

**Monitoring and Analyses of the  
2011 Nags Head Beach Nourishment Project**

**2018**

**BEACH MONITORING REPORT**

*Prepared for:*



Town of Nags Head  
PO Box 99 Nags Head NC 27959

*Prepared by:*

*High Value Services  
Sustainable Solutions*   
**COASTAL SCIENCE & ENGINEERING**  
PO Box 8056 Columbia SC 29202-8056

[CSE2458-YR7]  
October 2018

COVER PHOTOS: Orthophotos taken on 25 May 2018 by CSE's P4P System showing Nags Head Reach 3S (ie – south ~1 mile of beach from Limulus Drive to McCall Court, or project stations 975+00 to 1025+00). If measured to the FEMA depth limit of -19 ft NAVD, this stretch of beach has experienced the highest erosion rates compared to the other reaches of Nags Head, and all nourishment sand has left the “sand box” as of May 2018. Despite the 20–30 cy/ft/yr of sand loss, the back beach and dune areas have over 7 cy/ft more sand than pre-project conditions (November 2010), indicating natural dune growth by aeolian transport (ie – wind generating sand transport) since project completion.

— *THIS PAGE INTENTIONALLY LEFT BLANK* —

## EXECUTIVE SUMMARY

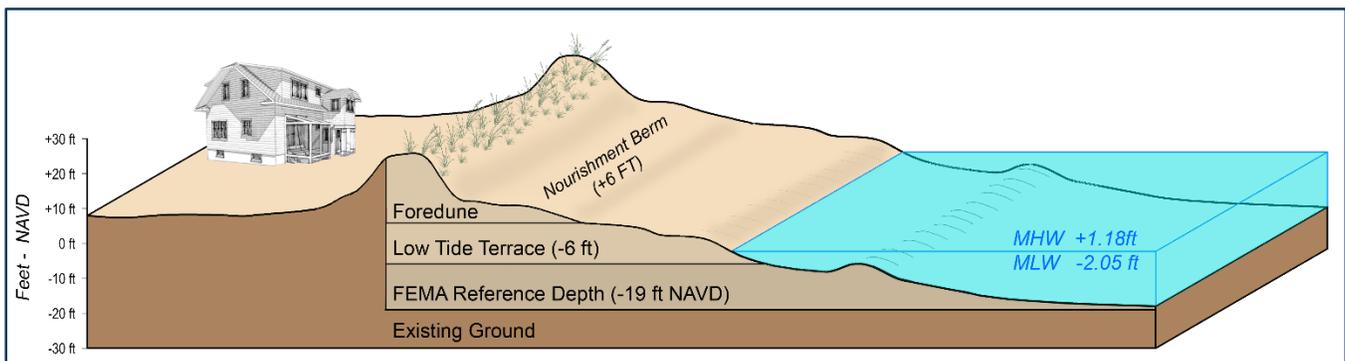
### Project Background Information and Volume Analysis Methodology

The Nags Head 2011 nourishment project was conducted between 24 May and 27 October 2011, during which time 4.6 million cubic yards of sand were placed along a 10-mile stretch of beach. Coastal Science & Engineering Inc (CSE) has conducted comprehensive beach condition surveys semi-annually in 2012 and annually since 2013. An additional survey was performed in October 2016 after the passage of Hurricane *Matthew*. Each survey provides a measure of the total volume of sand contained within the Nags Head littoral zone from the foredune out to a depth of the FEMA depth limit at 19 feet (ft) NAVD. This report includes the May 2018 survey results, and it is the seventh annual report following the 2011 project.

Similar to previous reports, CSE computed the volume of sand contained in the littoral zone (also called “sand box”) between the foredune and three reference depth contours as follows and illustrated in Figure A.

- Lens 1) **“Foredune”** – From the face of dune\* to +6 ft NAVD. The 2011 nourishment construction berm was designed at +6 ft with several areas up to +7 ft NAVD. This lens includes the sand quantities in the dune and the upper portion of dry-sand beach above +6 ft NAVD.
- Lens 2) **“Beach”** – Between +6 ft and -6 ft NAVD. It includes the dry-sand beach and the wet-sand beach and extends to low-tide wading depth.
- Lens 3) **“Underwater”** – Between -6 ft and -19 ft NAVD. It includes the underwater portion of the beach from low-tide wading depth to the depth set forth for the FEMA post-storm restoration criteria at -19 ft NAVD.

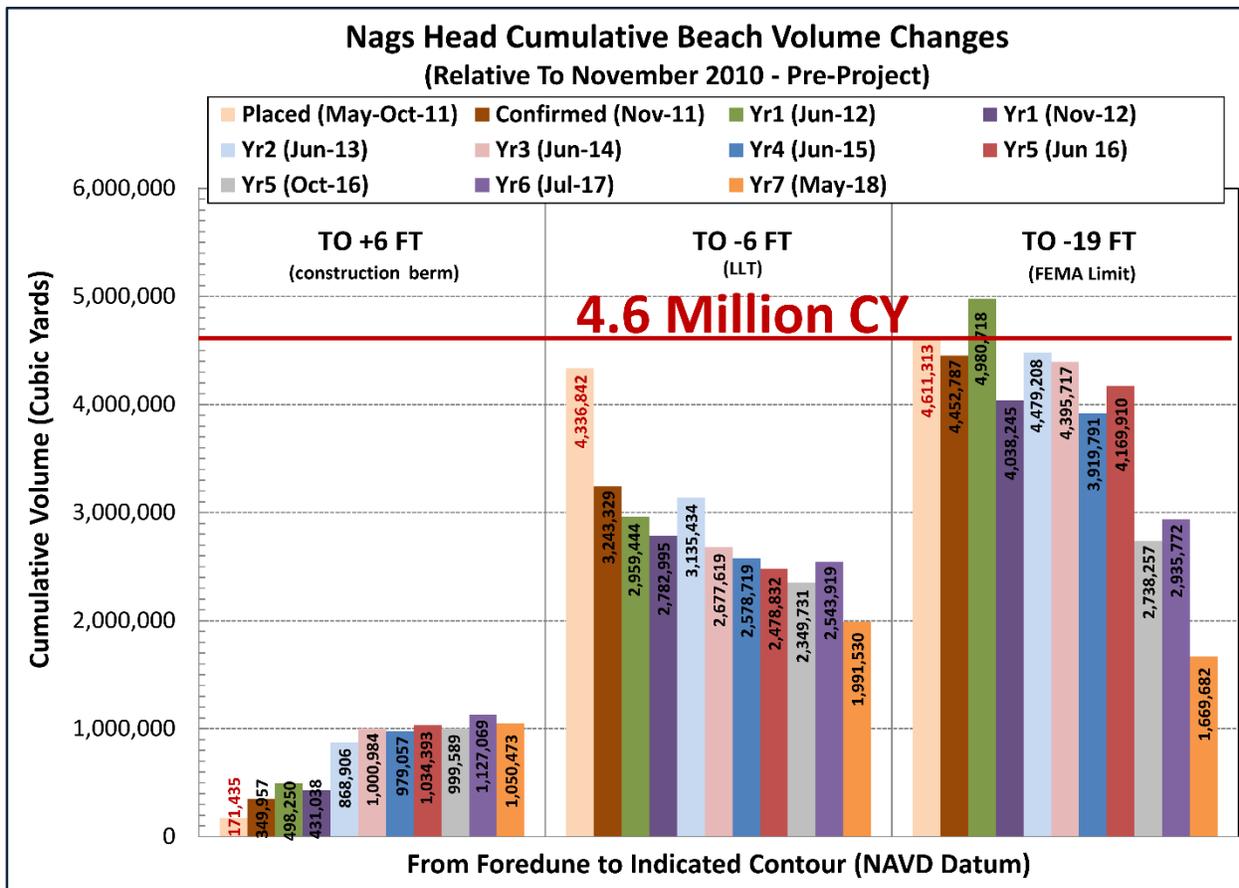
*\*[CSE surveys the beach including the dune area to the landward back of the dune along each survey station. A landward starting point for volume analysis of each station was originally determined at the time of project planning (CSE 2011a). It is normally located landward of the crest of the dune as illustrated in Figure A. This landward starting point may vary from station to station but remains the same for a certain station unless significant changes occur landward of the station that prevents data collection. If the landward starting point of a station has to be changed, volumes at this station will be recalculated for all survey dates so that volume comparison can be based on the same boundaries of a “sand box.”]*



**FIGURE A.** Illustration of the three (3) lenses used in the profile volume analysis for Nags Head.

## Overall Performance

The overall volumes of sand remaining in the “foredune” (Lens 1), the “foredune” and the “Beach” (Lenses 1 and 2), as well as the above two lenses plus the “underwater” portion (Lenses 1, 2, and 3 as illustrated in Fig A) were computed from the condition surveys, and compared in Figure B. The foredune section of the beach (the first set of bars in Fig B) remained stable over the past four years, retaining over 1 million cubic yards more sand in May 2018 than the pre-nourishment condition in November 2010. The recreational part of the beach from the foredune to the low tide wading depth (the second set of bars) retained ~2 million cubic yards in May 2018 compared to ~3 million cubic yards in June 2012 (Year 1 after project completion), indicating nourishment sand adjustment since project completion.



**FIGURE B.** Cumulative, overall beach-volume changes relative to November 2010 survey results between the foredune and indicated contours.

The third set of bars in Figure B show the total volume changes in the entire sand box measured from the foredune to the FEMA reference depth of -19 ft NAVD. Between June and October 2016, Nags Head lost a significant amount of sand primarily due to Hurricane *Matthew* which caused approximately 1.43 million cy of sand to leave the sand box. A portion of the *Matthew* volume losses (~200,000 cy) returned to the project area as confirmed by the July 2017 survey. However, the May 2018 survey indicated that **Nags Head lost another ~1.27 million cy of sand over the past year due to the higher-than-normal wave conditions.**

As of May 2018, the 10-mile project area retains ~1,669,682 cubic yards more sand than the pre-nourishment condition. This volume represents **~36 percent remaining** of the 4.6 million cubic yards of sand placed during the 2011 project. Sand losses have averaged ~440,000 cubic yards per year (cy/yr) or ~8.4 cubic yards per foot per year (cy/ft/yr) of beachfront over the past seven years. These “7-year” averages are higher than the historical erosion rate of 275,000 cy/yr (or 5.2 cy/ft/yr) that was adopted at the time of planning and designing the 2011 project (CSE 2005, 2011a). Under normal wave conditions, this higher rate would be expected to decline in the next couple of years bringing the net volume losses closer to long-term averages.

