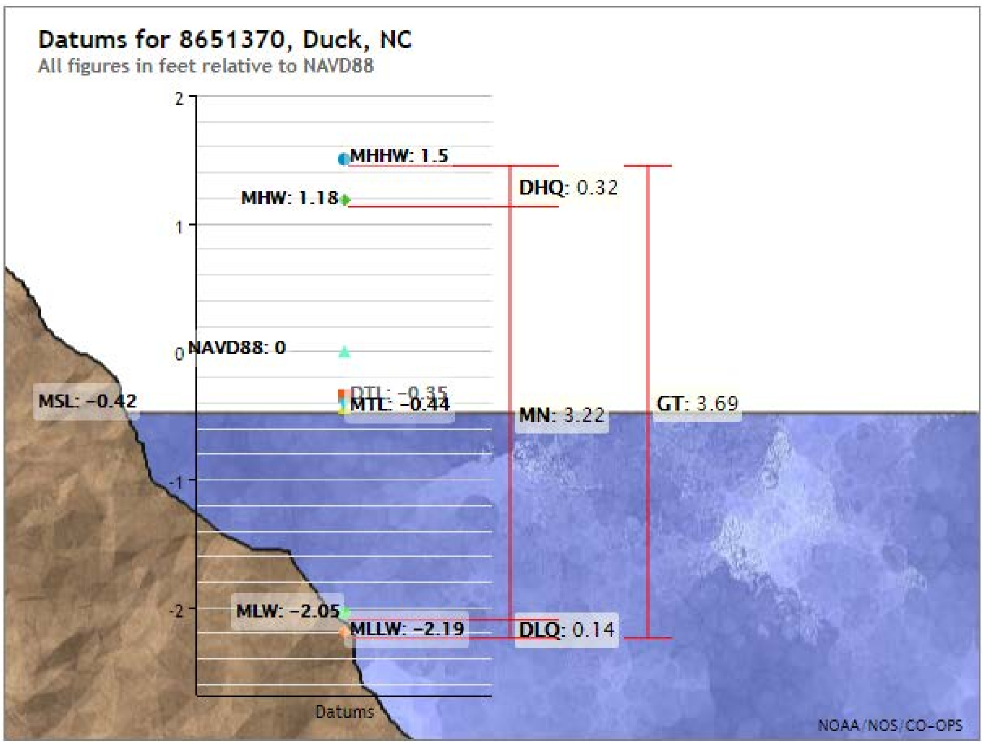


Figure 3-5: Tidal Datum Chart for Duck, NC Station 8651370

3.2.2 NOAA Tide Station #8652587, Oregon Inlet Marina Station

The Oregon Inlet Marina, NC tide station is another nearby operating gauge. This gauge was installed on August 14, 1974, and provides verified hourly water level measurements from 1974 to present. The gauge has also recorded 6-minute water level intervals since January 1996. The Oregon Inlet tide station is located within the Oregon Inlet Marina (Figure 3-1**)**, and as such does not accurately represent tidal water levels along the open Atlantic coast. However, the tide gauge data provides an applicable data set for inferring the effects of coastal storms (e.g., surge over predicted astronomical tides) and sea level rise trends.

NOAA's published tidal datum sheet indicates a range of 1.18 ft between MHHW and MLLW, with a range of 0.9 ft between MHW and MLW. Figure 3-6 shows the relationships of tidal datums MHHW, MLLW, and MSL in feet relative to NAVD88 at the Duck tide station based on NOAA's 1983-2001 tidal epoch.

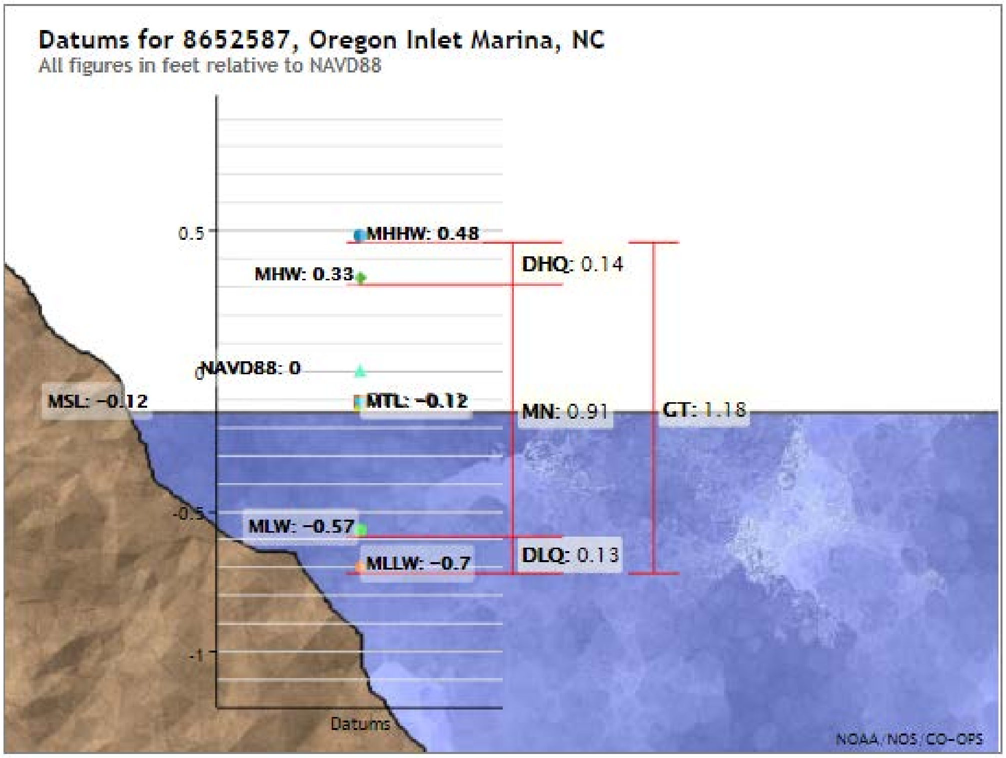


Figure 3-6: Tidal Datum Chart for Oregon Inlet Marina, NC Station 8652587

3.2.3 Storm Surge

Another short-term water level fluctuation is storm surge, which is the rise in water levels generated by a storm above the typical astronomical tide. This water level rise can have a significant impact on sand movement since it allows waves to travel further landward. Storm surges and fluctuating water levels allow waves to erode various elevations of the beach from the dunes to the berm, and beach foreshore.

Storm surge is included in the historical water level measurements at the Duck NOAA tide gauge. The top ten highest water level events at the Duck tide gauge from January 1980 to May 2023, and the respective surge components, are summarized in Table 3-1.

Table 3-1: Ten Highest Water Levels at Duck NOAA Tide Gauge

Date	Total Water Level (ft, NAVD88)	Predicted Tide Level (ft, NAVD88)	Storm Surge (ft)
2003-09-18	5.63	0.93	4.70
2006-11-22	5.36	1.80	3.56
2019-09-06	4.97	1.63	3.34
2022-01-03	4.96	2.08	2.88
1999-08-30	4.79	1.88	2.91
2021-11-07	4.68	2.54	2.14
2015-10-02	4.65	2.21	2.44
2009-11-13	4.49	1.80	2.69
2012-10-28	4.49	1.65	2.84
2000-05-29	4.43	1.34	3.09

3.2.4 Sea Level Change

Due to the multi-decadal nature of the overall beach nourishment master planning process, the impact of sea level rise on long-term beach behavior and project performance is a significant factor. It is recognized that the actual rate of relative sea level change experienced by Nags Head, including any potential acceleration of this rate, is not known with certainty. The resiliency and/or adaptability of the forward-looking plans and design generated by this study is improved by considering the impacts of sea level rise. The most recent federal guidance on sea level change is provided by NOAA's Global and Regional Sea Level Rise Scenarios for the United States (Sweet et al. 2022). This (2022) prediction was chosen as the most current and reliable estimate for sea level rise after a thorough review of available data.

<u>NOAA (2022) Relative Sea Level Change at Duck</u>

Relative mean sea level at the Duck NOAA tide gauge (Sta. 8651370) has been rising at a long-term average rate of approximately 4.74 mm/year (0.016 ft/year), as computed by NOAA from monthly mean sea level data between 1978 and 2022 (**Figure 3-7**). Over a 50-year future planning period, the continuance of this trend would result in a relative mean sea level increase of approximately 0.78 feet.

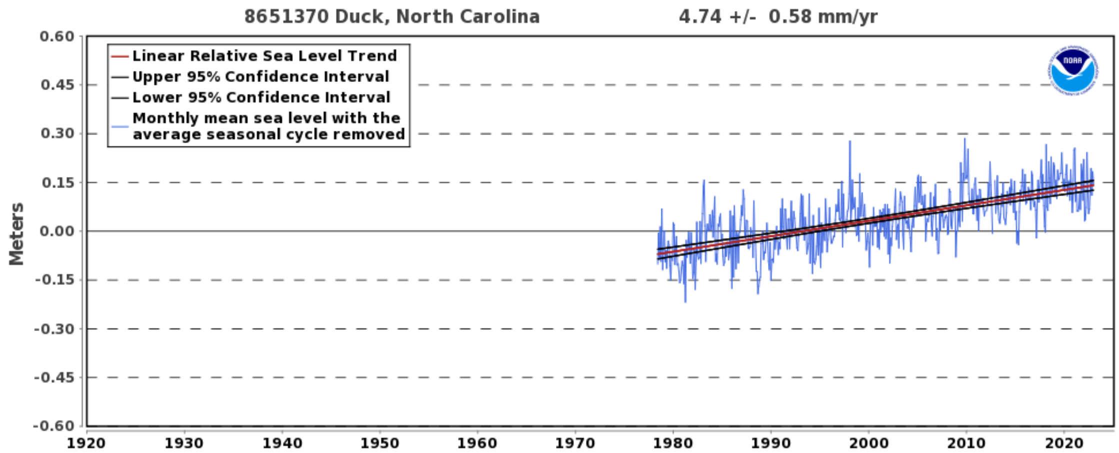


Figure 3-7: Relative Sea Level Trend - Duck, NC (Sta. 8651370) based on monthly mean sea level data from 1978 to 2022

In 2017, the U.S. Interagency Sea Level Rise Taskforce conducted a review of the research on global sea level rise projections and updated the scenarios of global mean sea level rise. In their report, the researchers defined six global sea level rise scenarios (Low, Intermediate Low, Intermediate, Intermediate High, High, and Extreme) decade by decade for this century based on the latest published and peer reviewed science. Regionally appropriate scenarios were then generated by NOAA (Sweet et al. 2017), integrating the refined global scenarios with regional factors contributing to sea level change for the entire U.S coastline. The researchers scaled these scenarios down to a one-degree gridded resolution, or roughly 70 miles. This effort was updated in 2022 (Sweet et al. 2022) to include additional observations and improved understanding of the drivers of sea level change. In addition, the Extreme scenario is no longer included.

Figure 3-8 presents the results of the updated study at Duck, NC. Based on the 2022 scenarios, local sea level at Duck, NC is very likely to rise at least 1 ft above 2022 levels by 2072 on a low-global-warming pathway. On future pathways with the highest global warming levels, sea level rise could reach approximately 3 ft above 2022 levels by 2070.

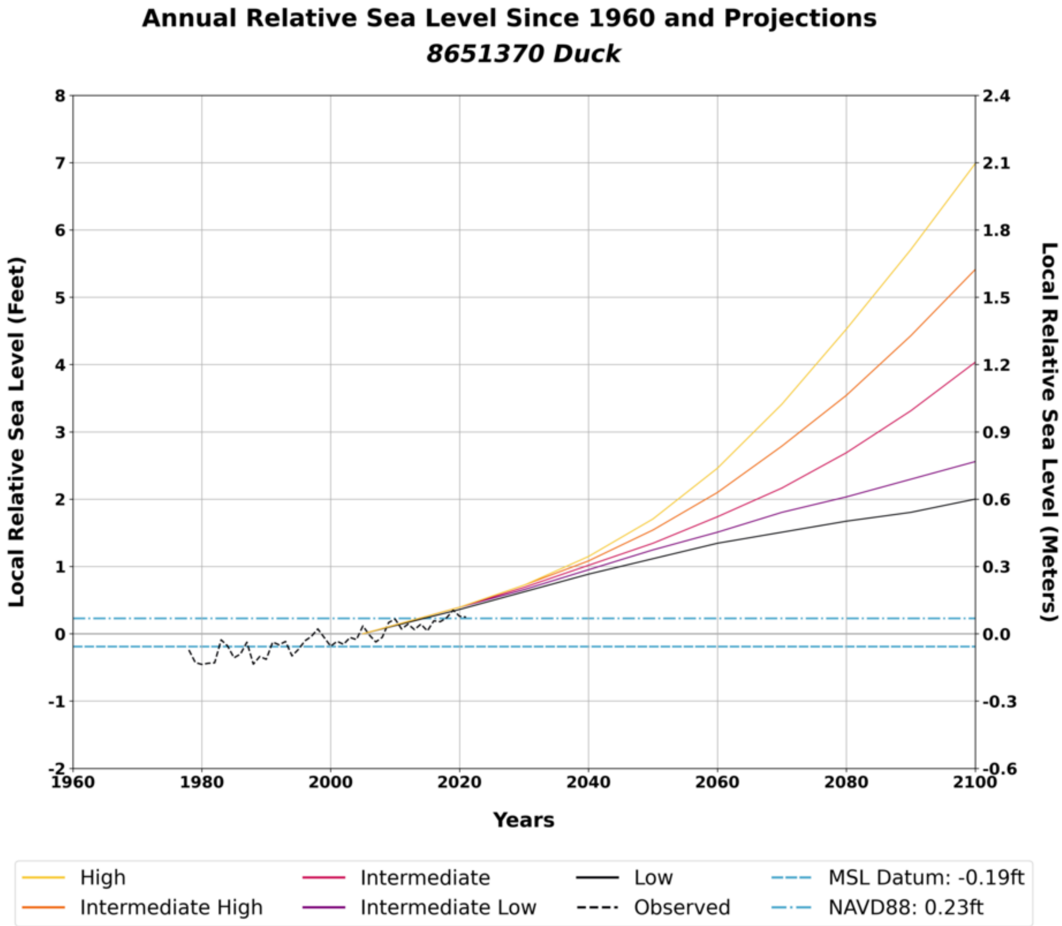


Figure 3-8: Relative Sea Level Change at Duck, NC Based on Sweet et al. (2022). The annual mean sea level for the year 2005 serves as the 'zero' for the figure with the elevation of NAVD88 also provided.

Realistic scenario estimates of sea level rise will be utilized for the project. Consideration of the specific impacts of sea level rise on the performance of project alternatives is discussed in Section 5.5.4.

3.3 Beach Topography and Nearshore Bathymetry

Beach topography and nearshore bathymetry are used to understand the physical characteristics of the coastal zone. By mapping the shape and elevation of beaches, as well as the depth and shape of the nearshore area, the susceptibility of the shore to erosion and sediment transport along the shore can be determined. This information is then used to assess the risk of erosion and storms and develop strategies to mitigate the risk and reduce the impact of these hazards.

3.3.1 Beach Monitoring Profiles

Beach profile data for the project study area is readily available as part of the ongoing monitoring program along Nags Head's ocean shoreline. Town of Nags Head began to consistently monitor the shoreline after the 2011 beach nourishment project. Table 3-2 shows the available survey data for Nags Head. Figure 3-9 shows the beach monitoring survey transect locations.

Table 3-2: Nags Head Beach Profile Surveys

Date	Source	Description	Transect Stations Included
November 2004	CSE	Hurricane Isabel Dune Recovery Project BD	430+00-1020+00
May 2005	CSE	Hurricane Isabel Dune Recovery Project AD	522+00-1020+00
December 2006	CSE		430+00 – 1020+00
March 2009	CSE		430+00 – 1020+00
November 2010	CSE		430+00 – 1080+00
June 2011	CSE	2011 Nourishment BD Survey	430+00 – 1025+00
November 2011	CSE	2011 Nourishment AD Survey	430+00 – 1025+00
June 2012	CSE	Annual Monitoring	430+00 – 1080+00
November 2012	CSE	Annual Monitoring	430+00 – 1080+00
June 2013	CSE	Annual Monitoring	430+00 – 1080+00
June 2014	CSE	Annual Monitoring	430+00 – 1080+00
June 2015	CSE	Annual Monitoring	430+00 – 1080+00
June 2016	CSE	Annual Monitoring	430+00 – 1080+00
July 2017	CSE	Annual Monitoring	430+00 – 1080+00
May 2018	CSE	Annual Monitoring	430+00 – 1080+00
April 2019	CSE	2019 Nourishment BD Survey	430+00 – 1080+00
August 2019	CSE	2019 Nourishment AD Survey	430+00 – 1080+00
November 2019	CSE	Post-Dorian Survey	495+00 – 1025+00
June 2020	McKim & Creed	Annual Monitoring	430+00 – 1300+00
July 2021	McKim & Creed	Annual Monitoring	430+00 – 1300+00
July 2022	McKim & Creed	Annual Monitoring	430+00 – 1300+00

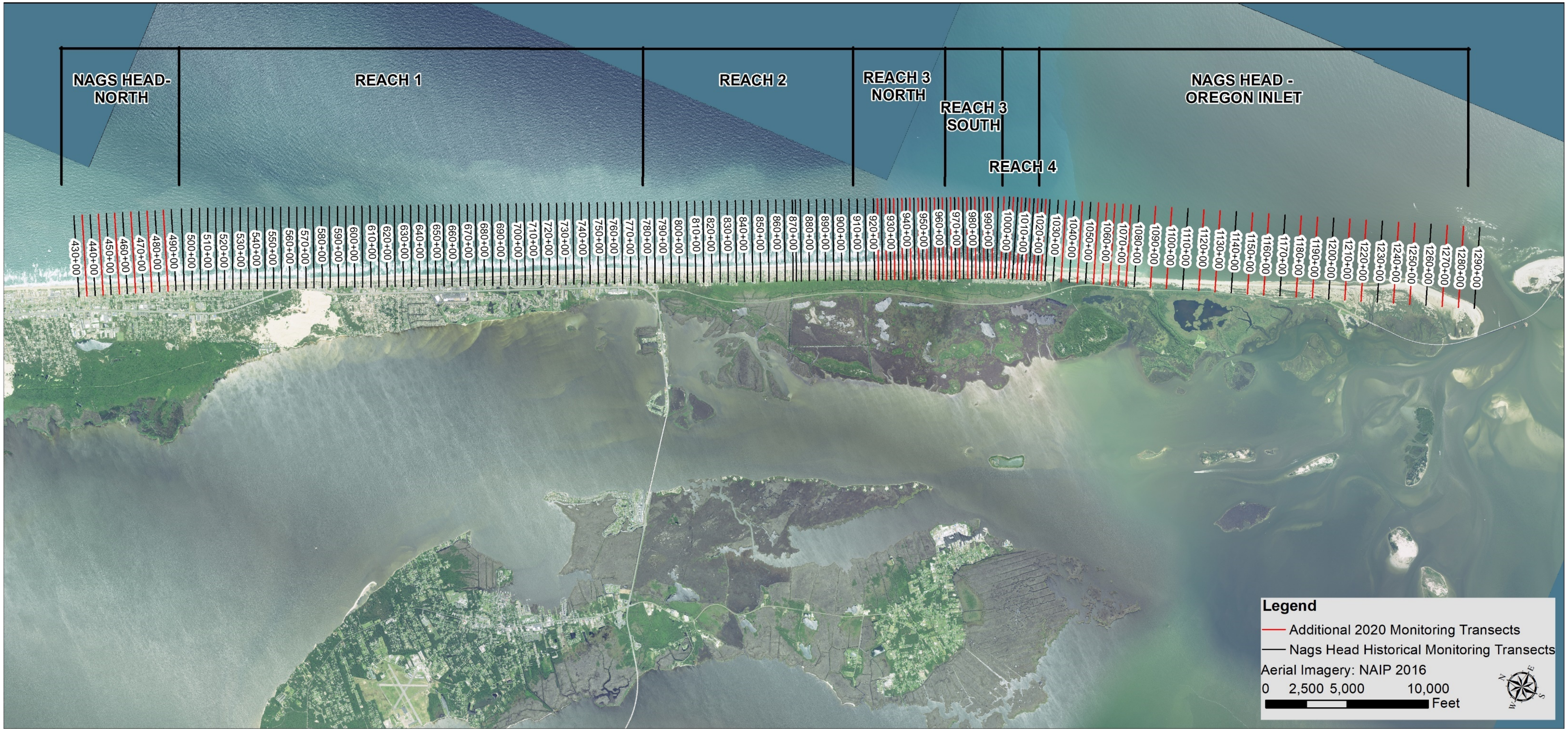


Figure 3-9: Nags Head Survey Transects

3.3.2 Bathymetric Data

NOAA Chart 12204, dated 06/2018, covers the entire project area and provides general bathymetry data based on a collection of data ranging from 1900 to the present. A majority of the data offshore of Nags Head in Chart 12204 is from 1970 - 1989**.**

In addition to NOAA Navigation Charts, NOAA's National Centers for Environmental Information (NCEI) and NC Emergency Management have developed a coarse Digital Elevation Model (DEM) which covers the Nags Head oceanfront by combining historical elevation data from a variety of sources, including (but not limited to) the NOAA Office of Coast Survey, NOAA National Geodetic Survey, NOAA Office for Coastal Management, USGS, and USACE. A continuously updated digital elevation model (CUDEM) is also available from NOAA's Digital Coast. A summary of the historical bathymetry data offshore of the Nags Head study area is presented in Table 3-3**.**

Table 3-3: Nags Head Bathymetric Data

Date	Source	Description	Resolution	Coverage
up to 1998	NOAA NCEI	Coastal Relief Model	3 Arc-Second	South East Atlantic
up to 2005	NC Emergency Management	Integrated data from various sources from various years to support inundation modeling	1 Arc-Second	North Carolina
up to 2023	NOAA NCEI	CUDEM	1/9 Arc-Second	USA

3.3.3 LiDAR Data

Light Detection and Ranging (LiDAR) is a method that uses light in the form of a pulsed laser to measure distances to the Earth. Agencies and local governments often acquire high-resolution LiDAR (Light Detection and Ranging) data for the purpose of creating elevation datasets. The data includes hydrographic and topographic data depicting the elevations above and below the immediate coastal waters. LiDAR data for Nags Head is available from various sources including USGS, USACE, NOAA and NASA. Table 3-4 shows the available LiDAR for the area.

Table 3-4: Nags Head Elevation Data

Date	Source	Resolution	Coverage	Description
Mar-2022	USGS CoNED	1 m	NC and SC Coast	Topobathy DEM
Jun-2019	USACE NCMP	1 m	NC	
Oct-2019	USACE NCMP	1 m	NC	Dunex
Oct-2018	USACE NCMP	1 ft	Southeast Coast	Post-Florence
Aug-2018	USACE NCMP	0.5 m	East Coast	
Jul-2017	USACE NCMP	1 m	East Coast	
Oct-2016	USACE NCMP	0.4 m	Southeast Coast	Post-Matthew
Mar-2014	NOAA OCM	1 ft	NC	Post-Sandy
Sep-2013	USACE NCMP	1 ft	NC	Post-Sandy
Nov-2012	USGS	1 m	Northeast Coast	Post-Sandy
Aug-2011	NOAA NGS	1 m	NC	Post-Irene
Nov-2009	USGS	2 m	NC	Post-Nor'easter Ida
Aug-2009	USACE NCMP	2 ft	NC	
Mar-2008	NOAA NGS	2 m	NC	
Oct-2005	USACE NCMP	2 m	East Coast	
Jul-2004	USACE NCMP	3 m	NC	
Feb-2001	NOAA OCM	4 m	NC	
Mar-2000	NOAA/USGS/NASA	2 m	NC	
Oct-1999	NOAA/USGS/NASA	3 m	NC	
Sep-1999	NOAA/USGS/NASA	3 m	NC	Post-Dennis
Sep-1999	NOAA/USGS/NASA	3 m	NC	Post-Floyd
Sep-1998	NOAA/USGS/NASA	3 m	NC	
Sep-1997	NOAA/USGS/NASA	3 m	NC	
Oct-1996	NOAA/USGS/NASA	3 m	NC	

3.4 Aerial Photography

Photography is available from various sources including USGS, NAIP, NOAA and NC CGIA. Starting from 1952, aerials of the Nags Head oceanfront shoreline were taken by USGS through various programs. The NAIP has obtained aerial photography for a variety of dates from 2004 to 2020. Additionally, NC CGIA also has a database of aerial imagery between 1996 -2020. In addition, Landsat Copernicus imagery exists from 1985- 2022 and has been compiled by Google Earth. Table 3-5 shows the available photography for the area.

Table 3-5: Nags Head Aerial Photography

Date	Source	Format	Color	Resolution	Coverage
NC CGIA (1996 - 2020)					
1996	NC CGIA	Tiff	B&W	0.5 ft	Nags Head
2002	NC CGIA	Tiff	Color	0.25 ft	Nags Head
2007	NC CGIA	Tiff	Color	0.25 ft	Nags Head
2012	NC CGIA	Tiff	Color	0.5 ft	Nags Head
2016	NC CGIA	Tiff	Color	0.25 ft	Nags Head
2020	NC CGIA	Tiff	4-band	0.5 ft	Nags Head
NAIP (2004 - 2020)					
2004	USDA (NAIP)	Tiff	Color	2 m	Nags Head
2005	USDA (NAIP)	Tiff	Color	2 m	Nags Head
2006	USDA (NAIP)	Tiff	Color	1 m	Nags Head
2009	USDA (NAIP)	Tiff	4-band	1 m	Nags Head
2010	USDA (NAIP)	Tiff	4-band	1 m	Nags Head
2012	USDA (NAIP)	Tiff	4-band	1 m	Nags Head
2014	USDA (NAIP)	Tiff	4-band	1 m	Nags Head
2016	USDA (NAIP)	Tiff	4-band	1 m	Nags Head
2018	USDA (NAIP)	Tiff	4-band	2 ft	Nags Head
2020	USDA (NAIP)	Tiff	4-band	2 ft	Nags Head
USGS Photography (1952 - 1999)					
1952, 1956, 1961, 1964, 1974, 1975, 1977, 1999	USGS	Photography	B&W		Nags Head
1970, 1972, 1973, 1976, 1982 (2), 1989, 1990 (2), 1992, 1993, 1999,	USGS	Photography	Color		Nags Head
1982, 1983	USGS (NHAP)	Photography	B&W		Nags Head
1993, 1998, 1999	USGS (NAPP)	Photography	Color		Nags Head
1993	USGS	DOQ	B&W		Nags Head
1998	USGS	DOQ	Color		Nags Head
USGS					
2009	USGS	Tiff	4-band	1 ft	Nags Head
NOAA (2008 - 2022)					
2008	NOAA/NCDEQ	Tiff	4-band	0.5 m	Nags Head
2014	NOAA NGS	Tiff	4-band	1 ft	Nags Head
2017	NOAA NGS	Tiff	4-band	1 ft	Nags Head
2018	NOAA NGS	Tiff	Color	1 ft	Nags Head
2019	NOAA NGS	Tiff	Color	1 ft	Nags Head
2020	NOAA NGS	Tiff	Color	1 ft	Nags Head
2022	NOAA NGS	Tiff	Color	1 ft	Nags Head
USACE (2017, 2018)					
2017	USACE	Tiff	4-band	0.04 m	Nags Head
2018	USACE	Tiff	Color	0.05 m	Nags Head
ESA (1985 - 2020)					
1985 - 2022 (Annually)	ESA(Copernicus)	Photography	Color	varied	Nags Head
Dare County					
2007	Dare County	Tiff	Color	0.25 ft	Nags Head
NCDIT					
2010	NCDIT (NC 911)	Tiff	Color	0.5 ft	Nags Head

3.5 Shoreline Positions

Shoreline data for the project study area is available through agencies such as NC DCM, USACE, USGS, USDA, and NCDOT for which in a majority of cases, the shoreline was interpreted as the wet/dry line digitized from aerial photography. The primary source of historical data is via interpretation of a multi-temporal collection of geo-referenced shoreline maps or "T-Sheets", provided by the NOAA Coastal Services Center. DCM has also collaborated with the USGS and USACE to document the shorelines based on delineation of wet-dry line as interpreted from orthophotography, as well as deriving the MHW based on LiDAR survey data. The available shoreline data and extents vary depending on the historical photographs. In addition, MHW data has been pulled from the various beach surveys that were mentioned in Section 3.3.1. Table 3-6 presents a summary of the available shoreline data and the extents covered.

Table 3-6: Nags Head Shorelines

Date	Reference	Description	Source	Location
Jan-1849, Dec-1949	Wet-Dry	NOS T-Sheets	NOAA	Outer Banks
Jan-1980	MHW	CERC Map	USGS	Outer Banks
Jan-1997	MHW	LIDAR	USGS	Outer Banks
Jul-1998	Wet-Dry	Interpreted from Imagery	Dare County	Dare County
Feb-2002	Wet-Dry	Interpreted from Imagery		Outer Banks
Aug-2004	MHW	USGS Swash	USGS	Outer Banks
Mar-2007	Wet-Dry	Interpreted from Imagery	NC CGIA	Nags Head
Jul-2009	Wet-Dry	Interpreted from Imagery	USDA NAIP	Nags Head
Apr-2010	Wet-Dry	Interpreted from Imagery	NC 911	Outer Banks
Feb-2012	Wet-Dry	Interpreted from Imagery	NC CGIA	Outer Banks
Jan-2016	Wet-Dry	Interpreted from Imagery	NC CGIA	Outer Banks
Jan-2020	Wet-Dry	Interpreted from Imagery	NC DCM	Outer Banks
Nov-2004, May-2005, Dec-2006, Mar-2009, Nov-2010, Jun-2011, Nov-2011, Jun-2012, Nov-2012, Jun-2013, Jun-2014, Jun-2015, Jun-2016, Jul-2017, May-2018, Apr-2019, Aug-2019, Nov-2019	MHW	Beach Profile Surveys	CSE	Nags Head
Jun-2020, Jul-2021, Jul-2022	MHW	Beach Profile Surveys	McKim & Creed	Nags Head

3.6 Sediment Resource Data

3.6.1 Recipient Beach Sediment Grain Size Data

Recipient beach data were initially collected by USACE as well as CSE in the early 2000s. These data indicate a recipient beach grain size ranging from 0.2 mm to 0.4 mm. Table 3-7 summarizes the available grain size data from these investigations.

Table 3-7: Historical Recipient Beach Data

Date	Source	Mean Grain Size (mm)	Median Grain Size (mm)	Coverage
2001	USACE	0.25	0.26	420+00 – 1000+00
May 2005 & November 2008	CSE	0.36	0.33	430+00 – 1050+00

The most recent comprehensive sediment data set was collected by CSE in 2016. The sediment distribution for the Town was defined based on the percent gravel, granular, sand, fine-grained, and calcium carbonate present in samples taken from 13 positions (e.g. dune toe, MHW, etc.) along transects spanning the length of the Town spaced no more than 5,000 ft apart as specified in North Carolina Administrative Code (NCAC) "Technical Standards for Beach Fill Projects" 15A NCAC 07H.0312 (1). These 13 cross-shore samples were then averaged to obtain a composite average across the profile for each transect. The composite average for each of the 14 transects (Figure 3-10) were then averaged to obtain a global (or overall project area) mean for all transects on the recipient beach.

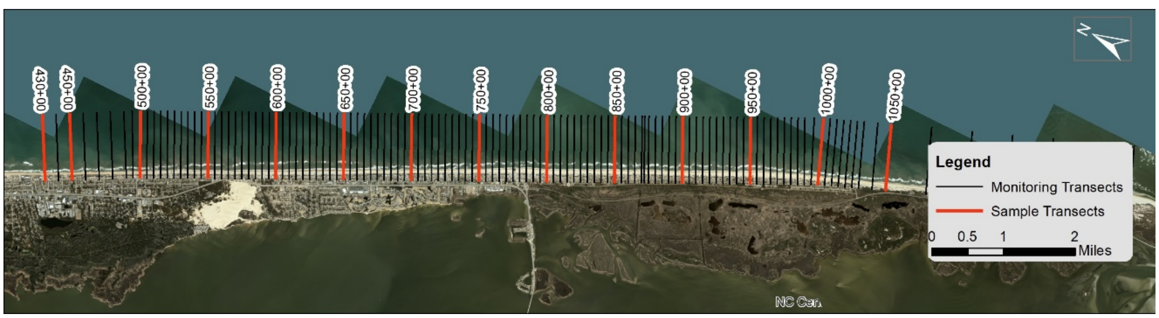


Figure 3-10: 2016 Recipient Beach Sediment Sample Transects (CSE)

The native beach characteristics and parameters identified by 15A NCAC 07H.0312 are presented in Table 3-8**.** Any borrow areas ultimately used for any beach nourishment activities must fall within these guidelines. A summary of the sediment grain size distribution and statistics is provided in Table 3-9.

Table 3-8: Recipient Beach Characteristics and NCAC Rule Parameters

Characteristic	2016 Global Mean (Overall Project Area)	NCAC Requirements	NCAC Maximum
Gravel (>#4)	Reported combined at 0.8%, Assumed 0.4% each	native + 5%	≤ 5.4%
Granular (>#10 & <#4)		native + 10%	≤ 10.4%
Sand (>#230 & <#10)	Reported: 96.96%	-	-
Fines (<#230)	Reported: 1.88%	native +5%	≤ 7%
Calcium Carbonate	Reported: 1.7%	native + 15%	≤ 17%

Table 3-9: Recipient Beach Sediment Statistics

Sediment Compatibility	2016 Global Mean (Overall Project Area)
Median (mm)	0.30
Median (φ)	1.73
Mean (mm)	0.32
Mean (φ)	1.64
Standard Deviation (σφ)	0.63

For Master Plan analysis and reporting purposes, a median grain size **of 0.3 mm** is selected as the best single-value representation of the recipient beach based updated samples analyzed by CSE in 2016.

3.6.2 Borrow Area Sediment Data

Sediment data has also been collected to locate potential suitable sand sources and identify borrow areas for previous nourishment projects. Initial data collection occurred during USACE (2000) and US Minerals Management Service (MMS) (2001) efforts to locate suitable sources of sand for Dare County beaches. Figure 3-11 presents the potential borrow area S1 identified by USACE (2000). Additional sediment cores were obtained by CSE to identify the offshore borrow areas (BA2, BA3, BA3A & BA4), shown in Figure 3-11, that were used for the 2011 and 2019 beach nourishment projects. Table 3-10 gives a summary of these investigations. Figure 3-12 shows the location of the vibracores.

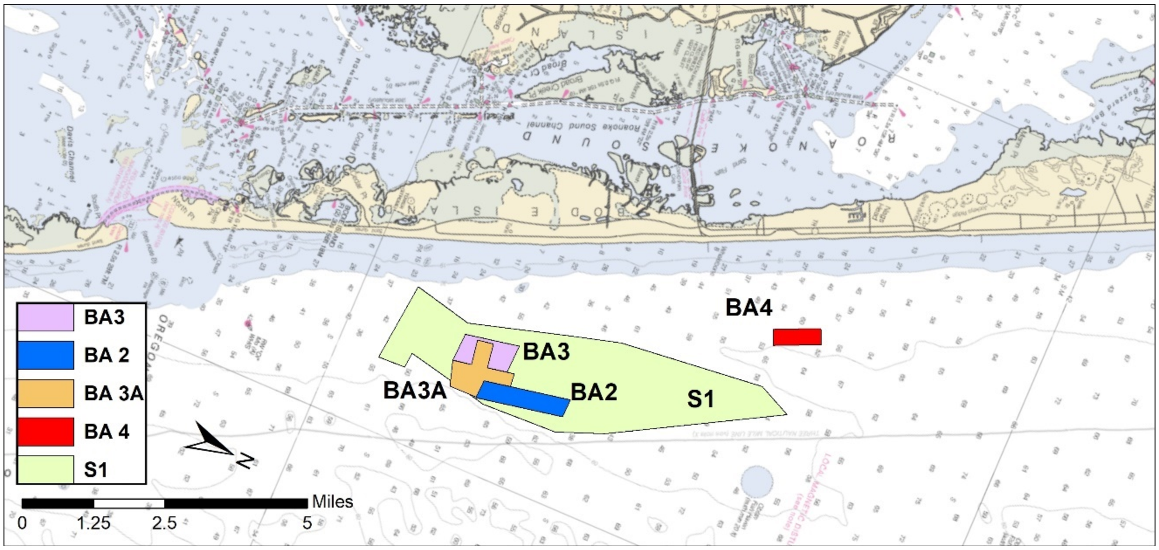


Figure 3-11: Borrow Area Locations

Table 3-10: Available Borrow Area Sediment Data from Previous Studies

Borrow Area	Year	# Cores	Source
Dare County Beaches	1996	30	USACE
	1996	56	US MMS
	1998	42	USACE
S1	2005	61	CSE
	2006	41	CSE
Borrow Area 3A	2017	23	CSE
Borrow Area 4	2017	15	CSE

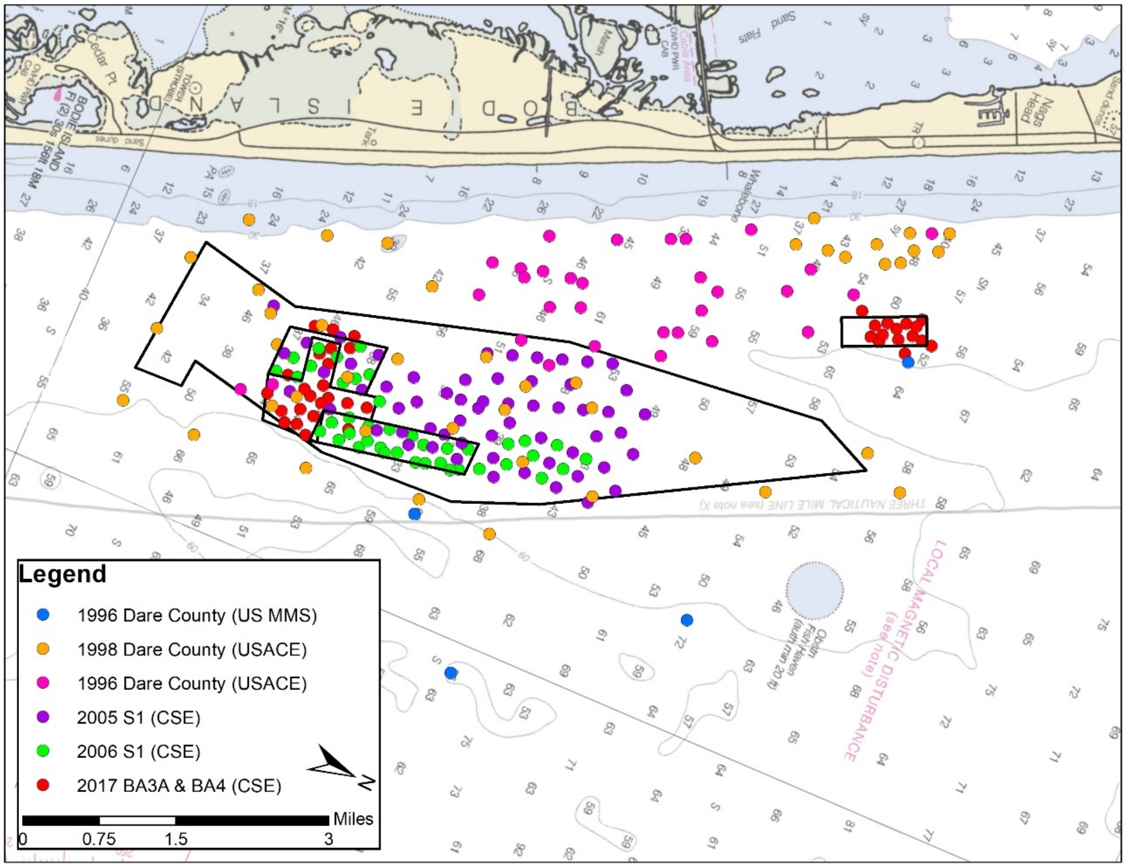


Figure 3-12: Borrow Area Vibracore Data Locations

3.7 Summary of Previous Beach and Dune Nourishments

The Town has conducted four beach and dune nourishment projects along the Nags Head oceanfront since 2004, including:

- 2004-2005 Post Hurricane Isabel Emergency Dune Restoration Project
- 2011 Town of Nags Head Beach Nourishment Project
- 2019 Town of Nags Head Beach Nourishment Project
- 2022 Post Hurricane Dorian Beach Restoration Project

Since 2004 approximately 9.5 Mcy of sand have been placed on Nags Head.

2004-2005 Post Isabel Emergency Dune Restoration Project

In 2003, Hurricane Isabel impacted Nags Head causing significant dune loss across the oceanfront. Through the Robert T. Stafford Relief and Emergency Assistance Act, the Federal Emergency Management Agency (FEMA) authorized funds for a dune restoration project. The dune restoration project consisted of hauling and placement of approximately 320,066 cy along 8 miles of shoreline from an upland borrow source at the Robbie Parker Construction Co. mines in Currituck County. On average, the dune template consisted of a

10-ft wide dune crest with 5H:1V slopes. The dune crest elevation varied between +16 and +17 ft NAVD88. Construction for the dune restoration initiated in spring 2004 with the placement of approximately 56,666 cy along 1.4 miles of the beach. At the end of April construction was stopped due to the environmental moratorium window. The construction reconvened in December 2004 and 210,300 cy of material was placed along various shoreline reaches. The project was completed on April 30, 2005.

2011 Beach Nourishment Project

The Town of Nags Head carried out a publicly funded beach nourishment project in 2011 along the Town's shoreline. The 2011 project encompassed approximately 10 miles of shoreline. Four reaches were delineated based on historical erosion rates. Two borrow areas 2 and 3 located in the USACE designated borrow area S1 were used in this project.

The purpose of the 2011 beach nourishment project was to restore a protective beach for a minimum of 10 years and expand the recreational beach for the community. The design template for the beach nourishment extended the berm 50-125 ft at elevation +6 ft NAVD88 and placed approximately 50-140 cy/ft of material.

The project placed approximately 4.6 Mcy of beach compatible material along the five reaches of Nags Head (Reaches 1, 2, 3N, 3S, and 4) between May 24 and October 27, 2011.

2019 Beach Nourishment Project

Construction of the 2019 Nags Head Beach Nourishment Project began on May 1, 2019, and was completed on August 18, 2019. The project was funded by Town of Nags Head. During the project, a total of 4 million cy of material was placed along approximately 10 miles of shoreline.

Two borrow sources were used for the project: borrow area 3A located in the USACE designated borrow area S1 and borrow area 4 located approximately 1.5 miles offshore from the north central portion of Nags Head beach (Figure 3-11). The entire project took just under 16 weeks, and 4,004,634 cy of material was placed along the five reaches of Nags Head.

2022 Post Hurricane Dorian Beach Restoration Project

In response to Hurricane Dorian in September 2019, Town of Nags Head applied for and received both federal and state funding through the FEMA Public Assistance Program and the N.C. Division of Emergency Management CSDM grants. This funding, which required some local matches, was the basis for the size of the targeted project.

Borrow areas 2 and 3 (Figure 3-11) within USACE designated borrow area S1 were used to complete the project. The project template consisted of a berm of variable width at +6 ft NAVD88 and a foreshore slope of 1:15 out to the existing ground, landward of the prominent offshore bar. The entire project took approximately 6 weeks to complete, and

614,106 cy of material was placed along four reaches of Nags Head (Reaches 2, 3N, 3S, and 4).