### Performance by Reach and Subreach

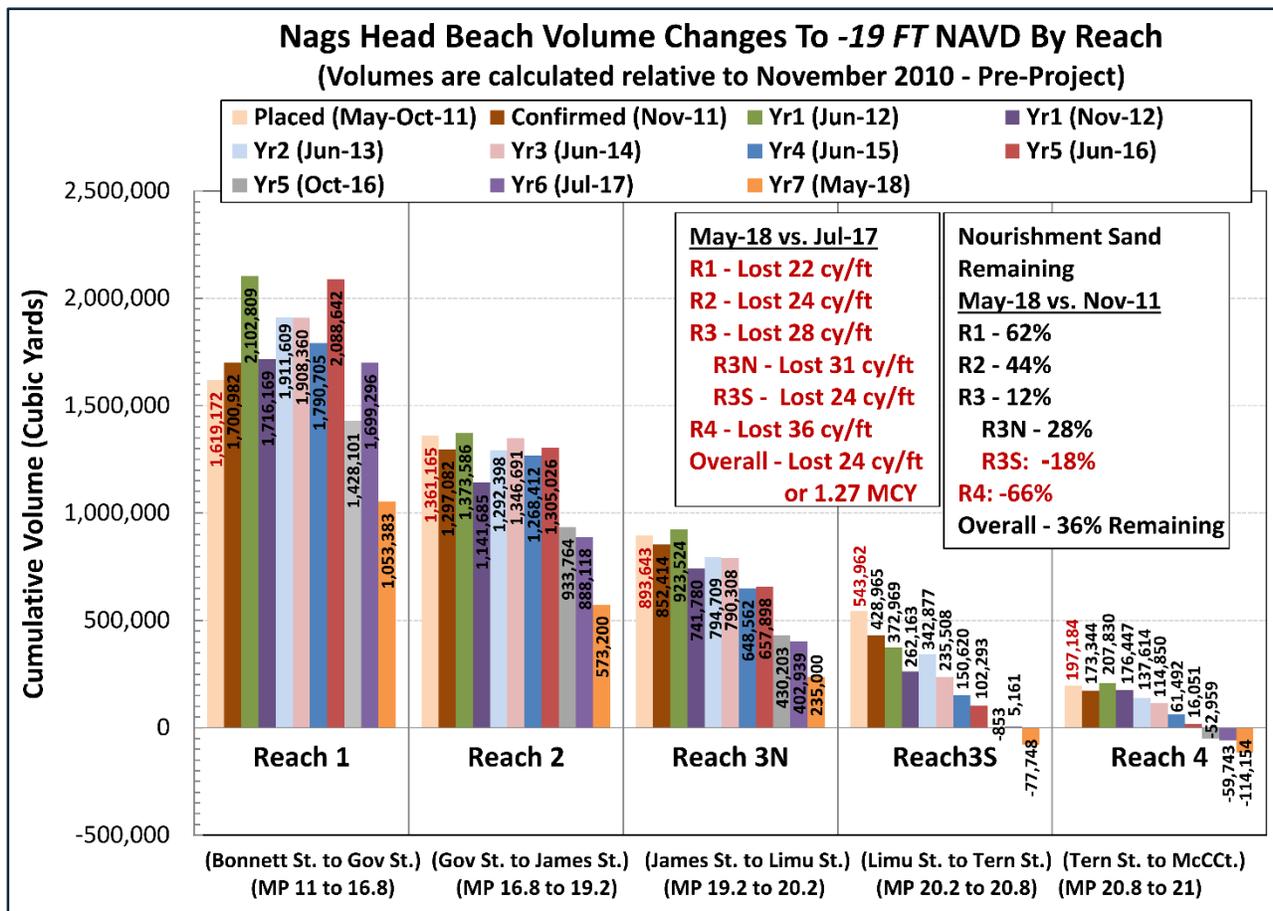
Four main reaches are referenced each year in these monitoring reports, and Reach 3 has been further divided into two subreaches (Reaches 3N and 3S) over recent years to better distinguish variations in sand volumes and erosion rates. Figure C shows the volumes (relative to the pre-project condition in November 2010) measured from the foredune to -19 ft NAVD along the reaches and subreaches. Reach 1 (the northern half of the project) lost ~22 cy/ft (~3.3 cy/ft/yr) and retained over 60 percent of the nourishment volume at Year 7 following project completion. Erosion rates increased from north to south. Reach 2 lost ~56 cy/ft (~8.4 cy/ft/yr), Reach 3N lost ~112 cy/ft (~17 cy/ft/yr), Reach 3S lost ~145 cy/ft (~22 cy/ft/yr), and Reach 4 lost ~192 cy/ft (~29 cy/ft/yr). The southernmost ~1 mile of Nags Head (Reaches 3S and 4) has less volume in 2018 than the pre-project condition. The results are summarized as follows.

**Reach 1 (R1)** — The northern ~5.8 miles of beach from Mile Posts 11 to 16.8 (CSE stations 497+00 to 790+00) lost ~645,913 cy\* over the past year (mainly due to the close passage of several hurricanes in September 2017 and a series of northeasters in March 2018). Compared to the condition after project completion in November 2011, Reach 1 contains ~60 percent of the nourishment volume as of May 2018.

\*[Unless otherwise specified, volumes in this section are measured from the foredune to the FEMA reference depth of -19 ft NAVD.]

**Reach 2 (R2)** – The center to southern ~2.4 miles of beach from Mile Posts 16.8 to 19.2 (CSE stations 790+00 to 920+00) lost ~314,918 cy over the past year, and has lost 723,882 cy (~56 cy/ft or ~8.4 cy/ft/yr) since project completion (November 2011). The total loss as of May 2018 is equivalent to ~56 percent of the nourishment volume in this reach. This loss rate is about the same magnitude as the loss rate of the entire project.

**Reach 3 (R3)** – The southern ~1.7 miles of beach from Mile Posts 19.2 to 20.8 (CSE stations 920+00 to 1010+00) lost ~250,847 cy over the past year. Compared to the condition after project completion, Reach 3 has lost ~1,124,126 cy (~125 cy/ft or ~19 cy/ft/yr), equivalent to ~88 percent of the nourishment volume placed along this reach. This rate is much higher than the average volume loss rate of Reach 2 and over two times the erosion rate for the entire project. To better document the nourishment performance and delineate erosion variations along south Nags Head, Reach 3 is further divided into two subreaches in some of the analysis.



**FIGURE C.** Beach volume changes by reach and subreach relative to November 2010 survey results from the foredune to -19 ft NAVD.

**Subreach 3N (R3N)** — The northern two-thirds of Reach 3 from Mile Posts 19.2 to 20.2 (CSE stations 920+00 to 975+00) lost ~227,695 cy over the past survey year. Compared to the condition after project completion in November 2011, Subreach 3N has lost 617,414 cy (~112 cy/ft or ~17 cy/ft/yr), which is equivalent to ~72 percent of the nourishment sand placed there. This rate compares favorably with the volume loss rate of 88 percent for the entirety of Reach 3.

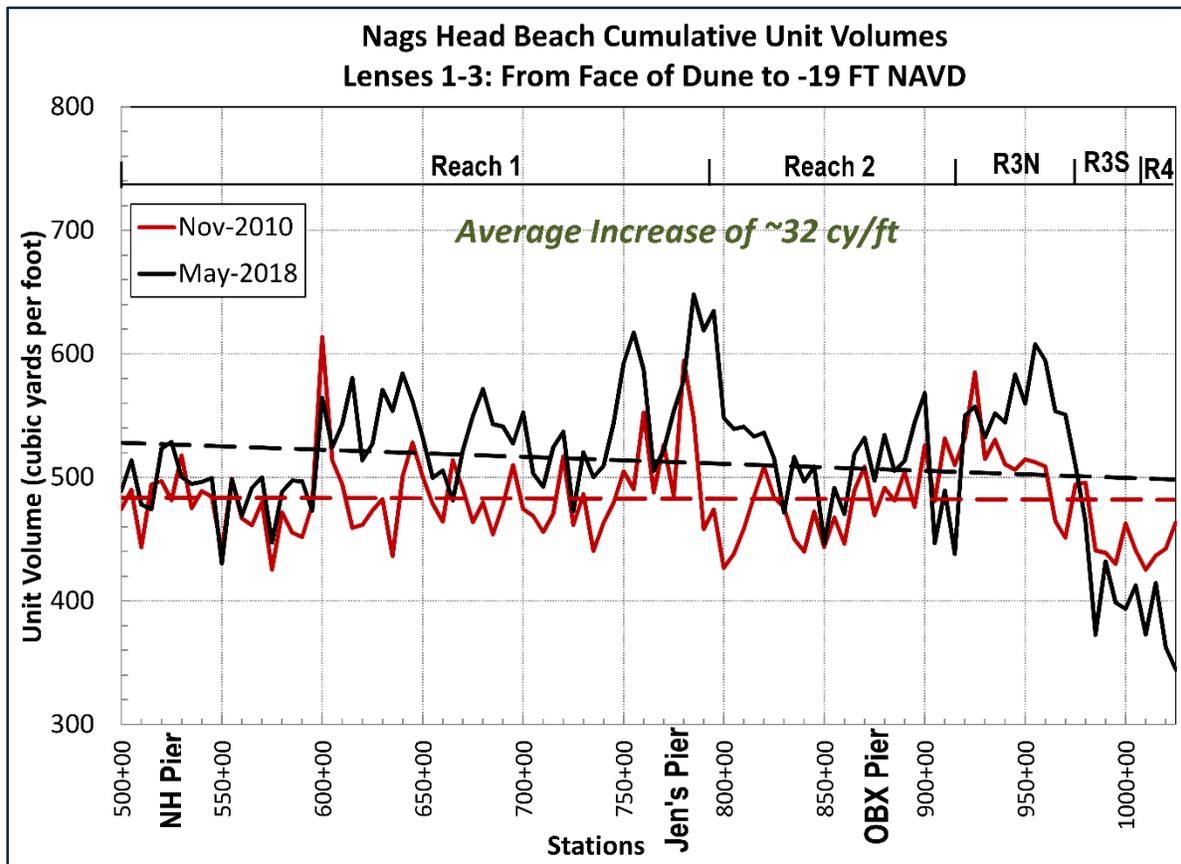
**Subreach 3S (R3S)** — The southern one-third of Reach 3 from Mile Posts 20.2 to 20.8 (CSE stations 975+00 to 1010+00) lost 82,908 cy over the past survey year between July 2017 and May 2018. Since project completion, Subreach 3S has lost 506,713 cy (~145 cy/ft or ~22 cy/ft/yr), which is equivalent to 118 percent of the nourishment volume placed.

**Reach 4** — The southernmost ~0.2 mile of beach from Mile Posts 20.8 to 21 (CSE stations 1010+00 to 1025+00) lost 54,411 cy over the past year. Compared to conditions following project completion, Reach 4 has lost 166 percent of the nourishment volume. The average erosion rate is as high as ~192 cy/ft (~29 cy/ft/yr) which is even higher than Subreach 3S. The beach condition since June 2016 along this 1,500-ft-long end of the project area has returned to conditions prior to nourishment based on the volume analysis.

Sand losses were projected to be higher along south Nags Head than north Nags Head based on historical trends, but the erosion rates of the last three years in these two reaches are significantly higher than CSE's original design estimate. This difference is likely related to the shoreline offset produced by placing a higher fill density at the south end of the project to account for higher erosion rates.

### **Performance Along Nags Head**

Annual profile surveys at 500-ft intervals have also documented large variations from station to station. The differences in sand volume reflect the dynamic nature of beaches and the underwater profile to the outer bar. Figure D shows such irregularity station by station comparing November 2010 (pre-nourishment) and May 2018. The dashed trend lines of November 2010 and May 2018 show the relative decrease in volume from north to south. Although these two lines have moved closer as Nags Head has lost more nourishment volume over recent years, most profiles contain more sand in 2018, averaging an increase of ~32 cy/ft compared to the November 2010 condition. However, there are several specific stations where the lines touch, meaning those particular localities in May 2018 had less sand than in 2010. Tracking of these specific "erosion hotspot" areas over the past few years show these areas tend to move alongshore from year to year, which accounts for some of the natural waviness of the shoreline, looking down the beach (CSE 2014; 2015; 2016; 2017). The lowest unit volumes occur south of station 975+00 (Subreach 3S and Reach 4) consistent with the sand loss trends previously illustrated in Figure C.