3.8 Previous Dune Stabilization and Preservation Efforts

The Town has historically supported both dune fencing and planting of vegetation to stabilize protective dunes. The Town currently supports annual winter American Beachgrass planting through a partnership with a local non-profit. Additionally, the Town uses approximately $25,000 from the beach nourishment fund each year to conduct dune preservation activities. The activities alternate every other year between planting and replacement or supplementation of sand fencing. Furthermore, approximately every two years, the Town initiates a large scale planting and/or sand fencing effort, depending on what is determined to be needed based on visual inspections by Town staff. Typically this is funded through a grant such as the CSDM grant administered by the NC DEQ. The most recent large-scale planting effort composed of 1.3 million sprigs of American beachgrass at various locations along the Town's shoreline was completed in early 2024.

In addition to these efforts, the Town operates a dune management cost share grant program to assist oceanfront property owners in maintaining their protective dunes. Eligible applicants include oceanfront single family homeowners, oceanfront residential condominiums, oceanfront cottage courts, and oceanfront motels and hotels. Up to $1,000 per lot is available to assist owners who would like to plant approved native vegetation on their properties. Applicants may apply for the cost share grants on a rolling basis annually. All plants must be planted according to the specifications detailed in the Town of Nags Head Dune Vegetation Recommended Planting Guidelines. These Guidelines detail recommendations for planting American beachgrass (cultivars Hatteras and Bogue), sea oats, and bitter panicum. Guidelines from NC Division of Coastal Management (DCM) and US Fish and Wildlife Service must also be followed during any planting or sand fencing operations.

The Town has also historically promoted dune stabilization and preservation efforts in conjunction with beach nourishment efforts. As part of the 2019 and 2022 beach nourishment projects, the Town contracted placement of sand fencing and planting of dune grasses. In 2019, sea oats and bitter panicum were planted across the entire 10-mile project area. In 2022, American beachgrass was planted after the beach nourishment was placed.

4.0 EVALUATION OF HISTORICAL BEACH PROFILE CHANGES

4.1 Purpose and Definitions

One of the most reliable ways to analyze beach behavior and develop estimates for potential future beach nourishment needs is to examine past beach evolution with recognition of prior nourishment projects. Historical shoreline positions and beach profile morphology (including the associated volume changes) provide a basis for understanding the physics and sediment processes that caused the beach evolution. This assessment is also necessary to calibrate and validate shoreline and profile change models of the region that are used to assess alternatives.

Historical surveyed beach profiles and volume changes have been documented consistently in Nags Head beach profile monitoring reports annually since 2011. In addition to these dates, additional complete surveys along Nags Head were completed in 2004, 2005, 2006, 2009 and 2010, as summarized in Table 3-2. These annual surveys (since 2011), including 114 profiles along the Nags Head shoreline, have been performed as part of the Town's Beach Monitoring Program. All the profiles cover both onshore (dune to wading depth) and offshore (wading depth to -30 feet NAVD) at the profiles shown in Figure 3-9. Each of the annual surveys since 2011 were evaluated and findings documented in annual monitoring reports. Those findings have been utilized to inform the beach nourishment master planning process.

The analytical/empirical and numerical modeling portions of the present study considered historical and present shoreline/volumetric change rates, pre-nourishment and post nourishment sand volumes, and forward-looking sand volumes required to achieve an equivalent level of protection (LoP) for property and infrastructure along developed reaches of the Town's shoreline.

4.2 Analytical/Empirical Assessments

4.2.1 Raw Historical Analysis

The first stage of the analytical/empirical analysis of historical data was to assess volumetric change over the 10 year period of 2012 to 2022. Beach profile volumes and changes were calculated based on the survey time periods and then annualized. The measured rates of change were then used along with a statistical model to estimate both anticipated background erosion and storm-induced erosion in the study area as described in Section 4.2.2.

A key aspect of the historical profile evolution assessment is to determine volumetric changes in the beach profile. Volumetric changes were assessed above the following elevations (NAVD88) (see Figure 4-1):

- +6 ft contour (represents the dune)
- +1.18 ft contour equivalent to MHW (dune and subaerial beach)

- -6 ft contour (dune, subaerial beach, and recreational beach)
- -14 ft contour (includes the offshore bar)
- -19 ft contour (apparent depth of closure)
- -30 ft contour (full extents of the possible active beach profile)

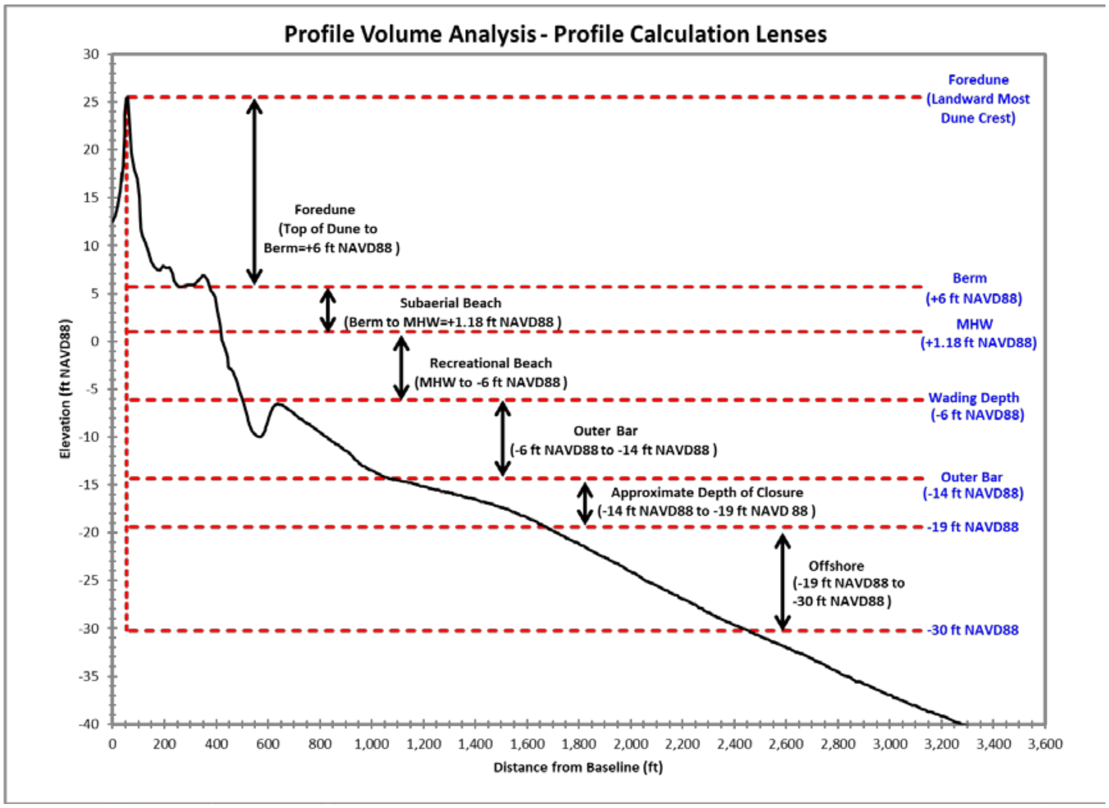


Figure 4-1: Volumetric Calculation Lenses for Historical Analysis

Past nourishment activities between surveys are also considered. The amounts of this nourishment were "netted out" by subtracting its volume, as determined by the historical profiles, to obtain estimates of historical background volume change rates.

Once the background erosion rates were determined per profile and annualized per year, the unit and cumulative volume change above each elevation could be plotted for comparisons of variability of change across the town oceanfront as well as to determine a preliminary estimate of annual need just to keep up with current conditions. Figure 4-2 presents the annualized unit volume change above -19 ft NAVD88 elevation from 2012-2022. As can be seen from Figure 4-2, the annualized volume changes can vary substantially between loss and accumulation both spatially and temporally, depending on longshore and cross-shore sediment transport within the study area and performance of previous projects.

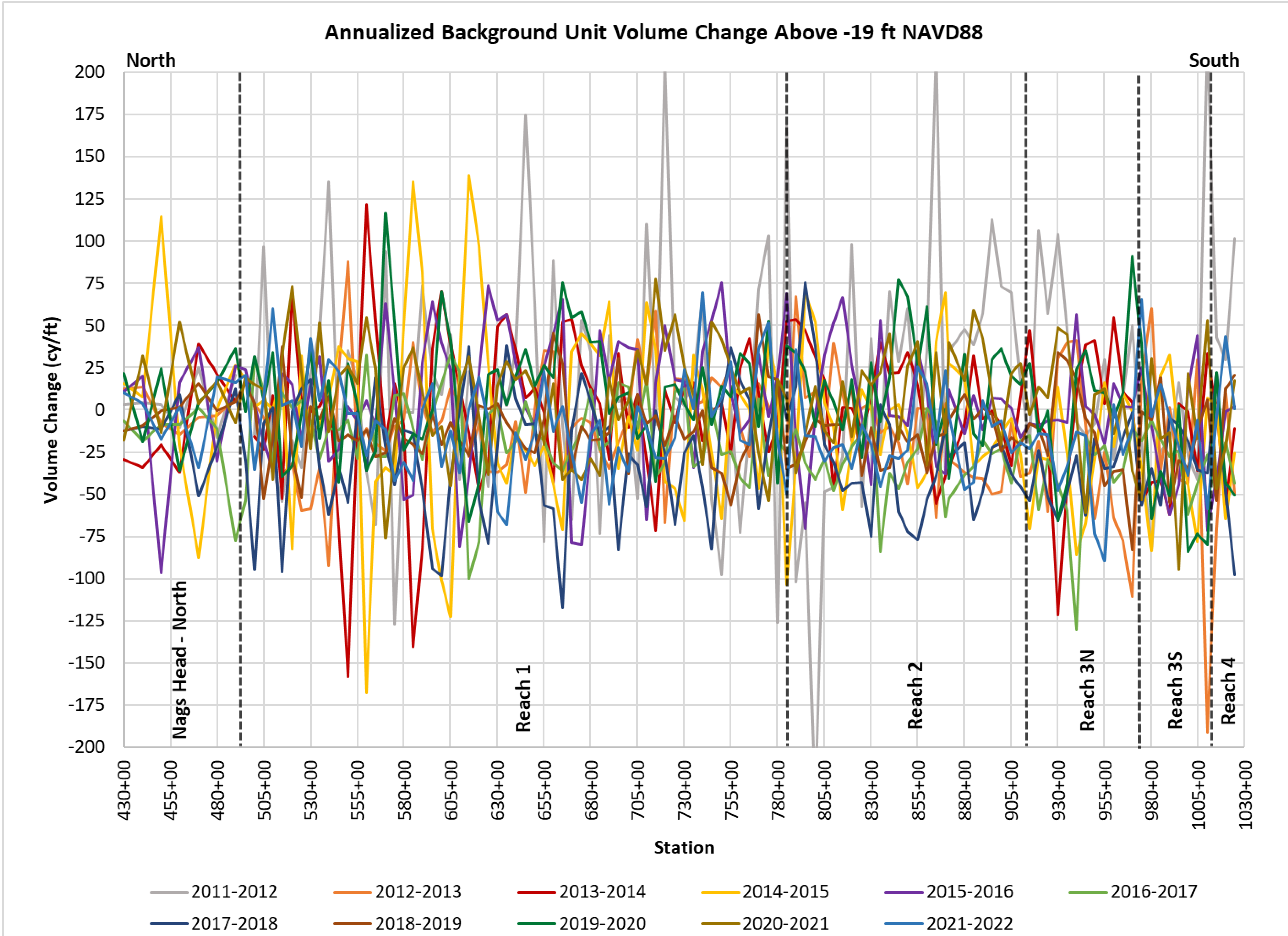


Figure 4-2: Annualized Background Unit Volume Change Above -19 ft NAVD88

Table 4-1 shows the average annualized volume change per reach calculated from 2012-2022 historical surveys. **Based on the results shown in this table, the peak volume losses occur above -19 ft NAVD88 and the overall average loss per year is approximately -450,469 cy/yr over all reaches.**

Table 4-1: Average Annual Volume Change by Reach, 2012-2022 (cy/year)

Reach	Above +6ft NAVD88	Above +1.2ft NAVD88	Above -6ft NAVD88	Above -14ft NAVD88	Above -19ft NAVD88
NH North	5,604	5,535	4,748	4,188	-4,928
Reach 1	33,608	-42,768	-127,682	-108,886	-124,566
Reach 2	13,851	-37,995	-99,523	-100,275	-106,537
Reach 3N	8,766	-23,331	-69,267	-88,176	-94,067
Reach 3S	-1,700	-24,626	-59,449	-70,847	-71,673
Reach 4	-2,597	-12,867	-30,782	-32,558	-48,699
Total	57,532	-136,052	-381,954	-396,554	-450,469

4.2.2 Statistical Analysis of Sediment Volume Needs

To enhance the accuracy of estimating future volume loss and determining the required sediment for beach nourishment over the next 50 years, a comprehensive analysis of historical volume losses was conducted. This analysis aimed to capture and statistically quantify the inherent variability present in the available data. By doing so, a more reliable basis for predicting and maintaining the desired level of protection can be established.

In order to understand the uncertainty and variability observed in the volume change data, Monte Carlo analysis was employed. Monte Carlo analysis is a powerful statistical modeling technique that utilizes random sampling to simulate a wide range of possible outcomes. By performing a Monte Carlo Simulation, we were able to generate a range of potential outcomes with associated probabilities for each result.

To facilitate the Monte Carlo Simulation analysis, the Crystal Ball software, developed by Oracle®, was utilized. This Microsoft Excel Add-in program provided the necessary tools and capabilities to perform the simulation effectively.

The analysis commenced by generating a model of possible outcomes. This involved substituting the historical annualized volume change observed at each transect with a normal distribution, characterized by its mean and standard deviation. Subsequently, the annual volume change was calculated repeatedly, with each calculation using a distinct set of random numbers within the range defined by the distribution curve. The simulation involved conducting 300,000 trials, with each iteration producing a new volume change estimate based on different random inputs. As the number of inputs increased, the accuracy of the outcomes improved, leading to a more refined analysis. The various outcomes generated by the simulation formed a distribution curve, with the most frequently occurring result positioned at the center.

These distribution curves can be utilized to derive non-exceedance probabilities, which describe the likelihood of volume change not surpassing a particular estimated value in any given year. For example, a 100% non-exceedance value indicates that, based on the available data, there is a 0% probability of erosion exceeding this threshold. Similarly, a 50% exceedance value implies that, in any given year, there is an equal chance of the annual erosion being greater or lesser than the indicated value. A 75% non-exceedance value signifies a 25% probability that a volume change will exceed the estimated value.

The individual results obtained for each profile were then aggregated across various sections of the beach to examine localized erosion/deposition patterns, as well as to determine overall volume needs on both an annual and long-term basis. The summary of the simulation outcomes for volume change over the designated beach management reaches, specifically established for the purposes of the master plan study, can be found in Table 4-2. Within the analyses, all reaches were erosional at the 50% probability level of non-exceedance. Results show an overall annual loss of approximately 451,218 cy (50%) and 771,341 cy (75%). Furthermore, Appendix B provides detailed results from the Monte Carlo simulation analysis for each study reach and analyzed elevation.

Table 4-2: Crystal Ball Analysis Results for Annual Background Volume Change

		Volume Change Above -19 ft, NAVD88 (cy/year)						
		North Reach	**Reach 1**	**Reach 2**	**Reach 3N**	**Reach 3S**	**Reach 4**	**Total**
Probability of Non-Exceedance	**5%**	+122,166	+129,596	+30,196	+15,350	+4,492	+26,583	+328,383
	10%	+92,382	+72,918	+975	-8,633	-12,635	+10,948	+155,955
	25%	+43,121	-21,294	-48,517	-48,633	-41,049	-15,302	-131,674
	50%	-11,834	-126,238	-103,228	-92,772	-72,653	-44,493	-451,218
	75%	-67,102	-231,117	-158,037	-137,131	-104,202	-73,752	-771,341
	90%	-145,722	-381,721	-236,973	-200,894	-149,497	-116,022	-1,230,829
	95%	-399,611	-815,692	-480,325	-388,371	-288,219	-252,286	-2,624,504

Since 2012, the Nags Head shoreline has experienced significant impacts from three major hurricanes: Hurricane Sandy (2012), Hurricane Matthew (2016), and Hurricane Dorian (2019). While the historical volume change data analyzed includes the effects of these past storms, it is essential to recognize the natural variability linked to the frequency and intensity of storm events. Furthermore, considering the potential intensification of storms due to climate change, it becomes even more critical to incorporate additional storm-induced volume losses in long-term planning.

To address this, a Monte Carlo Simulation was constructed using the Crystal Ball software, incorporating data on volumetric changes observed during Hurricanes Sandy, Matthew, and Dorian. Similar to the historical erosion analysis, this simulation involved generating a model of potential outcomes using the mean and standard deviation of volumetric losses recorded for each storm event. By conducting 250,000 trials, a distribution curve representing the range of possible outcomes per profile was developed. To assess the overall impact on the beach management reaches, the volumetric changes determined for each profile were aggregated across the designated reaches. A summary of these simulation results can be found in Table 4-3.

The results of this analysis indicate the expected volume change for 50% non-exceedance is -1,128,394 cy and 75% non-exceedance is -1,349,667 cy per storm event. Based on the recent history of storm impacts to Nags Head, it is anticipated that one storm event could potentially impact the oceanfront every 3 years, which corresponds to 16 storms over the planning period of 50 years. Therefore, annualized volume change is -361,086 cy and -431,893 cy for 50% and 75% non-exceedance probabilities.

Table 4-3: Crystal Ball Results for Storm Induced Volumetric Change

		Volume Change Above -19 ft, NAVD88							
		North Reach	Reach 1	Reach 2	Reach 3N	Reach 3S	Reach 4	Total	Annualized Total*
		cy/storm							cy/year
Non-Exceedance	5%	-8,196	-241,750	-154,342	-87,881	-82,708	-11,986	-586,862	-187,796
	10%	-37,730	-277,882	-175,778	-104,486	-91,025	-19,822	-706,722	-226,151
	25%	-86,892	-337,751	-211,851	-132,148	-105,057	-32,842	-906,542	-290,093
	50%	-141,710	-404,342	-251,576	-162,870	-120,477	-47,419	-1,128,394	-361,086
	75%	-196,271	-470,706	-291,408	-193,382	-136,026	-61,874	-1,349,667	-431,893
	90%	-246,081	-530,811	-327,093	-221,070	-149,833	-75,036	-1,549,924	-495,976
	95%	-275,942	-566,003	-348,650	-237,488	-158,160	-82,900	-1,669,143	-534,126

* *16 storms in 50 years*

In determining the long-term sand requirements, both the estimations for annual background volume change and additional storm-induced volume losses were taken into account. The approach involved combining the 50% non-exceedance probability results for annual background erosion, which represent the historical trends without variability, with the variability introduced by additional storms. To maintain a conservative approach, the 75% non-exceedance probability was selected to represent the potential range of variability.

By combining the annual background erosion and the additional storm-induced volume losses, the annual material need is estimated as 883,111 cy. This estimation approximately corresponds to an 80% non-exceedance probability when considering only the annual background analysis (as indicated in Table 4-2). This probability suggests that, based on the historical volume change data collected between 2012 and 2022, there is a 20% possibility of exceeding the estimated material volume.

Over the 50-year planning period, the cumulative long-term sand requirement resulting from both background erosion and additional storms is determined to be 44,155,550 cy, as presented in Table 4-4. It is important to emphasize that this estimation intentionally adopts a conservative approach to sand need determination, ensuring a cautious assessment of the overall sand requirements.

Table 4-4: Nags Head Long-Term Nourishment Need from Background Erosion and Additional Storms

Category	Volume Above -19 ft, NAVD88 (cy)
Annual Background Volume Change (50% non-exceedance probability)	-451,218
Annualized* Storm Volume Change (75% non-exceedance probability)	-431,893
Annual Total Volume Change	-883,111
50-yr Material Need	44,155,550

**16 storms in 50-years*

5.0 BEACH NOURISHMENT LEVEL OF PROTECTION ANALYSIS AND NOURISHMENT TRIGGER ASSESSMENT

5.1 Introduction

The Crystal Ball analysis outlined in Section 4.2.2 provides an estimate of the long-term sand volume needs to maintain the beaches based on historical background and storm erosion rates (approximately 1 Mcy/yr and 48.5 Mcy over a 50-year planning timeframe). The establishment of a long-term beach nourishment master plan also requires establishment of a preferred beach and dune profile design to achieve adequate protection for habitable structures and infrastructure, along with appropriate trigger conditions for renourishment actions. The preferred profile design, nourishment templates and renourishment triggers are generally based on establishing and maintaining a certain LoP from storm surge and waves along the Town's oceanfront.

A key element of the project purpose is to provide an equivalent LoP to upland structures across the Nags Head oceanfront **– not equal sand, but equal protection**. This LoP determination is also critical in confirming and adjusting the Town's nourishment triggers which are used both for Town nourishment project planning and for coordination with agencies such as FEMA. The current nourishment trigger is currently set at the condition where 50 percent of the material placed during the previous beach nourishment project has been lost across the whole island from the landward top of dune out to -19 ft NAVD88 (CSE, 2011). During the present master planning process, it is proposed to refine that condition to establish specific triggers for specific reaches and sub-reaches of the Town's shoreline, realizing that each reach and sub-reach has different erosion rates and different responses to storm conditions.

5.1.1 Representative Profiles and Reaches

The Nags Head beach profile monitoring program consists of 114 beach profiles along 59,500 ft of shoreline. The project and study area are divided into six reaches based on the shorefront characteristics. To evaluate the LoP for each of the shoreline reaches, 14 representative of existing conditions beach profile morphology in each reach and sub-reach were selected.

Table 5-1 presents the representative profiles that were chosen based on the May 2018 profile survey data. Since Nags Head received nourishment in May of 2019, the May 2018 data, considered to demonstrate a more natural state of the beach, was used to classify representative profiles. Representative profiles were selected based on physical beach characteristics such as berm elevation, dune height, volume of material above dune toe and historical erosion rates. and consideration of providing equivalent representation to all segments of the Town's shoreline. Detailed descriptions for each sub-reach, as well as the associated plots of the May 2018 profile surveys are contained in Appendix C. Figure 5-1 shows the profile locations within each reach.

Table 5-1: Reach Description and Representative Profiles

<table>
<tr><th>Reach</th><th>Nags Head Stations</th><th>Length (feet)</th><th>Representative Profile</th></tr>
<tr><td>Nags Head – North</td><td>430+00 – 490+00</td><td>6,250</td><td>460+00</td></tr>
<tr><td rowspan="6">Reach 1</td><td>495+00 – 520+00 & 540+00 - 550+00</td><td>4,500</td><td>520+00</td></tr>
<tr><td>525+00 – 535+00 & 555+00 – 590+00</td><td>5,500</td><td>535+00</td></tr>
<tr><td>595+00 – 660+00</td><td>7,000</td><td>625+00</td></tr>
<tr><td>665+00 – 715+00</td><td>5,500</td><td>715+00</td></tr>
<tr><td>720+00 – 775+00</td><td>6,000</td><td>735+00</td></tr>
<tr><td rowspan="2">780+00 – 800+00</td><td rowspan="2">2,500</td><td rowspan="2">785+00</td></tr>
<tr><td rowspan="5">Reach 2</td></tr>
<tr><td>805+00 – 855+00</td><td>5,500</td><td>855+00</td></tr>
<tr><td>860+00 – 880+00</td><td>2,500</td><td>865+00</td></tr>
<tr><td>885+00 – 905+00</td><td>2,500</td><td>895+00</td></tr>
<tr><td rowspan="2">910+00 – 930+00</td><td rowspan="2">2,500</td><td rowspan="2">920+00</td></tr>
<tr><td rowspan="2">Reach 3 - North</td></tr>
<tr><td>935+00 – 975+00</td><td>4,500</td><td>935+00</td></tr>
<tr><td rowspan="2">Reach 3 - South</td><td>980+00 – 995+00</td><td>2,000</td><td>980+00</td></tr>
<tr><td rowspan="2">1000+00 – 1025+00</td><td rowspan="2">2,750</td><td rowspan="2">1020+00</td></tr>
<tr><td>Reach 4</td></tr>
</table>

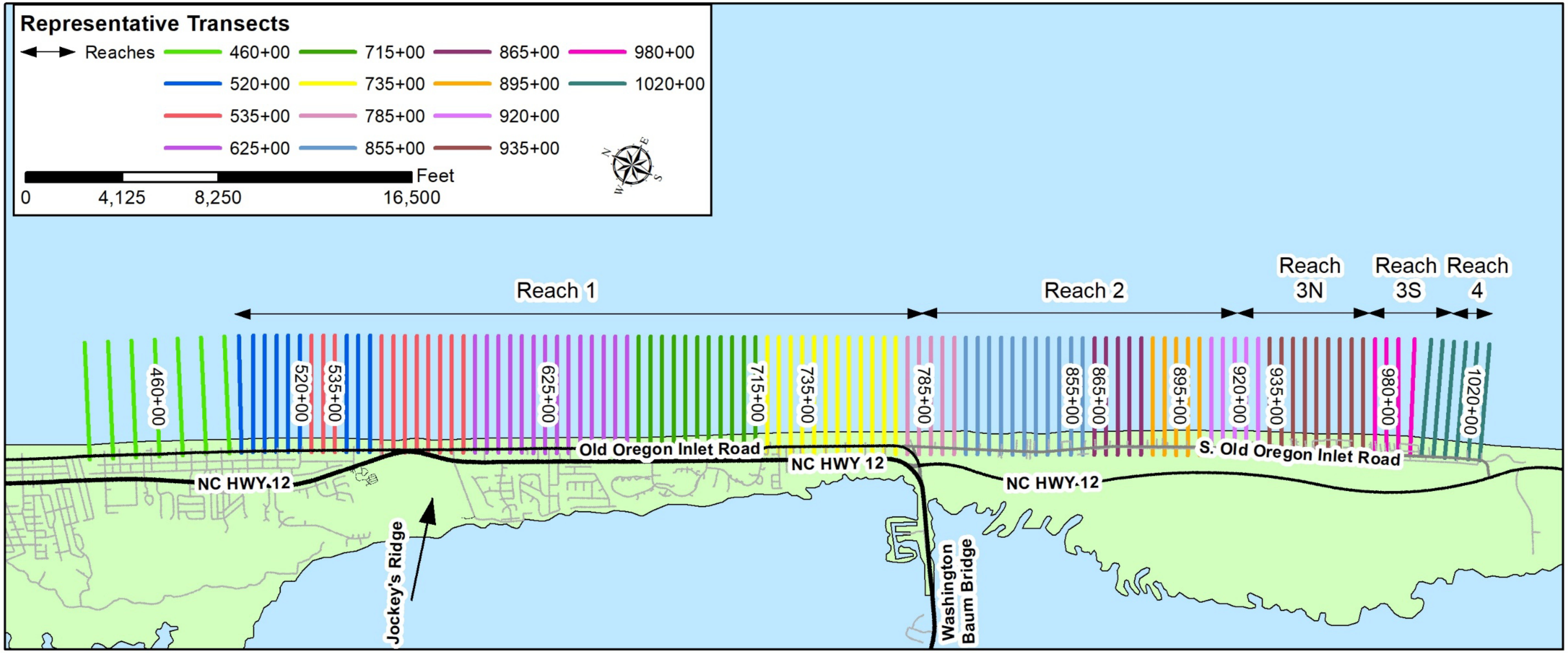


Figure 5-1: Location of Representative Transects

5.2 LoP Definitions

The LoP afforded is determined as the profile's ability to resist breaching and severe overtopping during extreme storm events of a certain annual probability of exceedance (stated as return period, the inverse of this probability) to avoid damage to upland structures and infrastructure.

The LoP is indicated as a set of qualitative categories indicating the degree to which the first row of structures would be impacted by a specific design storm. The LoP categories used in this study are illustrated in **Figure 5-2** and their definitions are given below.

- No Impact – Neither the eroded profile, water level, nor the maximum wave crest elevation indicate that sediment movement or moving water will occur at the first row of structures.

- Minor Overtopping – Eroded profile, water level, and maximum wave crest elevation indicate that the dune would be overtopped, but overtopping at first row of structures appears to be minimal. This category of impact is not considered, in the present study, as a severe impact for the LoP analysis.

- Major Overtopping – Eroded profile, water level, and maximum wave crest elevation, combined with position and elevation of first row of structures, indicate that the lower levels of structures are likely to be flooded or impacted by moving water. The threshold for this condition was defined as equal to or more than 0.65 ft^3/hr based on the values from EurOtop manual (EurOtop, 2018). This condition is considered as a severe impact for the present LoP analysis.

- Threatened – Profile eroded to very near the seaward limits of the first row of structures, such that the stability of the foundations may be threatened. This is considered a severe impact for the present LoP analysis.

- Undermined – Profile eroded to the position of (or landward of) the first row of structures, thus undermining their foundations. This is considered a severe impact for the present LoP analysis.

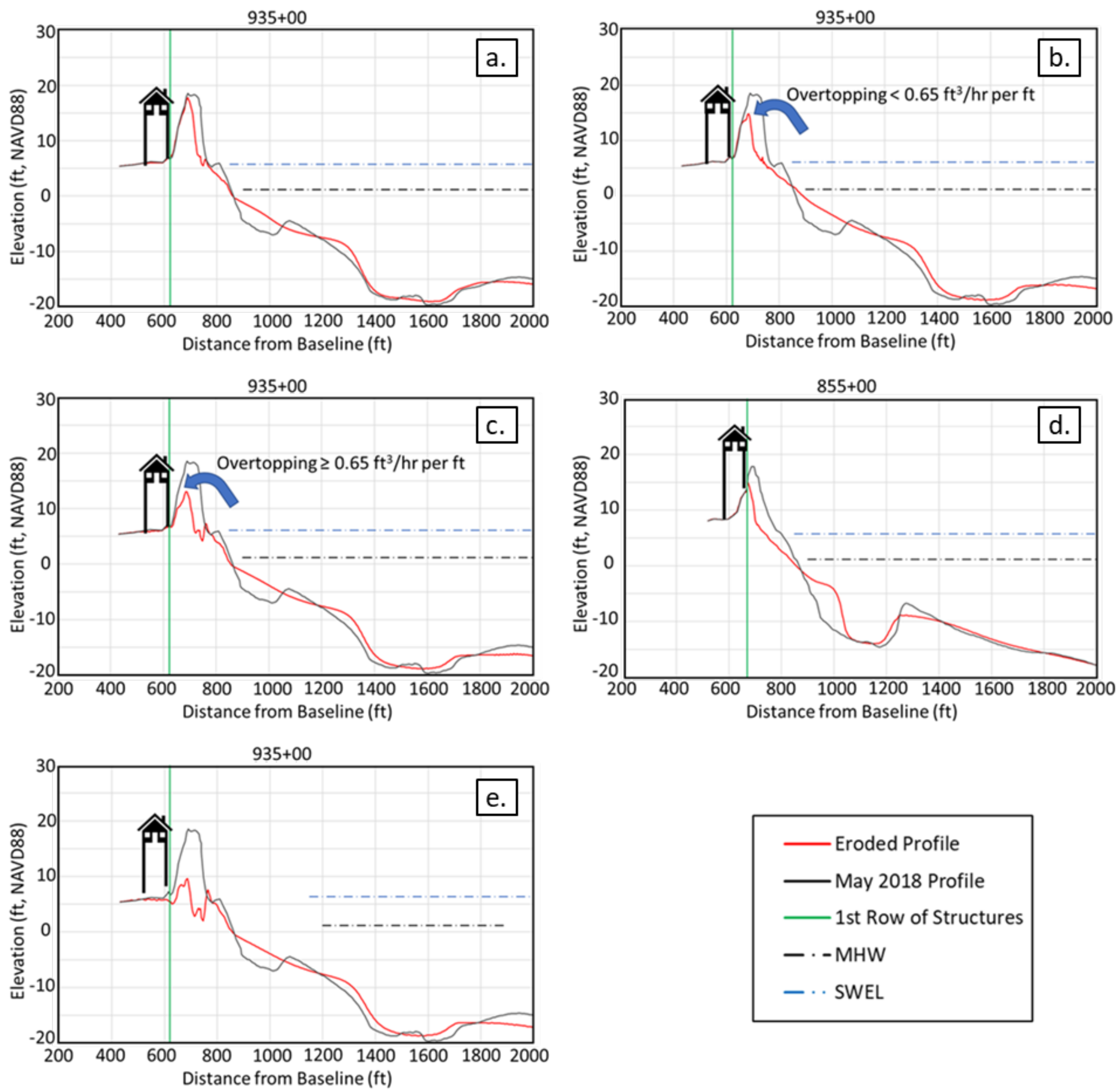


Figure 5-2: LoP Categories: (a) No Impact, (b) Minor Overtopping, (c) Major Overtopping, (d) Threatened, (e) Undermined

As described in Appendix C, the CSHORE design storm surge and wave conditions were developed synthetically based on analysis of historical hurricanes and tropical storms, combined with statistical estimates of extreme water levels (based on NOAA Duck tide gauge data) and offshore extreme wave conditions (based on FRF wave buoy data) at various return periods. A typical pattern or "shape" of storm surge and waves was created based on Hurricane Isabel's and Hurricane Dorian's patterns and an empirical relationship between peak storm wave intensity and duration of the rising and falling legs. **Hurricane Dorian and Hurricane Isabel were estimated to have been approximately 5-year and 50-year return period wave events at this location, respectively.**

Peak wave periods occurring during storms were found to be loosely correlated with storm peak significant wave height. A relationship between peak wave period (T_P) and significant wave height (H_s) was determined and applied to generate wave periods for each design storm during storms. Peak values of waves and water levels input to CSHORE are given in Table 5-2.

Table 5-2: Boundary Wave Height, Wave Period, and Total Water Level Conditions for CSHORE at Peak of Design Storm Simulations

Return Period	H_S (ft)	T_P (sec)	Water Level ft, NAVD88
2-year	14.7	10.1	4.88
5-year	16.1	10.4	5.18
10-year	20.1	11.8	5.41
25-year	23.2	12.4	5.73
50-year	26.2	13.8	6.06
100-year	29.9	14.1	6.39

5.3 Numerical Modeling: CSHORE Storm Profile Response

In addition to historical volume change, determination of how the beach would respond to various magnitude storm events is a significant factor in design. This response is evaluated through numerical modeling. Beach profiles respond most significantly to elevated water levels and waves associated with storms. Storm-induced beach profile evolution simulations were conducted for representative survey profiles in each reach / sub-reach using the CSHORE numerical model. The model was calibrated to observed beach profile morphology from the 2012 pre- and post-Hurricane Sandy survey data and verified using the 2016 pre- and post-Hurricane Matthew survey data.

The primary purpose of the beach profile evolution numerical modeling is to assess the LoP from storm surge and waves afforded by the beach and dune system – under existing conditions and with different project alternatives which are covered in later sections of this report.

5.3.1 CSHORE Model Description

CSHORE is a one-dimensional (1D) profile evolution model developed by University of Delaware, Center for Applied Coastal Research and USACE to predict waves, currents, and bed-evolution in the nearshore. The CSHORE domain assumes a shore-perpendicular (cross-shore) profile with uniform grid spacing, with the origin offshore (x = 0) and positively increasing with distance onshore. A foundational assumption of CSHORE is alongshore uniformity, although obliquely incident waves and longshore currents are included. The governing equations are a combination of the time-averaged, depth-integrated continuity, cross-shore and alongshore momentum, wave action, and roller energy equations. CSHORE also incorporates empirical formulas to account for irregular wave runup, overtopping, and seepage, as well as a probabilistic model of the intermittently wet/dry zone to predict wave runup and overwash. The model is described in detail in Johnson et al. (2012) and Kobayashi (2016).

The CSHORE model is based on cross-shore sediment transport and morphology processes, and it does not include the effects of longshore transport gradients. While it is recommended for FEMA assessments of foreshore and dune profile evolution (FEMA, 2018), CSHORE is not intended for simulating post-storm recovery of the beach profile, as would naturally occur in many coastal systems including Nags Head, or for long-term beach profile evolution. It is also not intended for direct support of long-term shoreline change studies, because long-term shoreline change is driven in part by longshore transport gradients and post-storm profile recovery. However, the use of CSHORE is appropriate to assess the ability of the beach and dune along Nags Head to protect landward properties and infrastructure from direct wave impact and erosion during storm waves and surges.

5.3.2 CSHORE calibration

CSHORE simulations are driven by the combined effects of storm waves acting on elevated storm water levels. At each calculation point along the profile, the model transforms the wave heights, periods and angles given as input using the linear wave and current theory. Wave runup is also computed. The model computes additional elevation of input water levels due to wave action (wave setup), and these adjusted wave and water level values are used in the profile change calculations.

Model calibration and validation allows for greater confidence in the model-predicted erosion results and engineering conclusions based on those results. Calibration was accomplished by iteratively adjusting several CSHORE parameters describing sediment transport processes. Modeled profile response was compared to the observed post-storm profiles at each representative profile, and CSHORE model parameters were adjusted to produce more accurate profile responses.

Initializing and running a CSHORE model simulation requires an initial bathymetry in the computational domain, as well as wave and water level boundary condition data to force the model. The main inputs to the CSHORE model include:

- Profile data – initial bed elevation at each node in the model domain;
- Wave and water level conditions – Wave height, wave period, wave direction and mean water level at the model boundary for each time step; and
- Sediment transport parameters – physical characteristics of the sediment comprising the beach and the empirical sediment transport parameters that are used to characterize cross-shore sediment transport and calibrate the model.

These inputs are discussed further in the following sections. NAVD88 was used as the common vertical datum for all of the CSHORE model inputs and outputs.

5.3.3 Profile Data

The CSHORE model was calibrated to observed beach profile morphology due to Hurricane Sandy, which impacted Nags Head at the end of October 2012. The pre-storm conditions that were used as input for the CSHORE model were represented by annual survey data that was collected in June 2012 prior to Hurricane Sandy. Post-storm survey data was collected within one month of the storm.

Following calibration of the CSHORE model, the calibrated model parameters were used to simulate profile changes due to a completely independent storm event, as validation that the model would perform acceptably for other storms. The model was validated to observed beach profile morphology due to Hurricane Matthew, which impacted Nags Head at the beginning of October 2016. The pre-storm conditions used in CSHORE were represented by annual survey data that was collected in June 2016 prior to Hurricane Matthew. Post-storm survey data was collected within two weeks of the storm in October 2016.

5.3.4 Water Levels and Wave Conditions

The wave and water level time series input to the CSHORE simulations for the calibration (Hurricane Sandy) and validation (Hurricane Matthew) storms are shown in Figure 5-3 and Figure 5-4.

Hurricane Sandy wave height, period, and direction were collected from the Duck, NC, FRF directional wave gauge 44056 (in 56 ft water depth) between October 25, 2012 and November 1, 2012. During this time, the peak significant wave height recorded was 21 ft with a peak wave period of 18 seconds. This wave height was determined to be equivalent to the 12-year return period storm wave condition (Appendix C).

Water level data was collected from the nearby FRF tide station 8651370. However, during the storm, the gauge malfunctioned and stopped recording after the peak storm surge. Before the FRF tide gauge malfunctioned, it measured significant storm surge of 4.5 ft NAVD88. This peak water level was calculated to be equivalent to the 10-year return period storm.

To generate the rest of the water level input for the CSHORE simulations the storm surges rising and falling legs were assumed to be similar and the water level data before the first peak (hour 78) was mirrored and affixed to the final recorded water level. This assumed trend was also observed in the closest tide station, Oregon Inlet Marina.

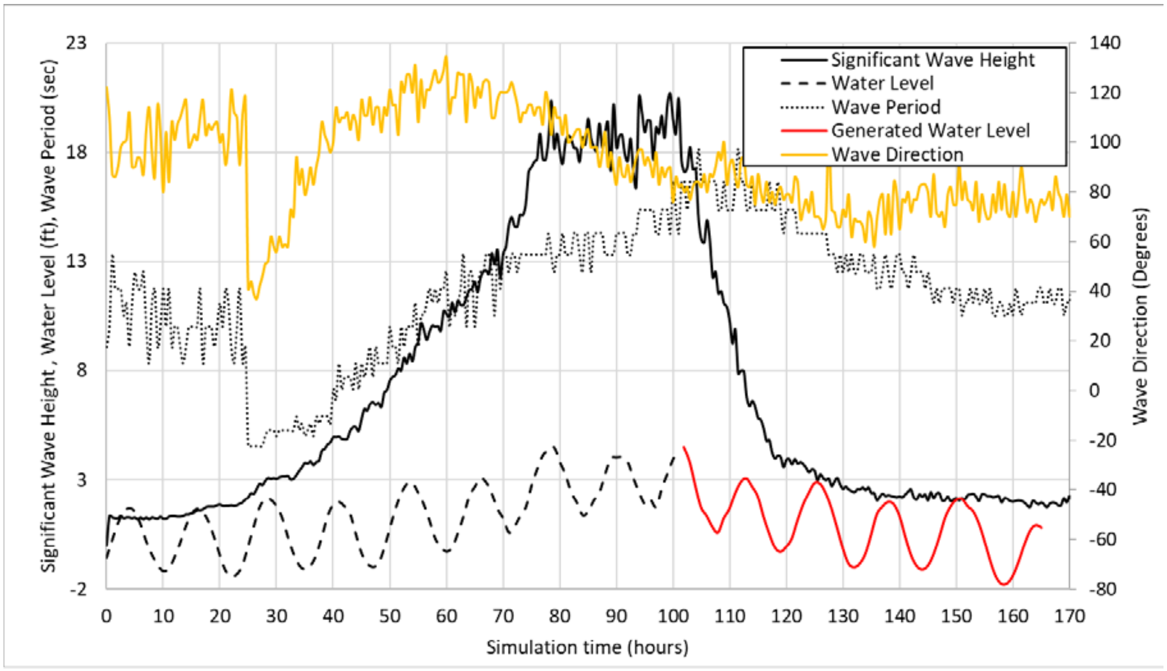


Figure 5-3: CSHORE Input Waves and Water Level, Hurricane Sandy (2012)

Hurricane Matthew impacted Nags Head at the beginning of October 2016. Wave height, period, and direction for this storm were collected from the FRF directional wave gauge 44056 between October 25, 2016 and November 1, 2016. During this time, the peak significant wave height recorded was 16.1 ft with a peak wave period of 13 seconds. This wave height was determined to be equivalent to the 5-year return period storm. Water level data was collected from the FRF tide station 8651370. The surge associated with Matthew was 3.2 ft (NAVD88) at FRF. The peak water elevation equates to the 3.1-year return period storm at Nags Head.

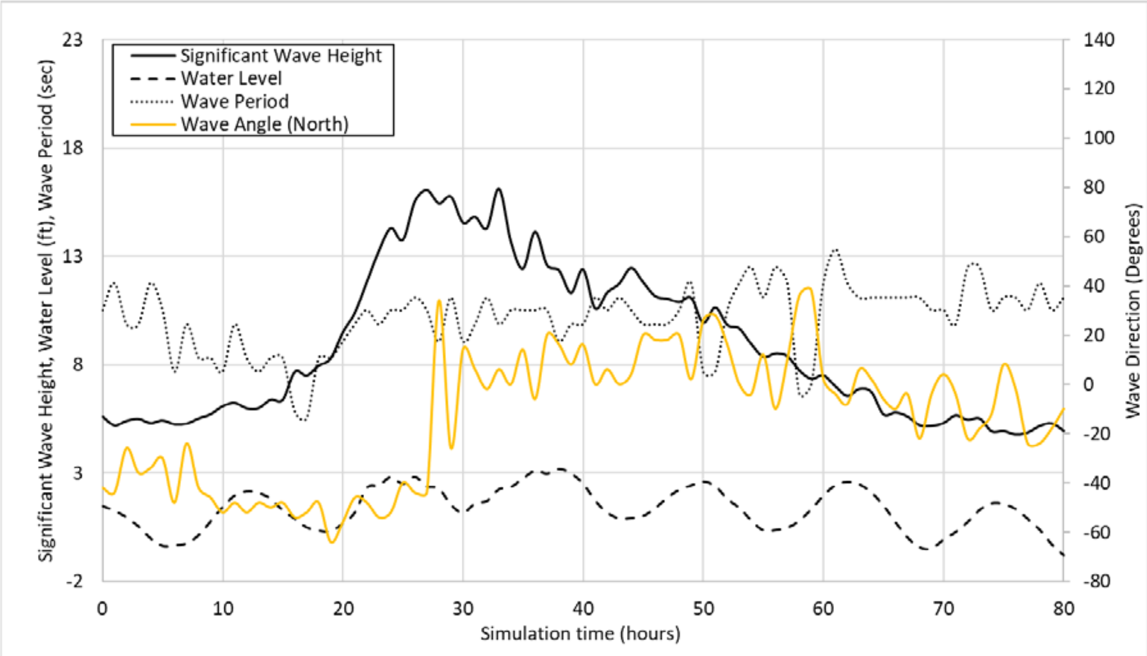


Figure 5-4: CSHORE Input Waves and Water Level, Hurricane Matthew (2016)

5.3.5 Sediment Transport Parameters

The CSHORE model input includes eight parameters that influence the rate of sediment transport. The median sediment diameter (D_{50}), the sediment fall velocity (w_f), the sediment maximum slope (tan Φ), and the specific gravity (s) parameters describe the physical characteristics of the beach and thus was not adjusted for the model calibration purposes.

Surface sediment sampling and laboratory gradation testing (CSE, 2018) indicated that a median grain size of D_{50} = 0.30 mm is representative of the sand comprising the beach and dune at the project site. Using this historical measured D_{50} for the study area, the sediment fall velocity is then calculated as 0.045 (m/s) based on Soulsby (1997) optimization. The default values for the Atlantic Ocean were used for the rest of the physical sediment characteristics (USACE, 2019).

CSHORE is primarily calibrated by adjusting the remaining four sediment transport coefficients: bedload parameter (b), suspended load parameter (a), and wave breaking (e_b) and bottom friction (e_f) suspension efficiency parameters.

5.3.6 Historical Storm Model Simulation Results

CSHORE parameters were calibrated to replicate, to the extent possible, the impacts of Hurricane Sandy at 14 representative profiles. The calibrated model results were then validated by simulating the impacts of Hurricane Matthew. Charts of the full set of CSHORE results for both storms are provided in Appendix C.

Figure 5-5, Figure 5-6, and Figure 5-7 show typical CSHORE calibration model results for Hurricane Sandy at Nags Head profiles 520+00, 715+00, and 1020+00, respectively. These profiles are representative of the CSHORE calibration set. The plots show the pre and post storm surveyed profiles and the modeled profile that was created at the end of the CSHORE simulation. CSHORE generally erodes the upper beach (above MHW) in a manner similar to the measured post-storm profiles, and it predicts the landward limit of erosion well at most profiles. However, CSHORE simulations are unable to capture the bar movements. The results show the trough landward of the nearshore bar being filled in, but the measured profiles do not indicate significant filling. CSHORE also erodes the seaward face of the bar, whereas the measured profiles show the bar remaining intact and moving seaward.

Part of the difference between the CSHORE simulations and post storm surveys might be due to the dynamic nature of the intertidal zone and sand bars compared to the subaerial beach. Since post storm surveys are not performed immediately after the storms, the surveys also include the recovery at these locations that occurs between the storm and post storm survey.

CSHORE is used in the present study primarily to estimate the degree of beach and dune erosion (including overtopping or breaching of dunes), with associated risk to upland structures landward of the dune, for determining the LoP afforded by existing and proposed beach profile scenarios. The CSHORE model calibration therefore focused on achieving agreement with measured profiles over the upper beach face, beach berm, and dune areas, and the calibration is generally successful in that regard. See Table 5-3 for a complete list of the calibration parameters used in this analysis.

Table 5-3: CSHORE Calibration Parameters

Variable Name	Default Value	Calibrated Value	
		430+00 – 975+00	975+00 - 1025+00
Median sediment diameter (D_{50})	0.3	0.30	
Sediment fall velocity (w_f),	-	0.045	
Sediment maximum slope (tan Φ),	0.63	0.63	
Specific gravity (s)	2.65	2.65	
Bedload parameter (b)	0.001	0.006	0.004
Suspended load parameter (a)	0.5	0.05	0.05
Wave breaking suspension efficiency (e_b)	0.005	0.02	0.01
Bottom friction suspension efficiency (e_f)	0.015	0.02	0.01

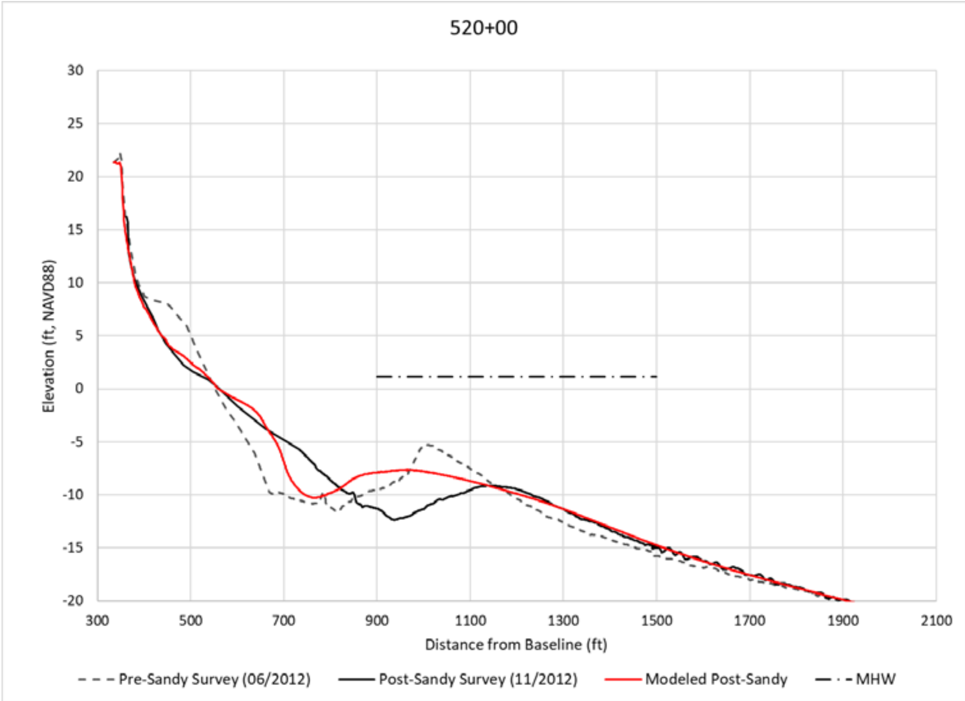


Figure 5-5: CSHORE Calibration: Hurricane Sandy at 520+00 (Bainbridge Street)

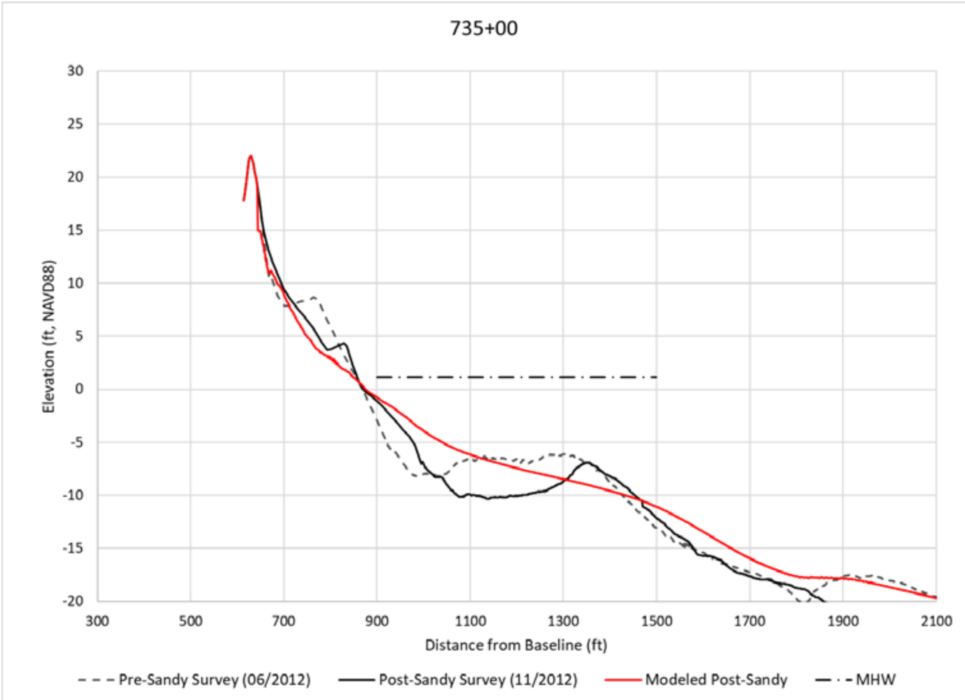


Figure 5-6: CSHORE Calibration: Hurricane Sandy at 735+00 (E. Flicker Street)

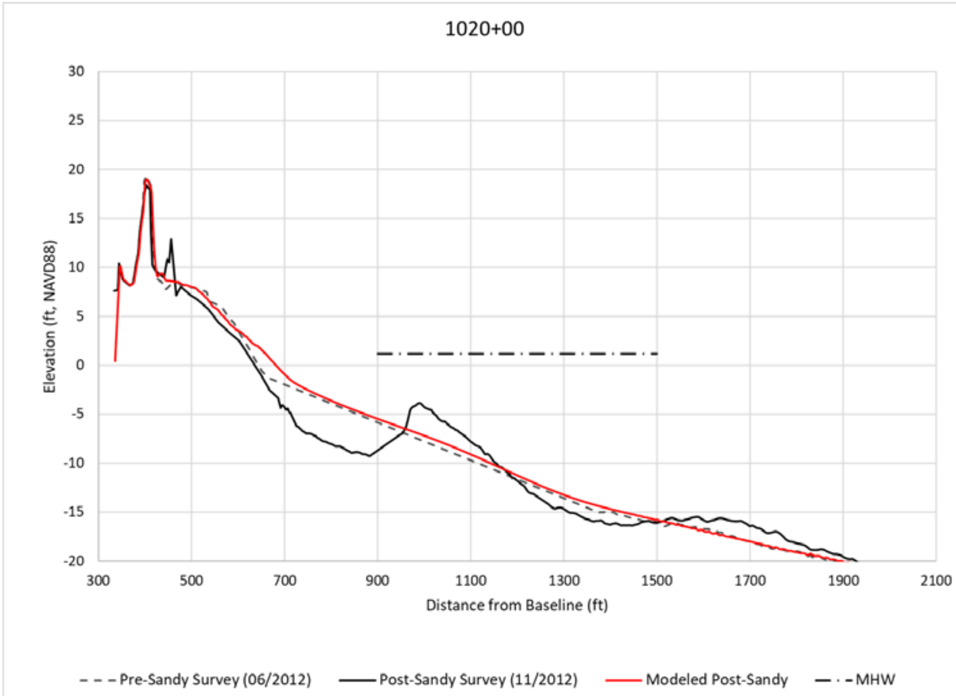


Figure 5-7: CSHORE Calibration: Hurricane Sandy at 1020+00 (E. McCall Court)

The calibrated CSHORE model parameters were used in simulations of Hurricane Matthew (October 2016), with representative results shown in Figure 5-8, Figure 5-9, and Figure 5-10. The Hurricane Matthew CSHORE simulations generally showed greater erosion of the intertidal and upper beach than the survey data indicate. In the validation dataset CSHORE was not able to reproduce the accretion on the upper beach between 0 ft and +7 ft NAVD88 that was observed in some profiles (Figure 5-8). Similar to the calibration simulations, the validation dataset also was unable to reproduce the bar patterns seen in the post-storm survey data.

The agreement between CSHORE and post-storm survey data, in terms of predicting upper beach and dune erosion and landward limits of erosion, is sufficient for the purposes of estimating levels of protection for this study. Section 5.4 describes the utilization of CSHORE to support LoP determinations.

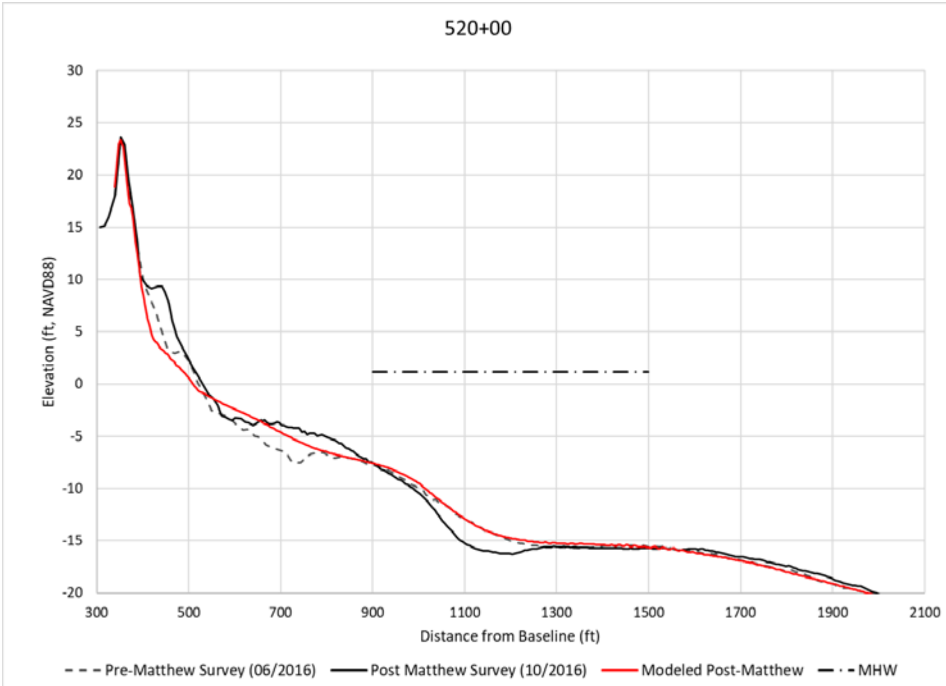


Figure 5-8: CSHORE Validation: Hurricane Matthew at 520+00 (Bainbridge Street)

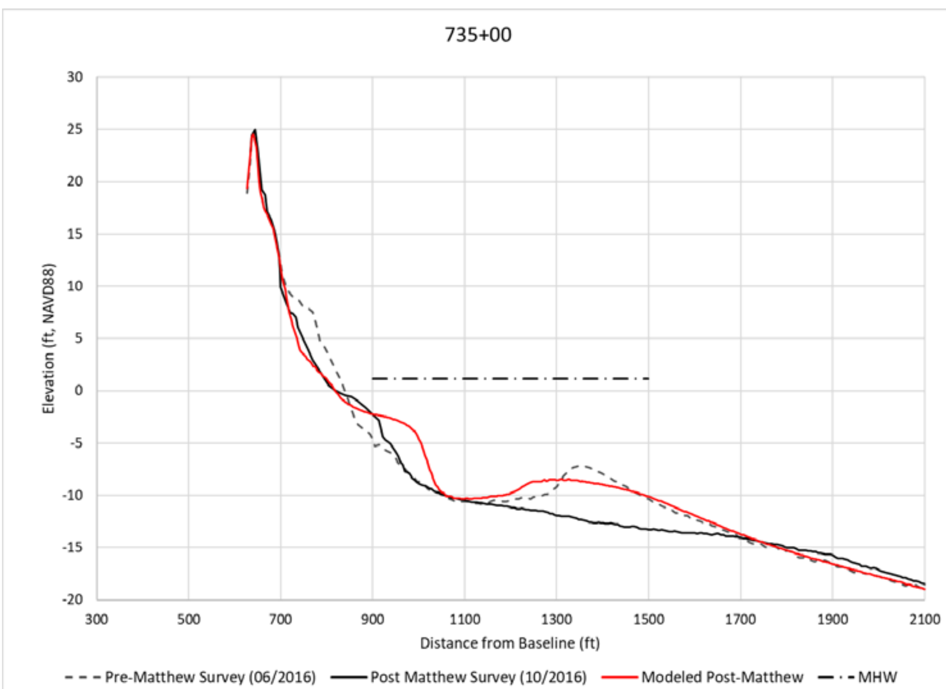


Figure 5-9: CSHORE Validation: Hurricane Matthew at 735+00 (E. Flicker Street)

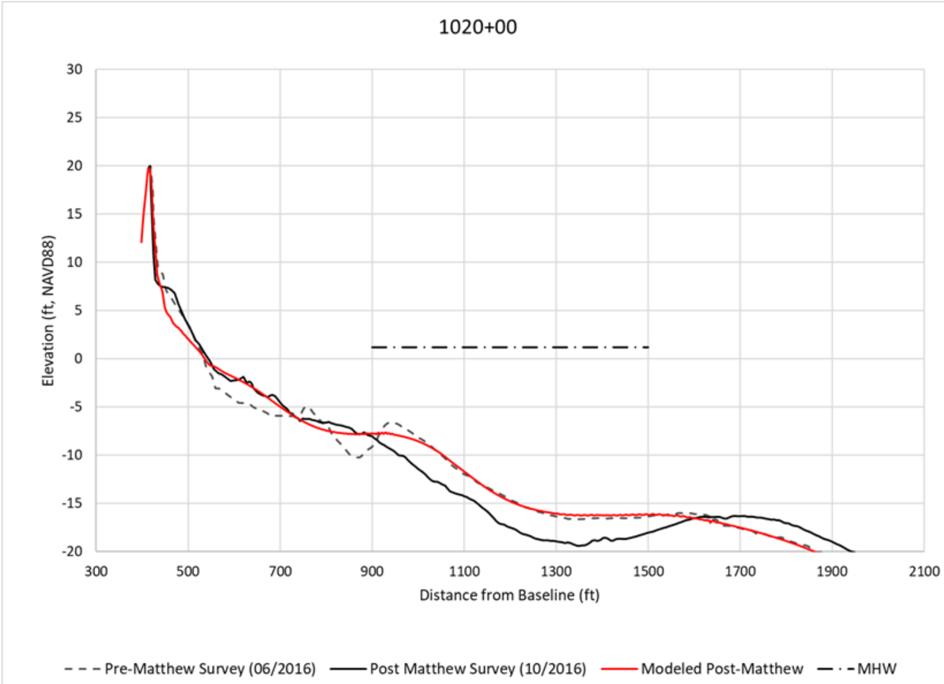


Figure 5-10: CSHORE Validation: Hurricane Matthew at 1020+00 (E. McCall Court)

5.4 LoP with Pre-Nourished Conditions (May 2018) Profiles

The LOP offered by the pre-nourishment conditions are of interest since they reflect the most vulnerable conditions that Town experienced during the most recent nourishment cycle. The May 2018 annual monitoring profiles which reflect the conditions before the 2019 Beach Nourishment Project were selected as representative of the pre-nourished conditions. The "first row of structures" positions utilized in the LoP evaluations were digitized from 2018 aerial photography. Structures positions used in the LoP analysis were an average of the positions adjacent to each representative profile, based on a line connecting the seaward edges of the structures along the Town's shoreline.

The post-storm beach and dune profiles resulting from the CSHORE simulations were inspected and coastal engineering judgment was applied to conclude the LoP afforded by the pre-nourishment profiles. The evaluation involved assessing the landward limit of dune erosion and potential for dune flooding / overtopping – indicated by the CSHORE simulations of the synthetic design storms – relative to the position of the most seaward line of development (most seaward or "first row" of upland structures) at each of the 14 representative profiles along Nags Head (Table 5-1).

Table 5-4 summarizes the LoP resulting at each of the 14 representative profiles for the 25-year, 50-year, and 100-year return period (4%, 2%, and 1% annual chance, respectively) synthetic design storms. Additionally, Appendix C presents LoP conditions of post-nourishment (August 2019) profiles.

Table 5-4: LoP for Pre-Nourished Conditions CSHORE Profiles

Reach	Rep. Profile	Initial Volume (cy/ft)	25-year RP LoP	50-year RP LoP	100-year RP LoP
Nags Head – North	460+00	578	No Impact	No Impact	No Impact
Reach 1	520+00	509	No Impact	Minor Overtopping	Threatened
Reach 1	535+00	472	No Impact	Threatened	Undermined
Reach 1	625+00	506	No Impact	Major Overtopping	Undermined
Reach 1	715+00	501	No Impact	Minor Overtopping	Threatened
Reach 1	735+00	490	No Impact	Major Overtopping	Undermined
Reach 1 Reach 2	785+00	610 446	No Impact	Threatened	Undermined
Reach 2	855+00	499	Threatened	Undermined	Undermined
Reach 2	865+00	485	Minor Overtopping	Undermined	Undermined
Reach 2	895+00	504	Threatened	Undermined	Undermined
Reach 2 Reach 3 - North	920+00	464 407	No Impact	Minor Overtopping	Undermined
Reach 3 - North	935+00	373	No Impact	Major Overtopping	Undermined
Reach 3 - South	980+00	509	Undermined	Undermined	Undermined
Reach 3 - South Reach 4	1020+00	472	Major Overtopping	Threatened	Undermined

The CSHORE simulations indicated that for the May 2018 pre-nourishment conditions, the beach and dune system provided a LoP equivalent to No Impact or Minor Overtopping at the first row of structures for 10 of the representative profiles in the 25-year return period design storm CSHORE simulations. All the profiles located in Nags Head North, Reach 1, and Reach 3 North provided adequate protection against the 25-year return period event while severe impacts were observed at the profiles at Reaches 2, 3 South, and 4.

At the 50-year return period design storm level, severe impacts to the first row of structures were indicated at 10 of the representative profiles. Finally, severe impacts were indicated at all representative profiles except within Nags Head North at the 100-year return period design storm level. Figure 5-11 through Figure 5-19 show sample May 2018 beach profiles, the seaward limits of the first row of structures, and CSHORE results for Nags Head Stations 520+00 (Reach 1), 865+00 (Reach 2) and 980+00 (Reach 3 South) for the three design storm levels in Table 5-2. Appendix C contains plots of the CSHORE results at all 14 profiles.

During the simulations, it was observed that several transects exhibited an instability within the profile, typically occurring once the dune had been undermined. Figure 5-16 provides an illustrative example of such instability observed at transect 865. The instability manifests as fluctuations within the profile and is attributed to inland sediment transport rates, as calculated by CSHORE, exceeding those observed on the beach face. Since the instability occurs subsequent to dune undermining and the assignment of the LoP to the profile, the impact of this instability on the analysis was considered negligible.

Figure 5-11: CSHORE Results, Pre-Nourished Conditions, 25-year RP, Station 520+00 (Bainbridge Street)

Figure 5-12: CSHORE Results, Pre-Nourished Conditions, 50-year RP, Station 520+00 (Bainbridge Street)

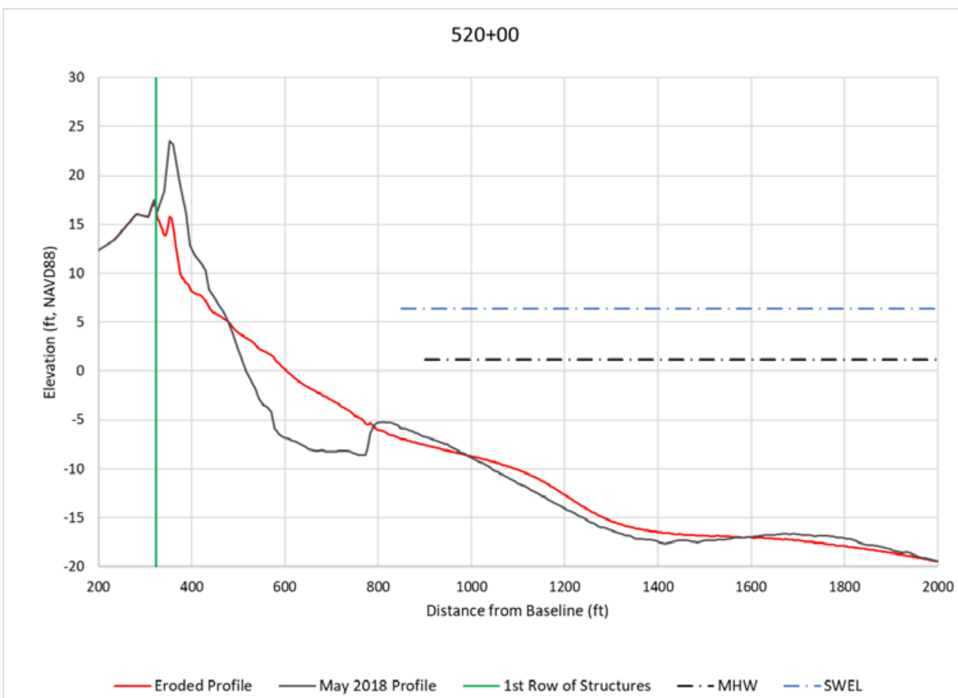


Figure 5-13: CSHORE Results, Pre-Nourished Conditions, 100-year RP, Station 520+00 (Bainbridge Street)

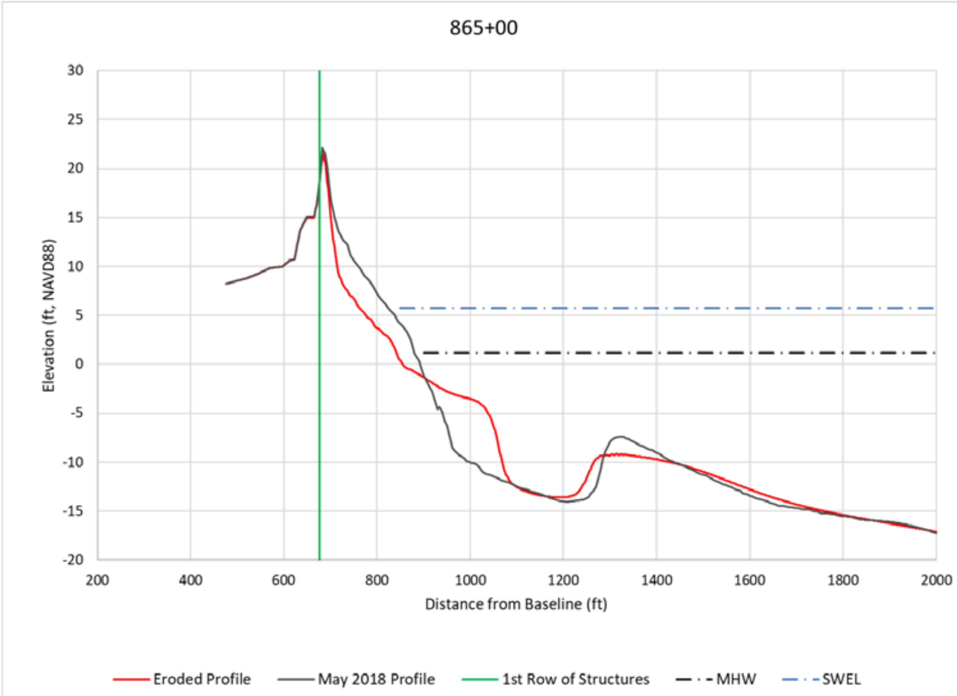


Figure 5-14: CSHORE Results, Pre-Nourished Conditions, 25-year RP, Station 865+00 (E Ida Street)

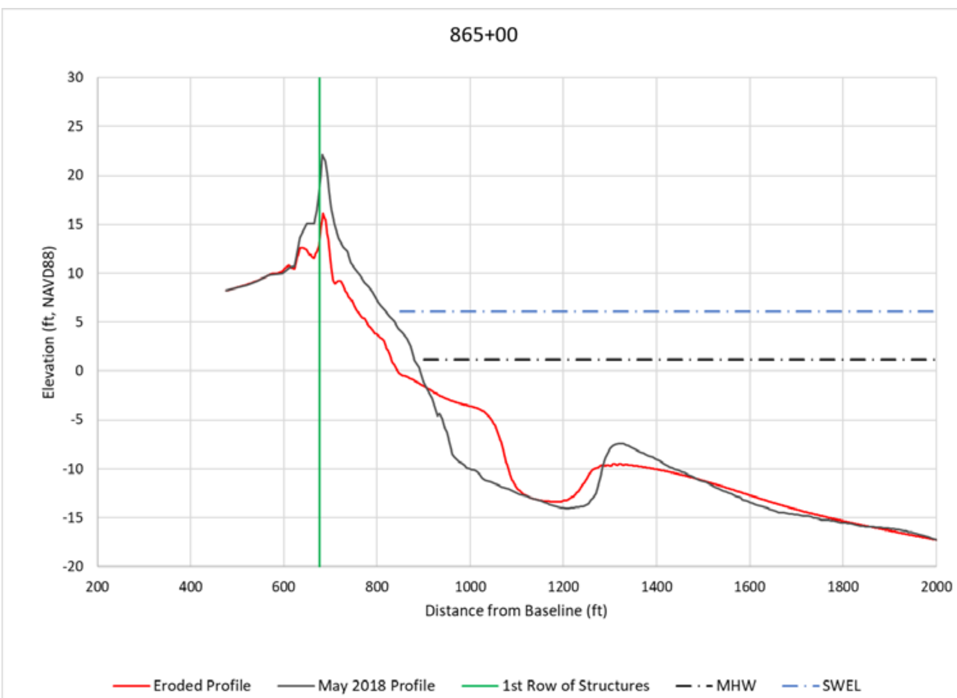


Figure 5-15: CSHORE Results, Pre-Nourished Conditions, 50-year RP, Station 865+00 (E Ida Street)

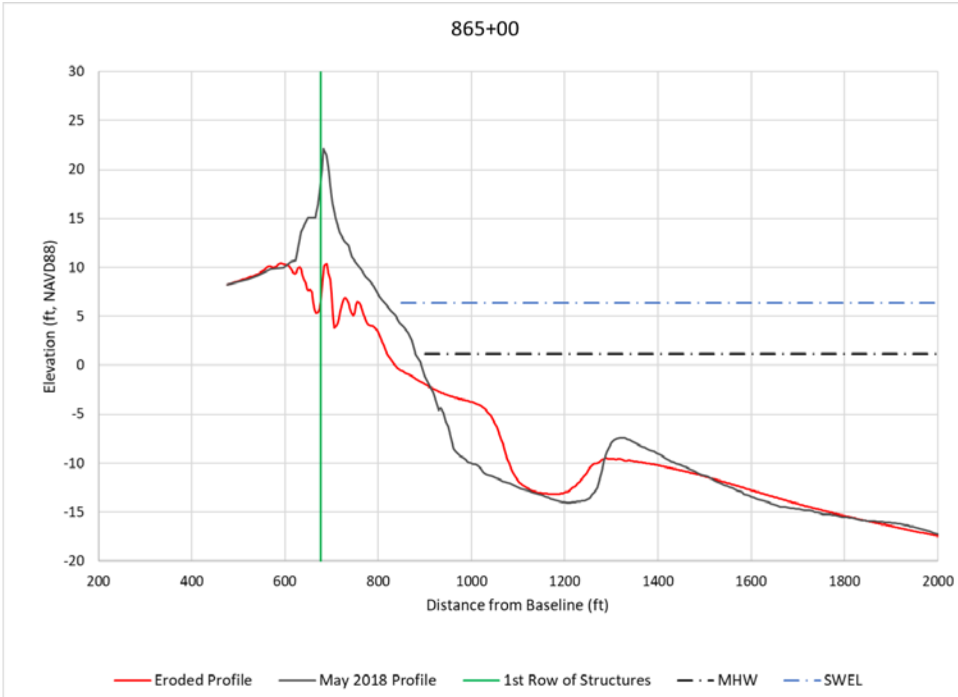


Figure 5-16: CSHORE Results, Pre-Nourished Conditions, 100-year RP, Station 865+00 (E Ida Street)

Figure 5-17: CSHORE Results, Pre-Nourished Conditions, 25-year RP, Station 980+00 (E Altoona Street)

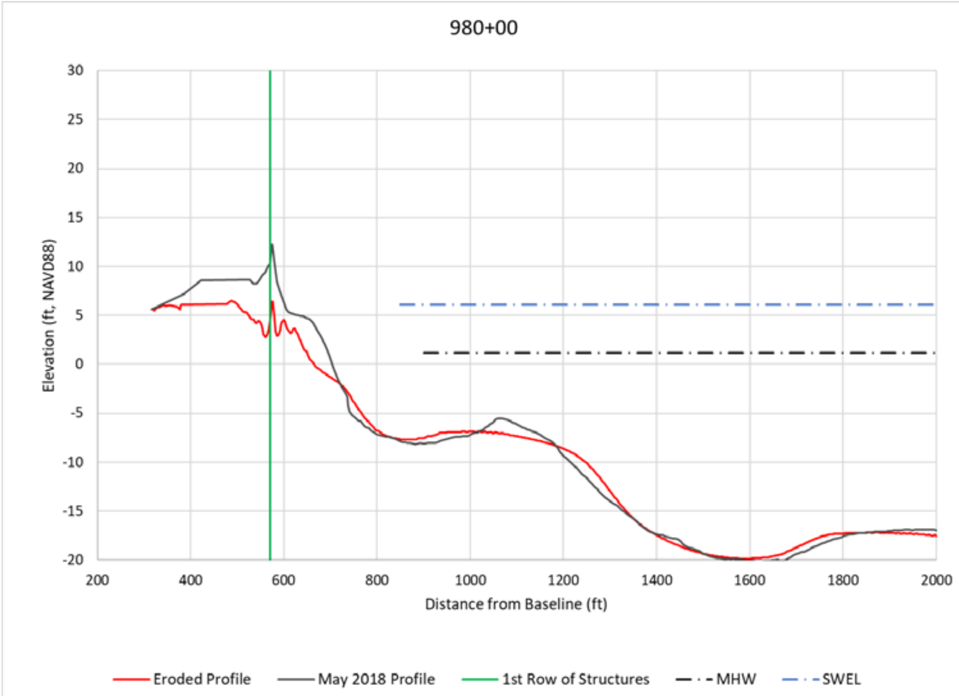


Figure 5-18: CSHORE Results, Pre-Nourished Conditions, 50-year RP, Station 980+00 (E Altoona Street)

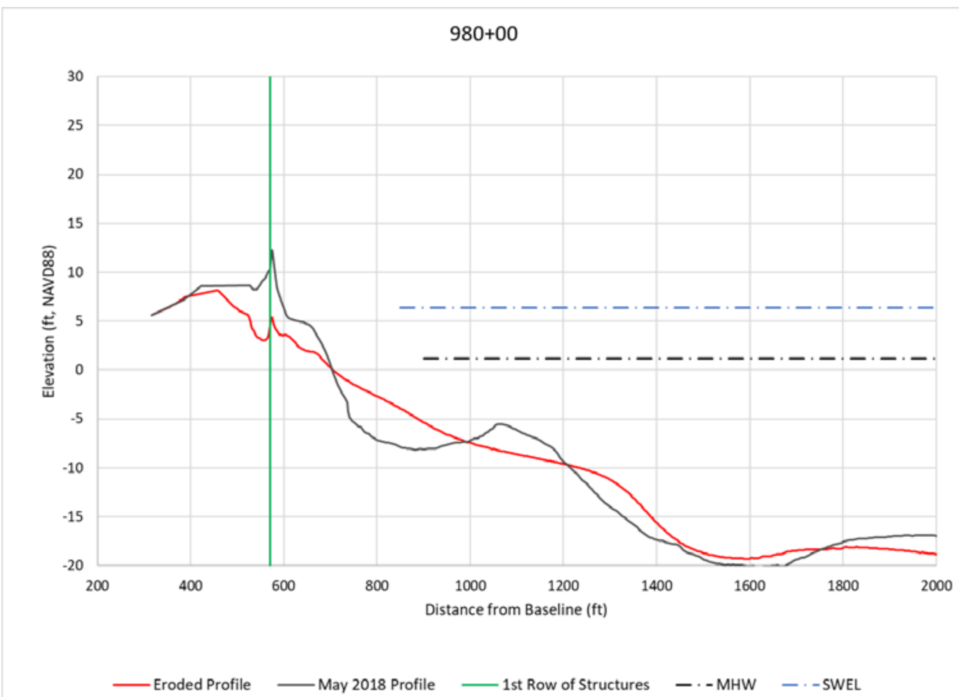


Figure 5-19: CSHORE Results, Pre-Nourished Conditions, 100-year RP, Station 980+00 (E Altoona Street)

Profile volumes seaward of the dune crest and above -19 ft NAVD88 computed on May 2018 pre-nourishment conditions CSHORE initial profiles (i.e. pre-storm profiles) are shown in Figure 5-20. The bars for all 14 profiles are color coded to indicate the LoP categories for the 25-year return period design storm. The green bars indicate No Impact, while the blue bars indicate Minor Overtopping and the red and orange bars indicate Severe Impacts.

Figure 5-21 and Figure 5-22 show the same type of information but with the bars color-coded to indicate LoP in the 50-year and 100-year return period design storms, respectively.

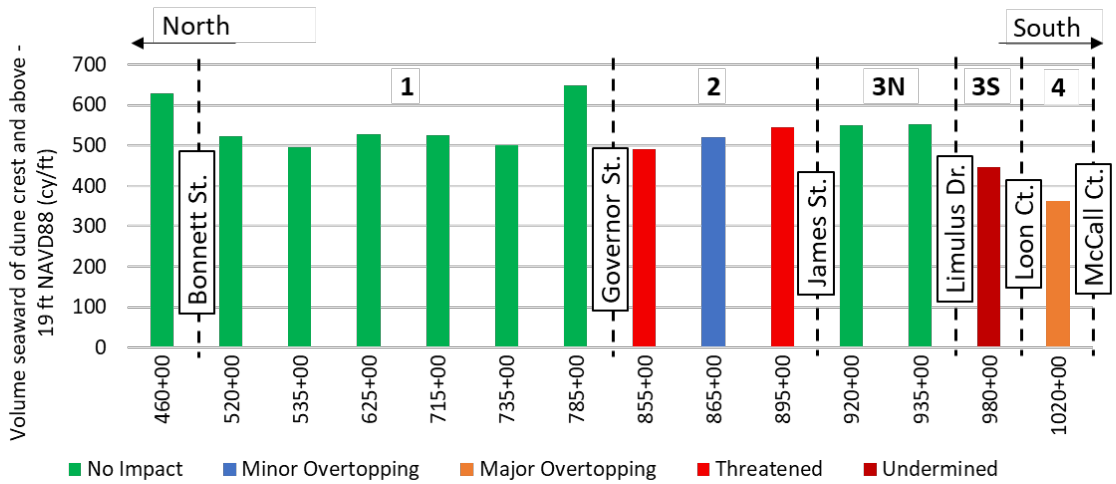


Figure 5-20: Pre-Nourishment Condition CSHORE Pre-Storm Profile Volumes Coded for 25-year Return Period LoP

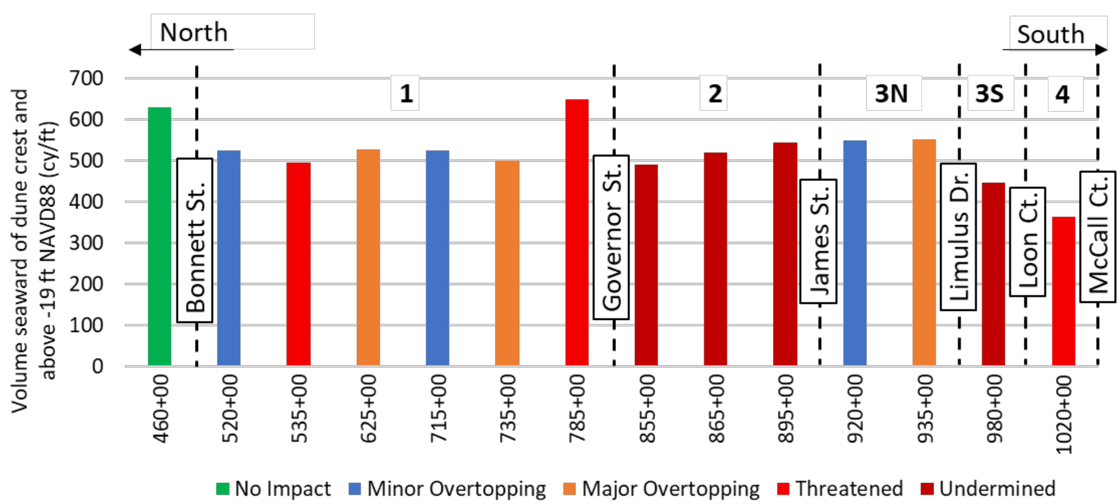


Figure 5-21: Pre-Nourishment CSHORE Pre-Storm Profile Volumes Coded for 50-year Return Period LoP

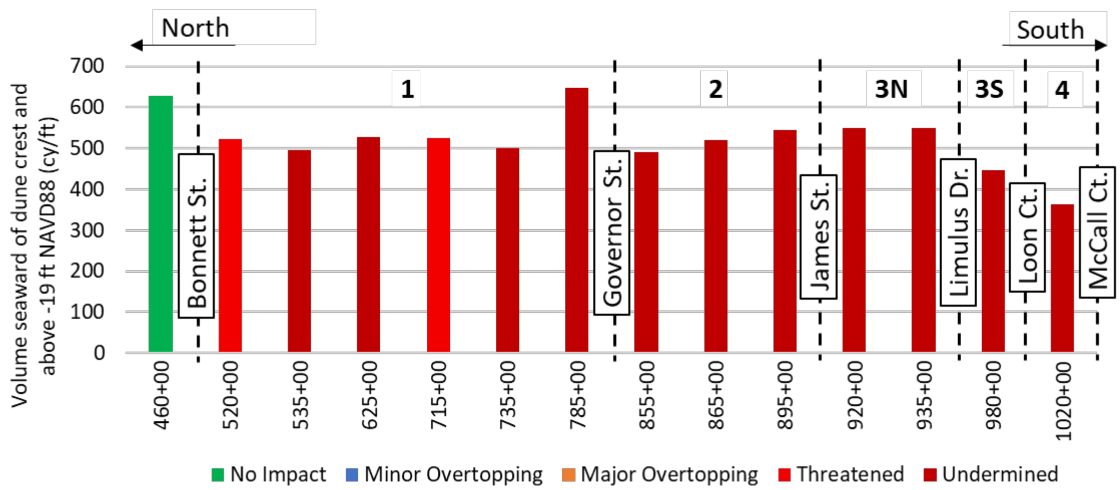


Figure 5-22: Pre-Nourishment CSHORE Pre-Storm Profile Volumes Coded for 100-year Return Period LoP

In summary, the May 2018 existing conditions of the beach and dune system are considered to provide a sufficient LoP along the northern and middle portions of Nags Head for up to a 25-year return period design storm event. Before the nourishment event, the representative profiles at Reaches 3 South and 4 do not have sufficient material available to protect the structures. With the 50-year return period design storm most of the representative profiles become vulnerable and all the profiles are severely impacted during the 100-year return period storm.

The next step in the process is to determine adjustments to the beach profile design that would achieve an acceptable LoP along the Town’s oceanfront in the design storm events. Section 5.5 of the report extensively examines and documents the specific beach profile configurations required to achieve desired levels of protection in these storms.