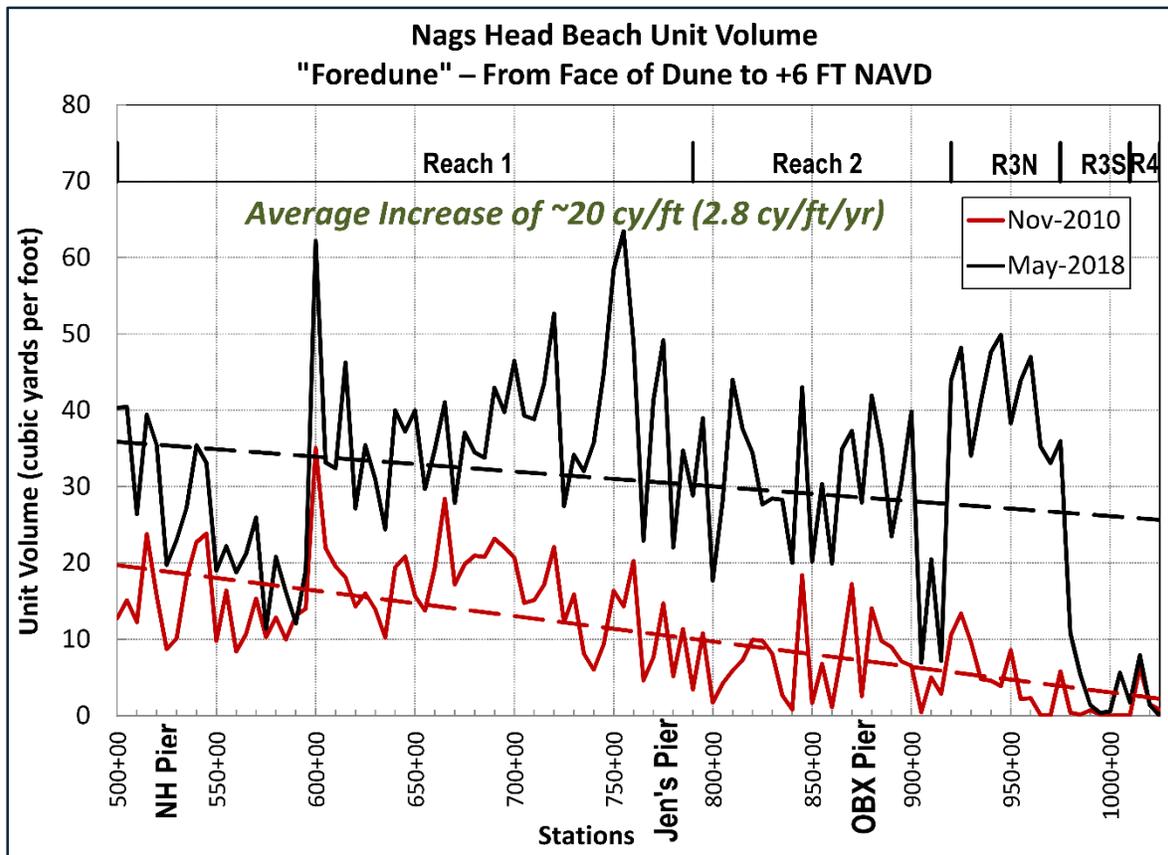


**FIGURE D.** Comparison of cumulative unit volumes by station between the face of dune and -19 ft NAVD.

### Dune Behavior Along Nags Head

This report also details the added dune protection gained by winds and sand fencing as a result of nourishment. Figure E shows there is much more sand in the foredune at nearly all stations. This is the portion of the profile that prevents wave runoff and overtopping of dunes during major storm events.

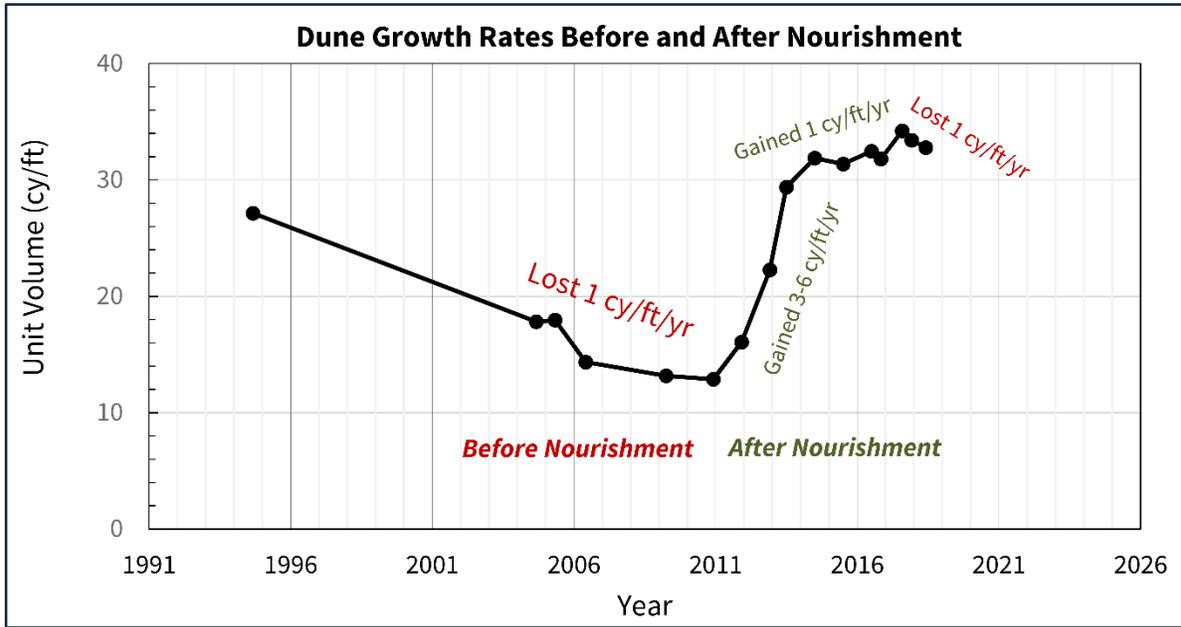
Before nourishment (1994–2010), Nags Head experienced sand losses averaging ~1 cy/ft/yr in the foredune area above elevation +6 ft NAVD. The nourishment berm was set to +6 ft NAVD along the majority of the project area with the exception of +7 ft NAVD in some areas where the natural beach was higher. No sand was placed on the foredune above the design berm elevation during the 2011 project. However, since completion of the nourishment in 2011, the foredune has gained over 700,000 cy along the 10-mile project beach as of May 2018, which is equivalent to a unit volume increase of ~13 cy/ft or ~2 cy/ft/yr since November 2011. Compared to the pre-project condition in November 2010, Nags Head dunes have gained an average of 20 cy/ft as of May 2018, equating to an accretion rate of ~2.8 cy/ft/yr (Fig E).



**FIGURE E.** Comparison of unit volumes along Nags Head from the face of dune to +6 ft NAVD contour before nourishment (November 2010) and the most recent survey condition (May 2018). This indicates a significant increase of unit volumes after the project at most stations. Unit volumes in previous surveys (November 2011, June 2012, November 2012, June 2013, June 2014, June 2015, June and October 2016, and July 2017) are plotted in earlier reports by CSE (2013a,b,c / 2014b / 2015 / 2016 / 2017).

Erosion and accretion rates before and after nourishment are summarized in Figure F. The wide dry beach constructed by nourishment provided a new sand source for aeolian transport and made natural dune growth possible. Sand fencing, installed after the project, has helped concentrate sand along the back beach and enhanced the foredune. Dune growth rates have declined over the past four years, and the rates over the past year have reversed from growing to declining to a rate similar to pre-project conditions. The dune growth rates are expected to increase again after the 2019 renourishment, at a comparable rate occurred over the first few years after the 2011 project.

Although incipient dunes started forming in many places along the Nags Head oceanfront, they have not developed into established dunes due to the short period of time since formation. Lack of dunes or low incipient dunes makes certain portions of beach vulnerable to dune overtopping and wave overwash into streets through beach accesses. Areas with high established dunes but a narrow dry-sand beach instead lead to dune escarpments after hurricanes or winter storms.



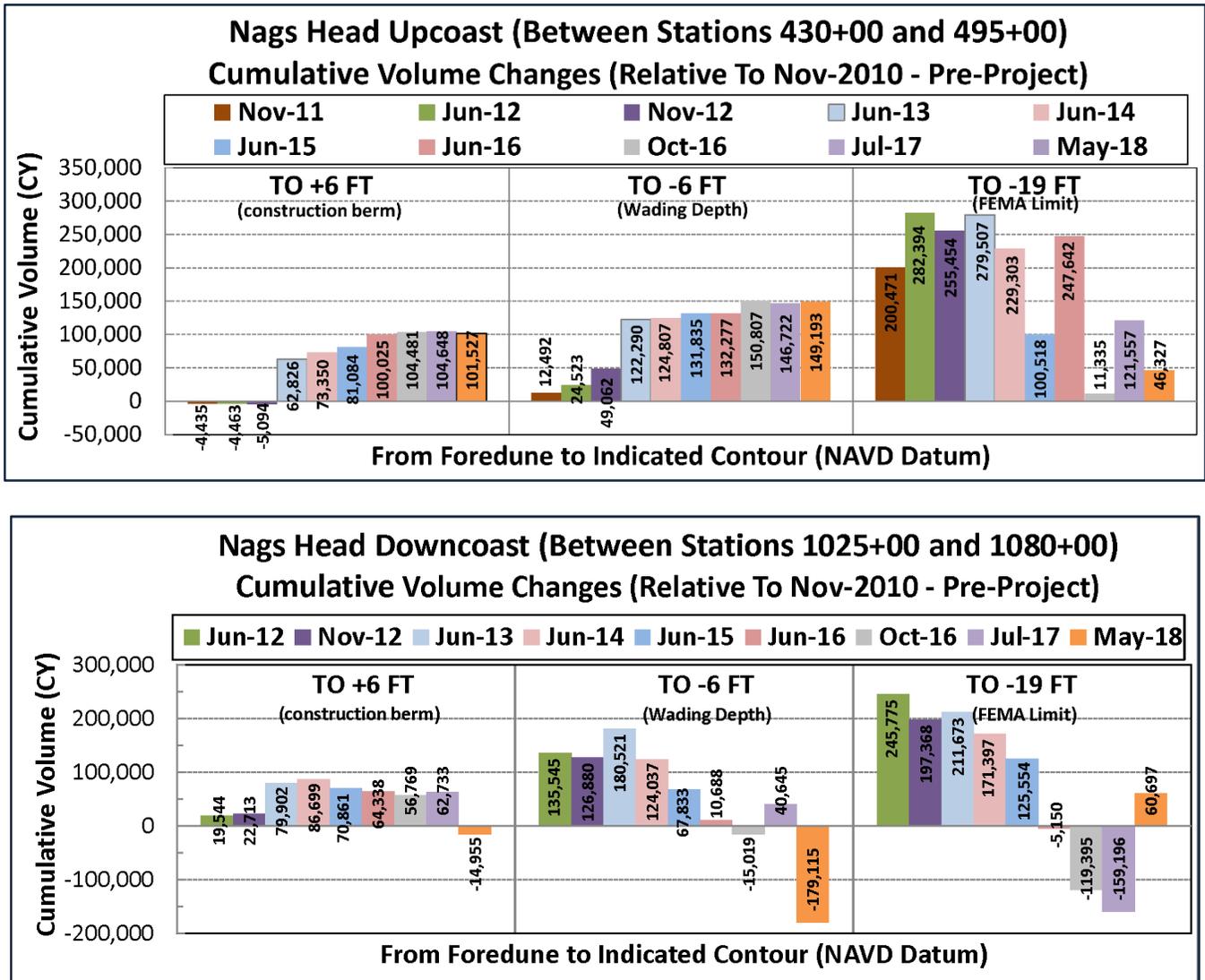
**FIGURE F.** Dune erosion and accretion rates before and after 2011 nourishment measured above the +6-ft NAVD contour.

Rhythmic variations in beach width have been a characteristic along the project area likely because of variations in the longshore bar offshore of Nags Head. Escarpments most commonly occur where an erosional arc or rhythmic topography is propagating through the area. The variable conditions alongshore result in localized “erosional hotspots” on the beach.

The upcoming 2019 beach renourishment project will replenish the sand deficit along the entire 10-mile project area and restart a new cycle of profile changes and evolution. The renourishment project incorporates an initial dune feature in the design. CSE will revise the final design at the time of construction and addresses the erosional hotspots to increase the longevity of the project.

## Upcoast and Downcoast

As the gray bars in the upper graph in Figure G illustrates, the ~1-mile upcoast area lost ~75,230 cy over the past year, indicating similar erosion trends as the Nags Head project area. As of May 2018, the upcoast ~1-mile of beach has ~46,327 cy more sand than pre-project conditions from the foredune to the FEMA depth limit (-19 ft NAVD). The overall volume change trends to -19 ft are similar to the trends that were observed along Reaches 1 and 2 in Nags Head.



**FIGURE G.** Cumulative volume changes from the foredune to the indicated contour relative to the November 2010 condition along upcoast (upper) and downcoast (lower) stations outside the project area.