5.5 Beach Nourishment Design Scenarios and LoP Determinations

The beach profile geometry, including dune height and width, as well as berm elevation and width, required to achieve the acceptable LoP (No Impact or Minor Overtopping) for targeted storm return periods, was developed iteratively using CSHORE simulations.

Various beach nourishment template alternatives were explored, aiming to construct initial dune and beach berm enhancements when required, in order to attain an acceptable LoP for each design storm. During the formulation of these beach profile templates, it was assumed that a constructed beach nourishment would incorporate additional advance fill to account for both background erosion and storms expected to occur between each planned nourishment interval. The primary objective was to ensure that, at the conclusion of the nourishment cycle, the minimum beach profile would be available, consistently enabling the achievement of the targeted LoP along the Town's oceanfront. The estimation of the required advance fill for each reach and sub-reach was based on historical monitoring data and findings from the Crystal Ball analysis outlined in Section 4.2.2.

5.5.1 Approach

CSHORE simulations were employed in an iterative manner to determine the beach profile geometry necessary to achieve the desired LoP for the design storms. Figure 5-23 illustrates the approach taken during this process.

During the development of design templates, some profiles were adjusted by adding volumes to the dune and berm, while others were modified by removing dune and berm volume.

At profiles where additional dune and berm construction was required to achieve No Impact or Minor Overtopping under the targeted return period storm, the approach involved increasing the berm width and making adjustments to the dune's height and width. Subsequently, CSHORE, was employed to assess the modified profile's performance during the design storm and determine its ability to achieve a satisfactory LoP. This iterative process continued until the profile demonstrated satisfactory performance for the targeted storm return period.

In cases where profiles exceeded the desired LoP for the targeted storm return period, the profile the iterative design process involved gradually reducing the volumes of the profiles to identify the point at which the profile would still provide acceptable performance during the CSHORE simulation for the targeted return period storm. This erosion process allowed for the determination of the minimum required beach and dune volumes necessary to maintain the desired LoP for the designated storm event.

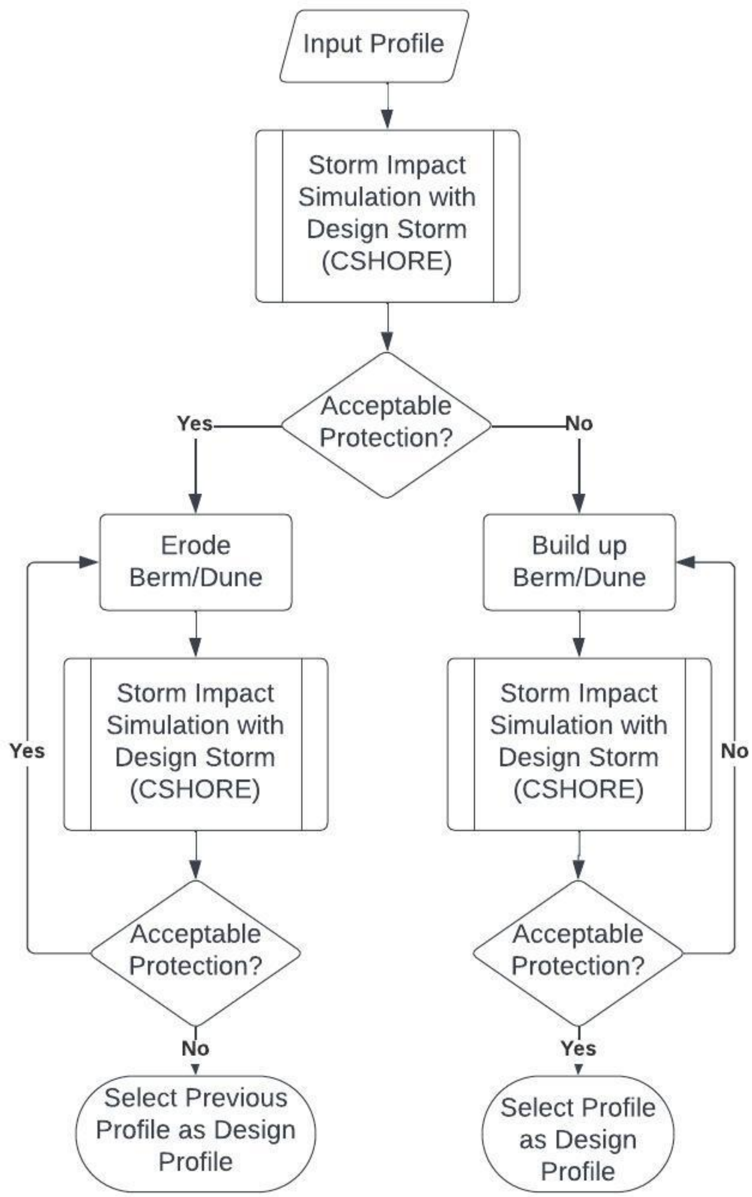


Figure 5-23: LOP Beach Nourishment Design Process

Input Profiles

The input profiles selected for the design process were representative profiles from the May 2018 pre-nourished conditions, which accurately reflected the conditions before the implementation of the 2019 Beach Nourishment Project. These profiles were chosen to initiate the design process from the least protected conditions, providing a starting point for assessing the necessary improvements in achieving the desired LoP.

Design Storms

During the development of design templates, storm return periods of 25 and 50 years were taken into account. Return periods less than 25 years were not considered, as most representative profiles demonstrated acceptable LoP, with no severe impacts observed, in the 25-year return period design storm. Consequently, for a significant portion of the Town's oceanfront, there would be no need for initial berm or dune expansion to create a beach nourishment template with satisfactory LoP for the 25-year return period storm. It is, therefore, justifiable to consider maintaining this LoP as the lower limit for proactive beach management planning going forward.

On the other hand, the 100-year return period storm was not included in the design considerations due to the substantial additional volume and corresponding cost required to achieve sufficient LoP. Results and interpretation of LoP design profile development for each of the design storms are discussed below.

5.5.2 Beach Nourishment LoP Design

25-year Storm Design Profiles

The CSHORE simulations described in Section 5.4 indicated that the 2018 pre-nourished conditions beach and dune system provided a LoP equivalent to No Impact or Minor Overtopping at the first row of structures for 10 of the representative profiles in the 25-year return period design storm CSHORE simulations. All the profiles located in Nags Head North, Reach 1 and Reach 3 North provided adequate protection against the 25-year event while the profiles at Reaches 2, 3 South and 4 indicated severe impacts. Therefore, during development of design templates some of the pre-nourishment profiles were modified by adding dune and berm volumes, while several others were modified by removing dune and berm volume.

Figure 5-24 through Figure 5-26 depict the profiles from May 2018, the design profiles (identified as CSHORE Input), and the results of the 25-year return period storm CSHORE simulations for profiles 520+00, 865+00, and 980+00. Appendix C contains plots of the CSHORE results at all 14 profiles.

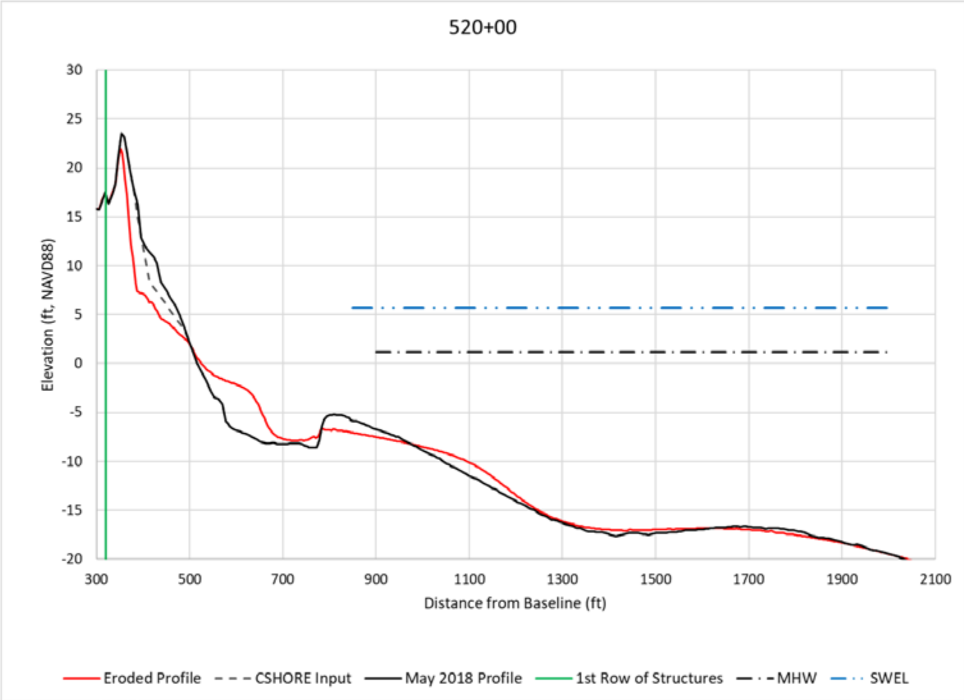


Figure 5-24: CSHORE Results, Design Scenario #2, 25-year RP, Station 520+00 (Bainbridge Street)

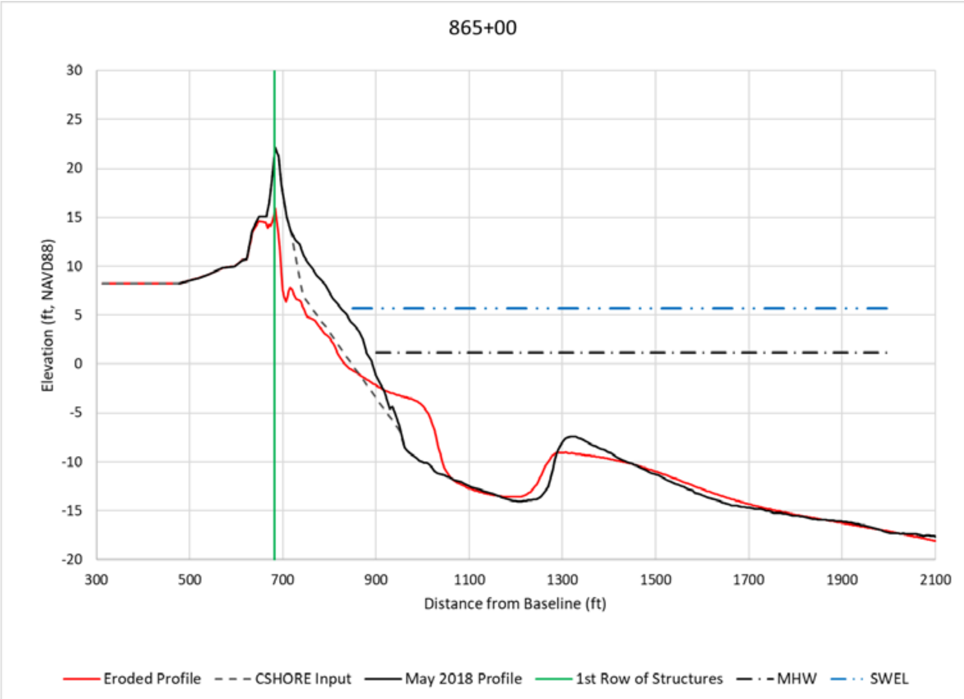


Figure 5-25: CSHORE Results, Design Scenario #2, 25-year RP, Station 865+00 (E Ida Street)

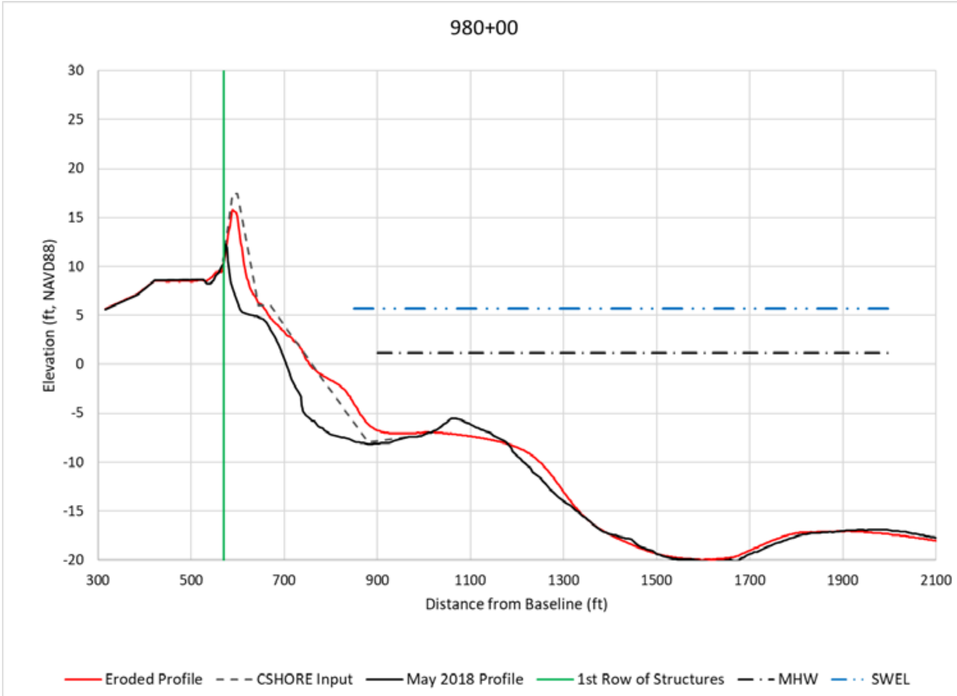


Figure 5-26: CSHORE Results, Design Scenario #2, 25-year RP, Station 980+00 (E Altoona Street)

The construction of additional dune and berm volume to create a beach nourishment design with acceptable LOP against 25-year design storm would require approximately 0.62 Mcy of quality beach sediment. The construction would be required in reaches as identified in Table 5-5, with the approximate required volumes per linear foot of shoreline. Charts for each profile in the table showing CSHORE initial and final (eroded) profiles plus May 2018 surveyed profiles and position of first row of structures are shown in Appendix C.

Table 5-5: Additional Dune and Berm Volume Required to Achieve 25-year Storm LoP

Reach	Length (ft)	Rep. Profile	Volume Above -19 ft, NAVD88 Required to Achieve 25-year LoP (cy/lf)	May 2018 Volume Above -19 ft (cy/ft)	Difference (cy/ft)
Nags Head – North	6,250	460+00	355	577.6	-222.6
Reach 1	4,500	520+00	503	509.4	-6.4
Reach 1	5,500	535+00	451	471.8	-20.8
Reach 1	7,000	625+00	478	506.3	-28.3
Reach 1	5,500	715+00	479	501.3	-22.3
Reach 1	6,000	735+00	443	489.5	-46.5
Reach 1 / Reach 2	2,500	785+00	604	610.3	-6.3
Reach 2	5,500	855+00	491	446.4	+44.1
Reach 2	2,500	865+00	471	499.1	-28.1
Reach 2	2,500	895+00	526	485.2	+41.0
Reach 2 / Reach 3 - North	2,500	920+00	463	504.1	-41.1
Reach 3 - North	4,500	935+00	464	464.2	-0.2
Reach 3 - South	2,000	980+00	461	407.0	+53.9
Reach 3 - South / Reach 4	2,750	1020+00	401	373.2	+28.0

50-year Return Period Storm Results

According to the CSHORE simulations discussed in Section 5.4 it was found that the beach and dune system in the 2018 pre-nourished conditions offered a LoP corresponding to No Impact or Minor Overtopping at the first row of structures for multiple representative profiles (460+00, 520+00, 715+00 and 920+00) . These profiles were subjected to erosion until the minimum volumed profile capable of delivering satisfactory results during a CSHORE 50-year storm simulation was attained. The remaining profiles were modified by adding dune and berm volumes, until acceptable LoP was achieved.

Figure 5-27 through Figure 5-32 depict the design profiles (identified as CSHORE Input), and the results of the 25-year and 50-year return period storm CSHORE simulations for profiles 520+00, 865+00, and 980+00. Appendix C contains plots of the CSHORE results at all 14 profiles.

Figure 5-27: CSHORE Results, 50-yr LoP Design, 25-year RP, Station 520+00 (Bainbridge Street)

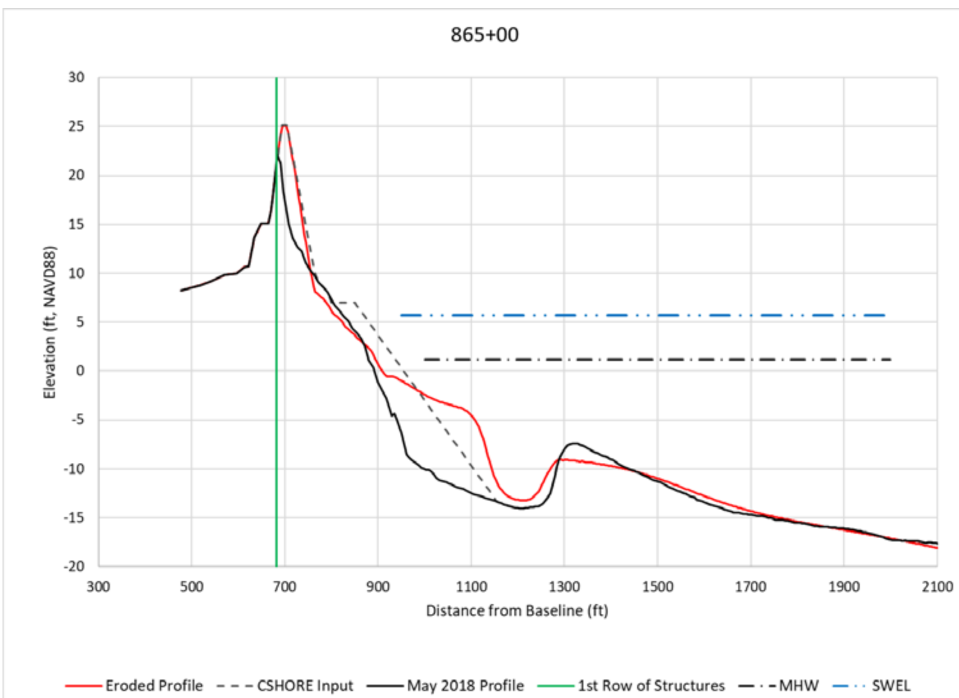


Figure 5-28: CSHORE Results, 50-yr LoP Design, 25-year RP, Station 865+00 (E Ida Street)

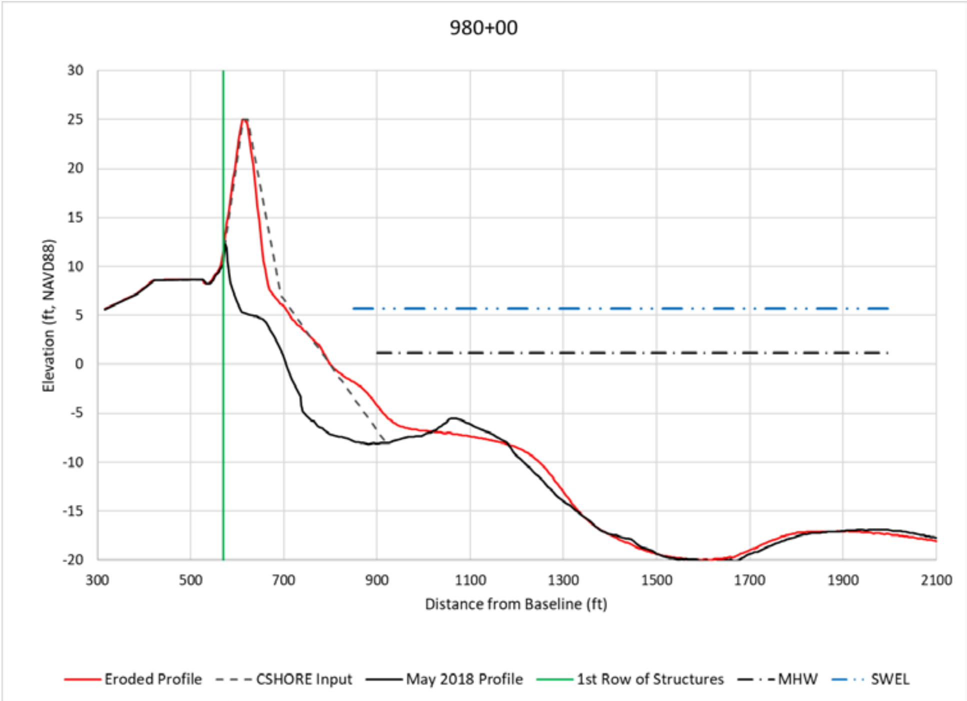


Figure 5-29: CSHORE Results, 50-yr LoP Design, 25-year RP, Station 980+00 (E Altoona Street)

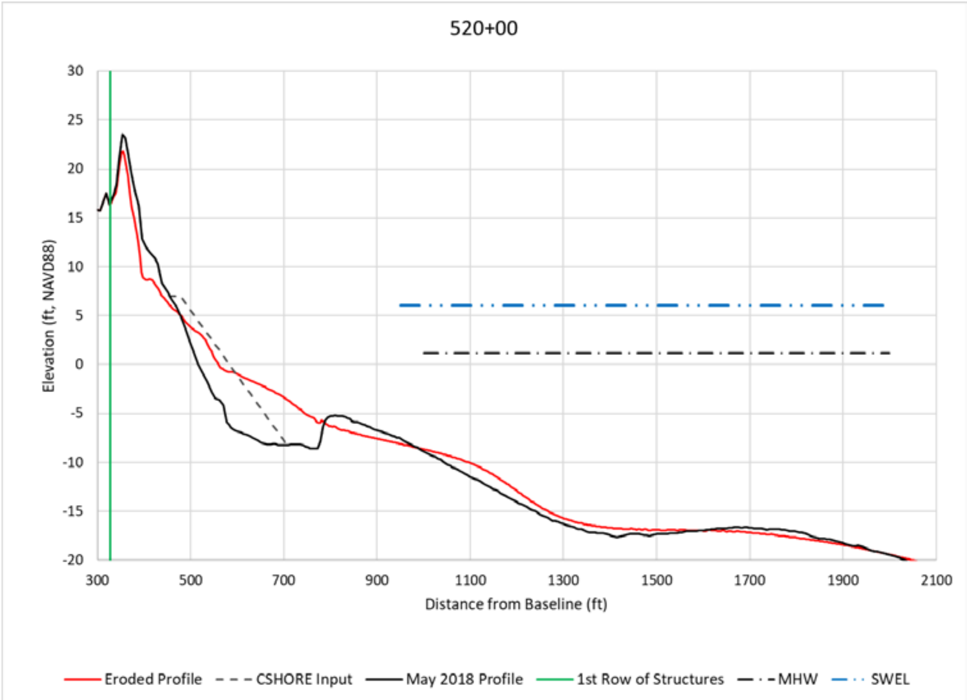


Figure 5-30: CSHORE Results, 50-yr LoP Design, 50-year RP, Station 520+00 (Bainbridge Street)

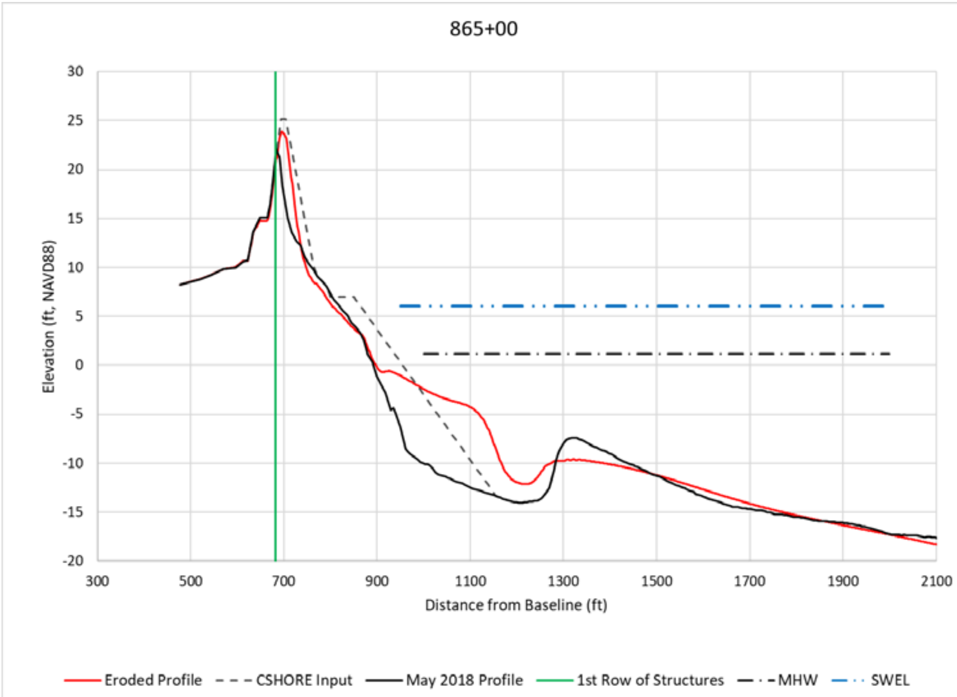


Figure 5-31: CSHORE Results, 50-yr LoP Design, 50-year RP, Station 865+00 (E Ida Street)

Figure 5-32: CSHORE Results, 50-yr LoP Design, 50-year RP, Station 980+00 (E Altoona Street)

The construction of additional dune and berm volume to create a beach nourishment design with acceptable LOP against 50-year design storm would require approximately 3.3 Mcy of quality beach sediment. The construction would be required in reaches as identified in Table 5-6, with the approximate required volumes per linear foot of shoreline. Charts for each profile in the table showing CSHORE initial and final (eroded) profiles plus May 2018 surveyed profiles and position of first row of structures are shown in Appendix C.

Table 5-6: Additional Dune and Berm Volume Required to Achieve 50-year Storm LoP

Reach	Length (ft)	Rep. Profile	Volume Above -19 ft, NAVD88 Required to Achieve 25-year LoP (cy/lf)	May 2018 Volume Above -19 ft, NAVD88 (cy/ft)	Difference (cy/ft)
Nags Head – North	6,250	460+00	466	577.6	-111.6
Reach 1	4,500	520+00	543	509.4	+34.1
	5,500	535+00	546	471.8	+74.13
	7,000	625+00	526	506.3	+19.7
	5,500	715+00	532	501.3	+30.7
	6,000	735+00	547	489.5	+57.1
Reach 1 / Reach 2	2,500	785+00	646	610.3	+36.2
Reach 2	5,500	855+00	586	446.4	+139.9
	2,500	865+00	570	499.1	+70.5
	2,500	895+00	588	485.2	+102.5
Reach 2 / Reach 3 - North	2,500	920+00	533	504.1	+28.6
Reach 3 - North	4,500	935+00	525	464.2	+61.3
Reach 3 - South	2,000	980+00	503	407.0	+101.0
Reach 3 - South / Reach 4	2,750	1020+00	463	373.2	+89.4

5.5.3 LoP Summary

As outlined in the previous sections, some targeted dune building and berm addition in various reaches would be required to provide protection for a 25-yr event along the entire Nags Head shoreline, while adequate protection against a 50-year event would require a wider profile which would be applied to all reaches but the Nags Head North reach. As stated previously, when representative pre-nourishment conditions are considered, a project of approximately 0.6 and 3.3 Mcy would be needed to provide 25-yr and 50-yr event LoP, respectively. Table 5-7 summarizes the volume placement required at each representative profile at representative pre-nourishment conditions to provide adequate protection against 25- and 50-year events. These volumes are dependent on the beach conditions before a nourishment event and can vary. As a conservative approach, the condition of the beach before the 2019 nourishment project was considered in this study to develop a likely maximum needed volume to provide adequate protection.

Table 5-7: Placement required for 25-yr and 50-yr LoP at May 2018 shoreline conditions

Reach	Length (feet)	Rep. Profile	25-yr LoP Placement (cy)	25-yr LoP Placement Density (cy/ ft)	50-yr LoP Placement (cy)	50-yr LoP Placement Density (cy/ ft)
North	6,250	460+00	0	0.0	0	0.0
Reach 1	4,500	520+00	0	0.0	153,450	34.1
	5,500	535+00	0	0.0	407,715	74.13
	7,000	625+00	0	0.0	137,900	19.7
	5,500	715+00	0	0.0	168,850	30.7
	6,000	735+00	0	0.0	342,600	57.1
Reach 1 / Reach 2	2,500	785+00	0	0.0	90,500	36.2
Reach 2	5,500	855+00	242,550	44.1	769,450	139.9
	2,500	865+00	0	0.0.	176,250	70.5
	3,000	895+00	123,000	41.0	256,250	102.5
Reach 2 / Reach 3 - North	2,500	920+00	0	0.0	71,500	28.6
Reach 3 - North	4,500	935+00	0	0.0	275,850	61.3
Reach 3 - South	2,000	980+00	107,800	53.9	202,000	101.0
Reach 3 - South / Reach 4	2,750	1020+00	77,000	28.0	245,850	89.4
TOTAL			**550,350**		**3,298,165**	

Figure 5-33 also shows the difference in the volume trigger above the -19 ft elevation (volume from top of landward dune out to -19 ft NAVD88, see Figure 4-1) that would be needed to provide protection for a 50-yr event versus the 25-yr event and the volume available in the representative profiles at May 2018 survey (before nourishment).

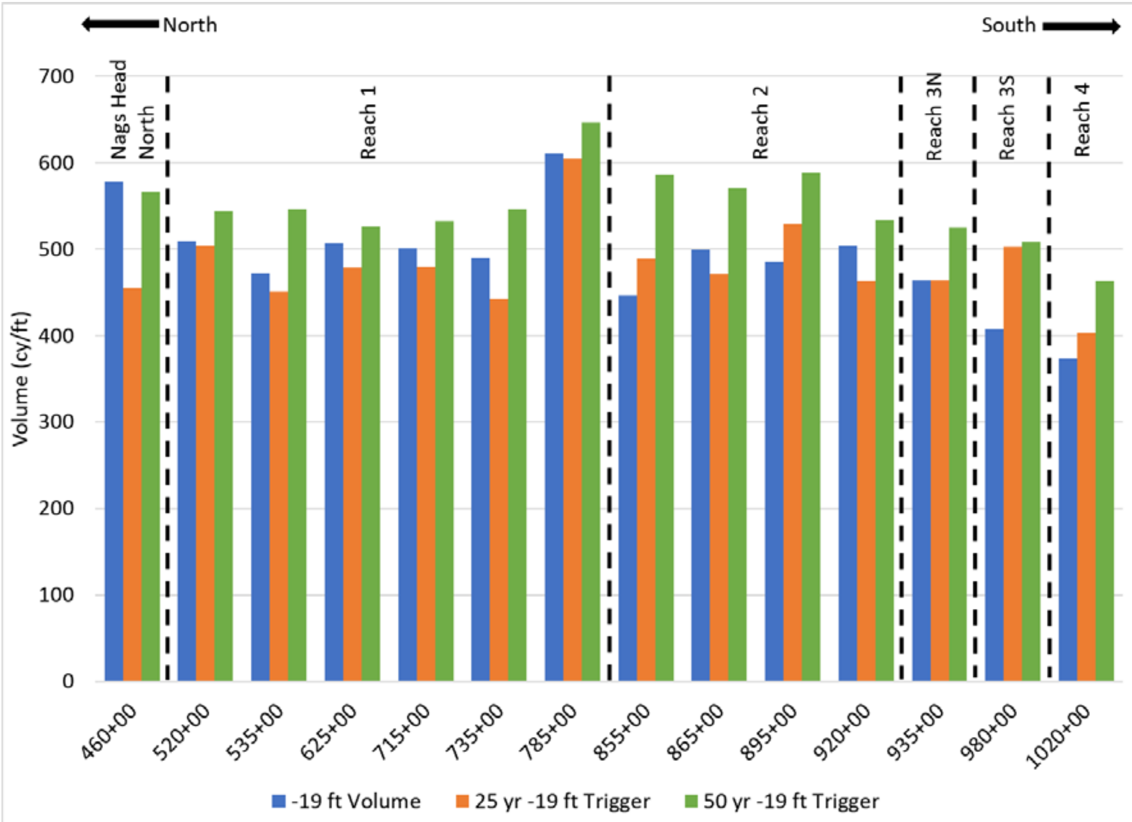


Figure 5-33: 50-yr Event Trigger vs. 25-yr Event Trigger vs. 2018 Volume (-19 ft NAVD88)

Figure 5-34 through Figure 5-47 also show how the 50-yr event trigger will be difficult to maintain over time given historical volumes over the monitoring dataset. While in some areas, the 50-yr LoP could be reached, it would be difficult to maintain it over the entire town. For the following figures, please note that the bars show the volume present above -19 ft NAVD88 for each of the years data are available. The top black line represents the 50-yr event volume trigger while the bottom red line represents the 25-yr event volume trigger.

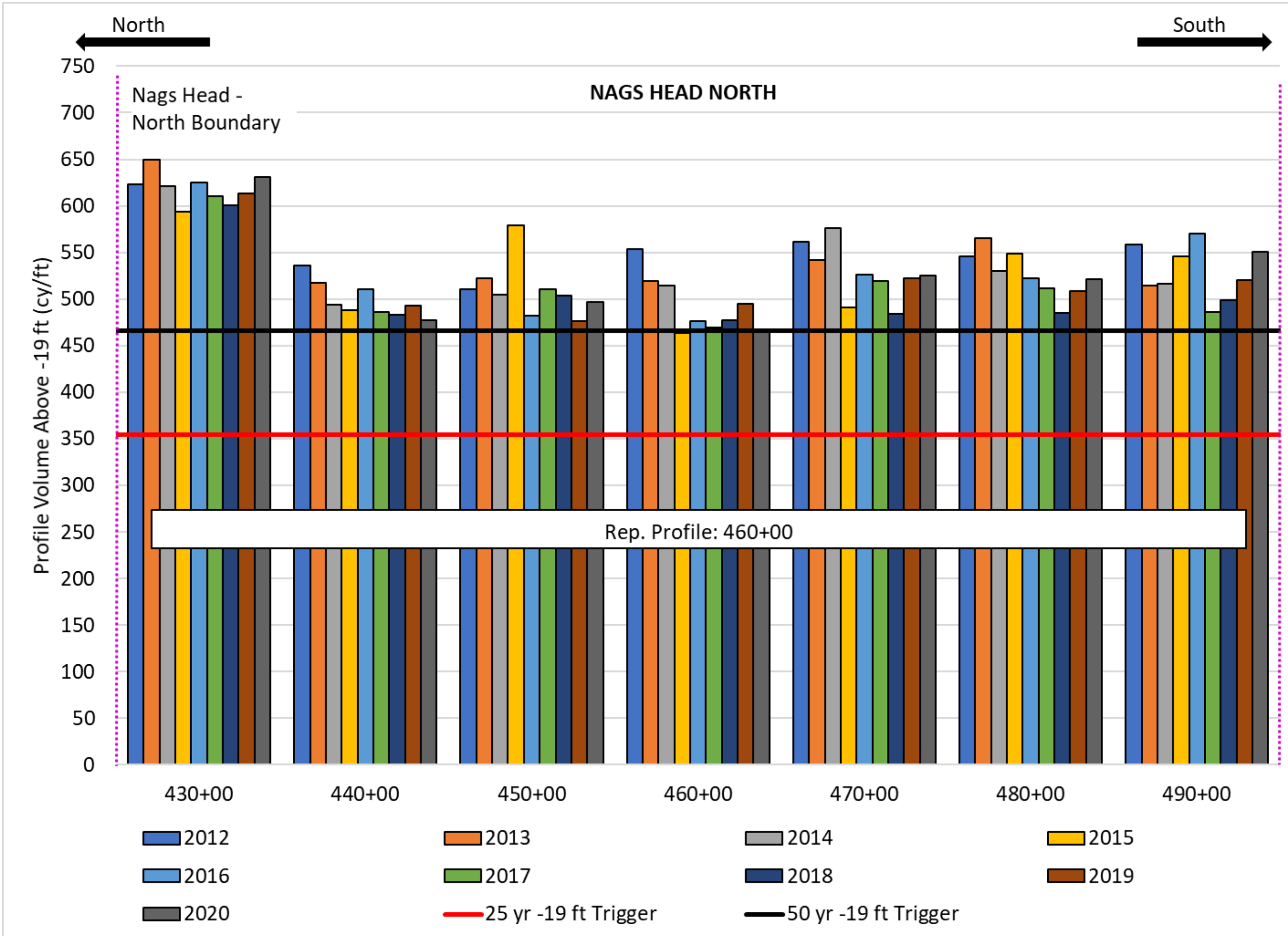


Figure 5-34: Profile Volume Above -19 ft NAVD88 – Representative Profile 460+00 (430+00 – 490+00)

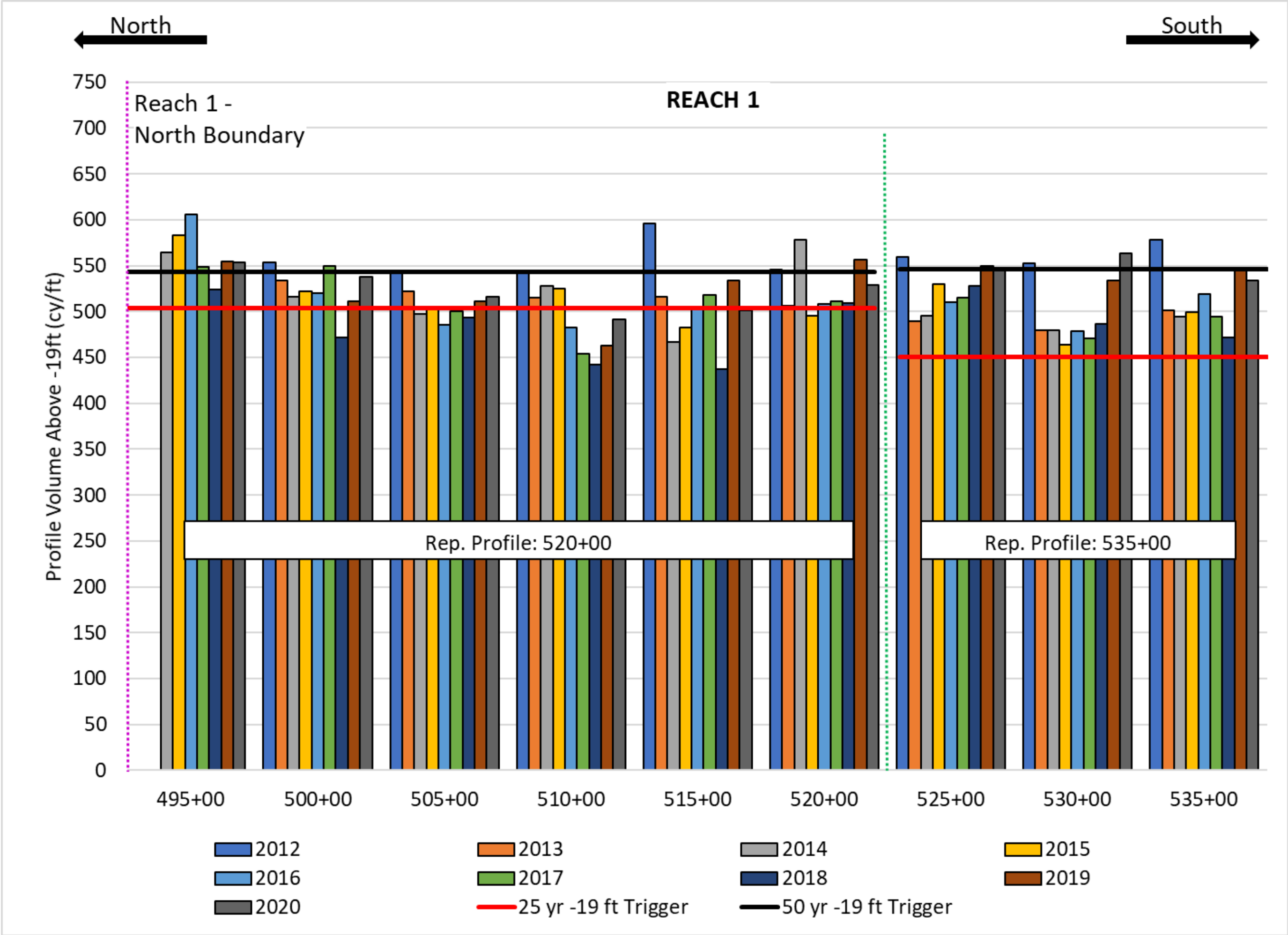


Figure 5-35: Profile Volume Above -19 ft NAVD88 – Representative Profiles 520+00 and 535+00 (495+00 – 535+00)

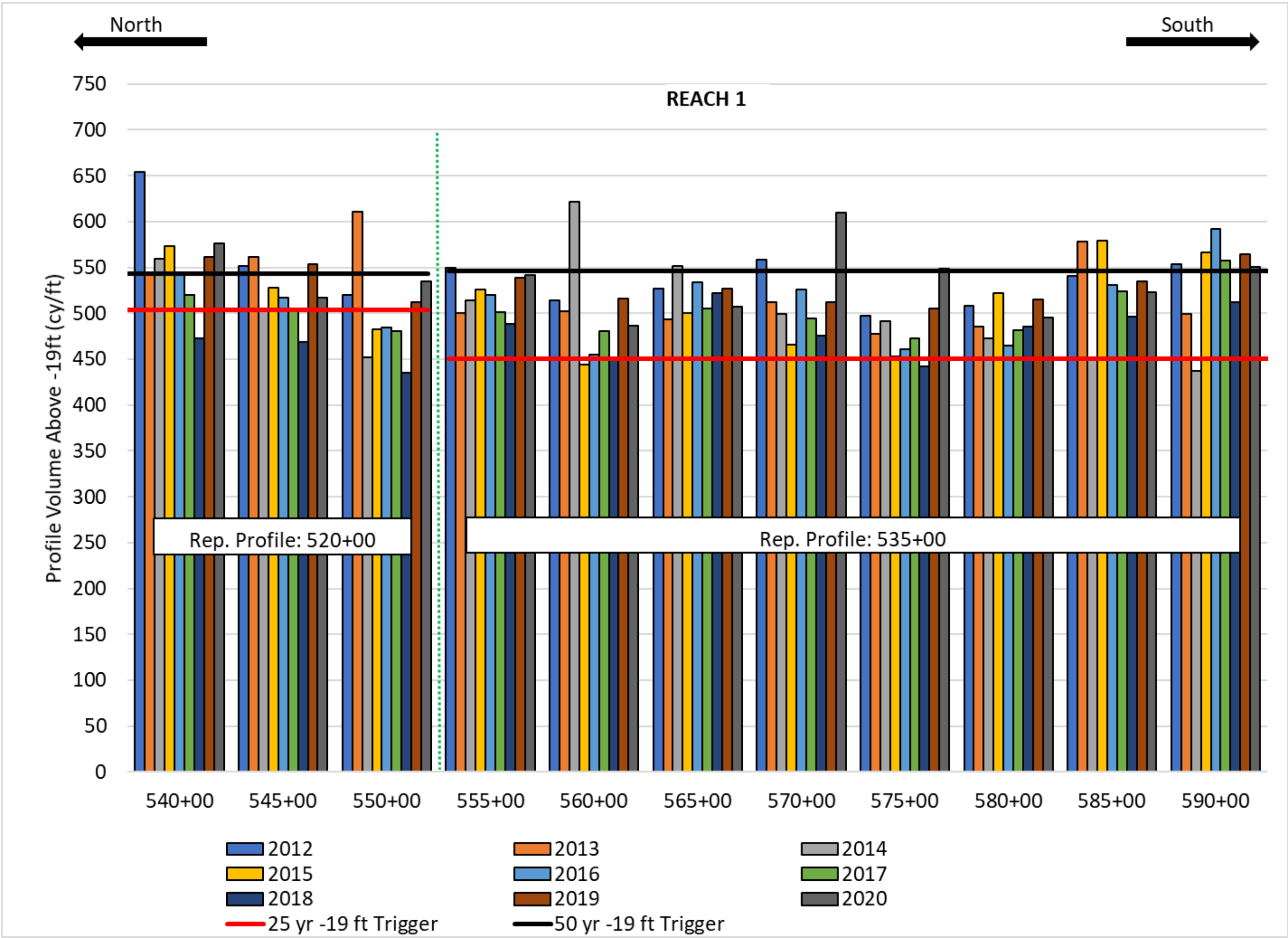


Figure 5-36: Profile Volume Above -19 ft NAVD88 – Representative Profile 520+00 and 535+00 (540+00 – 590+00)