There had been extra volumes in the downcoast reach between November 2011 and June 2015 relative to November 2010 conditions, measured from the face of dune to the -19 ft depth contour. However, the downcoast reach lost all the extra volume in 2016 and 2017, and its beach condition returned to the pre-project condition in those years. The high erosion rate (~53 cy/ft between June 2012 and July 2017 or ~11 cy/ft/yr) is comparable to the sand loss rate observed along the southern end of the project area with an offshore shift of the outer bar to deeper water (CSE 2017). The recent sand gain (~220,000 cy) over the past survey year could be caused by volume passed downcoast from Reach 3 and Reach 4 due to the southerly longshore sediment transport. As a result of the time it takes for sand to move downcoast and the relatively small amount, shoaling in Oregon Inlet over recent years is not likely caused by the sand loss of Nags Head but has been principally related to erosion along the National Seashore.

### **Monitoring and Maintenance Recommendations**

The Town of Nags Head has planned for a beach renourishment project to restore sand losses that have occurred since the 2011 nourishment project, and a construction agreement has been signed between the Town and Great Lakes Dredge & Dock Company (GLDD). The renourishment project will integrate a dune management plan including initial dune construction along south Nags Head, installation of sand fencing and planting of vegetation along the entire project area following renourishment. The project also incorporates a sand relocation plan along the areas where nourishment sand migrates landward causing encroachment onto existing structures. The overall purpose and goals of the renourishment project are as follows.

- 1) Restore sand losses due to chronic erosion and Hurricane *Matthew* (2016)
- 2) Provide a higher level of storm protection
- 3) Provide wider recreational beach and create habitat for wildlife
- 4) Address high erosion rates at the south end of Nags Head
- 5) Integrate a dune management plan into the renourishment design
- 6) Maintain Nags Head's eligibility for future FEMA community assistance funds

The renourishment project calls for a total of ~3.73 million cubic yards of beach-quality sand to be dredged from offshore borrow areas and placed along the previously nourished 10-mile-long shoreline. Permit application packages were submitted to the NCDEQ and the USACE in September, October, and November 2017 (CSE 2017b), and state and federal permits were received as of March 2018. The anticipated commencement date of construction is spring to summer 2019.

## ACKNOWLEDGMENTS

---

The Year 7 post-nourishment survey was funded by the Town of Nags Head under its budget for beach renourishment. CSE thanks the Nags Head Board of Commissioners, the Town staff, and the Shoreline Management Committee for their continued support (Cliff Ogburn, Town Manager; David Ryan, Town Engineer and Project Coordinator; Andy Garman, Deputy Town Manager). CSE also thanks Roberta Thuman (Administrative Assistant), Ralph Barile (Nags Head Public Works Department Director), and the Nags Head Police Department (Chief of Police – Kevin Brinkley) for their assistance during our surveys.

Field data collection and analysis were directed by Dr. Haiqing Liu Kaczowski (PE, NC 37281 – project engineer) and conducted by Drew Giles and Luke Fleniken. The report was written by Dr. Kaczowski with assistance by Dr. Tim Kana (PG, NC 1752), Trey Hair, Carrie Marks, and Diana Sangster.

— *THIS PAGE INTENTIONALLY LEFT BLANK* —

## TABLE OF CONTENTS

EXECUTIVE SUMMARY .....	i
ACKNOWLEDGMENTS .....	xi
1.0 INTRODUCTION .....	1
1.1 Project Background, Design, and Implementation .....	2
2.0 BEACH MONITORING REQUIREMENTS AND SCOPE OF WORK .....	9
2.1 Beach Monitoring Requirements .....	9
2.2 Data Collection Methodology.....	11
3.0 WIND AND WAVE CONDITIONS AT THE PROJECT SITE .....	13
3.1 Wave Buoy at USACE–FRF .....	13
3.2 Present Monitoring Period Wave Climate (July 2017 — May 2018).....	13
3.3 2017 Atlantic Hurricane Season .....	17
4.0 BEACH AND INSHORE SURVEYS AND PROFILE COMPARISONS .....	19
4.1 Beach Volume Analysis Method.....	19
4.2 Unit Volume Results .....	22
4.2.1 Foredune – Lens 1 (from Face of Dune to +6 ft NAVD) .....	22
4.2.2 Recreational Beach – Lens 2 (from +6 ft to –6 ft NAVD) .....	25
4.2.3 Underwater – Lens 3 (from –6 ft to –19 ft NAVD).....	27
4.2.4 Cumulative Unit Volumes — Lens 1–3 (from Face of Dune to –19 ft NAVD) .....	29
5.0 TOTAL VOLUME CHANGES AND VOLUME REMAINING .....	31
5.1 Total Volume Summary Before and After Nourishment .....	31
5.2 Total Volume Changes by Reach and Subreach .....	37
5.2.1 May 2018 Compared to July 2017 (Volume Changes over Present Monitoring Period) .....	38
5.2.2 May 2018 Compared to Project Completion (November 2011) .....	40
6.0 DUNE GROWTH, EROSION, AND ESCARPMENT .....	43
6.1 Overall Dune Growth After Nourishment .....	43
6.1.1 Dune Growth Mechanics–Aeolian Transport.....	44
6.1.2 Main Factors Affecting Aeolian Transport in the Beach Environment.....	46
6.1.3 Dune growth After the 2011 Nourishment .....	49
6.2 Erosional Hotspots and Dune Escarpments .....	51
7.0 UPCOAST AND DOWNCOAST CHANGES.....	57
7.1 Upcoast Reach .....	57
7.2 Downcoast Reach.....	59
8.0 MONITORING AND MAINTENANCE RECOMMENDATIONS.....	61
REFERENCES .....	63
APPENDIX	
1) Beach Monitoring & Maintenance Plan	
2) Baseline and Control Station Coordinates & Elevations	
3) Beach Profiles	
4) Unit Volumes	
5) Total Volumes	

— *[THIS PAGE INTENTIONALLY LEFT BLANK]* —

## 1.0 INTRODUCTION

---

This is the seventh annual report on the beach condition along Nags Head following successful completion of the 2011 beach nourishment project at Nags Head, Dare County, North Carolina. The 2011 project was constructed between 24 May and 27 October 2011, during which time 4.6 million cubic yards of sand were placed along a 10-mile-long stretch of Nags Head beach.

The state and federal permits for the project required the Town of Nags Head to prepare a monitoring and maintenance plan (Appendix 1). In accordance with the plan, a comprehensive beach condition survey was conducted in November 2011 right after the project was finished, and semi-annual or annual surveys have been conducted since project completion. Two semi-annual surveys were completed in June and November 2012 (Year 1). Annual surveys were conducted in June 2013 (Year 2), June 2014 (Year 3), June 2015 (Year 4), June 2016 (Year 5), July 2017 (Year 6), and May 2018 (Year 7). An additional survey was conducted in October 2016 after the passage of Hurricane *Matthew* to document volume losses caused by the storm. Post-project conditions and a summary of project implementation are provided in CSE (2012), and the results of Year 1–6 surveys documenting project performance are included in CSE (2013a,b / 2014b / 2015 / 2016 / 2017).

The present report covers the monitoring period from July 2017 to May 2018, representing the seventh year after completion of the 2011 project. It provides a summary of the surveys and physical condition of the beach in Year 7 after nourishment and quantifies sand volume changes relative to pre-project conditions (November 2010). The survey results are used to evaluate the project performance and storm damage, document volume changes within various calculation limits, and identify erosion hotspots.

The outline of this report includes:

- Brief review of the 2011 beach nourishment project
- Brief review of previous post-project monitoring efforts for Year 1 (2012) through Year 6 (2017)
- Beach monitoring requirement and scope of survey work
- Data collection methodology and survey control information
- Beach and inshore surveys and profile comparisons
- Profile volume analyses for representative contour intervals
- Net volume changes by profile and reach
- Calculation of nourishment volumes remaining in the project area
- Dune volume changes and management plan
- Upcoast and downcoast volume changes
- Representative aerial photos and ground photos
- Monitoring and maintenance recommendations

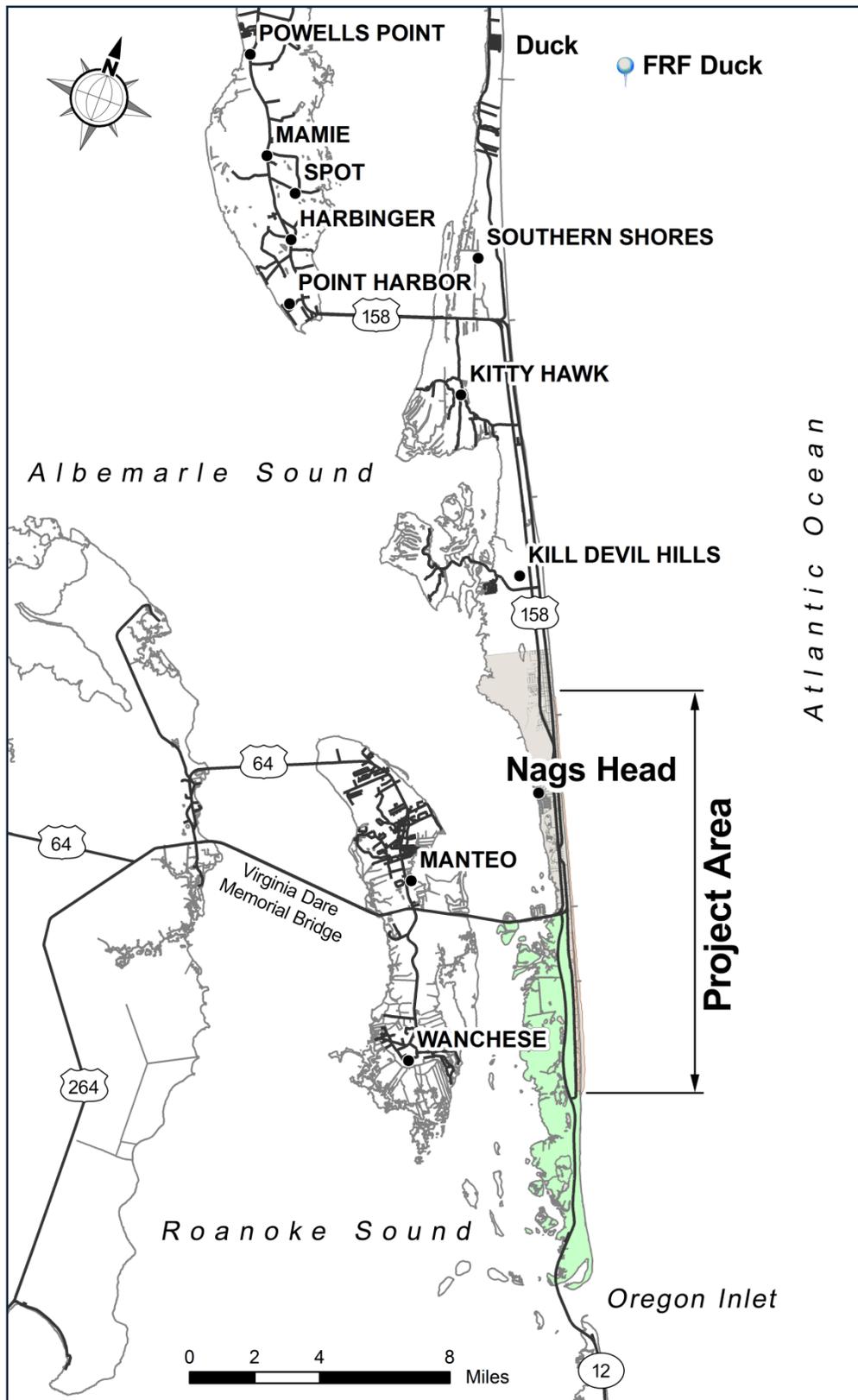
Specific information about the project and previous survey efforts are repeated in each monitoring report to aid the reader. The project planning, design, implementation, and initial performance are detailed in CSE's reports (2005, 2007a, 2008, 2011a-b, 2012). A summary of these project attributes is given in two papers presented at the International Conference of Coastal Engineering (Kana & Kaczkowski 2012, Kaczkowski & Kana 2012), and details of project performance and volume changes during Hurricane *Irene* were described in a paper published in a dedicated issue of *Shore & Beach* (Kana et al 2012). A recent paper published in *Ocean Dynamics* (Kaczkowski et al 2018), analyzed post-nourishment beach-fill equilibration and dune growth.

The Town of Nags Head has planned a beach renourishment project to restore sand losses that have occurred due to chronic erosion and Hurricane *Matthew* since the 2011 nourishment project (CSE 2017b). The sources of the funds for the renourishment project are ~55 percent from the Town and Dare County, and ~45 percent from FEMA under its Category G restoration policy. A Major CAMA Permit (#45-10) was received on 12 February 2018, and the USACE Permit (SAW 2017-02098) was obtained on 28 March 2018. Bid documents for renourishment were issued on 15 February 2018, and four (4) bids were received and opened on 15 March 2018. Great Lakes Dredge & Dock Company (GLDD) was the Apparent Low Bidder, and an Agreement between the Town of Nags Head and GLDD was signed on 16 July 2018 for nourishment of 3,731,661 cubic yards. Construction is expected to start in spring-summer 2019 and be completed by 15 December 2019.

## **1.1 Project Background, Design, and Implementation**

The Town of Nags Head encompasses ~11 miles of ocean shoreline along North Carolina's Outer Banks, a chain of barrier islands along the Atlantic Ocean, 90 miles south of Norfolk (VA). Figure 1.1 shows the project location. The Town faces east to northeast and is bordered by the Town of Kill Devil Hills to the north and Cape Hatteras National Seashore to the south. Roanoke Sound borders the Town on the west, and the Atlantic Ocean makes up the Town's eastern limits. The northern boundary of the Town is situated about 15 miles from the US Army Corps of Engineers (USACE) Field Research Facility (FRF) Pier at Duck (NC) and approximately 40 miles from the Virginia border. Oregon Inlet, the closest inlet to Nags Head, is located about 5 miles south of the Town line.

Nags Head is exposed to high-wave energy during storm events, particularly hurricanes in summer and northeasters which are common in fall and winter. The Town has sustained chronic erosion over the past 50 years due to storms and sand losses to Oregon Inlet. Net sand transport is south along Nags Head, and erosion rates increase from north to south and remain high in the ~5-mile-long National Seashore reach between Nags Head and Oregon Inlet. The purpose of the 2011 beach nourishment project was to restore a protective beach for a minimum of ten years, replace sand lost during the delayed implementation of the federal Dare County beach erosion control project, and expand the recreational beach for the community.



**FIGURE 1.1.** Nags Head (NC) project vicinity map.

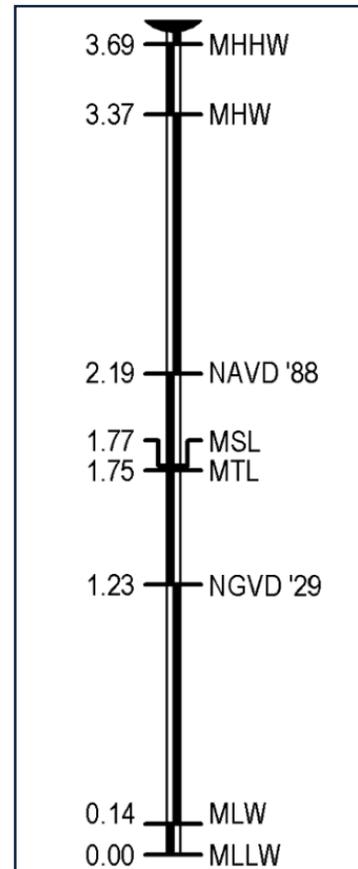
The 2011 project totaled ~10.0 miles of shoreline beginning ~1 mile from the Town’s northern limit near the Bonnett Street public beach access (milepost 11.25, CSE station 497+00) and extending south to the Town line (milepost 21, CSE station 1025+00\*) adjacent to the Cape Hatteras National Seashore. CSE reoccupied USACE 1994 survey lines and collected extensive profiles from the dunes to deep water as many as six times over the 5-year planning period between 2005 and 2010. [Estimated profile closure depth is -24 ft NAVD\*\* for this setting (CSE 2007a).]

*\*Stationing for profiles approximately matches USACE stationing established for the planned federal project. The specific coordinates for control points vary by a small amount from the USACE baseline (see Appendix 2 for baseline and control information.)*

*\*\*NAVD — North American Vertical Datum of 1988 which is 0.42 ft above local mean sea level (MSL). NGVD — National Geodetic Vertical Datum of 1929 which is 0.96 ft below NAVD datum of 1988 at FRF Duck (NC). Relationship of various water levels and survey datum at Duck is shown in Figure 1.2. [Source: NGS-NOAA]*

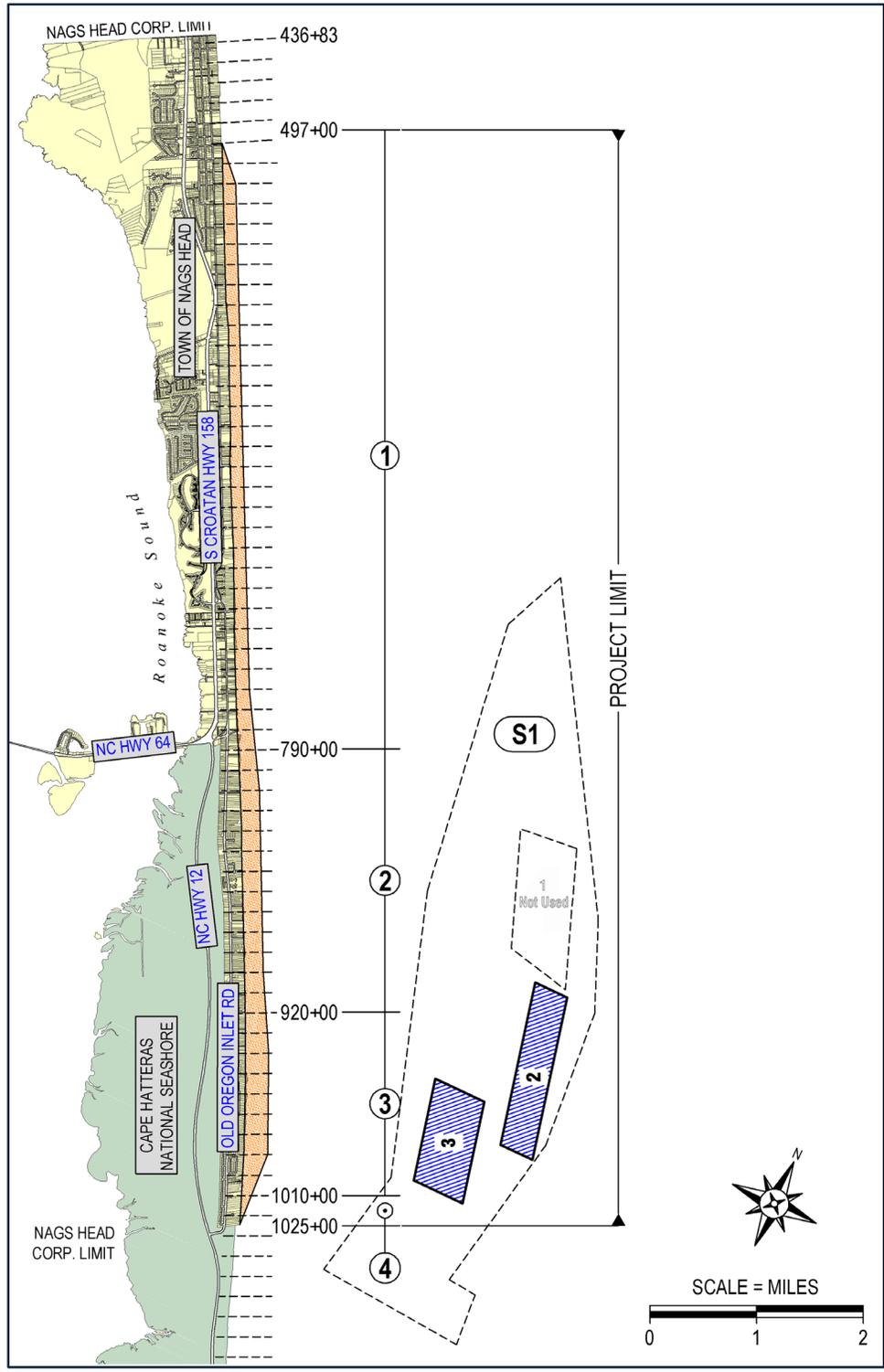
Compared field surveys revealed an average annual erosion rate of 275,000 cubic yards (cy) which was adopted in the planning and design of the project. Longshore and cross-shore numerical models were applied to refine the nourishment plan and increase potential longevity of the project. Model results were used to identify the potential occurrence of erosional hotspots and optimize the nourishment design to avoid or minimize their impacts wherever possible. Four reaches were delineated based on historical erosion rates and indicated a fill density of 87 cubic yards per foot (cy/ft) on average ranging 50–170 cy/ft from north to south.

The overall project limits and project reaches are shown in Figure 1.3 along with the borrow areas approved for use within USACE-designated borrow area S1. Subareas 2 and 3 contained over 7 million cubic yards of beach-quality sand (8-ft excavation) and were used in the 2011 project (CSE 2011). During the design and planning phases of the nourishment project, CSE collected and analyzed over 200 sediment samples of the native beach. The integrated result of cross-shore samples between the foredune and the ~18-ft NAVD depth contour show the beach is composed of medium sand with a mean grain size of ~0.306 millimeters (mm).



**FIGURE 1.2.** Relationship of various water levels and survey datum at Duck (NC).

[Source: NGS-NOAA]



**FIGURE 1.3.** Nags Head (NC) project reaches along with the fish-shaped USACE-designated borrow area. The Town limits are around stations 436+83 and 1025+00; the project limits are between stations 497+00 and 1025+00. Subareas 2 and 3 were used in the 2011 project.

CSE also obtained over 100 borings in the USACE-designated borrow area to locate the most compatible material. The borings [~8–10 ft long] are in water depths ranging from 45 ft to 60 ft. An average core density of 1 per 20 acres allowed CSE to prepare relatively detailed isopach maps of sediment quality for final delineation of borrow areas. The designated borrow areas met the updated North Carolina Coastal Resources Commission (NCCRC) sediment criteria and were selected to produce a stable project that would be economical and as environmentally compatible as possible.

The 2011 project was sponsored by the Town of Nags Head (Dare County NC), and the Town served as project owner and administrator. The favorable bid received from Great Lakes Dredge & Dock Company, Inc (GLDD, Oak Brook, Illinois) allowed the Town to initiate a single contract with GLDD to accomplish the maximum permit volume of 4,600,000 cy for a total of \$30,184,000. The unit price was \$6.56/cy including mobilization/ demobilization and placement of nourishment sand. Coastal Science & Engineering (CSE) (Columbia SC) served as the project engineer—planning and designing the project, preparing the approved environmental impact statement along with state and federal permit applications, collecting and analyzing field data, applying numerical models, and performing construction administration and observations (detailed in CSE 2011a–b, 2012).

The contractor (GLDD) used three ocean-certified hopper dredges (*Liberty Island*, *Dodge Island*, and *Padre Island*) and one cutterhead suction dredge (*Texas*) to construct the project between 24 May and 27 October 2011. Three months into construction, GLDD had placed ~3.8 million cubic yards on the beach, representing almost 85 percent of the contracted volume. Reaches 2 and 3 were complete by late August, leaving about half of Reach 1 and Reach 4 (the taper section at the downcoast end) incomplete when Hurricane *Irene* impacted the project area on 27 August 2011.

The newly placed sand served to absorb storm-wave energy, reduced the height of wave runup at the dune line, and prevented damage to the foredune, buildings, and roads during *Irene*. While the construction berm was overtopped by waves, no ocean overwash penetrated the dunes or left dune escarpments along the nourished sections. Several condemned properties on the active beach at Seagull Drive received nourishment about two weeks before the hurricane and weathered the storm without further damage. Numerous weather delays in September and October associated with at least five extratropical cyclones and the passage offshore of Hurricanes *Katia* (8 September) and *Maria* (16 September) caused the remainder of the project to be completed on 27 October 2011.