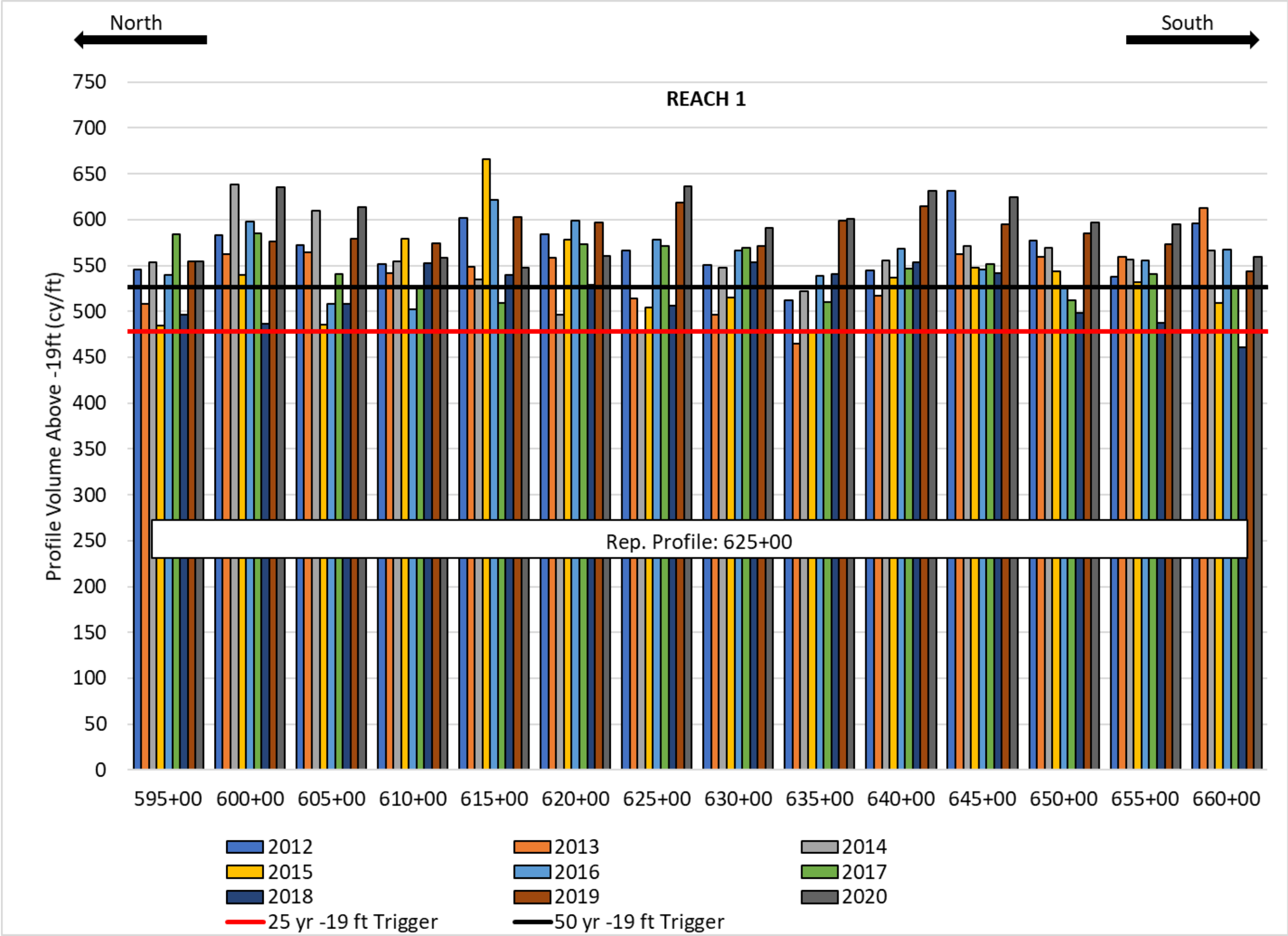


Figure 5-37: Profile Volume Above -19 ft NAVD88 – Representative Profile 625+00 (595+00 – 660+00)

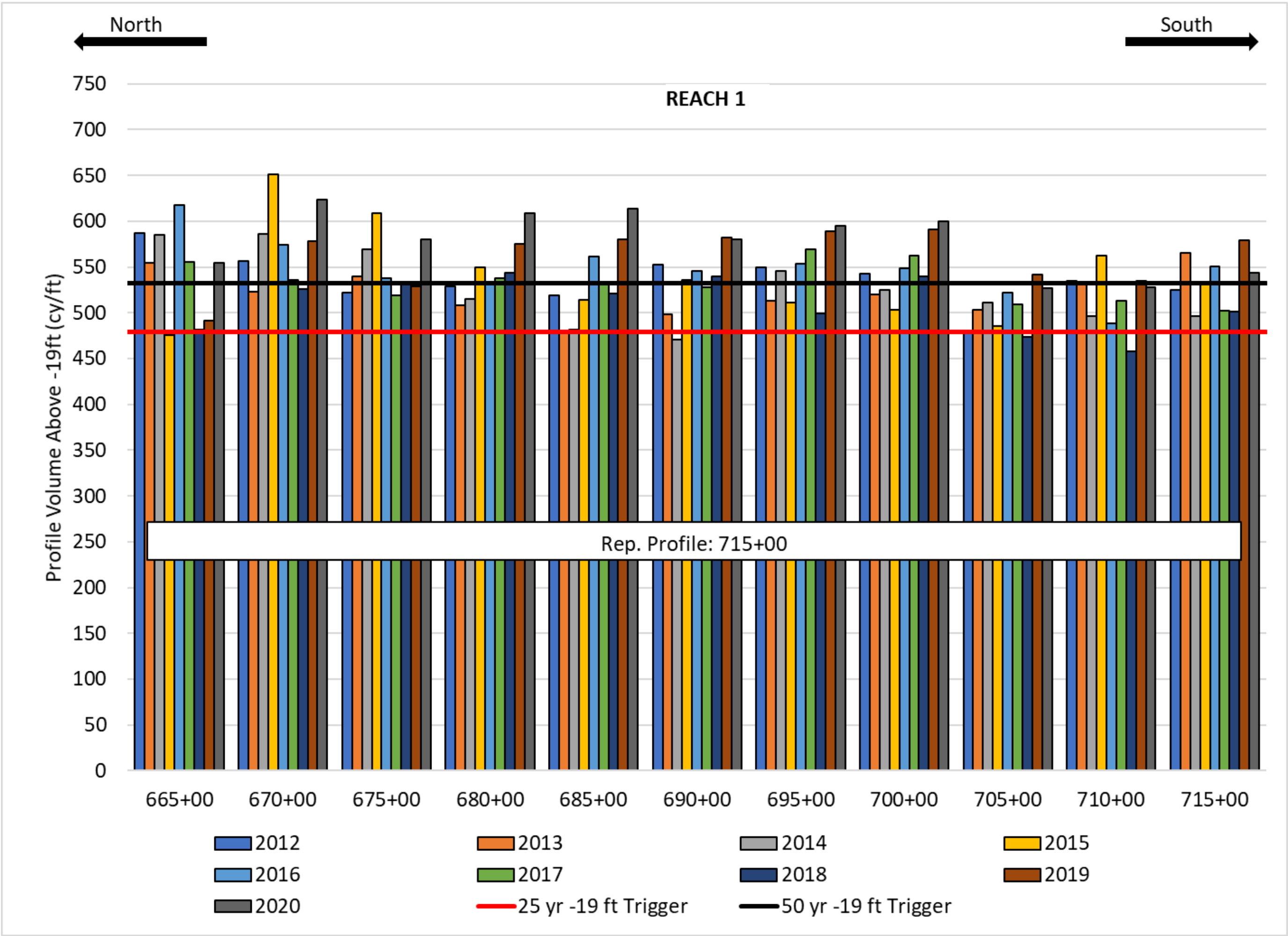


Figure 5-38: Profile Volume Above -19 ft NAVD88 – Representative Profile 715+00 (665+00 – 715+00)

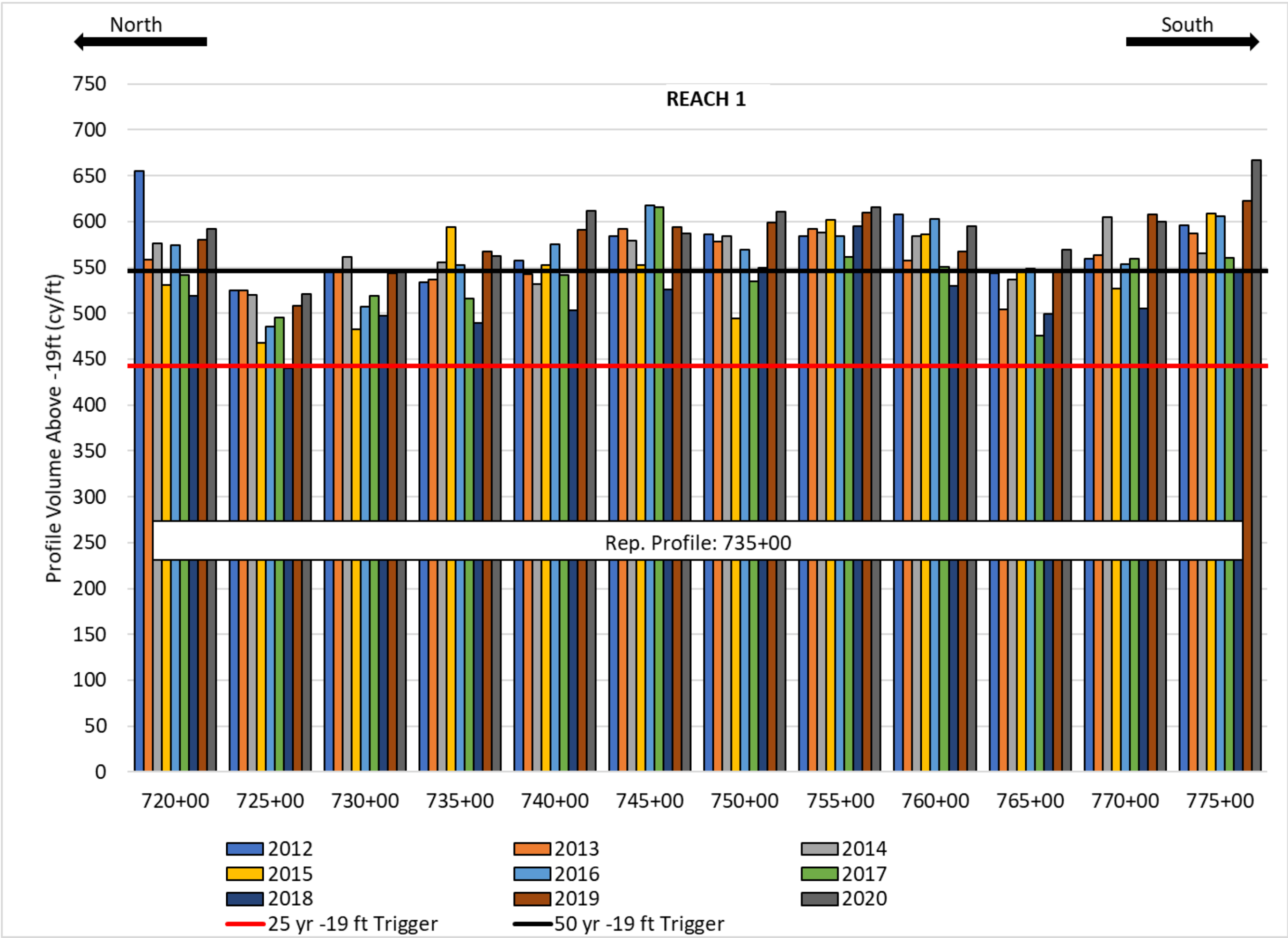


Figure 5-39: Profile Volume Above -19 ft NAVD88 – Representative Profile 735+00 (720+00 –775+00)

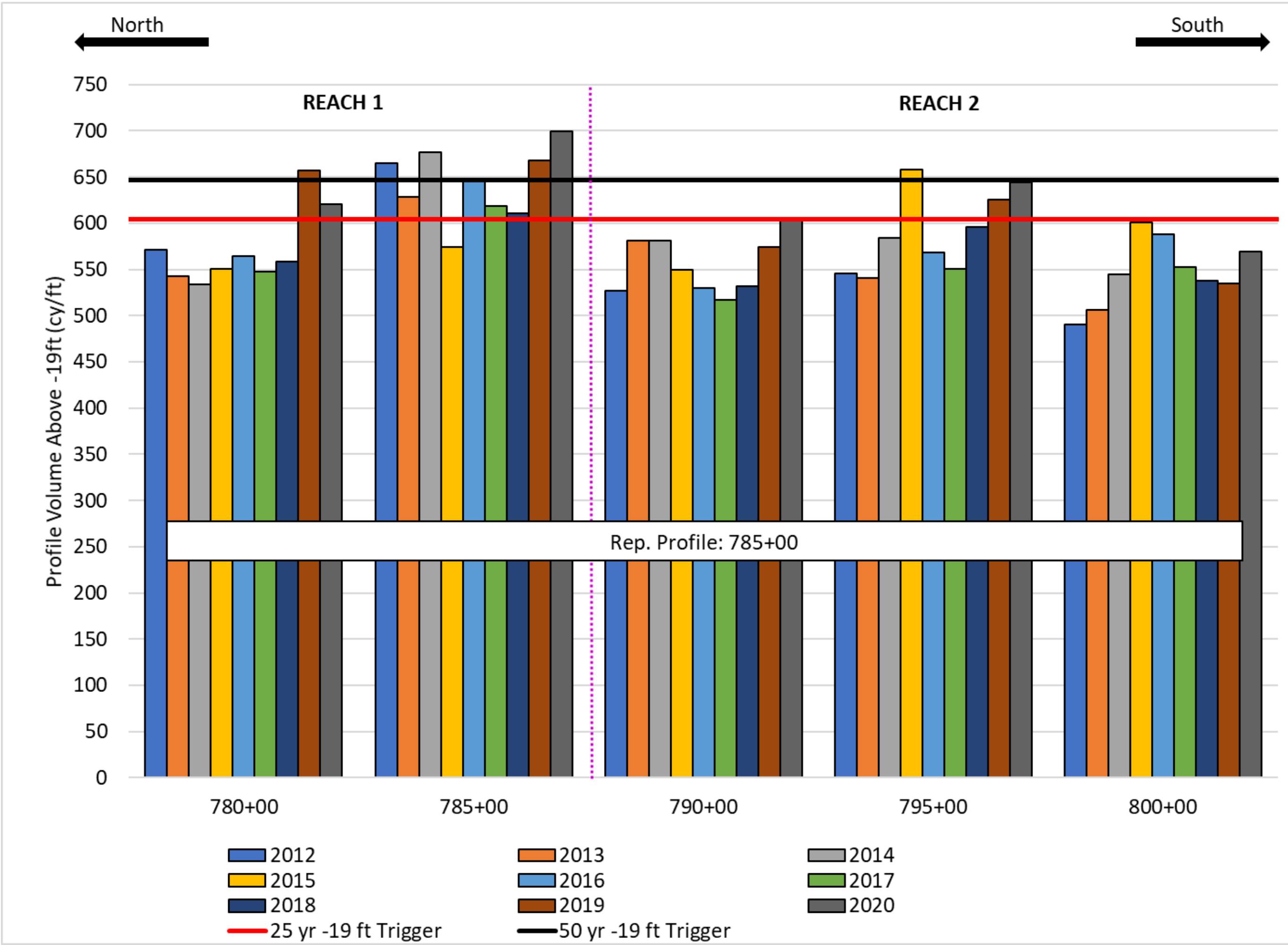


Figure 5-40: Profile Volume Above -19 ft NAVD88 – Representative Profile 785+00 (780+00 – 800+00)

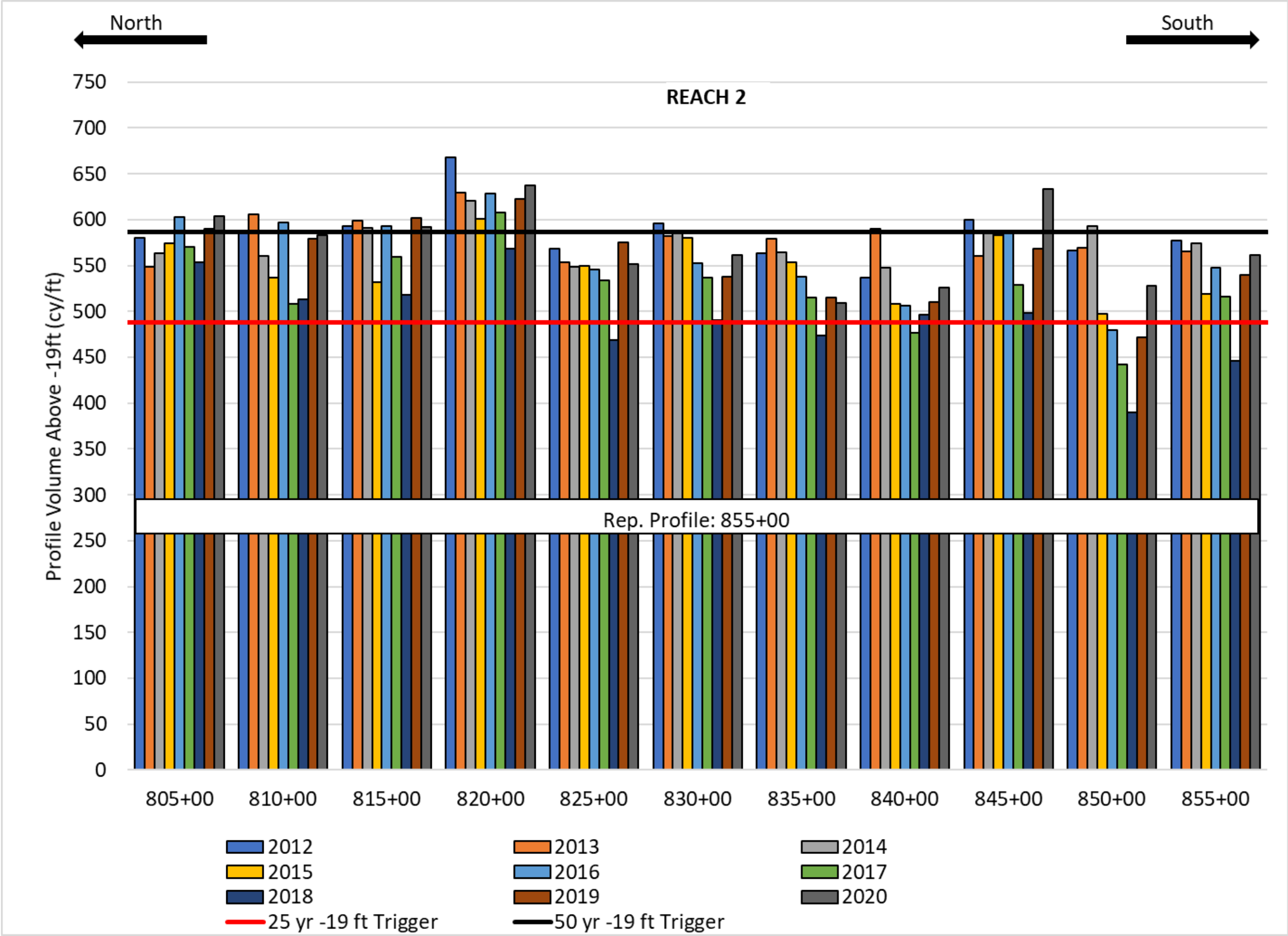


Figure 5-41: Profile Volume Above -19 ft NAVD88 – Representative Profile 855+00 (805+00 – 855+00)

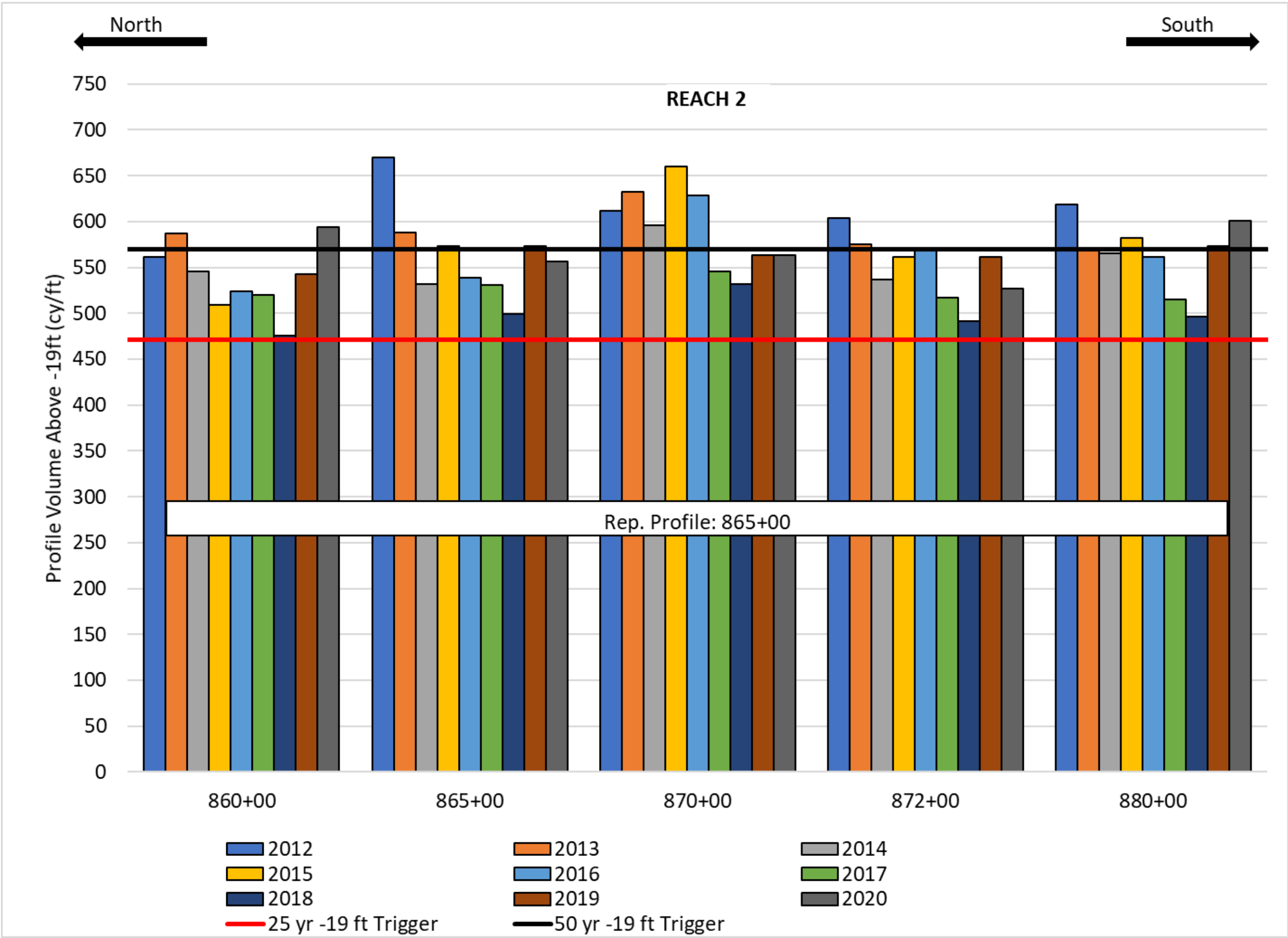


Figure 5-42: Profile Volume Above -19 ft NAVD88 – Representative Profile 865+00 (860+00 – 880+00)

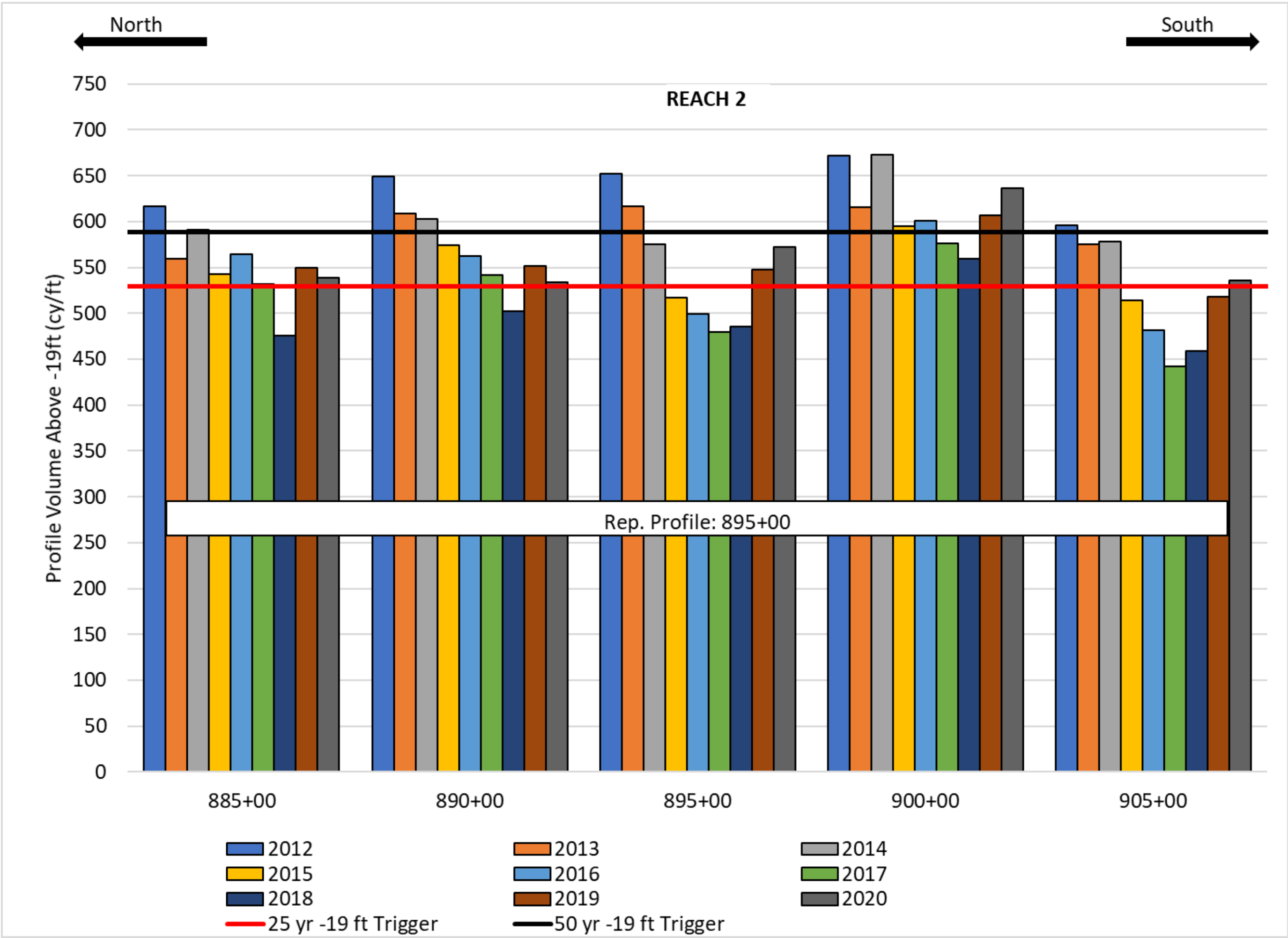


Figure 5-43: Profile Volume Above -19 ft NAVD88 – Representative Profile 895+00 (885+00 – 905+00)

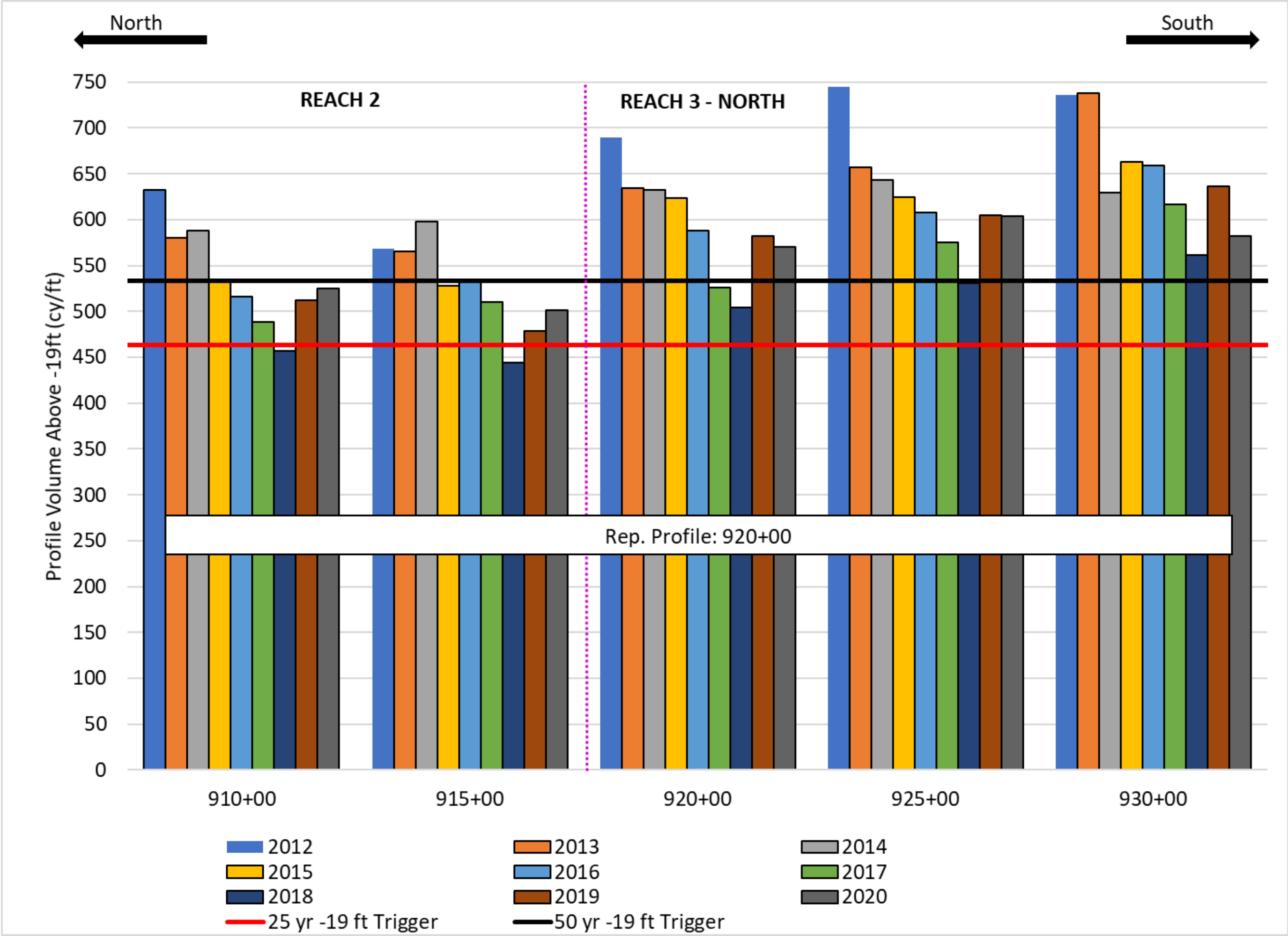


Figure 5-44: Profile Volume Above -19 ft NAVD88 – Representative Profile 920+00 (910+00 – 930+00)

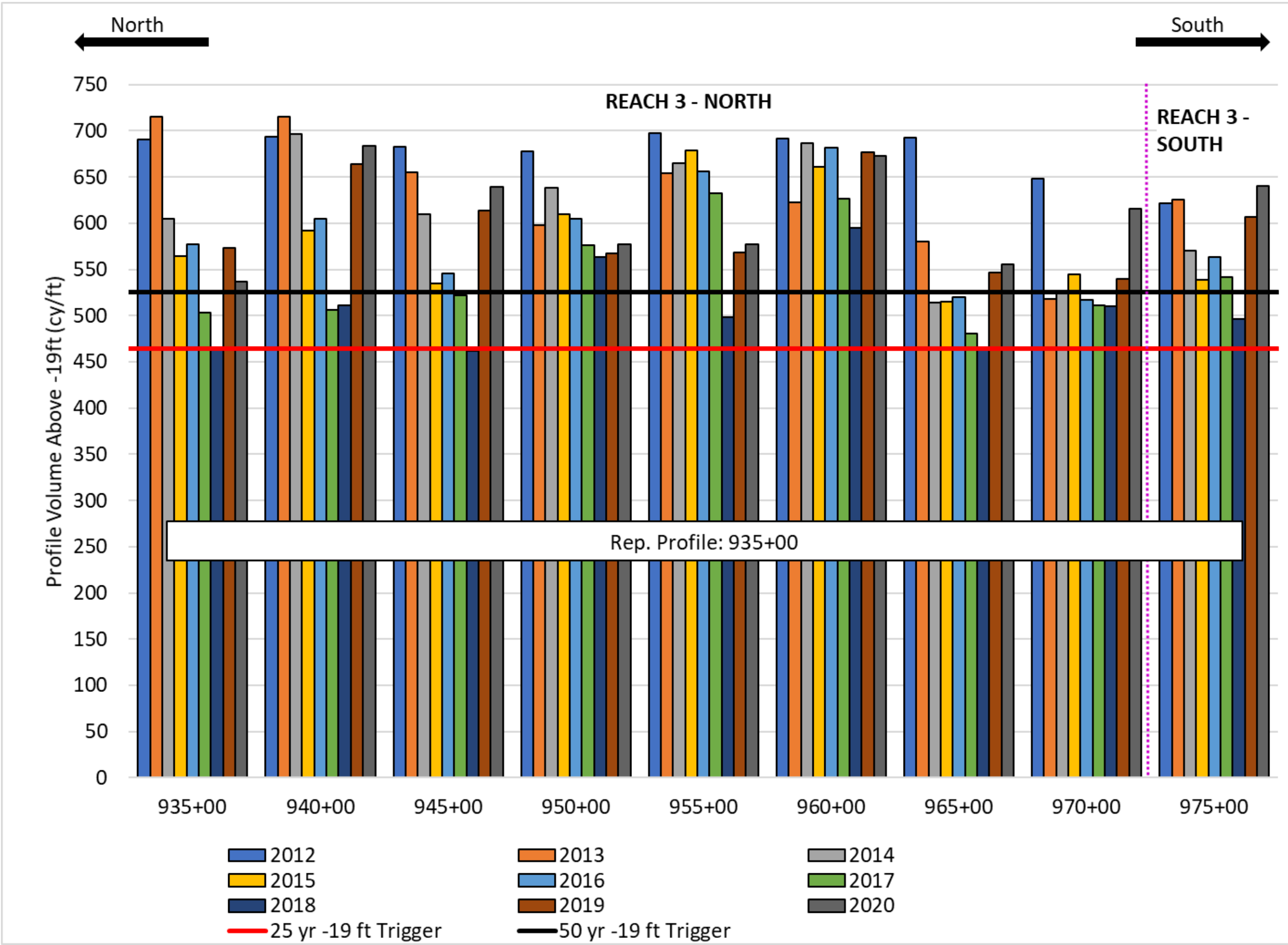


Figure 5-45: Profile Volume Above -19 ft NAVD88 – Representative Profile 935+00 (935+00 – 975+00)

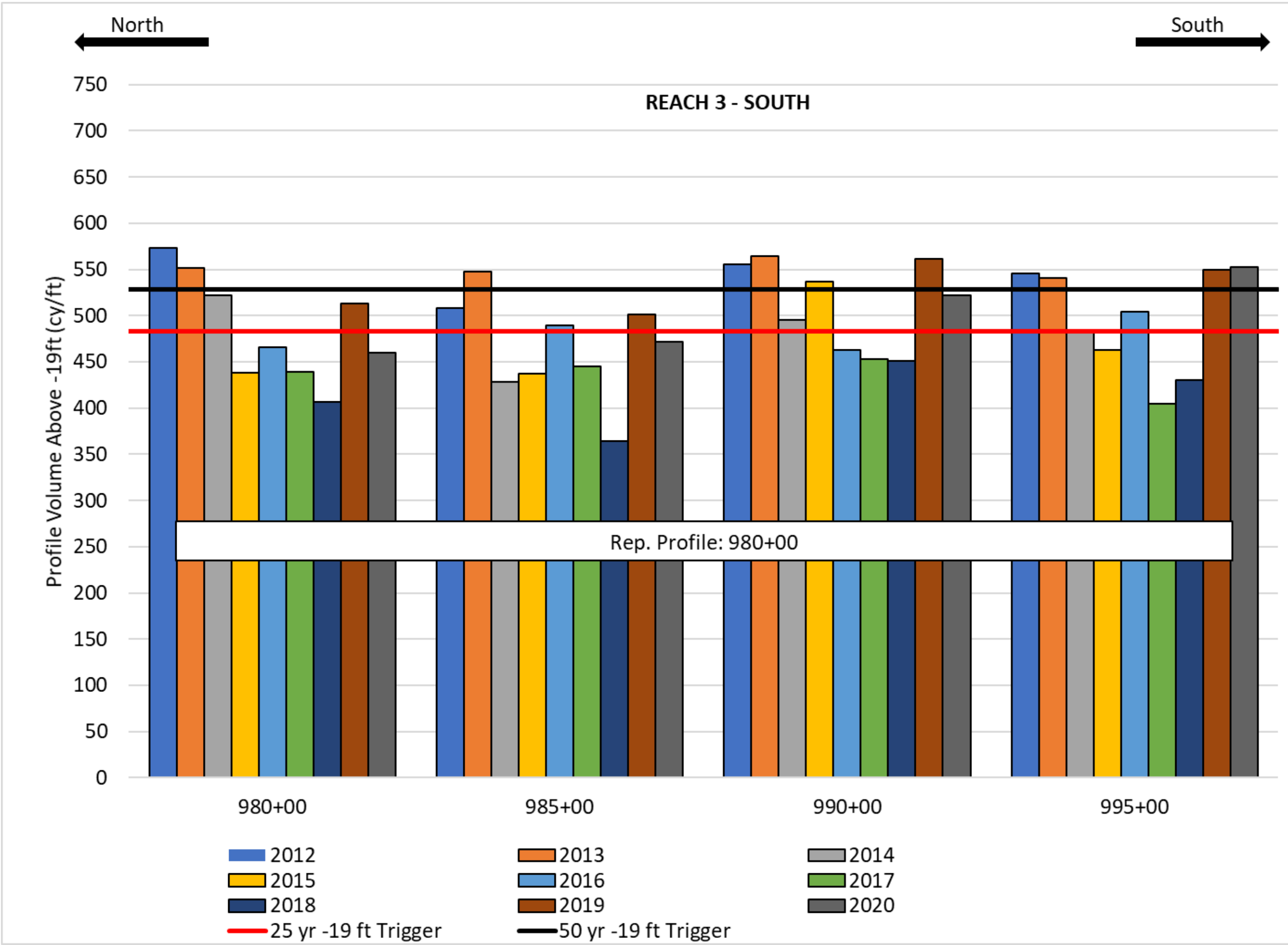


Figure 5-46: Profile Volume Above -19 ft NAVD88 – Representative Transect 980+00 (980+00 – 995+00)

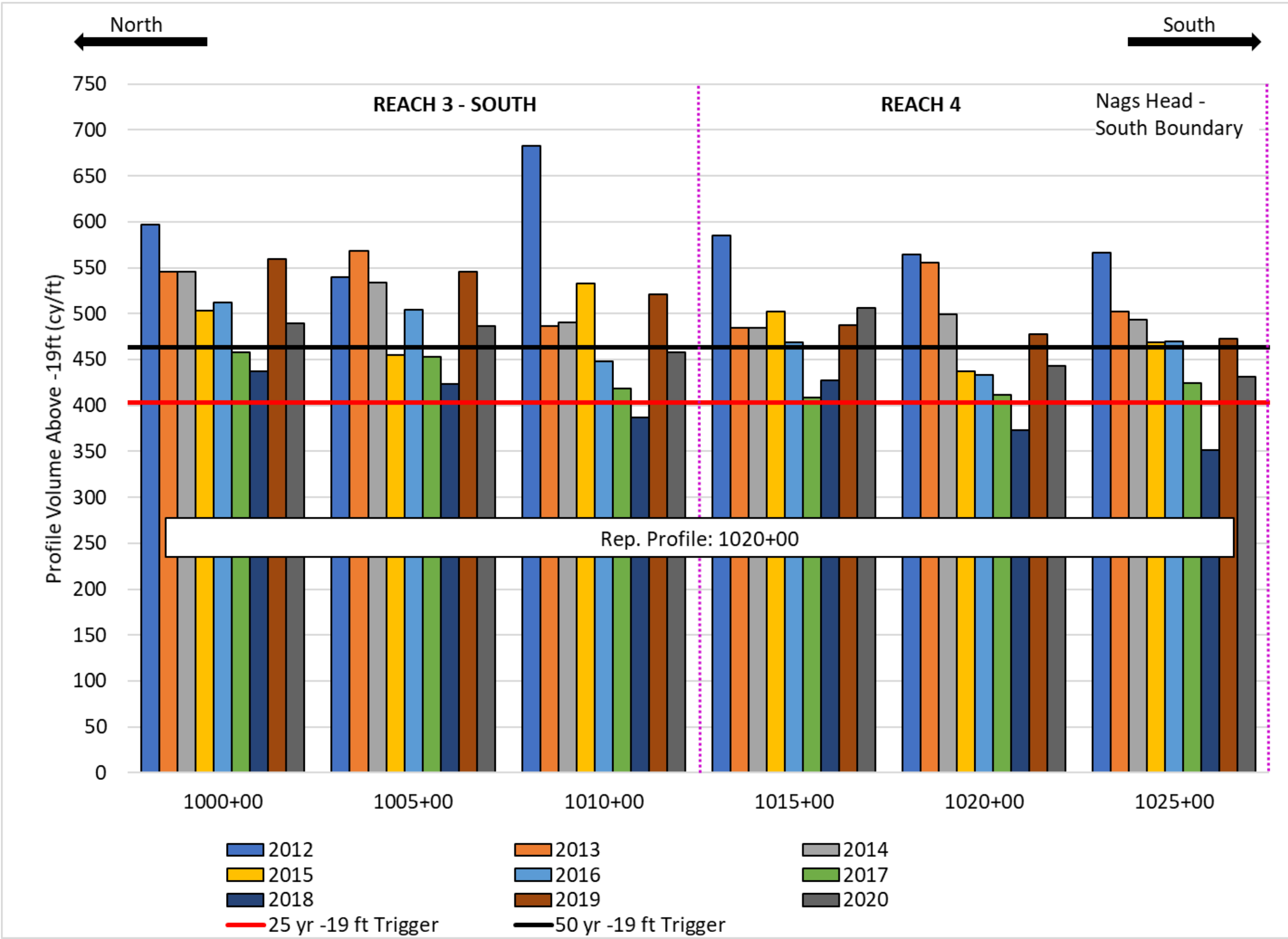


Figure 5-47: Profile Volume Above -19 ft NAVD88 – Representative Transect 460+00 (1020+00 – 1025+00)

5.5.4 Consideration of Sea Level Rise

As discussed in Section 3.2.4, NOAA guidance indicate relative sea level change (RSLC) values ranging from rise of approximately 1 ft to 3 ft in the project vicinity at a point in time 50 years into the future.

The designed dune height, and to a lesser extent the berm height, have been optimized to provide acceptable LoP in a specific design storm return period event. An implication of sea level rise is that the shoreline is expected to retreat in response to the changes in sea level if no action is taken. The dune crest and berm elevations would need to rise by approximately the same amount as relative sea level to maintain an equivalent LoP. An evaluation of the amount of sand volume (V) that would be required to accommodate this required increase in dune crest and berm height and maintain the shoreline position has been performed using the Bruun Rule (Brunn, 1962), Equation 5.1:

$$V = L_{shoreline} \times S \times w_{profile} \qquad \text{Equation 5.1}$$

Where $L_{shoreline}$ is the length of the Nags Head shoreline, S is the amount of sea level rise (SLR) anticipated during the 50-year master plan timeframe, and $w_{profile}$ is the profile width from the dune crest to the -14 ft contour. The analysis has been performed using the representative profiles described in Section 5.1.1. The distance ($w_{profile}$) between the dune crest and the -14 ft NAVD88 contour was measured for each of the profiles and the average value was determined to be approximately 850 ft. RSLR scenarios were determined using the Duck tide gauge location (Section 3.2.4), and adjusted to consider only rise between 2022 and 2072. Equation 5.1 was then used to determine the estimated volume to accommodate this rise. Results are presented in Table 5-8.

Table 5-8: Additional Volumes Needed to Adapt to RSLC Scenarios

Sea Level Change Scenario	2022 RSLR (ft)	2072 RSLR (ft)	2072 RSLR adjusted to 2022 baseline (ft)	$L_{shoreline}$ (ft)	$W_{profile}$ (ft)	Volume (Mcy)
Intermediate Low	0.45	1.86	1.41	59,500	850	2.6
Intermediate	0.45	2.28	1.83	59,500	850	3.4
Intermediate High	0.45	2.95	2.5	59,500	850	4.7

It is noted that changes to the target beach profiles due to sea level change would be made gradually over the project lifetime. The approximate volumes in Table 5-8 are provided for inclusion in planning efforts for sediment need. In practice, monitoring data would be used to adjust individual maintenance renourishments, dune enhancement projects, and post-storm recovery nourishments as needed as time progresses. In this way, the required elevation and volume changes would be achieved progressively over the plan's lifetime.

5.6 Nourishment Trigger Determination

With the 25-yr event selected as the finalized LoP, the nourishment triggers were developed. Table 5-9 shows the various trigger volumes above -19 ft NAVD for both the 25-yr event as well as the amount in place as of May 2018 (pre-nourishment).

Nonetheless, while determination of the individual sub-reach triggers was needed, it would not be practicable to have individual nourishment actions be dictated by a single sub-reach while adjacent sub-reaches would not require sand placement. Therefore, the individual sub-reaches were combined in a weighted average to determine reach-wide triggers as shown in Table 5-9.

Table 5-9: Trigger Volumes Above -19 ft NAVD88 for 25-yr Event

Reach	Length (ft)	Rep. Profile	25-yr Trigger Volume (cy/ ft)	Reach Trigger for 25-yr event (cy/ft) (Weighted)	May 2018 Volume Above -19 ft (cy/ ft)
North	6,250	460+00	355	355	578
Reach 1	4,500	520+00	503	470	509
	5,500	535+00	451		472
	7,000	625+00	478		506
	5,500	715+00	479		501
	6,000	735+00	443		490
Reach 1 / **Reach 2**	2,500	785+00	604		610
Reach 2	5,500	855+00	491	502	446
	2,500	865+00	471		499
	2,500	895+00	526		485
Reach 2 / **Reach 3 - North**	2,500	920+00	463		504
Reach 3 - North	4,500	935+00	464	446	464
Reach 3 - South	2,000	980+00	461		407
Reach 3 - South / **Reach 4**	2,750	1020+00	401		373
TOTAL	59,500			464	

5.7 Long-Term Sediment Volume Need

The volumes from the beach profile statistical analysis presented in 4.2.2 are combined with the initial LoP volume need (Section 5.5.2), and the relative sea level rise need (Section 5.5.4) to develop a long-term sediment volume need, presented in Table 5-10. A relatively high estimate of potential volumetric losses during dredging has also been computed. This volume estimate is considered to be conservative and can be compared with sand volumes available from identified borrow sources to provide assurance that the beach nourishment master plan can be executed successfully.

Table 5-10: Long-Term (50-Year) Sediment Volume Need

Crystal Ball	**Background Erosion 50 years (50%)**	22.5 Mcy		
	Additional Storms (75%)	21.5 Mcy		
LoP (25 year) Design		0.6 Mcy		
Relative Sea Level Rise (NOAA, 2022)		**Intermediate Low**	**Intermediate**	**Intermediate High**
		2.6 Mcy	3.4 Mcy	4.7 Mcy
TOTAL		**46.7 Mcy**	**47.5 Mcy**	**48.8 Mcy**
Assumed 20% losses during dredging		*56.0 Mcy*	*57.0 Mcy*	*58.6 Mcy*

6.0 EVALUATION OF HISTORICAL SHORELINE EVOLUTION

6.1 Purpose and Definitions

In addition to designing nourishment profiles, the predicted life of the nourishment projects and their effect on neighboring stretches of beach must also be determined. Using the knowledge gained from historical monitoring and the cross-shore profile evolution modeling in CSHORE about the LoP required, the longshore behavior of these projects must then be analyzed to fully understand the effect on the system. In order to perform these analyses, an understanding of historical shoreline behavior/evolution is needed.

6.2 Analytical/Empirical Analysis

DCM has developed average long-term rates of shoreline change over approximately 50 years from 1949 to 2016. Figure 6-1 shows the 2020 DCM erosion rates along Nags Head (NCDCM, 2020). It should be noted that these erosion rates inherently include the nourishment activities which took place on the island. Therefore, actual erosion rates are higher than those computed by NCDCM. These erosion rates do provide some insight into shoreline change patterns along the island. The shoreline erosion rate increases from north to south with the most severe erosion occurring at the southern end of the town. This is in agreement with the monitoring data from the past decade.

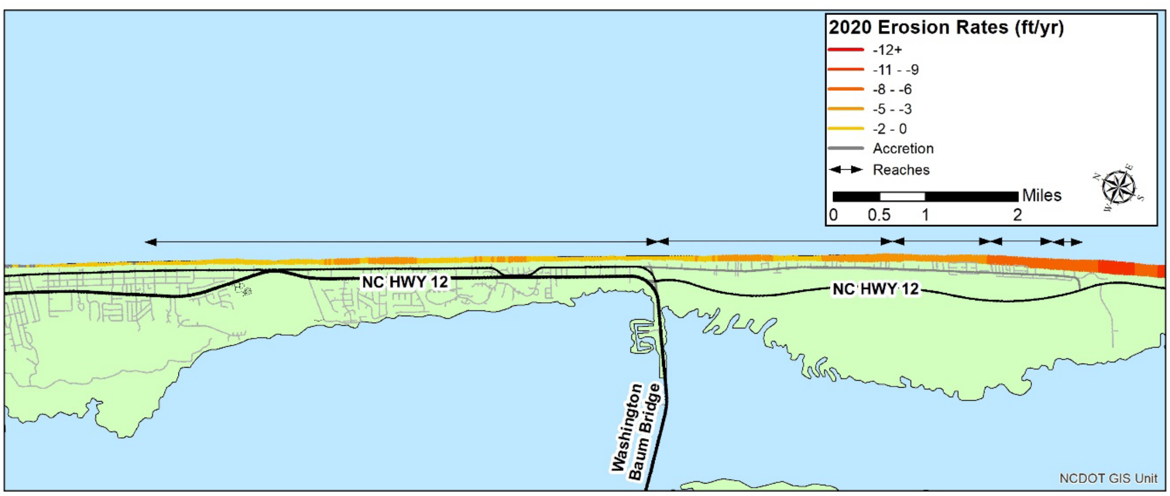


Figure 6-1: NCDCM 2020 Long-Term Erosion Rates

6.3 Numerical Modeling: GenCade

GenCade is a 1-D numerical model that combines the capabilities of GENESIS and Cascade, allowing for engineering design level calculations with the ability to span long, regional segments of shoreline that may contain inlets. GenCade is designed to simulate long-term shoreline change based on spatial and temporal differences in longshore sediment transport induced primarily by wave action. The GenCade modeling system allows for a number of user-specified inputs including wave inputs, initial shoreline positions, coastal structures and their characteristics, beach fills; and inlet system shoal volumes, all of which aid in the calculation of sediment transport and shoreline change. This model was developed at the U.S. Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC), Coastal Inlets Research Program (CIRP). For a more detailed description of the GenCade model, the reader is referred to the GenCade Version 1 Model Theory and User's Guide (Frey, et al., 2012). GenCade operates within the Surface-water Modeling System (SMS), a suite of tools developed by Aquaveo. The software version used is GenCade 1.6 updated July 2015, obtained from CIRP's website (http://cirp.usace.army.mil/products/gencade.php).

The GenCade model has the potential for many applications in the coastal environment, including evaluation of longshore sediment transport, analysis of beach fill performance, or the analysis of the impact of coastal structures on shoreline change.

The main inputs to the GenCade model include:

- Shoreline Position Data – one-dimensional description of the shoreline position relative to a straight baseline position,
- Wave Data – long-term time dependent description of wave heights, periods, and directions applicable to the study srea,
- Coastal Structures – position and characteristics of coastal structures (breakwaters, groins, jetties, or seawalls) acting along the study area,
- Beach Fill – starting and ending dates and location of beach fill defined by an added berm width,
- Inlet Shoal Volumes – Ebb, Flood, Left Bypass, Left Attachment, Right Bypass, and Right Attachment
- Sediment and Beach Characteristics – effective grain size, average berm height, and closure depth for the study area,
- Regional Contour – an offshore contour to account for bathymetry which may affect wave direction/energy
- Boundary Conditions – seaward boundary conditions for the input wave data and lateral boundary conditions for the shoreline (left and right).
- Sediment Transport Parameters – used to characterize longshore sediment transport and calibrate the model.

6.3.1 Modeling Scope

Application of the GenCade model enhances the understanding of historical longshore sediment transport and erosional patterns along the Nags Head study area. It also provides additional information to evaluate shoreline stabilization and restoration alternatives.

To establish the appropriate model parameters, the GenCade model was calibrated and validated for the June 2015 to April 2019 time period using historical Mean Sea Level (MSL) shoreline positions from periodic survey evaluations and coinciding wave data transformed to nearshore from the offshore wave data. GenCade is primarily calibrated by adjusting the longshore sand transport coefficients (K_1 and K_2). Additionally, the model may be calibrated by adjusting the characteristic transmissivity or permeability of offshore breakwaters, groins, or jetties, where applicable. Furthermore, boundary condition parameters (e.g. smoothing, wave input adjustments) may be altered to achieve calibration, or to test the model sensitivity. An offshore regional contour may also be incorporated to account for any bathymetric features that may impact wave direction and energy along the shoreline.

Once a calibrated model was developed, the model was run for a verification time period from June 2012 to June 2016. This verification time period included Hurricane Sandy and an absence of multiple engineering projects, ensuring that the model performed correctly during large gaps in between nourishment intervals. Shoreline positions from the periodic survey evaluations were used in conjunction with wave data transformed to nearshore from the offshore wave data.

The GenCade model coverage extended from Nags Head – north end (Station 460+00) to south of Nags Head (Station 1080+00).

6.3.2 Calibration Model

The GenCade model was calibrated to reflect the historical trends of longshore sediment transport and the resulting shoreline change over the study area. The overall calibration time period was based on the availability of quality measured shoreline data and measured wave gauge data.

For this study, the general calibration procedure involved:

- establishing known model inputs including shoreline position, waves, locations of structures, sediment and beach characteristics, and boundary conditions,

- establishing initial sediment transport parameters and adjusting these parameters until the relative shoreline response (erosion/accretion) and sediment transport rates matched historical trends, and

- adjusting the regional contour to account for bathymetric influences on targeted areas of shoreline (erosion hotspots).

This calibration sequence was followed using known inputs and default initial parameters. Then, particular input parameters (sediment transport parameters, smoothing, wave input adjustments etc.) were revisited and the sensitivity of the model response to changes in these parameters was tested. In many cases, a given parameter was adjusted to yield a more accurate shoreline response. The final determined input data for the calibration model is presented in the following sections. Neither beach nourishment nor coastal structures were present during the calibration time period.

Shoreline Position Data

For shoreline input, the GenCade model requires the shoreline be specified in a station-offset formulation whereby the station represents a position along a landward baseline and the offset is the perpendicular distance from this baseline to the shoreline. The initial shoreline used in the GenCade model was the June 2015 MSL shoreline, based upon the CSE June 2015 survey. The final reference shoreline to which the model was calibrated was the April 2019 shoreline, based upon the CSE 2019 pre-nourishment survey.

Wave Data

The wave transformation study was conducted utilizing the MIKE 21 Spectral Waves (SW) model (DHI, 2014) to calculate wave conditions approaching the beach of Town of Nags Head, NC. MIKE 21 SW simulates the growth, decay and transformation of wind-generated waves and swells in offshore and nearshore coastal areas. The MIKE 21 SW model discussed in Appendix A was used to transform the offshore time series of waves from the relatively deep water NDBC stations to nearshore positions at Nags Head. The model simulated nearshore wave conditions were extracted at 12 stations with approximate depths of -33.0 ft NAVD88 along the shoreline. The nearshore wave data, which include both storm and non-storm wave conditions, were utilized as representative wave conditions to evaluate long-term shoreline changes.

For the long-term wave transformation simulations, NDBC 44095 measured wave data was used for the open boundary conditions. The wave transformation model was run for the period of 2012 to 2019.

Sediment and Beach Characteristics

The selected effective grain size assumed in the GenCade model was 0.35 mm. This grain size was determined based on analysis of measured sediment data collected and analyzed by CSE (2005).

The average berm height was defined as +7 ft NAVD88 and the closure depth was set to -15 ft NAVD88. These values were determined based on observations of measured survey data during the calibration and verification time period from the ongoing periodic surveys.

Sediment Transport Parameters

Longshore sediment transport is characterized by the transport parameters K_1 and K_2 in GenCade. The transport rate coefficient, K_1, is used to control the time scale and magnitude of the simulated shoreline change, while K_2 is used to control shoreline change and longshore sand transport in the vicinity of structures. Although the values of K_1 and K_2 have been empirically estimated, these coefficients are treated as calibration parameters in GenCade and range in value from 0 to 1.0.

The calibration models were initially run with the default K_1 and K_2 coefficients, where $K_1 = 0.5$ and $K_2 = 0.25$. The resulting April 2019 model shoreline was compared with the measured April 2019 shoreline and the coefficients were adjusted to achieve the closest match in the model results and the measured shoreline position. Through this procedure, it was determined that slightly decreasing the K_1 value resulted in shoreline response which was most indicative of historical patterns. The final calibration transport coefficient values were chosen to be $K_1 = 0.3$ and $K_2 = 0.25$.

Regional Contour

The regional contour is one of the many adjustment tools within GenCade that allows the model to more realistically represent the behavior of the prototype shoreline. The use of a regional contour allows the modeler to specify the underlying shoreline shape that the model will evolve towards, rather than having the model evolve toward a straight line. It is the result of all the large-scale, alongshore forcing-function non-homogeneities and underlying geology that are not accounted for in GenCade and that, in combination, cause the real-world shoreline to attain a non-straight, long-term equilibrium planform shape. A regional contour was applied in the current model study. The regional contour was initially developed based on initial shoreline and fine-tuned during the calibration.

Boundary Conditions

The required boundary condition inputs for GenCade include the seaward wave data boundary conditions and the lateral boundary conditions at the left (north) and right (south) ends of the shoreline as described following.

Seaward Boundary Conditions

Within the seaward boundary conditions, the user may modify the input wave conditions (wave height and direction) by factors to analyze the impact changes in modeled wave conditions have on the resulting shoreline response. During calibration it was determined that the input wave height and wave angle derived from the MIKE 21 SW model results were representative of nearshore conditions and were used without modification.

Lateral Boundary Conditions

The north (left) boundary of the model was established at north of the historical nourishment area of Nags Head where a moving boundary of -3.7 ft/yr was established based on the initial and reference shoreline position data.

The south (right) boundary of the model was located south of Nags Head town limits. It was determined that due to the historical erosion, a moving boundary of -18.3 ft/yr would be appropriate.

Calibration Model Results

Multiple GenCade model runs were completed to achieve a reasonably calibrated model. The GenCade model calibration parameters are presented in Table 6-1.

Table 6-1: Calibrated GenCade Model Setup Parameters

No.	Parameter Name	Value
1	Cell size	40 ft
2	Grain size	0.35 mm
3	Average berm height	7 ft
4	Closure depth	15 ft
5	Longshore sand transport coefficient, K1	0.3
6	Longshore sand transport coefficient, K2	0.25
7	Lateral boundary for North boundary	Moving (-3.7 ft/yr)
8	Lateral boundary for South boundary	Moving (-18.3 ft/yr)

Shoreline Change

Figure 6-2 illustrates the comparisons between the observed (solid blue line) shoreline changes at each survey transect and model simulated shoreline changes (solid red line) at the MSL water location between June 2015 and April 2019. In general, the simulated shoreline changes are in reasonable agreement with the observed shoreline changes at most locations along the Nags Head beach between June 2015 and April 2019.

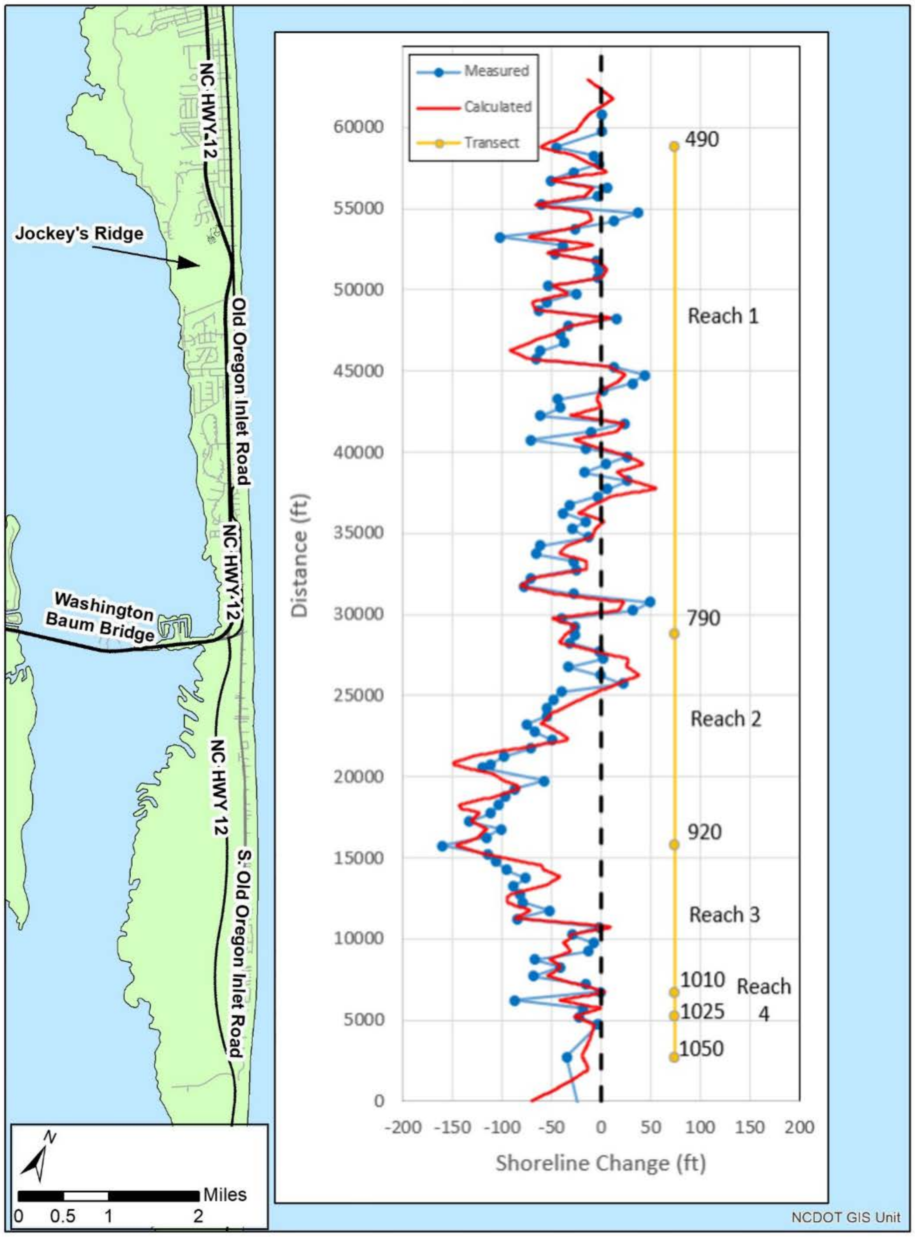


Figure 6-2: GenCade Calibration – Comparison of Model Simulated and Measured Shoreline Changes (Model Calibration, Jun. 2015 to Apr. 2019)

Longshore Sediment Transport

The calculated net longshore sediment transport rates between June 2015 and April 2019 are illustrated in Figure 6-3. In Figure 6-3 the positive sediment transport is from north to south, and the negative sediment transport is from south to north. The shoreline model simulated net longshore sediment transport rates are between approximately -200,000 cy/yr (sediment transport to north) and 240,000 cy/yr (sediment transport to south) between June 2015 and April 2019. Note that a reversal of transport direction is modeled within Reach

2, where north of this location sediment transport is to the north, and south of this location sediment transport is to the south.

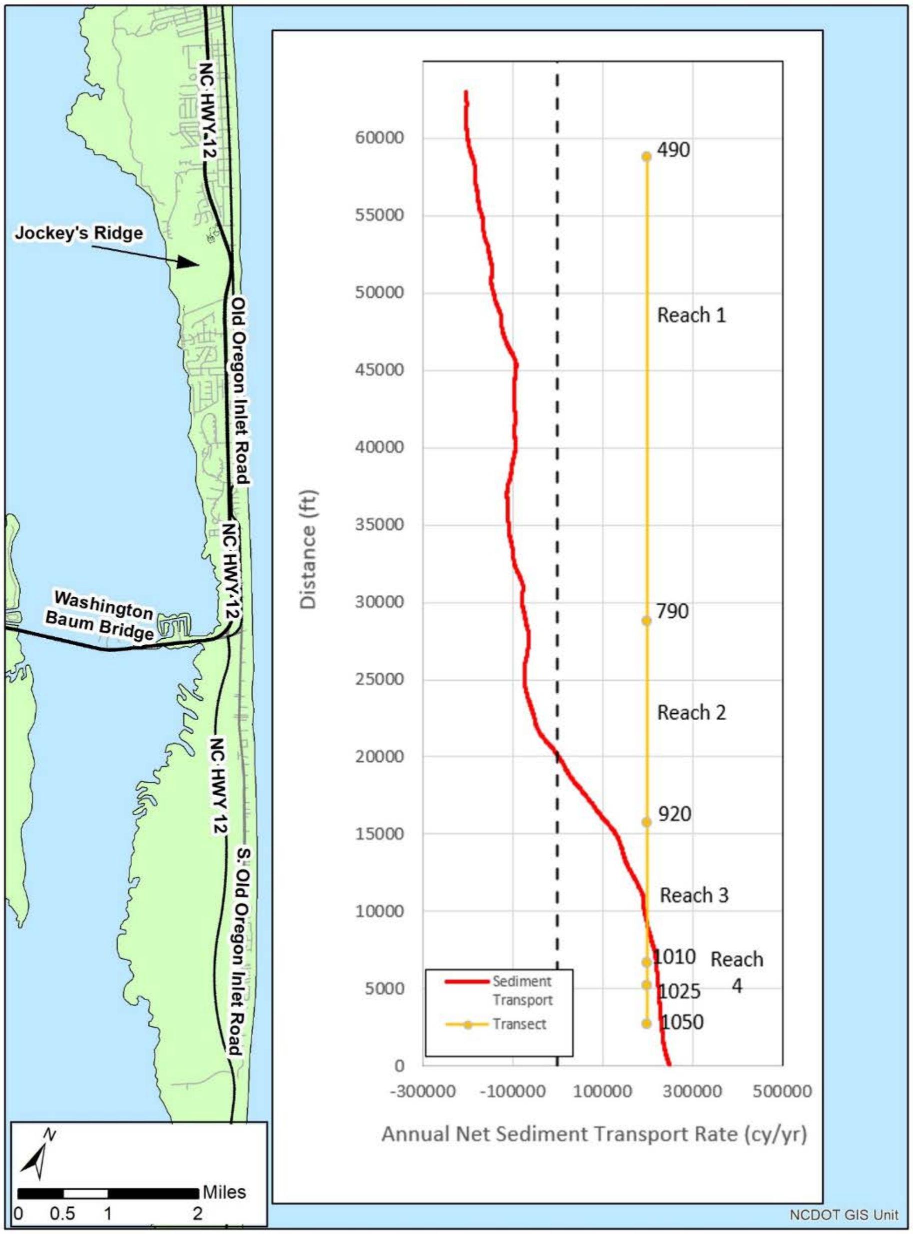


Figure 6-3: GenCade calibration – Calculated Net Longshore Sediment Transport Rates (Jun. 2015 to Apr. 2019)

6.3.3 Model Validation

To validate the shoreline response in GenCade based on the calibration coefficients chosen during the calibration process, a validation model was set up from June 2012 through June 2016. Only input shorelines, beach fills, wave data, and boundary conditions were varied from the calibration model to reflect the new time period being modeled. All structures, beach characteristics, and sediment transport parameters were held consistent with those used in the calibration model (Table 6-1**)**.

Shoreline Position Data

The initial shoreline used in the GenCade model validation was the June 2012 MSL shoreline, based upon the CSE June 2012 survey. The final reference shoreline to which the model was validated was the June 2016 shoreline, based upon the CSE 2016 annual monitoring survey.

Wave Data

As with the calibration model, MIKE 21 SW model (Appendix A) was used to transform the offshore time series of waves from the NDBC station to nearshore positions to develop a wave time series from June 2012 to June 2016. The nearshore wave data were then extracted at 12 stations with approximate depths of -33.0 ft NAVD88 along the shoreline to be used in GenCade validation.

Boundary Conditions

As mentioned previously, the required boundary condition inputs for GenCade include the seaward wave data boundary conditions and the lateral boundary conditions at the left (north) and right (south) ends of the shoreline. The boundary conditions for model validation were the same as those in the calibration model.

Validation Model Results

Figure 6-4 illustrates the comparisons between the observed (solid blue line) shoreline changes at each survey transect and model simulated shoreline changes (solid red line) at the MSL location between June 2012 and June 2016. The simulated shoreline changes are in reasonable agreement with the observed shoreline changes at most locations along the Nags Head beach between June 2012 and June 2016.

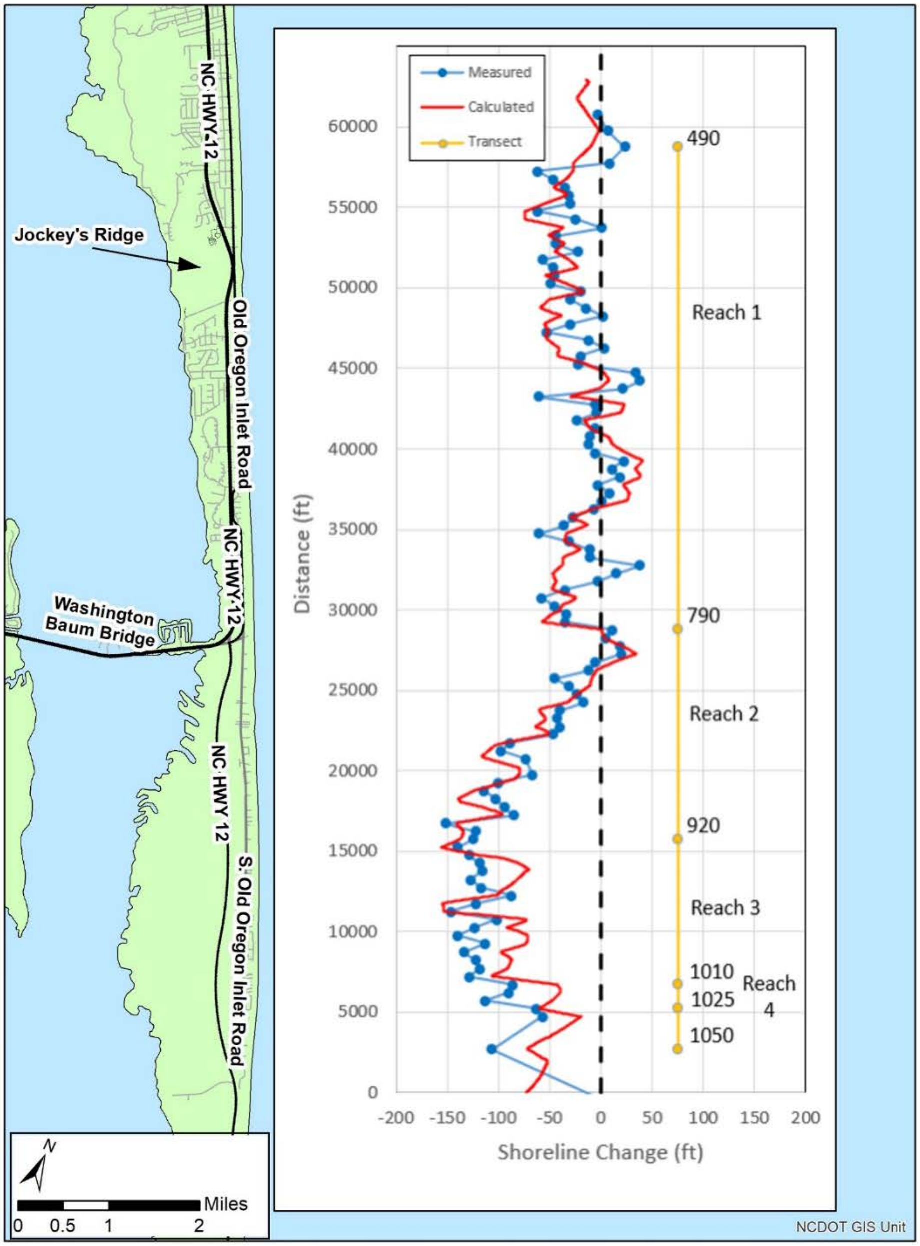


Figure 6-4: GenCade validation - Comparison of Model Simulated and Measured Shoreline Changes (Model Validation, Jun. 2012 to Jun. 2016)

The calculated net longshore sediment transport rates between June 2012 and June 2016 are illustrated in Figure 6-5. The shoreline model simulated net longshore sediment transport rates are between approximately -100,000 cy/yr (sediment transport to north) and 450,000 cy/yr (sediment transport to south) between June 2012 and June 2016. For this time period, a reversal of transport direction is modeled within Reach 1, where in the northern part of Reach 1, sediment transport is to the north, and south of this location sediment transport is to the south.

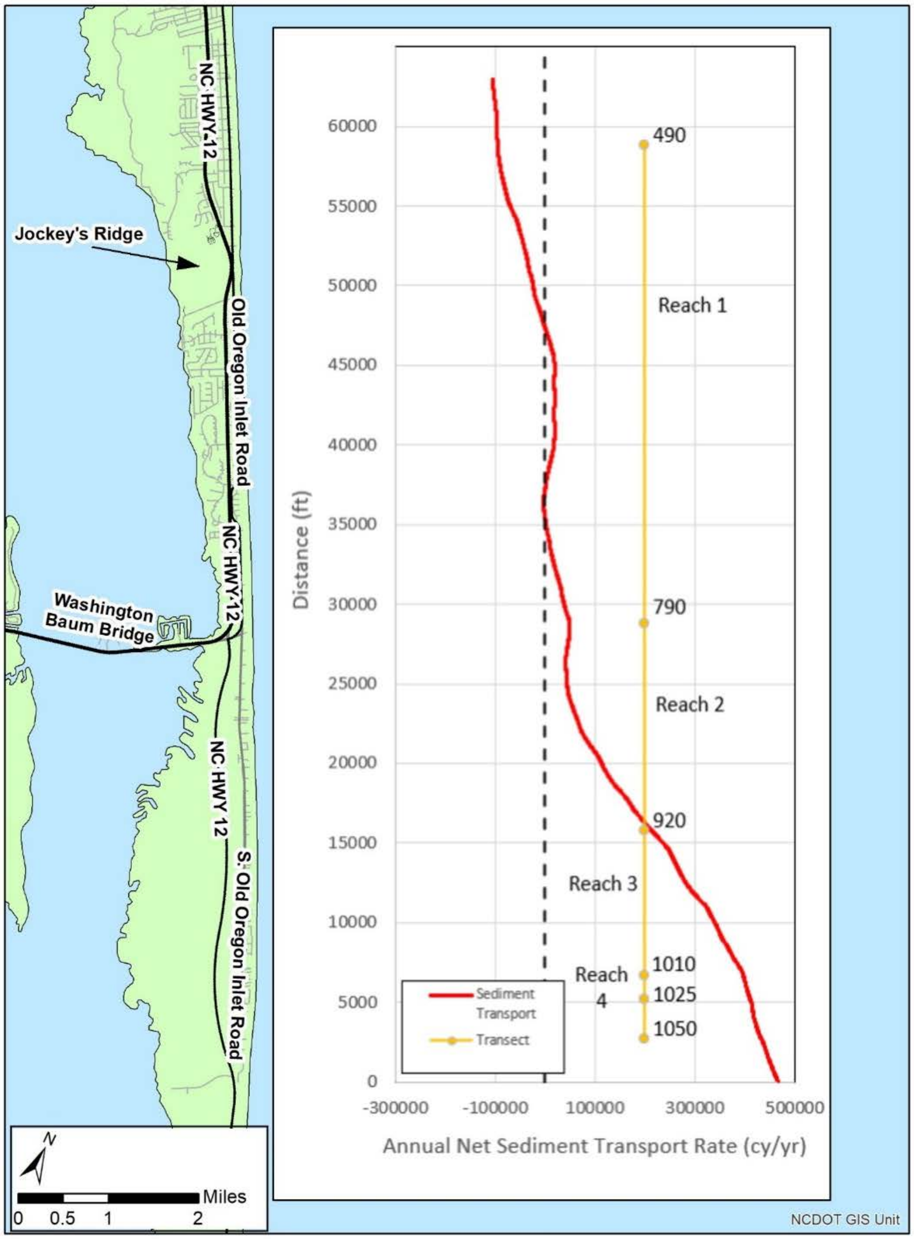


Figure 6-5: GenCade validation - Calculated Net Longshore Sediment Transport Rates (Jun. 2012 to Jun. 2016)

7.0 ENGINEERING ALTERNATIVES CONSIDERED

This chapter provides an evaluation of various alternatives aimed at managing the Nags Head shoreline. By examining the benefits, costs, and disadvantages associated with each option, this analysis equips decision-makers with crucial information necessary to establish a robust management framework for the town's shoreline over the next 50 years.

7.1 No Action: No Further Beach Nourishment

The Town of Nags Head has conducted four beach and dune nourishment projects along the Nags Head oceanfront since 2004 as described in Section 3.7, with approximately 9.5 Mcy of sand placed on Nags Head. In order to evaluate the consequences of discontinuing beach nourishment, a numerical modeling analysis was completed using the calibrated and validated model described in Section 6.3 to develop a forecast shoreline position for the 50-year planning horizon.

This numerical modeling forecast began with the most-recent surveyed shoreline dated May 2022. Because the future wave conditions are unknown, modeled past wave conditions from 2012-2019 repeated consecutively for the 50-year time frame were used as an approximation of likely future conditions. The resulting modeled shoreline was then imported into ArcGIS and compared with structure locations along the length of the town's shoreline. Modeled shoreline recession ranged from approximately 4 ft/yr at the northern end of Reach 1 to 18 ft/yr at the southern end of Reach 4. The land value, building value, and miscellaneous value of the impacted parcels were totaled to estimate the potential value of damage that could occur if no nourishment activities were performed. Structures, and their associated parcels, were considered impacted if the modeled 50-year shoreline came within 20 ft of the main structure footprint. According to rule 15A NCAC 07H.0308(a)(2), NC DCM considers a structure imminently threatened if "its foundation, septic system, or right-of-way in the case of roads is less than 20 feet away from the erosion scarp". Based on this analysis, approximately 1330 parcels were impacted, containing a total value of $805 million, which constitutes approximately 21% of the total property value of the Town of Nags Head. Table 7-1 presents a summary of the values.

Table 7-1: Value of Impacted Parcels

Value Type	Value Amount ($)
Land Value	$453,790,300
Building Value	$331,614,300
Misc. Value	$19,816,900
Total	**$805,221,500**

In addition to the actual land and building values, the Town would incur losses to annual property tax collections. The current tax structure imposes a 0.3300 tax rate for the Town of Nags Head with an additional 0.1430 tax rate to oceanfront homeowners. A further 0.005

tax rate is assessed to homeowners in the northern portion of the Town that does not receive as much nourishment and a 0.010 tax rate to homeowners in the southern portion of the Town that typically receives more nourishment. It is estimated that based on the impacted parcels, potential losses to annual property tax could reach $3.9 million. It should be noted that Nags Head makes up approximately 18% of the property tax base for Dare County. Any impacts to property values and tax collections would likely resonate throughout the County as well. Table 7-2 presents a summary of the property tax values.

Table 7-2: Property Tax Values

Tax Description	Tax Rate	Tax Amount
Town of Nags Head	0.330	$2,657,231
Beach Nourishment - Oceanfront	0.143	$1,151,467
Beach Nourishment – North	0.005	$40,261
Beach Nourishment - South	0.010	$80,522

It should also be considered that a well-maintained beach has a large economic impact on the Town of Nags Head, which is highly dependent on tourism. Nags Head beach is a major economic driver for the Town and the surrounding Dare County. The economy generates economic activity through home rentals, hotel visitation, food and beverage services, recreational fishing and water-sports charters, commercial fishing, fishing tournaments and associated support services. Based on the 2016 Beach and Inlet Management Plan Update, beach recreation values for the Town of Nags Head total almost $594 million when direct impacts, total impacts, and local sales tax revenue were considered. If the beach were not maintained, the Town would have the potential to lose revenue from beach recreation. Table 7-3 presents a summary of beach recreation values, in 2014 dollars, for the Town of Nags Head.

Table 7-3: Beach Recreation Values (BIMP, 2016)

Value Type	Value
Direct Impact Expenditures	$186,572,268
Total Impact Output/Sales/Business Activity	$393,410,745
Local Tax Revenue	$13,730,542
Total	**$593,713,555**

For reference, gross occupancy tax collections for the Town of Nags Head totaled $210,802,662 in 2022. This value could be greatly impacted if the beaches are not maintained and impacts would likely resonate throughout the County as well. Figures showing the impacted parcels overlain on February 2022 aerial photography are presented in Appendix D.

7.2 Beach Nourishment Alternatives

This section considers beach nourishment alternatives that would place beach-compatible sand along the Nags Head shoreline from Reach 1 to Reach 4, with volumes based on the Crystal Ball analysis of historical volumetric erosion rates. Different placement intervals are considered and the volume need for each project is adjusted to develop typical project cost estimates (2023 dollars). Detailed cost estimates are presented in Appendix E.

7.2.1 North Reach Considerations

As described in Section 1.1, the Nags Head – North reach extends from stations 430+00 to 490+00, a distance of 6,250 ft. This section of shoreline is currently eroding at less than 5,000 cy/year (above the -19 ft contour, see Section 4.2.1). At that rate, and with current beach and dune volumes, there would only be one beach nourishment needed in this reach to meet background erosion needs during the 50-year master plan time frame, approximately 48 years in the future. (It is noted that storm impacts could necessitate additional nourishment.) For this reason, the North Reach has not been included in the beach nourishment master plan alternatives discussed. However, the volumetric needs for both background and storm erosion in this reach have been included in the long-term sediment volume need presented in Section 5.7.

7.2.2 Initial Volume to Attain Equivalent Level of Protection (LoP)

In order to provide an equal level of protection to each reach of the Town's shoreline, an initial volume of sand placement is required as described in Section 5.5.3. This volume of 0.6 Mcy was added to each of the alternatives for the first project in the 50-year master plan. The cost of this initial placement was estimated at approximately $6.5 M (2023 dollars).

7.2.3 Nourishment Interval Comparisons

Nourishment intervals of 4, 5, 6, and 8 years were considered with nourishment placed along the entire nourished shoreline of Nags Head (Reach 1 to Reach 4), as shown in Figure 7-1. Volume requirements for each nourishment at these intervals were determined using the Crystal Ball volumetric estimates described in Section 4.2.2. The volumetric requirements for each maintenance project at these intervals are presented in Table 7-4.