The contractor's construction surveys for purposes of payment showed a total of 4,615,126 cy were placed along 10.0 miles of project area between 24 May and 27 October 2011. CSE completed a detailed survey of the beach and inshore zone in November 2011 within one month of project completion and compared the post-project conditions against the pre-project November 2010

condition (same-season comparison). Post-nourishment CSE confirmed there were 4,713,927 cy more sand volume in the 10-mile project area as indicated in the volume comparisons by reach listed in Table 1.1.

**TABLE 1.1.** Summary of fill volume versus design volume for each reach based on before-dredging and after-dredging surveys by GLDD and November 2010 (pre-project) and November 2011 (post-construction) surveys by CSE. Volume calculations for the November 2011 survey extended to the -12 ft depth contour ~800 ft from the foredune.

Reach	Limits	Length (ft)	CSE Design Volume (cy)	GLDD Applied Fill Volume (cy)	Diff between Design and Fill (%)	CSE Verified Volume (cy)
1	497+00 to 790+00	29,900	1,634,700	1,645,812	0.68%	1,819,532
2	790+00 to 920+00	13,000	1,366,500	1,405,498	2.85%	1,358,359
3	920+00 to 1010+00	9,000	1,480,000	1,423,771	-3.80%	1,377,313
4	1010+00 to 1025+00	1,500	118,800	140,045	17.88%	158,723
<b>Total</b>	<b>497+00 to 1025+00</b>	<b>52,800</b>	<b>4,600,000</b>	<b>4,615,126</b>	<b>0.33%</b>	<b>4,713,927</b>

In summary, the 2011 Nags Head beach nourishment project was completed under budget, on time, and without any environmental incidents. CSE’s November 2011 survey after hurricanes and fall storms showed two positive outcomes:

- 1) No loss of sand by natural processes occurred within the project limits between November 2010 and November 2011
- 2) A gain of at least 4.6 million cubic yards resulted via the 2011 nourishment.

At the time of the survey, the beach profiles were adjusting to a shape and configuration which was indistinguishable from a natural beach.

— *THIS PAGE INTENTIONALLY LEFT BLANK* —

## 2.0 BEACH MONITORING REQUIREMENTS AND SCOPE OF WORK

---

### 2.1 Beach Monitoring Requirements

Before commencement of the 2011 nourishment project, the Town of Nags Head obtained permits under the National Environmental Policy Act (NEPA) and the state Coastal Area Management Act (CAMA) permitting process.

The North Carolina major CAMA permit (45-110) was received on 29 April 2010, and the federal permit (SAW 2006-40282) was obtained on 30 November 2010. The state and federal permits required a beach monitoring and maintenance plan (Appendix 1), and such a plan is also a pre-requisite for FEMA's post-storm beach restoration funding. Certain thresholds are specified for renourishment, including:

- Net sand losses due to a storm (declared disaster) must measure within defined project limits, which (for Nags Head) span 10 miles of oceanfront between the foredune and the -19 ft NAVD offshore contour (or -18-ft NGVD). [See Fig 1.2 for explanations on NAVD and NGVD datums.]
- Chronic sand losses must equate to more than 50 percent of the placed sand (ie - more than 2.3 million cubic yards) at six years. If 50 percent or more of the sand remains on the beach at six years' post-initial project renourishment cannot commence until 50 percent or more is lost.

As per special conditions of the USACE permit, annual sediment compaction tests are required (following completion of the nourishment project) before the next three sea-turtle nesting seasons along the Nags Head project area and adjacent unnourished reaches. Compaction measurement methods and evaluation criteria are prescribed by Item 2 in the US Fish and Wildlife Service (USFWS) Biological Opinion (18 August 2008, page 31-32). [Note: "The applicant" is the Town of Nags Head in the following paragraphs.]

- 2) *Immediately after completion of the beach construction project and prior to May 1 for three subsequent years, sand compaction must be monitored in the project area in accordance with a protocol agreed to by the USFWS, the North Carolina Wildlife Resources Commission, and the applicant. The applicant should not be allowed to routinely till all or part of the constructed beach as a substitute for systematic sand compaction monitoring. At a minimum, the protocol provided under 2a and 2b below must be followed . . . A report on the results of the compaction monitoring shall be submitted to the Raleigh Field Office of the USFWS prior to any tilling actions being taken. Out-year compaction monitoring and remediation are not required if sediment imported for beach construction no longer remains on the dry beach.*

2a) *Compaction sampling stations must be located at 500-foot intervals along the project area. One station must be at the seaward edge of the dune/bulkhead line (when material is placed in this area), and one station must be midway between the dune line and the high water line (normal wrack line).*

*At each station, the cone penetrometer will be pushed to a depth of 6, 12, and 18 inches three times (three replicates). Material may be removed from the hole if necessary to ensure accurate readings of successive levels of sediment. The penetrometer may need to be reset between pushes, especially if sediment layering exists. Layers of highly compact material may lie over less compact layers. Replicates will be located as close to each other as possible, without interacting with the previous hole and/or disturbed sediments. The three replicate compaction values for each depth will be averaged to produce final values for each depth at each station. Reports will include all 18 values for each transect line, and the final six averaged compaction values.*

2b) *If the average value for any depth exceeds 500 pounds per square inch (psi) for any two or more adjacent stations, then that area must be tilled immediately prior to May 1. If values exceeding 500 psi are distributed throughout the project area but in no case do those values exist at two adjacent stations at the same depth, then consultation with the USFWS will be required to determine if tilling is required. If a few values exceeding 500 psi are present randomly within the project area, tilling will not be required.*

In the event USFWS deems it necessary and as required by the monitoring plan, the Town of Nags Head is to conduct tilling/disking of the compacted beach fill area prior to 1 May to reduce the likelihood of impacting sea turtle nesting and hatching activities.

Overall, based on the monitoring requirements specified in the state and federal permits, physical condition surveys after the project include the following:

- Beach compaction tests for three years prior to the start of turtle nesting season
- Beach and inshore profiles at minimum 500-ft spacing at USACE/CSE stations (including upcoast and downcoast areas) to track the project condition and the spread of nourishment sand to adjacent areas
- Data analysis to determine nourishment volumes remaining by reach and volumes remaining with respect to the renourishment threshold
- Sediment sample collection and analysis for monitoring the as-built quality of sand on the visible beach every other year

- Aerial photography to document the general conditions of the shoreline each year and periodic controlled vertical photography approximately once every three years
- Contour movement analysis and mapping to illustrate for the community the shift of key reference contours over time including local mean high water (MHW), the edge of the dry-sand beach, and the face of the foredune

Based on the above-stated monitoring requirements, for Years 1–3 (2012–2014) after the project, beach compaction measurements were made in March. There was no need to conduct sediment compaction tests after Year 3 (2014), but profile surveys in subsequent years continue to be performed annually in May to July (weather permitting). Therefore, two semi-annual profile surveys were performed in June and November 2012 (for Year 1) and one annual profile survey was performed in June 2013, June 2014, June 2015, June 2016, July 2017, and May 2018 (for Years 2 through 7). These surveys provide pre-storm condition data and serve as the annual baseline for comparison with post-storm condition surveys. In addition to the annual pre-storm surveys, one post-storm survey was conducted in October 2016 after Hurricane *Matthew*. The October 2016 survey confirmed that Nags Head lost ~1.43 million cy of sand due to *Matthew* which resulted in FEMA approval for assistance in Permanent Work Category G.

## 2.2 Data Collection Methodology

Hydrographic data collection methodology followed procedures outlined in the USACE Hydrographic Surveying Manual (EM 1110–2–1003; January 2002, updated April 2004). CSE’s survey was completed using an RTK-GPS (Trimble™ Model R10 GNSS) for data collection. All offshore work was performed using an Applanix™ POS MV inertial motion unit for positioning, which provides centimeter-level precision for positioning and corrects for pitch and roll in real time. The Applanix™ POS MV is linked to a Teledyne Odom™ Echotrac CV100 precision survey fathometer for direct measurements of the bottom without the need for tide corrections. Measurements over subaerial portions of Nags Head extended to low-tide wading depth.

Offshore profiles were collected at 50 Hz (hertz—a unit of frequency) at high tide overlapping the wading-depth measurements. The raw data were then filtered to eliminate spikes and to provide a floating average and smoothed inshore data were edited to a manageable size and merged with subaerial data. Survey baseline and control USACE/CSE station coordinates and elevations are listed in Appendix 2 and plotted beach profiles for selected dates are provided in Appendix 3.

Ground photos were taken at representative monitoring stations and compared to pre- and post-project images of the same areas to offer a simple visual assessment of dry beach width, dune condition, vegetative growth, escarpments, and general condition of the beach through time. Photos were also taken of any areas or features of particular importance or interest observed

during the monitoring event. Although these photos are not required under the maintenance and monitoring plan, they are used to provide a convenient visual record for illustrating pre-storm conditions to FEMA officials and the community.

Oblique aerial photos were taken from an aircraft to obtain views of the overall project. Representative images are included in the monitoring report along with pre- and post-construction photos to illustrate the general condition of the beach.

The most recent town-wide aerial orthophotos of the project area were taken by GPI Geospatial Inc (Charlotte, NC) on 12 December 2017 to facilitate the final design of the beach renourishment project. Orthophotography provides spatially rectified images representing the earth's surface which can be imported and used to create a Geographic Information System (GIS) database with a defined coordinate system.

CSE maintains and operates a DJI Phantom 4 Pro (P4P) unmanned aerial system (UAS) and as required per federal regulations a Federal Aviation Administration (FAA)–licensed UAS pilot oversees the safe operation of the UAS. The P4P is equipped with a 20 megapixel, 1-inch CMOS image sensor and a mechanical shutter which results in a powerful camera that eliminates distortion when flying at high speeds and can be used for oblique aerial photography. It is also capable of capturing the greater detail needed for the advanced production of orthomosaics. Its ability to map ~150 acres with a flight time of ~30 minutes on a single battery allows multiple batteries to cover larger areas on numerous flights. Photos taken by the device can be processed using Pix4D software to create point clouds, orthomosaics, and digital surface models (DSM).

In the May 2018 survey, CSE utilized the P4P system to take oblique aerial photos and orthophotos along the south ~1 mile of the project area where erosion rates have been several times higher than the rest of Nags Head. These oblique aerial photos provide unique perspectives of the littoral zone up to an above-ground level of 400 ft (FAA ceiling for UAS), and the orthophotography provides a spatially rectified image representing the earth's surface in the area of coverage (see the cover photo). These images can be imported and used to create a Geographic Information System (GIS) map and defined coordinate system for potential emergency recovery measures.

## 3.0 WIND AND WAVE CONDITIONS AT THE PROJECT SITE

### 3.1 Wave Buoy at USACE-FRF

The USACE Field Research Facility (FRF) in Duck (NC), located about 15 miles north of the northern boundary of Nags Head (see Fig 1.1), has been monitoring littoral processes for nearly 40 years. Due to its proximity to the project area, the wave data collected at FRF were used to approximate wave conditions at Nags Head.

Waverider Buoy 630 is located ~1.9 miles offshore of the FRF site in ~57 ft of water (Fig 3.1), and it computes mean wave direction, significant wave height, and wave period from recorded wave data. A 21-year record (1986–2006) of wave data at Buoy 630 was used to determine seasonal variations in the wave climate at Nags Head (CSE 2011a). Wave height, period, and direction were summarized by month and are listed in Table 3.1.



**FIGURE 3.1.**

Datowell Directional Waverider 630 (WMO ID 44056) is located at 36°11.993N, 75°42.843W, 3 km (~1.9 miles) offshore where water depths are ~17.4 m (57 ft). It has collected wave height, period, and directional data since 1997.

[Source: USACE-FRF]

Average significant wave heights are greatest from September to April (3.4–3.9 ft) and decrease from May to August (2.1–3.0 ft). Average wave periods remain consistent (~8–9 seconds) with highest wave periods occurring September to coincide with the peak of the Atlantic hurricane season. Wave direction during the fall and winter is from the east-northeast, averaging between 70° and 80° from the north, coinciding with larger waves produced from northeaster storms. During the spring and summer months, waves approach more from the east and average between 84° and 96°.

### 3.2 Present Monitoring Period Wave Climate (July 2017 – May 2018)

Buoy 630 wave records for the present monitoring period were downloaded and analyzed from the USACE-FRF website. With the exception of no record between July 1 and 18, the 11-month wave data was completed.