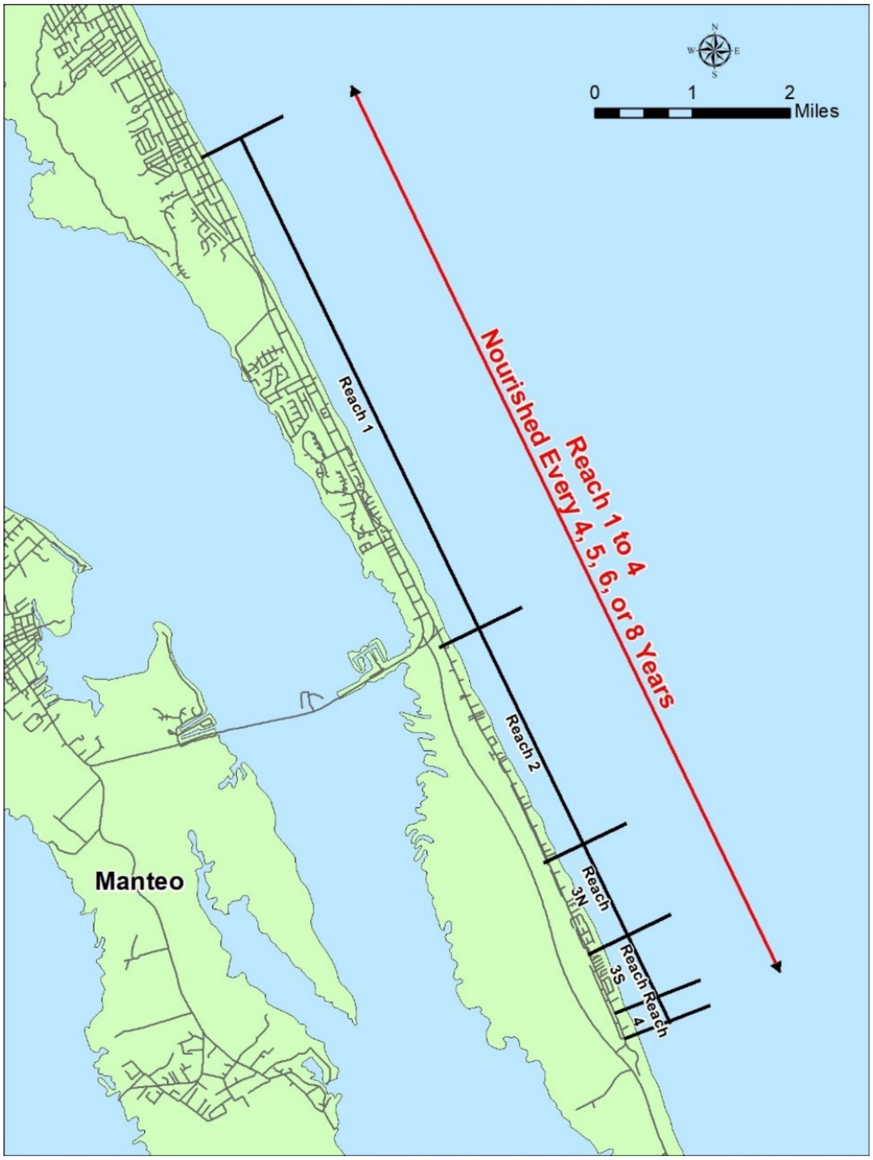


Figure 7-1: Beach Nourishment Alternatives

Table 7-4: Placement Volumes for Varying Nourishment Cycles

Reach	Annual Volumetric Loss (cy/year)	Placement Volume (4 year cycle) cy	Placement Volume (5 year cycle) cy	Placement Volume (6 year cycle) cy	Placement Volume (8 year cycle) cy
Reach 1 (500+00 - 785+00)	126,238	504,952	631,190	757,428	1,009,904
Reach 2 (790+00 - 915+00)	103,228	412,912	516,140	619,368	825,824
Reach 3N (920+00 - 970+00)	92,772	371,088	463,860	556,632	742,176
Reach 3S (975+00 - 1005+00)	72,653	290,612	363,265	435,918	581,224
Reach 4 (1010+00 - 1025+00)	44,493	177,972	222,465	266,958	355,944
Total Volume Per Project		**1,757,536**	**2,196,920**	**2,636,304**	**3,515,072**

These volumetric requirements were used to develop cost estimates for each project (in 2023 dollars) as shown in Table 7-5. These costs were multiplied by the number of nourishment cycles over the 50-year master plan timeframe, and the cost to attain the 25-year LoP with the first project was added to the first nourishment, to obtain the estimated 50-year total cost. This was then divided by either 48 or 50 years (depending on the interval, to give comparable estimates) to obtain an average annual cost for beach maintenance over the 50 years (Table 7-5). Additionally, to evaluate potential differences in costs due to occurrence of projects in varying future years, engineering economics calculations were performed. These variations in timing did not significantly affect the cost comparison of alternatives.

It is noted that the costs for post-storm recovery projects have not been included in these estimates because they are anticipated to be covered by FEMA reimbursement per 44 CFR § 206.226(j)(2). Additionally, the approximations of future volumes that could be needed to meet the demands from sea level rise are provided in Section 5.5.4 and are included in the overall sediment volume need presented in Section 5.7.

Table 7-5: Project Costs for Varying Nourishment Cycles (2023 dollars)

Nourishment Interval	Number of Nourishment Cycles	25-Year LOP Cost	Single Nourishment Cost	50-Year Total Cost	Cost Per Year
4-year	12	$6.50 M	$24.71 M	$303.01 M	$6.31 M*
5-year	10	$6.50 M	$29.14 M	$297.85 M	$5.96 M**
6-year	8	$6.50 M	$33.43 M	$273.94 M	$5.71 M*
8-year	6	$6.50 M	$42.33 M	$260.45 M	$5.43 M*

*Based on 48 Years
**Based on 50 Years

7.2.4 Discussion

As shown in Table 7-5, the least cost beach nourishment alternative evaluated over the 50-year master plan timeframe is the 8-year nourishment cycle. This is due to this alternative requiring fewer projects and placing more sand in each project, which allows for lower mobilization and demobilization costs and lower costs per cubic yard of sand placement. However, a 6-year cycle has some advantages and is not substantially more expensive than the 8-year cycle alternative. The 6-year cycle allows for less expensive individual projects and more frequent ability to adapt to changes in volumetric erosion rates. The nourishment interval is also flexible in that if volumetric triggers are not reached, the time period between projects can be extended.

Some general advantages of nourishing all reaches in each project are that this practice reduces the number of projects required over the 50-year planning horizon, and therefore minimizes mobilization/demobilization costs as well as the number of times the permitting process is required. Additionally, it may be perceived as equitable by residents and property owners as all of the reaches are nourished each time. One disadvantage of choosing this approach is that because of the lower volumetric erosion rate in Reach 1, there is a higher unit cost for material placed with less fill density (fewer cy per ft of beach). Additionally, a larger area is affected by the disruptions associated with the nourishment project each time.

7.3 Phased Beach Nourishment Alternatives

This section considers beach nourishment alternatives with a phased approach, where the interval between placement events would differ between Reach 1 and Reaches 2 to 4, as shown in Figure 7-2. Because the volumetric erosion rate in Reach 1 is less than that of the other reaches, this approach would provide some efficiencies in placement of material within Reach 1. Required volumes are again based on the Crystal Ball analysis of historical volumetric erosion rates. Different phasing intervals are considered and the volume need for each project is adjusted to develop typical project cost estimates (2023 dollars).

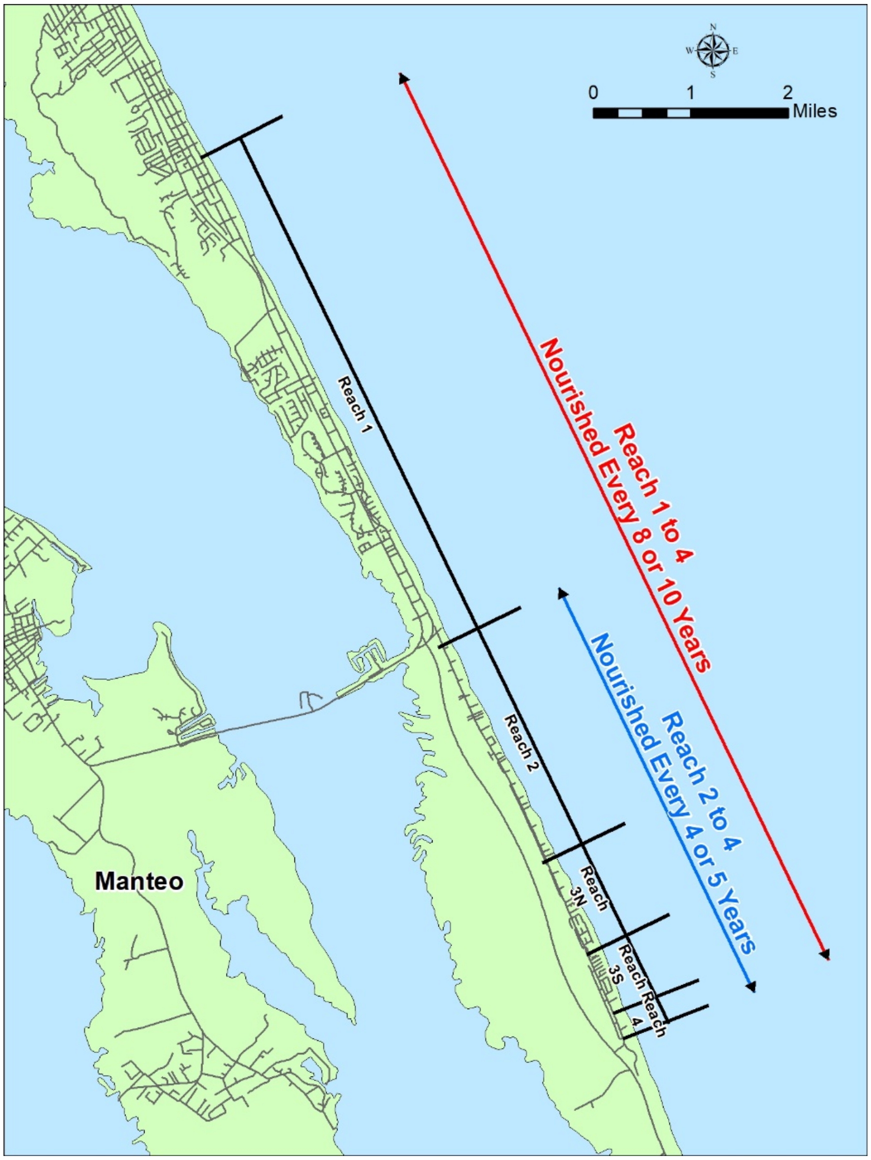


Figure 7-2: Phased Beach Nourishment Alternatives

7.3.1 Phased Interval Comparison

Two phased beach nourishment intervals were considered:

(1) Reaches 2 to 4 nourished every 4 years, and Reach 1 added to the nourishment area every 8 years, and

(2) Reaches 2 to 4 nourished every 5 years, and Reach 1 added to the nourishment area every 10 years.

The volume requirements for each cycle are presented in Table 7-6. The placement volumes for each project for Reach 2, Reach 3N, Reach 3S, and Reach 4 are the same as in the 4-year cycle and 5-year cycle for the non-phased approach. For Reach 1, the placement volume at the 8-year cycle is twice that of the 4-year non-phased cycle, and the placement volume at the 10-year cycle is twice that of the 5-year non-phased cycle. Essentially, in this approach the Town would nourish Reach 1 at a longer interval with more volume placed each time.

Table 7-6: Placement Volumes for Phased Nourishment Cycles

		Phased with 4/8 year cycles		Phased with 5/10 year cycles	
Reach	Annual Volumetric Loss (cy/year)	Placement Volume (cy) every 4 years	Placement Volume (cy) every 8 years	Placement Volume every 5 years	Placement Volume (cy) every 10 years
Reach 1 (500+00 - 785+00)	126,238	--	1,009,904	--	1,262,380
Reach 2 (790+00 - 915+00)	103,228	412,912	412,912	516,140	516,140
Reach 3N (920+00 - 970+00)	92,772	371,088	371,088	463,860	463,860
Reach 3S (975+00 - 1005+00)	72,653	290,612	290,612	363,265	363,265
Reach 4 (1010+00 - 1025+00)	44,493	177,972	177,972	222,465	222,465
Total Volume Per Project		**1,252,584**	**2,262,488**	**1,565,730**	**2,828,110**

As with the non-phased alternatives, volumetric requirements were used to develop cost estimates for each project (2023 dollars) as shown in Table 7-7. These costs were multiplied by the number of nourishment cycles over the 50-year master plan timeframe and the cost to attain the 25-year LoP with the first project was added to obtain the estimated 50-year total cost. This was then divided by either 48 or 50 years (depending on the interval) to obtain an average annual cost for beach maintenance over the 50 years (Table 7-7). The 5/10 phased approach has a lower cost over the lifetime of the master plan due to the lower number of projects required. To evaluate potential differences in costs due to occurrence of projects in varying future years, engineering economics calculations were performed. The variations in timing of projects did not significantly affect the cost comparison of alternatives.

Table 7-7: Project Costs for Phased Nourishment Cycles (2023 dollars)

Nourishment Interval	Number of Nourishment Cycles	25-Year LOP Cost	Single Nourishment Cost (4 year cycle)	Single Nourishment Cost (8 year cycle)	50-Year Total Cost	Cost Per Year
R2-4: 4-yr, R1-4: 8-yr	6 & 6	$6.50 M	$18.18 M	$30.64 M	$299.43 M	$6.24 M*
Nourishment Interval	**Number of Nourishment Cycles**	**25-Year LOP Cost**	**Single Nourishment Cost (5 year cycle)**	**Single Nourishment Cost (10 year cycle)**	**50-Year Total Cost**	**Cost Per Year**
R2-4: 5-yr, R1-4: 10-yr	5 & 5	$6.50 M	$21.15 M	$36.46 M	$294.51 M	$5.89 M**
*Based on 48 Years **Based on 50 Years						

7.3.2 Discussion

By waiting longer to nourish Reach 1 (longer interval cycle), the phased approach requires higher volumetric density of the placement in that reach and therefore results in lower costs per cubic yard. In addition, the Reach 1 portion of the Town's shoreline is not subject to the disturbances associated with project construction as often. Phasing also alternates between a lower-cost and a higher-cost project, which may have financing advantages for the Town. However, because there are more frequent projects (short interval cycle) in the phased approach than in the 6-year cycle or 8-year cycle where all of the reaches are nourished, overall mobilization and demobilization costs for the 50-year master plan timeframe are higher. Additionally, more frequent projects increase the number of times the environmental permitting process is required.

7.4 Beach Nourishment with Structures Alternatives

Because of the high rates of erosion in South Nags Head (Reach 3S and Reach 4), structural alternatives were considered to reduce these erosion rates, and therefore the required beach nourishment volumes. The structures considered were nearshore breakwaters and a terminal groin. The structural alternatives evaluated were paired with beach nourishment. Placing structures without a designed beach nourishment program could result in additional erosion and shoreline recession, especially downdrift of the structures.

7.4.1 Nearshore Breakwaters with Beach Nourishment

Four nearshore breakwater layouts were considered in this analysis. All of the layouts were designed to allow for some sediment bypassing to minimize downdrift impacts. The calibrated and validated shoreline change model described in Section 6.3 was used to evaluate the effectiveness of each alternative in reducing shoreline erosion. The reduced erosion was considered in developing beach nourishment designs for the breakwater alternatives. Costs were estimated for breakwater construction and for beach nourishment for each alternative.

<u>Breakwater Alternatives 1/1A</u>

The first breakwater alternative (1) included breakwaters with typical length of 250 ft, gap width of 250 ft, and distance from the nourished shoreline of 280 ft, as shown in Figure 7-3. This alternative was modified as 1A by removing the northernmost five of these breakwaters to minimize the impact footprint.

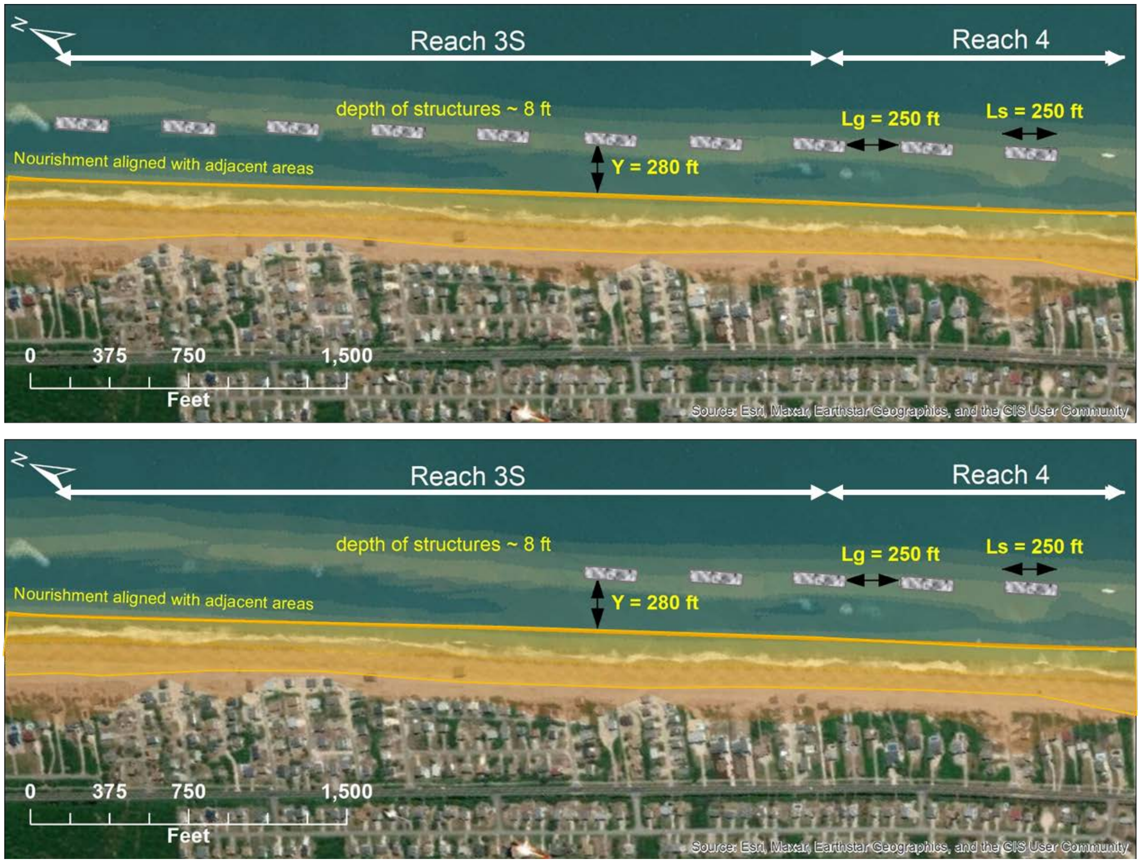


Figure 7-3: Breakwater Alternatives 1 (top panel) and 1A (bottom panel). Alternative 1 includes ten (10) breakwaters and Alternative 1A includes only the southernmost five (5) breakwaters.

Breakwater Alternatives 2/2A

The second breakwater alternative (2) included shorter breakwaters with typical length of 175 ft, an increased gap width of 400 ft, and an increased distance from the nourished shoreline of 350 ft, as shown in Figure 7-4. Alternative 2A was developed by removing the northern four breakwaters and consists of the southernmost five breakwaters (Figure 7-4).

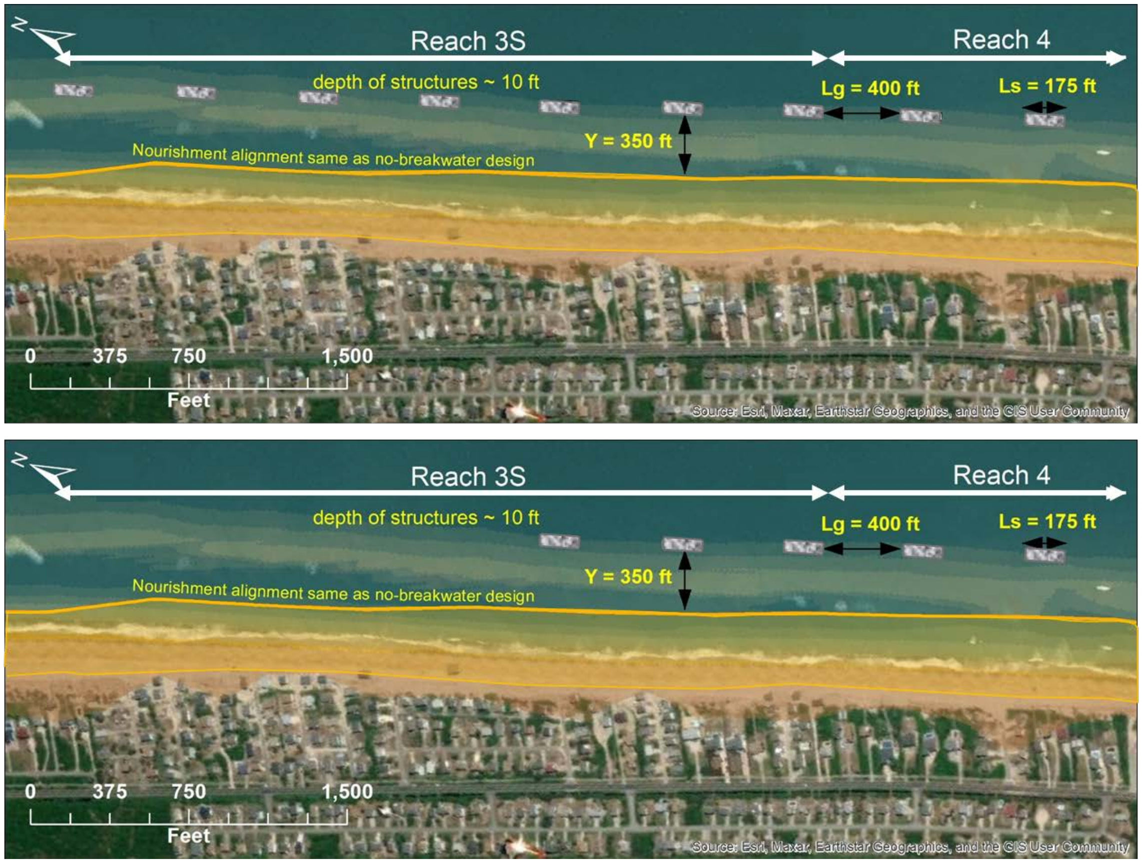


Figure 7-4: Breakwater Alternatives 2 (top panel) and 2A (bottom panel). Alternative 2 includes nine (9) breakwaters and Alternative 2A includes only the southernmost five (5) breakwaters.

7.4.2 Shoreline Modeling: Nearshore Breakwaters

These alternatives were further examined using the calibrated and validated GenCade model described in Section 6.3 to estimate the potential reduction in erosion rates if nearshore breakwaters were constructed. Results are shown in Figure 7-5 for a 6-year time period, with wave conditions from July 2013 to June 2019.

All of the nearshore breakwater alternatives decreased erosion in the associated reaches compared with nourishment only. Most of the benefit of the breakwaters was retained when only the southernmost five breakwaters of each alternative were constructed. As expected, the longer breakwaters with smaller gaps, constructed closer to the nourished shoreline

(Alternative 1/1A), were more effective at retaining sand. Alternative 1A shows the best performance in reducing erosion compared with nourishment only, however, there is still a substantial amount of erosion when the final shoreline is compared with the initial nourished shoreline in the GenCade model analysis.

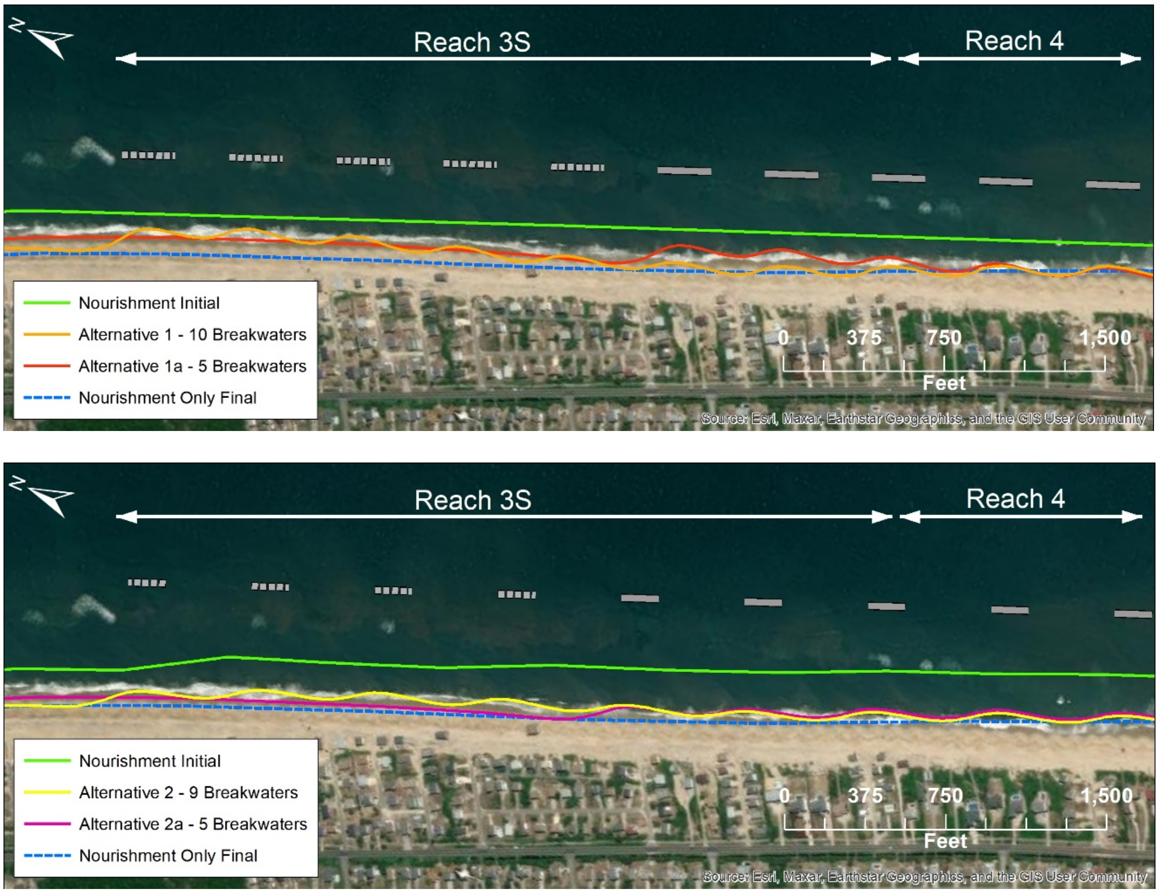


Figure 7-5: GenCade Shoreline Modeling Results for Nearshore Breakwaters Alternatives. Top panel shows Alternatives 1/1A, bottom panel shows Alternatives 2/2A. Dashed breakwaters are removed for the 1A and 2A alternatives.

7.4.3 Nearshore Breakwaters Comparisons

Placement volumes for nearshore breakwater alternatives were developed using the reduction in erosion rate due to the breakwaters to determine the annual volume needs for beach nourishment and are shown in Table 7-8. As noted previously, Alternative 1A, with five breakwaters, required the smallest placement volume in Reach 3S and Reach 4 of all of the breakwater alternatives examined.

To develop cost estimates, an initial project was considered to be constructed concurrently with the breakwaters, and those volumes were identical to the 6-year cycle alternative described in Section 7.2.3. Subsequent project volumes were as shown in Table 7-8 and Table 7-9.

Table 7-8: Placement Volumes for Nearshore Breakwater Alternatives1 and 1A

Reach	Alternative 1 Annual Volumetric Loss (cy/year)	Alternative 1 Placement Volume (6 year cycle) cy	Alternative 1A Annual Volumetric Loss (cy/year)	Alternative 1A Placement Volume (6 year cycle) cy
Reach 1 (500+00 - 785+00)	126,238	757,428	126,238	757,428
Reach 2 (790+00 - 915+00)	103,228	619,368	103,228	619,368
Reach 3N (920+00 - 970+00)	92,772	556,632	92,772	556,632
Reach 3S (975+00 - 1005+00)	68,963	413,778	66,948	401,688
Reach 4 (1010+00 - 1025+00)	42,911	257,466	42,048	252,288
Total Volume Per Project		**2,604,672**	**--**	**2,587,404**

Table 7-9: Placement Volumes for Nearshore Breakwater Alternatives 2 and 2A

Reach	Alternative 2 Annual Volumetric Loss (cy/year)	Alternative 2 Placement Volume (6 year cycle) cy	Alternative 2A Annual Volumetric Loss (cy/year)	Alternative 2A Placement Volume (6 year cycle) cy
Reach 1 (500+00 - 785+00)	126,238	757,428	126,238	757,428
Reach 2 (790+00 - 915+00)	103,228	619,368	103,228	619,368
Reach 3N (920+00 - 970+00)	92,772	556,632	92,772	556,632
Reach 3S (975+00 - 1005+00)	68,287	409,722	69,177	415,062
Reach 4 (1010+00 - 1025+00)	42,622	255,732	43,003	258,018
Total Volume Per Project		**2,598,882**	**--**	**2,606,508**

Cost estimates for construction of each of the nearshore breakwater alternatives along with a 6-year beach nourishment cycle were developed and are shown in Table 7-10. Details of the estimate and cost estimates for other nourishment intervals are presented in Appendix E. The overall lowest cost breakwater alternative is Alternative 2A, which includes the lowest breakwater construction cost. The alternative that is most effective in reducing erosion rates and therefore has the lowest repeat nourishment cost was Alternative 1A.

Table 7-10: Cost Estimates for Nearshore Breakwater Alternatives with Beach Nourishment on a 6-Year Cycle (1 initial nourishment project and 7 repeat nourishment projects, 2023 dollars).

Nearshore Breakwater Alternative	25-Year LOP Cost	Initial Nourishment Cost	Repeat Nourishment Cost (6 year cycle)	Breakwater Cost	50-Year Combined Total Cost	Cost Per Year
1	$6.50 M	$33.43 M	$33.10 M	$118.57 M	$390.21 M	$8.13 M*
1A	$6.50 M	$33.43 M	$32.92 M	$60.08 M	$330.47 M	$6.88 M*
2	$6.50 M	$33.43 M	$33.04 M	$75.54 M	$346.77 M	$7.22 M*
2A	$6.50 M	$33.43 M	$33.12 M	$42.61 M	$314.38 M	$6.55 M*
						*Based on 48 Years

In general, none of the nearshore breakwater alternatives provided enough of a reduction in erosion to offset the cost of breakwater construction, and are all more expensive than any of the non-phased or phased beach nourishment alternatives.

7.4.4 Terminal Groin with Beach Nourishment

An alternative with a terminal groin at the southern end of the Town was also evaluated. The terminal groin preliminary design was comparable to the terminal groin constructed within the Town of Ocean Isle Beach in 2021/2022. The groin extended approximately 750 ft seaward of the 2022 mean high water shoreline with a rubble mound section, and 300 ft landward of mean high water with a sheet pile section to prevent flanking. The position of the groin centerline was approximately located at Transect 1025+00 at the southern limit of Reach 4. This groin would be constructed with an accompanying beach nourishment project. The conceptual alternative is shown in Figure 7-6.

Figure 7-6: Terminal Groin Alternative

7.4.5 Shoreline Modeling: Terminal Groin

The terminal groin alternative was further examined using the calibrated and validated GenCade model described in Section 6.3 to estimate the potential reduction in erosion rates if a groin were constructed. Wave conditions were the same as those evaluated in the nearshore breakwater alternatives, a 6-year time period, from July 2013 to June 2019. Varying permeability coefficients were considered to capture a range of effects. It is noted that in practice, groins are generally not very permeable as they are designed to retain sand. Results from the GenCade model are presented in Figure 7-7.

Figure 7-7: GenCade Shoreline Modeling Results for Terminal Groin Alternative.

As shown in Figure 7-7, the less permeable groins were more effective at retaining sand, with the groin with permeability 0.3 only slightly different than the nourishment only option. As is typical with groins, the downdrift area for both the permeability 0.1 and 0.2 cases showed adverse effects due to interruption in the longshore transport towards the south.

7.4.6 Terminal Groin Comparison

The modeled terminal groin with permeability 0.1 was shown to retain the most sand and was therefore considered in developing cost comparisons. This groin reduced volumetric losses within Reaches 3S and 4 to essentially zero, as shown in Table 7-11.

Table 7-11: Placement Volume for Terminal Groin Alternative (Permeability 0.1)

Reach	Annual Volumetric Loss (cy/year)	Terminal Groin Placement Volume (6 year cycle) cy	Terminal Groin Placement Volume (8 year cycle) cy
Reach 1 (500+00 - 785+00)	126,238	757,428	1,009,904
Reach 2 (790+00 - 915+00)	103,228	619,368	825,824
Reach 3N (920+00 - 970+00)	92,772	556,632	742,176
Reach 3S (975+00 - 1005+00)	0	0	0
Reach 4 (1010+00 - 1025+00)	0	0	0
Total Volume Per Project		**1,933,428**	**2,577,904**

The volume estimates in Table 7-11 were used to develop the cost estimates presented in Table 7-12. An initial project was assumed to be identical to either the 6-year or 8-year nourishment project, with subsequent projects developed using the volume requirements presented in Table 7-11. Details of the groin construction and nourishment project cost estimates are presented in Appendix E. While the terminal groin alternative appears to show the lowest costs over the master plan timeframe, these costs do not consider any mitigation that may be required due to adverse downdrift effects. These costs could become significant to the Town and negate any advantages provided by groin construction.

Table 7-12: Cost Estimates for Terminal Groin Alternative with Beach Nourishment. Costs consider initial nourishment cost plus either 7 (6-year cycle) or 5 (8-year cycle) repeat nourishment projects (2023 dollars).

Terminal Groin Alternative	25-Year LOP Cost	Initial Nourishment Cost	Repeat Nourishment Cost	Groin Cost	50-Year Combined Total Cost	Cost Per Year
6-year nourishment cycle	$6.50 M	$33.43 M	$26.15 M	$28.04 M	$251.05 M	$5.23 M*
8-year nourishment cycle	$6.50 M	$42.33 M	$32.82 M	$28.04 M	$240.99 M	$5.02 M*
						*Based on 48 Years

7.4.7 Discussion

Structural alternatives to reduce erosion rates in South Nags Head (Reach 3S and Reach 4) were considered in the alternatives analysis. Nearshore breakwaters added significant costs because the reduction in erosion provided by the breakwaters is not enough to substantially reduce the nourishment requirements. A groin alternative is shown to significantly reduce the erosion rates in Reaches 3S and 4, however, adverse downdrift effects are modeled within the Cape Hatteras National Seashore. These downdrift effects would likely add costs for required mitigation/downdrift sand placement. Finally, oceanfront erosion control structures are currently not allowed under North Carolina G.S. § 113A-115.1, with the exception of terminal groins constructed at the terminus of an island or on the side of an inlet. Because the town is not immediately adjacent to Oregon Inlet, the groin approach would not fall within this exception.

7.5 Additional Beach Nourishment Considerations

This section provides an overview of some of the additional factors that influence the decision-making process for beach nourishment projects. These include project funding sources, feasibility of construction, and tourism and recreation considerations. Future project costs may also be affected by the condition of the beach, timing of bidding, and utilization of existing dredge capacity.

7.5.1 Project Funding

Previous beach nourishment projects conducted by the Town have been funded using a combination of local (Town and County) and State funds. In addition, post-storm damage restoration of sand loss has been funded by the Federal Emergency Management Agency (FEMA). The Town typically secures municipal bonds to pay for its portion of the cost at the time of construction, and the bonds are then paid back throughout the life of the project.

The Town has developed Municipal Service Districts (MSDs) to levy additional property taxes to provide funding for beach nourishment. The funding plans recognize that the benefits of beach nourishment extend beyond the immediate oceanfront, and the MSD boundaries and rates take this into account. Beach nourishment maintains the beach as a key piece of the Town's infrastructure. A well-maintained beach not only provides protection to properties throughout the Town but also results in increased property values.

In addition to these Town funds, Dare County maintains a Beach Nourishment Fund which has historically supported the Town's beach renourishment projects. A 2 percent portion of the County's 6 percent Occupancy Tax is allocated to this fund. This fund is restricted by legislation to be used for the placement of sand from other sources, planting of vegetation and building of structures that are in conformity with the North Carolina Coastal Area Management Act (CAMA), e.g. dunes and sand fencing, for the purpose of widening the beach to benefit public recreational use and to mitigate damage and erosion from storms to inland property.

The State's CSDM Fund program accepts applications for grant funding by local governments to support beach nourishment, dune construction, or other projects that mitigate or remediate coastal storm damage to the ocean beach and dune systems of the State. Local cost share of at least one non-State dollar for every dollar from the fund is required.

For post-storm repairs of beach nourishment projects, FEMA has provided funding under the Category G Public Assistance program for Permanent Work - Engineered Beaches. The post-Dorian beach nourishment project constructed in 2022 was undertaken utilizing these funds. Documentation of losses of beach sand, vegetation, and sand fencing is necessary to obtain approvals for the FEMA Category G funding.

Funding considerations may constrain a beach nourishment project in terms of the volume that is able to be placed with the available funds, as well as the timing of projects if funding sources take time to secure or favorable bids are not received from contractors. This may result in delays or constrain the amount of advance fill that is able to be placed. In general, the sooner a project is advertised in advance of the desired construction window, the more favorable the bids.

7.5.2 Constructability

For beach nourishment project construction, there is generally a minimum fill volume density that is economically feasible for a contractor to construct. This volume density may vary depending upon the borrow source characteristics, dredging and placement methodology, and desired template. For example, a larger dredge may lose some efficiency when trying to construct a smaller fill density template due to the higher quantity and velocity at which sand is pumped onto the beach, causing them to have to temporarily stop pumping one or more times while emptying a load in order to allow time for crews on the beach to grade the fill template before moving down the beach. This anticipated downtime is calculated into the contractor's bid prices, raising the unit price (price per cubic yard) of sand.

Therefore, for any given nourishment event, there may be reaches of beach where additional quantity is warranted – above and beyond what is required based on actual erosion rates – to achieve the most economically feasible construction template for that nourishment event. That being said, additional quantity to achieve this economic efficiency equates to overall higher project costs. The engineering design and permitting of each nourishment event should include analysis to determine whether higher volumes with lower unit costs or lower volumes with higher unit costs will be more advantageous for the Town in terms of overall project cost.

Previous experience has indicated that minimum fill densities of approximately 20 cy/ft are economically feasible for the medium to large hopper dredges that exist in the current dredging plants of contractors qualified to do this type of work. Therefore, this value of 20 cy/ft is often used to analyze the above-mentioned scenario and determine the most cost-effective construction template for the Town that provides the desired storm protection.

7.5.3 Tourism and Recreation

In addition to beach nourishment providing protection for the Town's infrastructure, there are also recreational benefits to consider. The Town's beaches drive tourism, with thousands of visitors annually. In the winter season, beach driving is allowed, while in summer only emergency vehicles are permitted. The available width of beach for recreation is increased in the short term after each nourishment project, with advance fill placed in anticipation of equilibration and long-term erosion taking place until the next project.

For the purposes of this discussion, recreational beach width is defined as the horizontal distance between the seaward toe of the dune and the Mean High Water (MHW) shoreline position. Because the MHW shoreline is highly variable, adjusting to monthly and seasonal wave conditions, there is significant variability in the beach width in both the short- and long-term. Examination of the annual monitoring data reveals that changes in the shoreline position on the order of 50-90 ft are common from year to year, and even shorter-term changes can occur after storm events. This results in corresponding changes in beach width, as the position of the dune is less variable from year to year. In general, the Town's beaches are narrower in winter than in summer, as material is transported from the beach face into the nearshore under higher wave conditions. The beach typically widens during the summer months, when conditions tend to be less severe.

When the beach width is very narrow, space for recreational activities is constrained, resulting in a negative experience for beach users. Desirable beach widths for lower-volume winter season usage (beach driving, surf fishing, walking, etc.) are a minimum of 50 ft from the dune toe to the MHW line (typical high tide line). During heavier usage in summer, desirable beach widths are approximately 100 ft or greater. Beach widths at representative profiles for each reach were examined as of the 2023 annual monitoring

(June) and fall monitoring (October). Table 7-13 presents the measured beach widths at these profile locations.

Table 7-13: Representative Beach Widths in Summer and Fall 2023

Rep. Profile	Summer 2023 Beach Width (ft)	Fall 2023 Beach Width (ft)
460+00	67	not surveyed
520+00	83	42
535+00	92	64
625+00	67	76
715+00	68	63
735+00	35	57
785+00	82	95
855+00	122	77
865+00	142	87
895+00	105	70
920+00	79	84
935+00	91	62
980+00	69	53
1020+00	80	76

As shown in Table 7-13, several reaches within the Town currently have beach widths less than the desirable summer (and/or winter) recreational beach width. In many of these areas, the dunes are large enough along with the existing beach width to provide the design level of protection (See Section 5.5) to the landward infrastructure. However, the Town may choose to increase the volume of a planned beach nourishment to provide additional recreational beach width. Considering the distance between the active berm height (+6 ft NAVD88) and the depth of closure (-19 ft NAVD88) of 25 ft and placement along 1 ft of beachfront, for every additional 1 ft of beach width desired, 1 ft * 1ft * 25 ft/27 cy/ft = 0.92 cy of sand should be placed. A general rule of thumb for project planning and budgeting could consider each additional 1 cy of sand placed could provide approximately 1 ft of additional beach width. It is noted that this approximation is based upon the assumption of an equilibrium profile that is translated in the cross-shore direction, and that the natural beach response is variable.

Given the dynamic nature of coastlines, the volume needed to sustain a recreational beach width is anticipated to fluctuate between nourishment events. Nonetheless, using the rule of thumb outlined above it is possible to estimate the additional material required by the LOP profiles described in Section 5.5 to maintain the desired 100 ft beach width on average during the nourishment interval. Figure 7-8 illustrates this design concept, with the orange line indicating the advanced fill necessary to counteract background erosion and the purple line representing the fill essential for maintaining the desired beach width during the nourishment period. Table 7-14 presents the additional volume required to attain an approximately 100 ft beach width during the nourishment interval, considering the base LOP profile. It is noted that for a specific beach nourishment event, these volumes would vary depending upon the condition of the beach at the time of design.

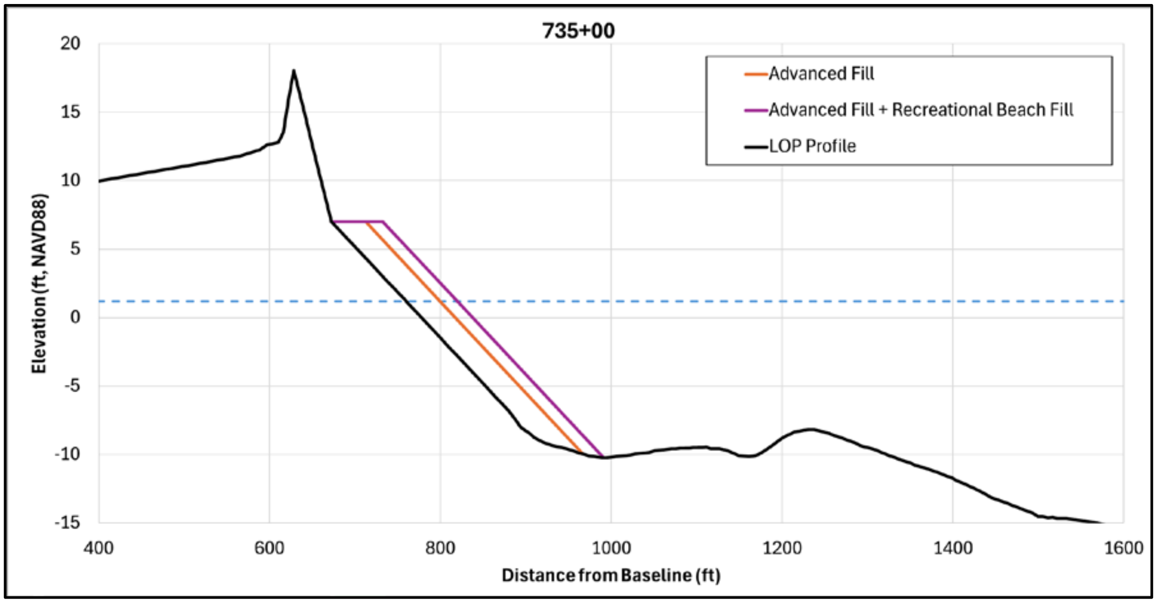


Figure 7-8: Example Design Fill for Achieving Recreational Beach Width

Table 7-14: Additional Berm Volume Required by the LOP Profiles to Achieve Recreational Beach Width

Reach	Length (ft)	Rep. Profile	Volume Above -19 ft, NAVD88 Required to Achieve 25-year LoP (cy/lf)	Additional Volume Required to Achieve Recreational Beach Width (cy/ft)
Nags Head – North	6,250	460+00	355	13
Reach 1	4,500	520+00	503	39
Reach 1	5,500	535+00	451	35
Reach 1	7,000	625+00	478	14
Reach 1	5,500	715+00	479	13
Reach 1	6,000	735+00	443	13
Reach 1 / Reach 2	2,500	785+00	604	19
Reach 2	5,500	855+00	491	15
Reach 2	2,500	865+00	471	13
Reach 2	2,500	895+00	526	n/a
Reach 2 / Reach 3 - North	2,500	920+00	463	28
Reach 3 - North	4,500	935+00	464	13
Reach 3 - South	2,000	980+00	461	3
Reach 3 - South / Reach 4	2,750	1020+00	401	n/a

7.5.4 Future Project Costs and Cost Variability

In addition to the funding, constructability, and recreational considerations discussed, there are other factors affecting the decision-making process and future project costs. Dredging market conditions play a large role in the overall cost of a project. Due to the limited number of dredging contractors that can perform this type of work, dredge plant availability is often at a premium. Availability can be impacted by high numbers of projects on the horizon and/or late timing of the bidding process. Hurricane damage on any portion of the east coast or gulf coast during a particular year could tie up dredge plant availability for years to come with storm damage restoration projects. Lower dredge plant availability leads to higher prices for construction by contractors who are assuming a risk to perform the work on time. In addition, the timeliness of a bid could also impact total project cost. The earlier the project can be bid, the more likely it is to receive lower prices due to less scheduling conflicts by the contractors.

Due to the impact of dredge market conditions on overall project price, it is difficult to estimate future project costs. Table 7-15 examines the mobilization/demobilization and sand placement costs of reach of the three nourishment projects constructed in the Town of Nags Head. For the 2011 and 2019 Town of Nags Head renourishment costs, prices for sand placement ($/cy) increased approximately 5% per year in the eight years between projects, elevating the cost from $5.55/cy in 2011 to $8.16/cy in 2019. For the 2022 post-Dorian renourishment project, prices for sand placement ($/cy) increased approximately 6% per year in the three years since the 2019 renourishment project, elevating the cost from $8.16/cy in 2019 to $9.76/cy in 2022. In terms of mobilization/demobilization, for the 2011 and 2019 Town of Nags Head renourishment projects, prices increased approximately 6.5% per year in the eight years between projects, elevating the cost from $2.4M in 2011 to $4.0M in 2019. For the 2022 post-Dorian renourishment project, prices increased approximately 7.9% per year in the three years since the 2019 renourishment project, elevating the cost from $4.0M in 2019 to just over $5M in 2022.

Table 7-15: Historical Project Costs

Project	Mob/Demob Lump Sum ($)	Sand Placement Unit Cost ($/cy)
2011 Nourishment Project	$2,399,000	$5.55
2019 Nourishment Project	$4,000,000	$8.16
2022 Post-Dorian Project	$5,023,000	$9.76

However, it should be noted that the 5% to 6% inflation in sand placement prices and 6% to 8% inflation in mobilization/demobilization prices previously experienced may not always be the case for future nourishment projects which will strongly depend on dredge plant availability at the time of bidding. There also may exist certain dredging market conditions where dredging prices may go down from one year to the next. For example, the 2019 Town of Nags Head renourishment project was originally bid with the anticipation of construction in 2018. However, dredge market conditions were such that the lowest qualified bid for 2018 construction was 42% higher than the lowest qualified bid for 2019 construction. Therefore, the project construction was postponed until 2019 in order to take advantage of the significantly better pricing. Table 7-16 presents the difference in sand placement and mobilization/demobilization bid costs received for the project which was ultimately constructed in 2019. As can be seen, for 2019 construction the mobilization/demobilization costs decreased by more than 50% whereas sand placement unit costs decreased by approximately 25% compared to the 2018 construction bids.

Table 7-16: 2018 versus 2019 Project Construction Bid Costs

Project	Mob/Demob Lump Sum ($)	Sand Placement Unit Cost ($/cy)
2018 Nourishment Project Bids	$8,500,000	$10.89
2019 Nourishment Project Bids	$4,000,000	$8.16

Acknowledging the difficulty in estimating future project costs, it is anticipated the 2027 project will cost approximately $38.2M based on current market conditions and volume estimates. A breakdown of the estimated costs is presented in Table 7-17. It should be noted that the estimated sand placement costs ($13.72/cy) would equate to an annual increase of 7% since the 2022 project, and the estimated mobilization/demobilization costs ($6.0M) would equate to a 3.6% annual increase from the 2022 project. Therefore, current market conditions indicate a slightly larger increase in sand placement costs than has historically been seen for Town projects but a smaller than average increase in mobilization/demobilization costs than has historically been seen.

Table 7-17: Estimated Project Costs for 2027

Item	Approximate Costs
Sand Placement Cost (2,222,800 cy)	$30.5 M
Mob/Demob Cost	$6.0 M
Sand Fencing and Dune Planting Cost	$400,000
Engineering & Permitting & Construction Administration	$850,000
Field Investigations*	$420,000
Total	$38.2 M

*TBD if this would be required by agencies.

This information provides context for considerations that will likely affect future project costs. The Town's ongoing monitoring efforts will provide updated information on beach conditions and estimated volume needs.

7.6 Dune Stabilization and Preservation

As noted in Section 3.8, the Town has historically included dune stabilization efforts such as sand fencing and dune grass planting in beach nourishment efforts. In addition to beach nourishment, maintenance of established dunes through best management practices is an important part of preserving and growing a healthy dune system. Dune planting is a proven method of stabilizing dunes and capturing sand, contributing towards dune growth. In addition, the wind conditions in Nags Head allow for a considerable amount of aeolian transport for which sand fencing has proven successful in capturing sand as well.

In order to create a robust vegetation system, it is recommended to participate in seasonal inspections and planting so as to allow for planting of multiple species of dune vegetation throughout the year. Inspection in the spring (March/April timeframe), after nor'easter season, is recommended followed by Sea Oats and Bitter Panicum planting from May to September. Inspection in late fall (October/November timeframe), after hurricane season, is also recommended followed by planting of American Beachgrass from November to March.

The Town receives $24,000 annually from the Dare County Beach Nourishment Fund for dune stabilization efforts. The Dare County funds have been used towards annual sand fence installation or beach grass plantings. This amount may be supplemented periodically by the Town to provide more extensive treatments along the oceanfront. Areas where dunes have minimal or no stabilization/vegetation will be targeted to ensure full coverage throughout the project area. Dune stabilization efforts are typically conducted during the fall/winter months annually. Additionally, grant funding has permitted large scale stabilization efforts to occur across beach nourishment project area. An example of this is the Coastal Storm Damage Mitigation (CSDM) grant that was awarded in 2022 to provide vegetative sprigging along a 10-mile stretch of the Town's oceanfront. Grant funding can provide opportunities to implement a variety of plant species to provide a more diverse and habitat friendly environment.

Regarding sand fencing replacement or supplementation, the Town typically seeks to maintain a minimum of one (1) row of functional sand fencing. Environmental agency concerns over endangered species interaction with sand fencing has caused the Town to recently take a less aggressive approach to maintaining and supplementing sand fencing than in previous years. In areas where existing sand fence is exposed less than 12 inches, it may be possible to augment the fencing by installation of new fencing immediately adjacent to the existing fence.

It should be noted that any planting or sand fencing damages associated with FEMA Public Assistance Category G storm events should be catalogued with the post-storm inspection and are often replaced through a FEMA reimbursement project which typically replaces sand lost during the storm and then replants vegetation and reinstalls sand fencing in areas that were damaged.

Please refer to Appendix F for additional dune planting and sand fencing guidelines from the Town of Nags Head, NC DCM, and US Fish and Wildlife Service.

Typical unit costs for sand fence and dune vegetation are presented in Table 7-18 for reference, in 2023 dollars. It is important to note that American Beachgrass requires three (3) sprigs per hole while Sea Oats and Bitter Panicum only require one (1) sprig per hole.

Table 7-18. Sand Fence and Dune Vegetation Costs

Stabilization Technique	Unit	Unit Price (2023)
Sand Fence	LF	$8.27
American Beachgrass	Sprig	$0.36
Sea Oats/Bitter Panicum	Sprig	$1.29

7.7 Summary of Alternatives

While there are advantages and disadvantages of each of the presented alternatives, some of the alternatives are more beneficial than others.

If the Town prefers to nourish the entire beach in each project, a 6-year nourishment cycle is recommended. Although an 8-year cycle minimizes the overall costs during the timeframe of the master plan, the 6-year cycle includes a more reasonable volume of placement in the reaches with the highest volumetric erosion rates. The 6-year cycle allows for less expensive individual projects and more frequent ability to adapt to changes in volumetric erosion rates. The nourishment interval is also flexible in that if volumetric triggers are not reached, the time period between projects can be extended, or the spatial limits of the project can be customized. Some general advantages of nourishing all of the reaches in each project are that this practice reduces the number of projects required over the 50-year planning horizon, reducing mobilization/demobilization costs as well as the number of times the permitting process is required. Additionally, it may be perceived as equitable by residents and property owners as all of the reaches are nourished each time. However, in this case all of the reaches are affected by the disruptions and potential environmental impacts associated with the nourishment project every time.

If the phased approach is preferred, the 5/10 year cycles are the less expensive option over the 50-year master plan timeframe. The phased approach results in lower unit costs for sand placement in Reach 1, because there is higher fill density for each project. In addition, the Reach 1 portion of the Town’s shoreline is not subject to the disturbances and environmental impacts associated with project construction as often. Phasing also alternates between lower-cost and higher-cost projects, which may have financing advantages for the Town. However, because there are more frequent projects in Reaches 2 to 4 under the phased approach than in the 6-year cycle where all of the reaches are nourished, overall mobilization and demobilization costs for the 50-year master plan timeframe are higher. Additionally, more frequent projects increase the number of times the environmental permitting process is required.

Additional considerations for beach nourishment project design include project funding sources, feasibility of construction, and tourism and recreation. These factors can influence design and construction and can be evaluated on a project-by-project basis. Funding considerations may constrain a beach nourishment project in terms of the volume that is able to be placed with the available funds, as well as the timing of projects if funding sources take time to secure or favorable bids are not received from contractors. For beach nourishment project construction, there is generally a minimum fill volume density that is economically feasible for a contractor to construct. This volume density may vary depending upon the borrow source characteristics, dredging and placement methodology, and desired template. In addition to beach nourishment providing protection for the Town’s infrastructure, there are also recreational benefits to consider. The Town may choose to increase the volume of a planned beach nourishment to provide additional recreational beach width.

Maintenance of established dunes through best management practices is an important part of preserving and growing a healthy dune system. Dune planting along with installation of sand fencing is a proven method of stabilizing dunes and capturing sand, contributing towards dune growth. To create a robust vegetation system, it is recommended to participate in seasonal inspections and planting to allow for planting of multiple species of dune vegetation throughout the year.

The structural alternatives have more disadvantages than advantages and are not recommended at this time.

8.0 BORROW SOURCE ANALYSIS

Based on the results of the Crystal Ball analyses and sea level rise estimates (Section 5.7), it is anticipated that the Town needs to identify borrow site(s) with approximately 49 Mcy of sand to meet the Town's 50-year nourishment need. Along with information available for borrow area S1 (Section 3.6), additional evaluations were conducted in effort to delineate an overall long-term borrow site containing a minimum of 49 Mcy of beach-compatible sand meeting the 15A NCAC 07H.0312 (1) rule parameters for recipient beaches.

Using the previous USACE delineation for borrow area S1 as the basis (Figure 8-1), additional data were obtained in effort to delineate multiple regions within this borrow area that contain a cumulative volume of 49 Mcy. A portion of borrow area S1 has been previously dredged for prior Town projects including the most recent post Hurricane Dorian project completed in 2022.

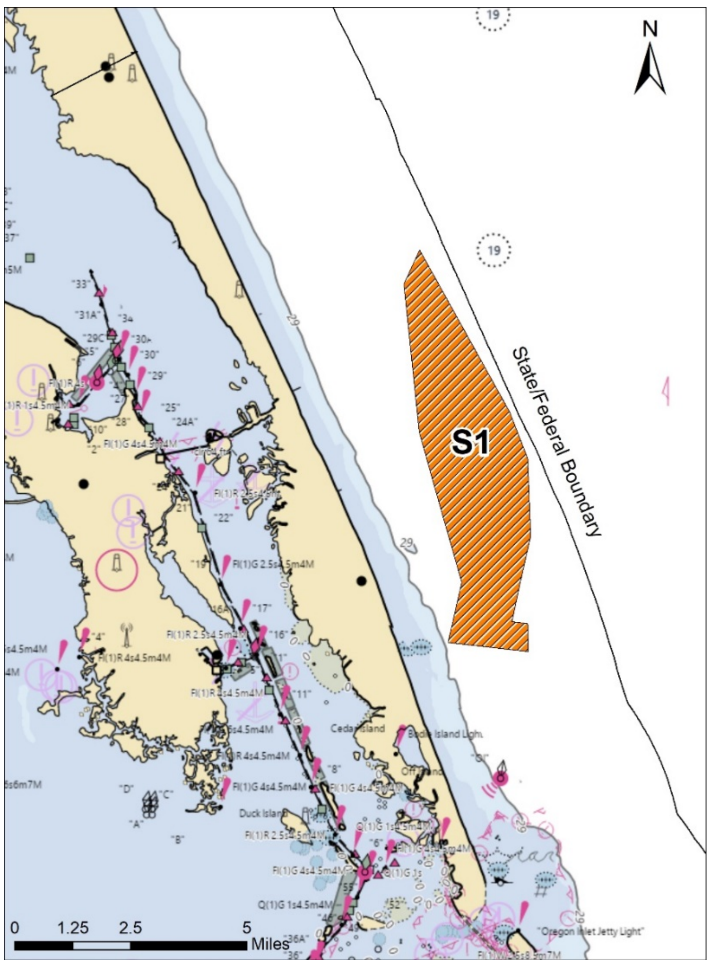


Figure 8-1: Borrow Area S1

8.1 Borrow Area Bathymetry

There are two recent bathymetric surveys. A July 2021 survey conducted by Geodynamics covers the full borrow area S1. To capture post-dredge conditions following the Town's 2022 Post-Dorian Renourishment Project, a survey was completed in August 2022 by Gahagan & Bryant Associates, Inc. The 2021 survey data was employed to estimate the total sediment volume within the proposed borrow area above the designated cut elevation(s). The 2022 survey data was utilized to quantify the material removed from the locations within the S1 borrow area that were utilized since the 2021 survey and exclude those areas from the future sediment availability calculations.

8.2 Geotechnical Investigations

Vibracore investigations within Borrow Area S1 were conducted under three individual mobilizations as shown in Figure 8-2. In June 2021, 43 vibracores were acquired by Athena Technologies, Inc.) for the design of the 2022 Post-Dorian Renourishment Project. An additional 250 vibracores were acquired in August/September 2021 by Amdrill, Inc. in the northern two thirds of Borrow Area S1. The southern third of the Borrow Area was had vibracores extracted in August 2022 (Amdrill, Inc.). The selection of vibracore locations in these investigations were chosen to conform to the current state rules and regulations governing sediment investigations, as outlined in 15A NCAC 07H.0312.

Based on the coring logs and the visual changes in material characteristics, the vibracores collected by Athena were divided into 262 sub-samples, while the Amdrill vibracores were split into 960 sub-samples, following the guidelines outlined in ASTM D 2487. These sub-samples were then subjected to grain size distribution analysis, adhering to ASTM D 6913, which involved the use of the following sieve sizes: 3/4-inch, 5/8-inch, 7/16-inch, 5/16-inch, No. 3.5, No. 4, No. 5, No 7, No. 10, No.14, No. 18, No. 25, No. 35, No. 45, No. 60, No. 80, No. 120, No. 170, No. 200, and No. 230. Additionally, the sub-samples underwent analysis to determine carbonate content, employing the Twenhofel and Tyler acid digestion method (1941). The shell content was visually estimated using the Terry and Chilingar method (1955). The laboratory results of the sediment sample analyses are presented in Appendix G.

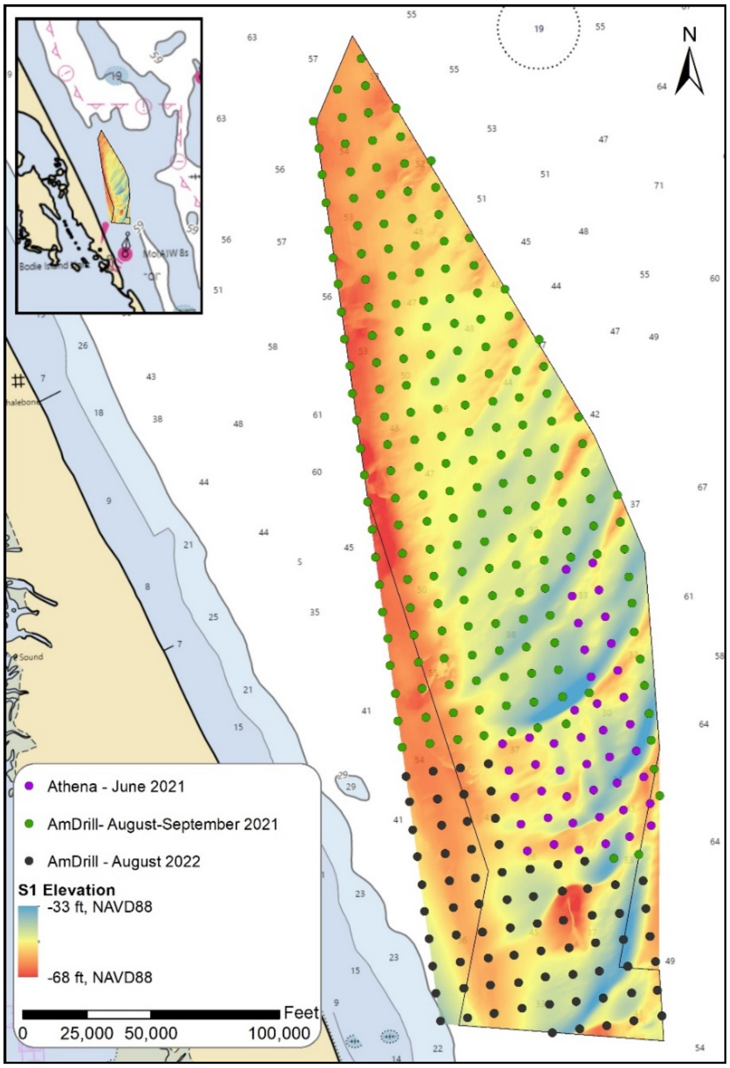


Figure 8-2: Vibracore Locations

8.3 Potential Borrow Area Delineation

Based on the sediment analysis of each vibracore, a preliminary maximum dredge cut elevation (bottom of allowable cut elevation) of compatible material was delineated two feet above the boundary with non-compatible material (Figure 8-3). This two-foot buffer accounts for potential variability in dredging, uncertainties in extrapolating conditions between core samples, and it is intended to avoid dredging non-compatible material.

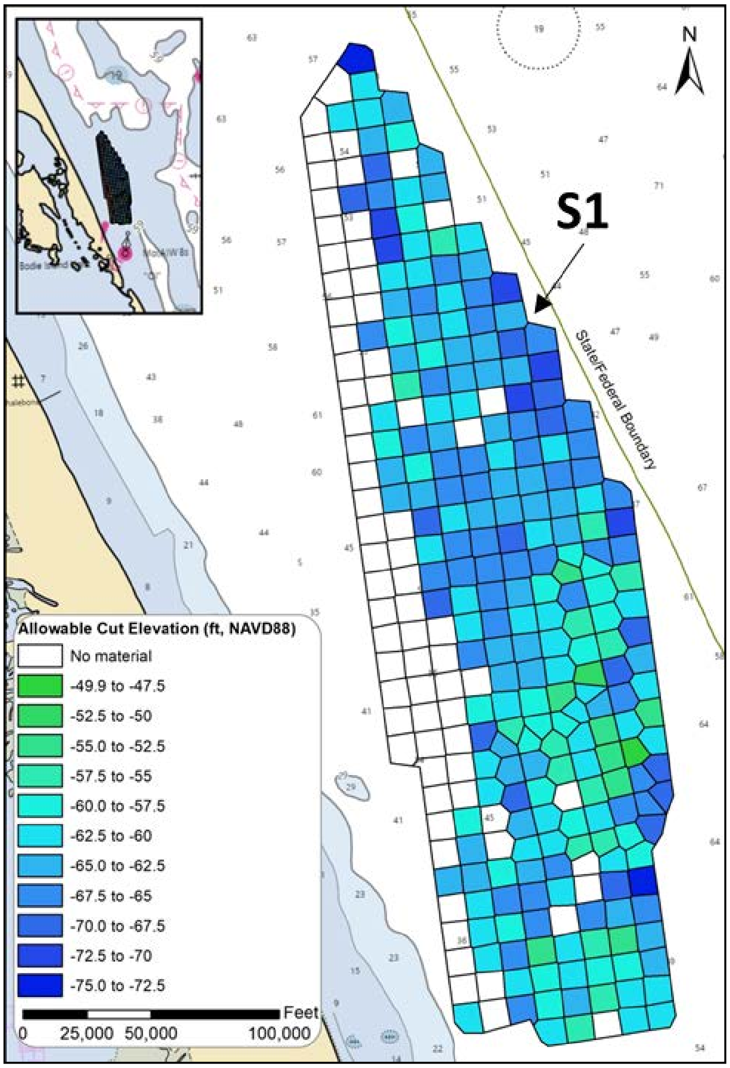


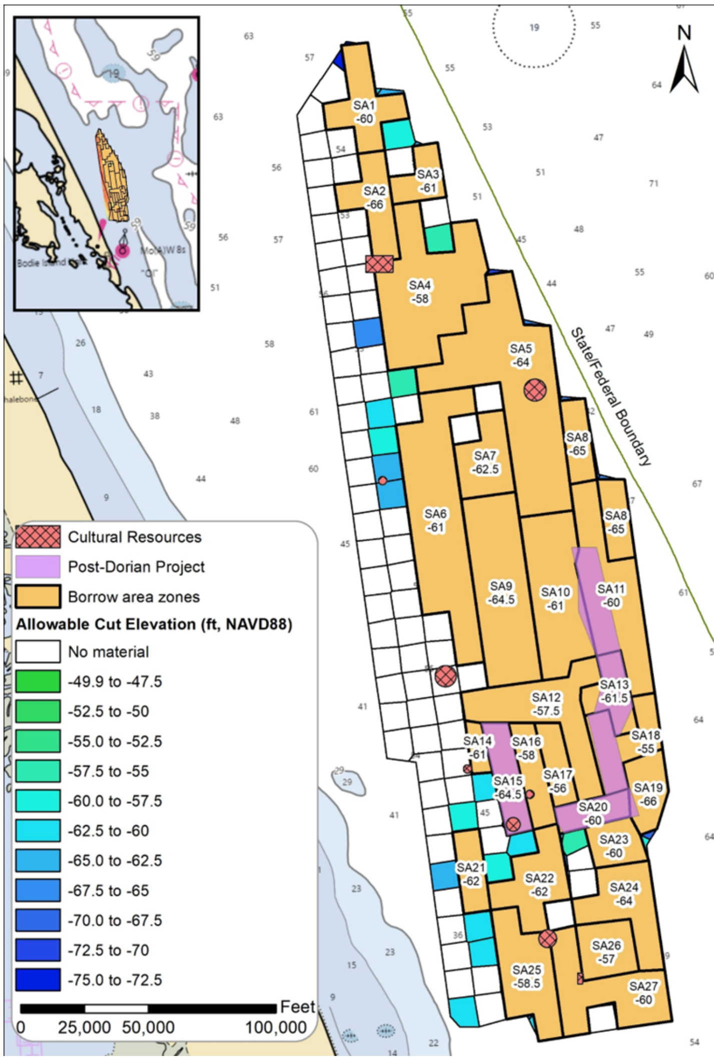
Figure 8-3: Bottom of Allowable Cut Elevation

To provide economical and constructable dredge cut lengths and elevations, the analyzed cores were grouped into larger zones within borrow area S1 where the dredging elevation was made consistent for the zone. The lowest cut elevation that still maintained a two-foot buffer above non-compatible material was selected as the maximum dredge cut elevation for each borrow area zone. Figure 8-4 illustrates the identified borrow area zones and their corresponding cut elevations.

Once the borrow area zones were established, the material between the sub-area cut elevation and the surface was determined using the following steps:

(1) Creating a difference surface by comparing the July 2021 surface with the cut elevation assigned to sub-areas.
(2) Creating 400 ft buffers around cultural resources and excluding these areas from consideration.

(3) Removing the areas that were utilized during the 2022 Post-Dorian Renourishment Project.
(4) Adding the "positive" surfaces and multiplying them by the cell area.
(5) By following this process, the areas containing compatible material between the cut elevation and the surface were identified, considering cultural resources, previous renourishment activities, and surface variations.



Zone	Allowable Cut Elevation (ft, NAVD88)	Available Sand to Cut Elevation (cy)
SA1	-60	236,947
SA2	-66	1,476,340
SA3	-61	423,663
SA4	-58	2,306,244
SA5	-64	10,013,758
SA6	-61	5,949,522
SA7	-62.5	2,308,713
SA8	-65	2,902,471
SA9	-64.5	8,501,582
SA10	-61	5,796,575
SA11	-60	3,917,228
SA12	-57.5	4,195,481
SA13	-61.5	420,665
SA14	-61	329,510
SA15	-64.5	111,967
SA16	-58	692,023
SA17	-56	473,870
SA18	-55	1,272,303
SA19	-66	1,320,016
SA20	-60	USED
SA21	-62	626,489
SA22	-62	2,474,583
SA23	-60	1,374,315
SA24	-64	3,308,557
SA25	-58.5	2,160,860
SA26	-57	1,867,713
SA27	-60	3,424,295
SUM		67,885,691

Figure 8-4: Borrow Area Sub-zones and Corresponding Maximum Dredge Cut Elevations

Based on the maximum dredge cut elevation established for the borrow area zones within borrow area S1, approximately 67.9 Mcy of beach compatible material is made available. This quantity is considered sufficient to accommodate the estimated placement requirement of approximately 49 Mcy for the town's beach management efforts over the next 50 years.

8.4 Potential Impacts of Borrow Site Dredging on the Nearshore Wave Climate

To quantify any potential impacts of dredging the borrow site on the wave climate along the Nags Head shoreline, a numerical modeling study was performed. Appendix A contains the full modeling study report. The MIKE 21 Spectral Waves (SW) model was employed to transform offshore wave conditions to the nearshore. Once the model was calibrated and validated (Appendix A), two bathymetric conditions were considered: 1) existing surveyed conditions based on the 2021 bathymetric survey, and 2) a conservative case where material was removed from the entire S1 borrow area based on maximum feasible dredge depths (Figure 8-5). Seven years of wave conditions (2012 to 2019) were modeled to evaluate potential impacts.

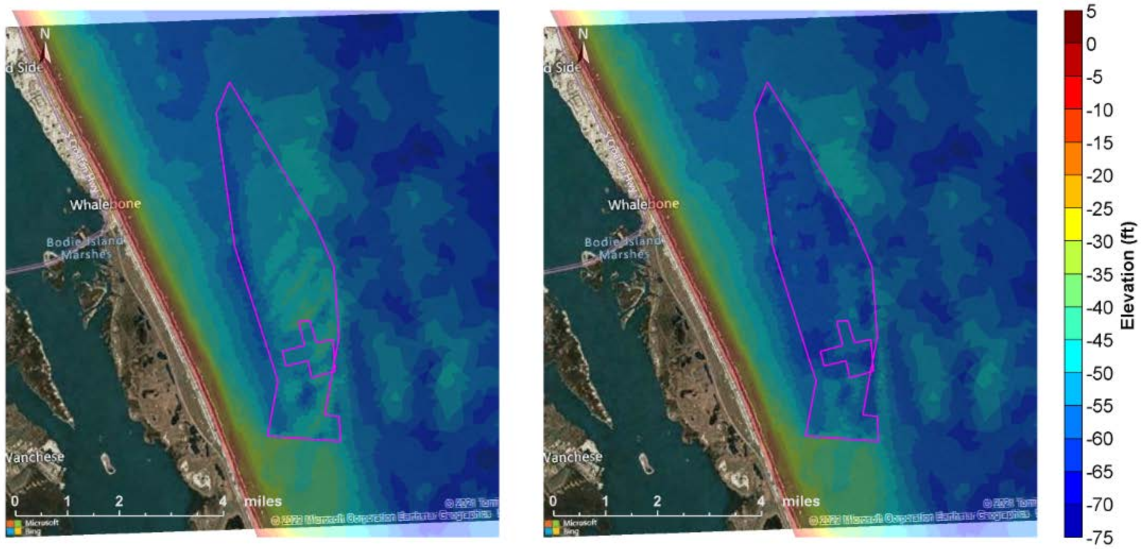


Figure 8-5: Updated model bathymetry around S1 borrow area without (left) and with (right) dredging

Comparison of median (50th percentile) wave-heights showed very little noticeable difference in the simulated wave-heights under the two conditions. Some differences were observed for larger storm events (at about the 90th percentile) mostly in the borrow area and shoreward of the southern limit of the borrow area. Differences elsewhere were found to be negligible under almost all simulated conditions. Amplification of wave heights appears to be mostly restricted to a limited area where the borrow area is closest to the coastline, and the magnitude of the wave-height amplification rarely exceeds 0.5 ft. Similar treatment of wave-period results showed very little noticeable change in expected wave-periods with the offshore borrow area dredging. Some slight changes in wave direction were observed due to the removal of material in the borrow area as well (Appendix A).

The nearshore wave conditions with and without dredging were also used along with the calibrated GenCade model described in Section 6.3 to evaluate the potential effect of dredging on shoreline changes within the Town of Nags Head. Table 8-1 shows the average shoreline change modeled in each reach over a 6-year period for the with- and without-dredging conditions. Slight increases in shoreline erosion were modeled with dredging effects in Reach 1 and Reach 3N; all other reaches had slightly less erosion under the dredged condition. In general, shoreline change differences modeled with and without borrow site dredging were relatively small.

Table 8-1: Average Shoreline Changes after 6 Years

Dredging	**Shoreline Change (ft)**				
	Reach 1	Reach 2	Reach 3N	Reach 3S	Reach 4
Without Dredging	-17.1	-61.0	-173.9	-162.8	-116.1
With Dredging	-19.7	-56.5	-182.0	-158.7	-103.5
Net Difference (ft)	-2.6	+4.5	-8.1	+4.1	+12.6
Percentage Difference	+15.2%	-7.4%	+4.7%	-2.5%	-10.9%

9.0 REGULATORY PATHWAYS AND PROJECT TIMELINES

The master plan approach is designed to make the regulatory process more efficient and predictable by developing volumetric requirements and evaluating borrow sources in advance of an imminent project. This section provides a brief overview of permitting requirements and timelines for regularly scheduled maintenance projects and post-storm recovery projects.

The required permitting process for a beach nourishment project includes both CAMA and USACE permits, as well as a State Water Quality Certification, along with coordination with multiple state and federal resource agencies. Construction moratoriums and avoidance and minimization measures are required to minimize environmental impacts of each project. Because of the coordination required as well as the time needed for project engineering design, bidding, and financing the project, it generally takes on the order of two years to complete a project from initiation to construction start.

9.1 Maintenance Projects

Ongoing beach profile surveys performed as part of the Town's Annual Beach Monitoring program are used to determine whether triggers are likely to be met within the next two years. If this occurs, the permitting, design, and construction process for the next project is initiated. The next project construction then generally occurs after May 1 of the second year after initiation. Figure 9-1 shows a typical timeline for maintenance projects addressing long-term background erosion.

9.2 Post-Storm Restoration Projects

If a storm occurs and results in a federally declared disaster, the permitting, design, and construction process are initiated immediately along with an application for FEMA post-disaster assistance under 44 CFR § 206.226(j)(2). FEMA then conducts a review of the application which typically takes on the order of six months. If the storm occurs before or in early fall and FEMA review occurs concurrently with the design and permitting of the project, a post-storm project then occurs after May 1 of the second year after initiation. Figure 9-2 shows a typical timeline for post-storm restoration. It is noted that if the storm occurs late in hurricane season and if FEMA review occurs prior to initiation of the permitting and design, the project may not be constructed until May 1 of the third year after storm occurrence.

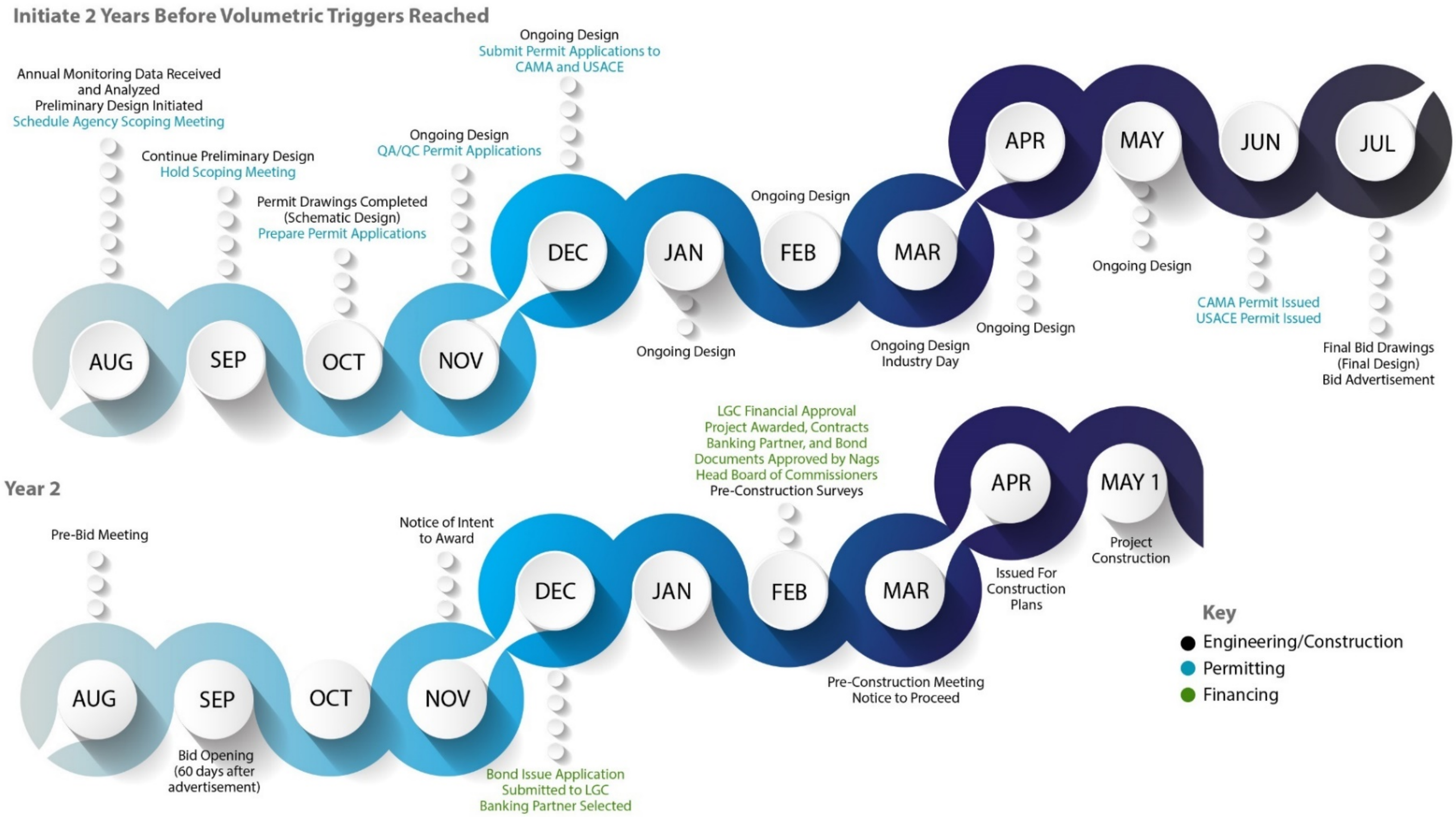


Figure 9-1: Maintenance Project Timeline

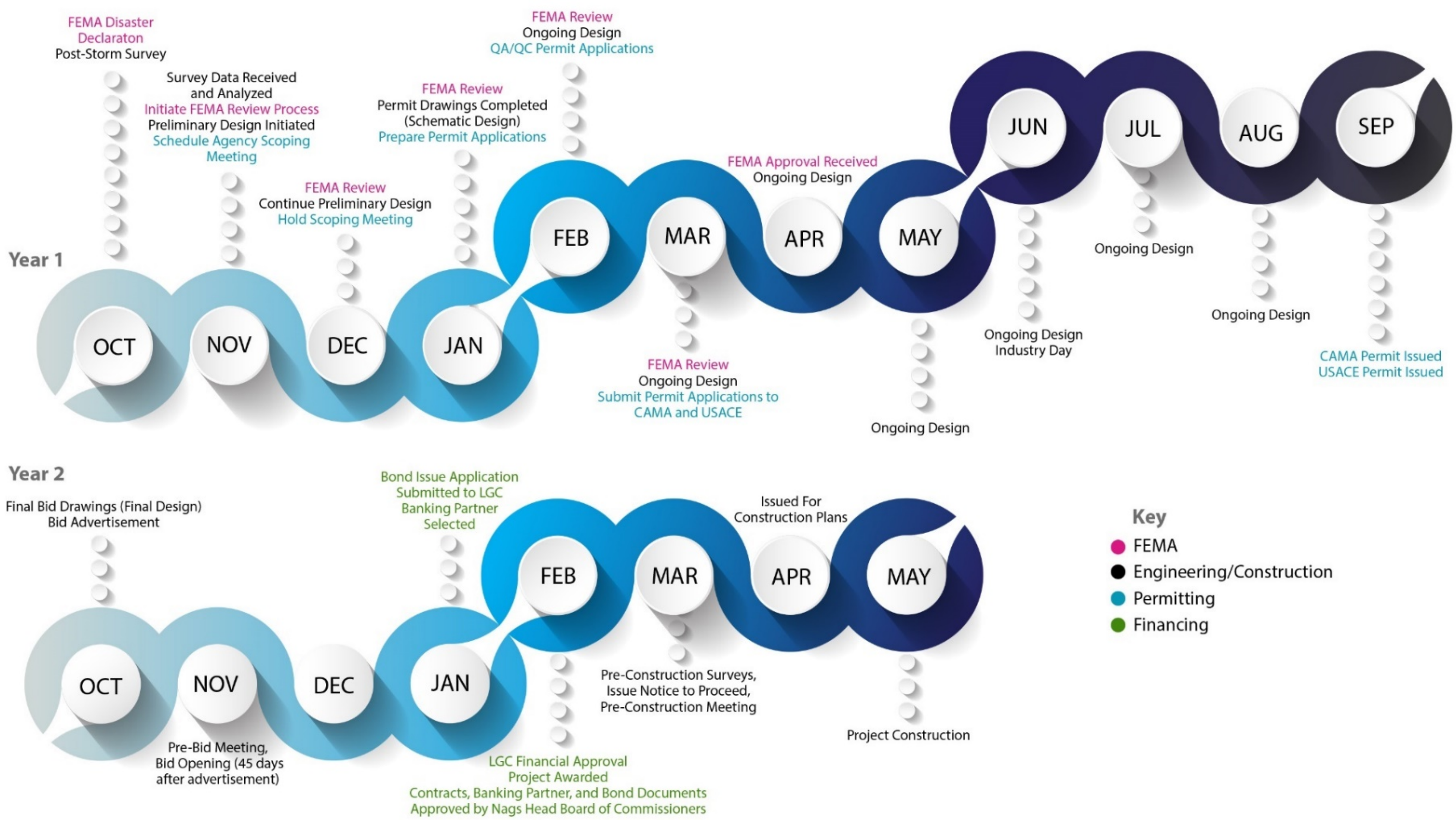


Figure 9-2: Post-Storm Project Timeline

10.0 CONCLUSIONS AND RECOMMENDATIONS

The key elements of the Nags Head Beach Nourishment Master Plan are summarized in this section. The framework developed here allows for proactive planning and execution of sustainable beach management over the 50-year planning horizon.

- The Town has conducted four beach and dune nourishment projects along the Nags Head oceanfront since 2004, with a total of approximately 9.5 Mcy placed.

- Equivalent 25-year LoP and nourishment triggers have been developed to guide planning for beach nourishment projects.

- The total sediment need estimated using Crystal Ball analysis for background erosion over the 50-year timeframe is 22.5 Mcy, and the need estimated due to potential additional storms is 21.5 Mcy.

- Anticipated SLR could require up to 4.7 Mcy of additional sand over the 50-year master plan timeframe under the intermediate high scenario.

- Total anticipated long term sediment need is estimated at approximately 48.8 Mcy including background erosion, storm impacts, and sea level rise.

- The approximately 8.5 square mile borrow area S1 has been determined to contain sufficient beach compatible sand to meet the anticipated 50-year nourishment need, with geophysical and geological data collected to meet state standards. Sub-areas within S1 have been developed to facilitate cost-effective dredging for beach nourishment projects. These sub-areas also facilitate permitting and tracking the use and sedimentation rates of the borrow area.

- If the Town ceased beach nourishment activities, there would be severe economic impacts, including over $800M in lost property value and up to $3.9M in annual property tax losses. Substantial losses to tourism revenues would also be anticipated.

- A planned 6-year beach nourishment interval (non-phased) allows for responsiveness to changing conditions and provides a lower total cost over the 50-year master plan timeframe than the 4-year and 5-year interval. Additionally, if volumetric triggers are not reached within 2 years of the 6-year planned interval, the Town could potentially extend the time between projects and reduce the total mobilization/demobilization costs. The typical time span for regulatory requirements and contractor procurement is 2 years. This is the Town's preferred alternative.

- Initial estimated costs for each alternative are developed based on the volume requirements and can be used to develop a long-term funding plan, including requests for funding from Dare County and the State of North Carolina.

- Structural alternatives, such as breakwaters or groins, to reduce erosion rates in South Nags Head (Reach 3S and Reach 4) are not recommended for several reasons:

  - Nearshore breakwaters added significant costs because the reduction in erosion provided by the breakwaters was not enough to substantially reduce the nourishment requirements.

  - While a groin alternative was shown to significantly reduce the erosion rates in Reaches 3S and 4, and corresponding nourishment costs, adverse downdrift effects were modeled within the Cape Hatteras National Seashore. These downdrift effects would likely add significant costs for required mitigation/downdrift sand placement.

  - Oceanfront erosion control structures are currently not allowed under North Carolina G.S. § 113A-115.1, with the exception of terminal groins constructed at the terminus of an island or on the side of an inlet.

- Additional considerations for beach nourishment project design include project funding sources, feasibility of construction, and tourism and recreation. These factors can influence design and construction and can be evaluated on a project-by-project basis.

- Future project costs can vary due to timing of bidding, beach conditions, and utilization of available dredge plant at the time of construction.

- Dune planting along with installation of sand fencing is a proven method of stabilizing dunes and capturing sand, contributing towards dune growth. To create a robust vegetation system, seasonal inspections and planting are performed to allow for planting of multiple species of dune vegetation throughout the year.

- Ongoing beach profile surveys performed as part of the Annual Beach Monitoring program are used to determine whether triggers are likely to be met within the next two years. If this occurs, the permitting, design, and construction process for the next project is initiated. The next project construction then occurs starting May 1 of the second year after initiation.

- If a storm occurs and results in a federally-declared disaster, the permitting, design, and construction process are initiated immediately along with FEMA review. If the storm occurs in early fall and FEMA review occurs concurrently with the design and permitting of the project, a post-storm project then occurs starting May 1 of the second year after initiation. If the storm occurs later in the season and if FEMA review occurs prior to initiation of the permitting and design, the project may not be constructed until May 1 of the third year after storm occurrence.

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moffatt & nichol

Contact:
Moffatt & Nichol
4700 Falls of Neuse Road, Suite 300
Raleigh, NC 27609
P: (919) 781-4626

101 W. Main Street, Suite 3000
Norfolk, VA 23510
P: (757) 628-8222

moffattnichol.com