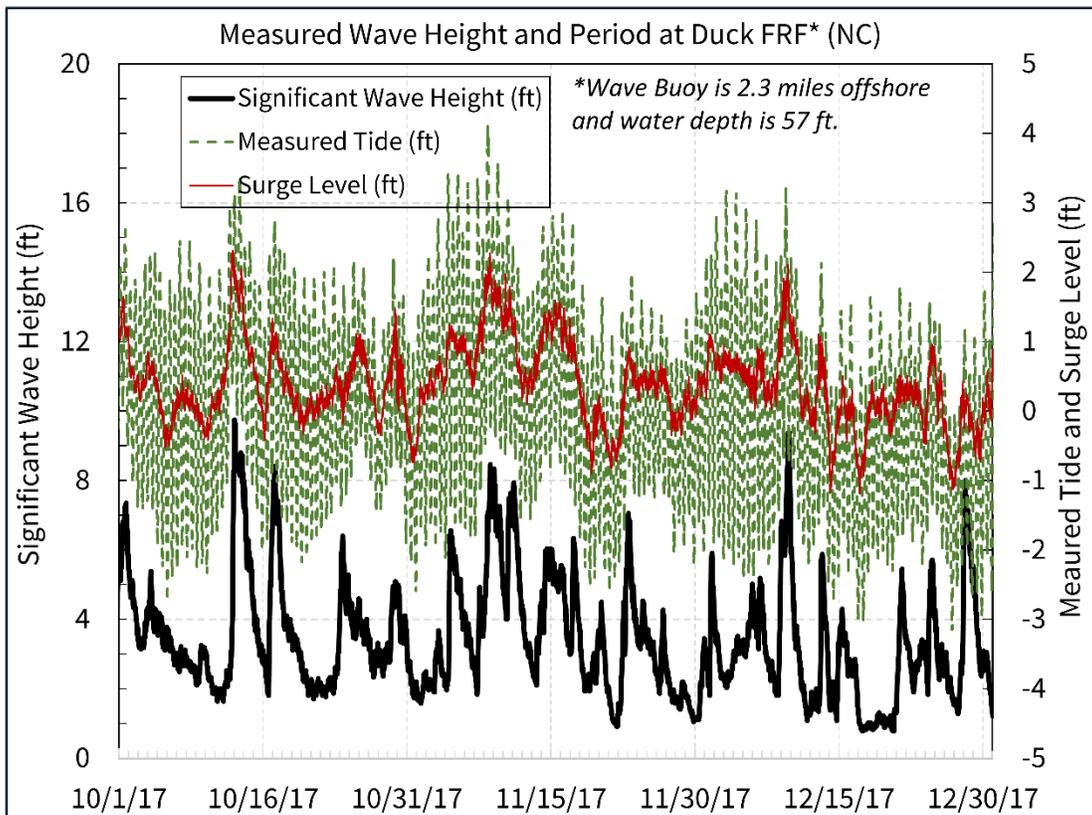
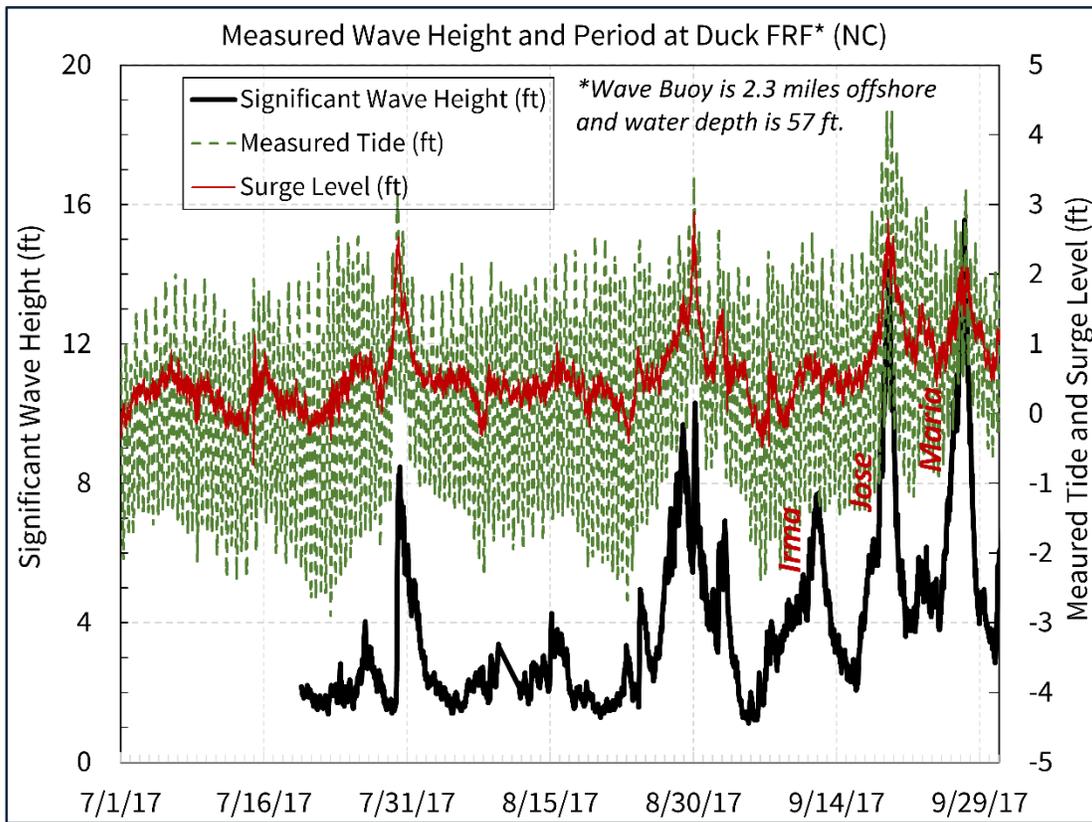
Table 3.1 lists the monthly results of the present monitoring period compared with the 21-year wave record. It shows that average significant wave heights in six out of the eleven months were higher (as highlighted in the table), especially in March 2018 when the average significant wave height was 1.61 ft higher than the long-term average (ie – 5.45 ft versus 3.84 ft). This variance is associated with a series of northeasters which occurred during that month. The 11-month average significant wave height for this period was ~0.31 ft higher than the 21-year average. Overall, last year's wave climate is comparable in all three parameters (ie – wave height, period, and direction), but slightly higher-than-normal averages in most months over the past year.

**TABLE 3.1.** Monthly, average wave climate from 1986 through 2006 (CSE 2011) and from July 2017 through May 2018. [\*Note: No wave record between 1 and 18 July 2017.] Wave direction is defined as from which direction the waves at the dominant period are coming. The units are degrees from true North, increasing clockwise, with North as 0 (zero) degrees and East as 90 degrees.]

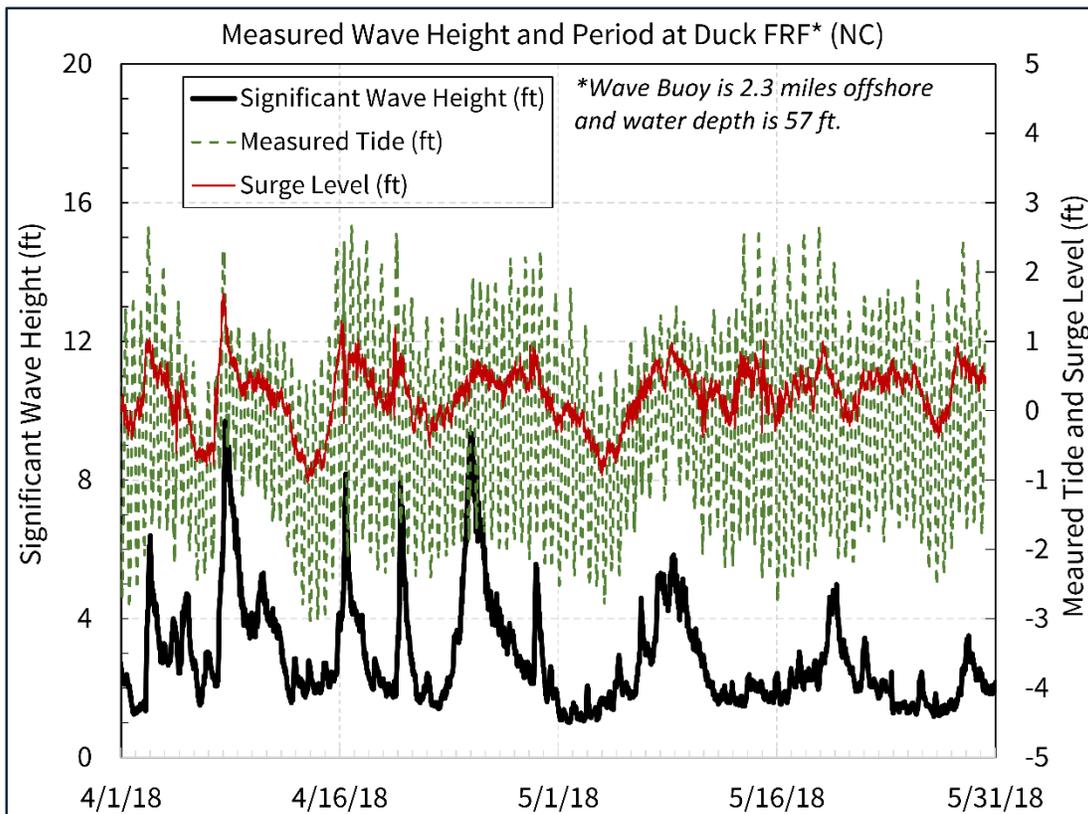
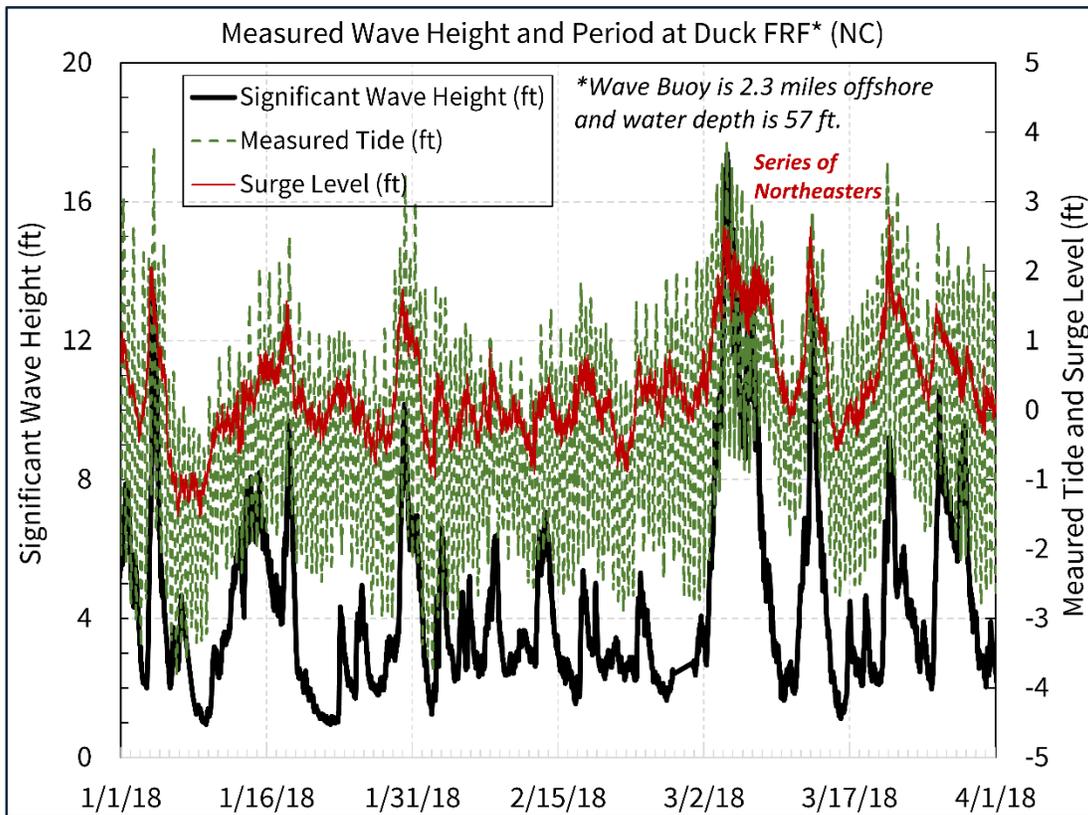
	21-Year Record (1986–2006)			1-Year Record (Jul 2017 to May 2018)		
	Wave Height (ft)	Wave Period (s)	Wave Direction	Wave Height (ft)	Wave Period (s)	Wave Direction
January	3.58	8.58	75.3	4.14	8.5	73.9
February	3.84	8.55	71.2	3.29	8.8	81.5
March	3.84	8.74	79.0	5.45	11.1	68.0
April	3.42	8.60	79.4	3.40	8.5	80.9
May	3.01	8.45	84.2	2.30	8.4	109.4
June	2.45	8.13	96.4	—	—	—
July	2.11	8.15	95.2	2.72	9.5	89.1
August	2.75	8.66	92.6	3.05	8.6	96.9
September	3.58	9.16	84.9	5.05	11.3	88.9
October	3.86	8.67	76.7	3.63	8.9	89.4
November	3.50	8.53	72.0	3.61	8.7	70.7
December	3.68	8.49	70.5	3.02	7.8	76.7
<b>Average</b>	3.30	8.56	81.5	3.61	9.1	84.1

The waves measured at Buoy 630 from July 2017 to May 2018 were predominantly from the east. Figure 3.2 shows significant wave heights (left vertical axis) of the present monitoring period along with the measured wave level and surge level (right vertical axis). High waves occurring in September 2017 and March 2018 in the figure were associated with hurricanes and northeasters. Significant wave heights, associated with wave periods from July 2017 to May 2018 at this buoy are also summarized in 10° increments in Table 3.2 and compared with the long-term record (1997–2006). [Note: There is no wave direction record prior to 1997.] Waves beginning from north and ending at 150° from south represented 98.9 percent of the waves in the one-year record and 99.3 percent in the ten-year record. More than 69 percent of the waves in the one-year record were from between 70° and 130° (measured from north), while 59 percent of the waves in the ten-year record were from the same directions.

The highest-energy waves originated from the northeast. During the present monitoring period, waves from all directions (except for between 80° and 90°) were higher than the 10-year average. Waves originating from northeasterly directions (between 0° and 90° from north) represented ~53 percent of the waves and had an average significant wave height of 1.34 meters (m) (~4.4 ft), which is half foot higher than the ten-year record (ie – significant wave height is 1.20 m or 3.92 ft with ~52 percent occurrence). The relatively high occurrence of waves from 60° to 120° True (70 percent) in the past year is similar to what is shown in the long-term statistics (67 percent). This relatively high occurrence of waves likely produced a higher-than-normal southerly transport along Nags Head during the July 2017 to May 2018 period. [Nags Head shore-normal wave direction is ~68° True.]



**FIGURE 3.2a.** Significant wave height (left vertical axis) along with measured water level and surge level (right vertical axis) at Duck Pier FRF during the present monitoring period from **July 2017 to December 2017**.



**FIGURE 3.2b.** Significant wave height (left vertical axis) along with measured water level and surge level (right vertical axis) at Duck Pier FRF during the present monitoring period from **January 2018 to May 2018**.

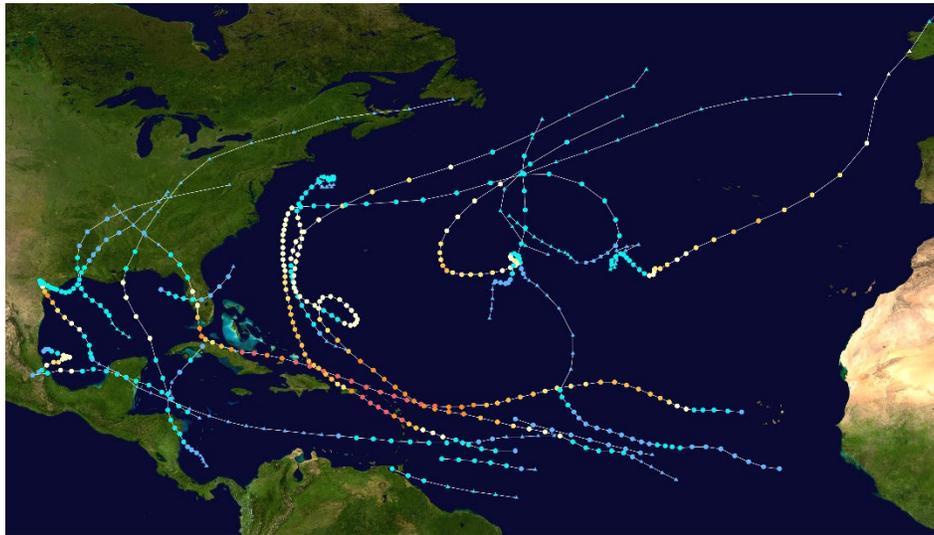
**TABLE 3.2.** Significant wave heights (meters and feet), associated wave periods (seconds), wave directions (degrees true by 10° sectors), and their probability of occurrence at Buoy 630 for the periods of 1997–2006 and July 2017 to May 2018. [\*Note: There is no direction record prior to 1997. Nags Head shore-normal wave direction is ~68° True.]

Wave Direction (° True North)	10-Year Record (1997–2006)*			11-Month Record (Jul 2017 to May 2018)		
	Wave Height (ft)	Wave Period (s)	Probability (%)	Wave Height (ft)	Wave Period(s)	Probability (%)
0–10	3.45	4.54	1.19	3.82	4.54	1.27
10–20	4.12	5.10	2.13	4.44	5.03	0.06
20–30	4.31	5.55	3.59	5.00	5.64	3.27
30–40	4.26	6.05	4.42	4.85	5.98	4.49
40–50	4.20	6.77	5.19	4.82	6.49	5.21
50–60	4.34	8.17	6.10	4.97	8.12	6.40
60–70	3.98	9.69	8.22	4.83	10.41	8.52
70–80	3.51	10.47	10.85	3.94	11.08	14.28
80–90	3.13	10.25	11.08	2.97	10.10	9.87
90–100	2.70	9.79	11.85	2.75	9.62	11.60
100–110	2.56	9.42	13.24	2.86	9.45	15.13
110–120	2.70	8.82	12.09	3.01	9.21	10.66
120–130	2.63	7.60	5.94	3.00	7.44	3.78
130–140	2.31	6.49	2.56	2.52	6.08	1.39
140–150	2.12	5.16	0.83	2.36	4.61	0.51
<b>Totals</b>	-	-	<b>99.29</b>	-	-	<b>96.43</b>

### 3.3 2017 Atlantic Hurricane Season

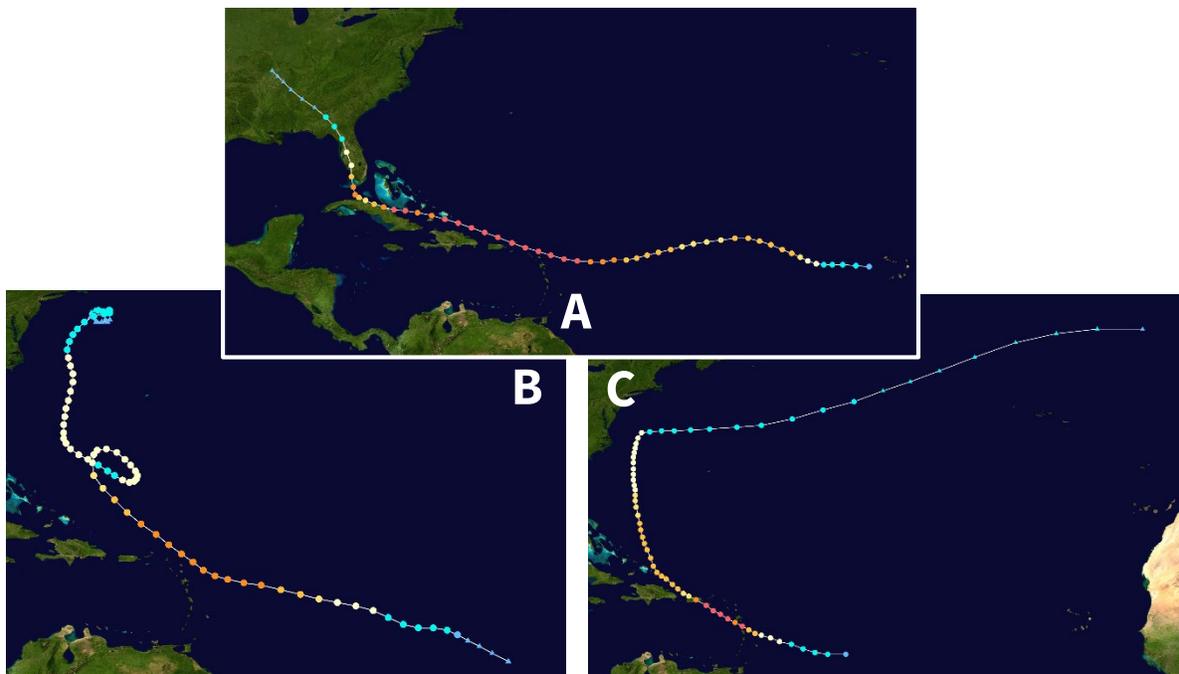
The 2017 Atlantic hurricane season is one of only six years on record to feature multiple Category 5 hurricanes, and more than 99.7 percent of the season’s damages were due to three of the season’s major hurricanes – *Harvey*, *Irma*, and *Maria*. Hurricanes of the season, which officially began on 1 June 2017 and ended on 30 November 2017, are summarized in Figure 3.3. The season’s first tropical cyclone, *Arlene*, developed on April 19, and activity concluded with the formation of tropical storm *Rina* in early November.

September 2017 featured copious activity with the forming of four hurricanes (*Jose*, *Katia*, *Lee*, and *Maria*), the final of which became the tenth most intense Atlantic hurricane on record. Summary maps (Fig 3.4) of hurricanes that impacted the North Carolina coastline the most during the 2017 season include *Irma* (30 August to 13 September), *Jose* (5 September to 25 September), and *Maria* (16 September to 2 October). Track and intensities of the storms are according to the Saffir-Simpson Hurricane Wind Scale. Associated waves and surge are plotted in Figure 3.2 in the previous section.



**FIGURE 3.3.** 2017 Atlantic hurricane season summary map. The points show the location of each storm at six-hour intervals, and the colors represent a storm’s maximum-sustained wind speeds as classified in the Saffir-Simpson Hurricane Wind Scale. [Source: Wikipedia]

Saffir-Simpson Hurricane Scale					
■ Tropical depression	0–39 mph	0–62 km/h	■ Category 3	111–130 mph	178–209 km/h
■ Tropical storm	39–73 mph	63–117 km/h	■ Category 4	131–155 mph	210–249 km/h
■ Category 1	74–95 mph	119–153 km/h	■ Category 5	≥156 mph	≥250 km/h
■ Category 2	96–110 mph	154–177 km/h	■ Unknown		



**FIGURE 3.4.** Summary maps of 2017 hurricanes that impacted the North Carolina coastline the most. The points show the location of the storm at six-hour intervals, and the colors represent the storm’s maximum-sustained wind speeds as classified in the Saffir-Simpson Hurricane Wind Scale. (a) Hurricane *Irma* (30 Aug to 13 Sept), (b) Hurricane *Jose* (5 Sept to 25 Sept), and (c) Hurricane *Maria* (16 Sept to 2 Oct). [Source: Wikipedia]

## **4.0 BEACH AND INSHORE SURVEYS AND PROFILE COMPARISONS**

---

CSE collected beach and inshore profile data during the week of 21 May 2018 following the protocol and permit requirements discussed in Section 2. During and after data collection, CSE performed QA/QC on the measurement systems and output by using a combination of procedures. These procedures included the measurement of speed of sound, sounding-bar checks, direct soundings in deep water, real-time overlays with historical data using Hypack™ software, and cross-tracking lines for statistical analysis of survey accuracy.

Field data were entered into CSE's beach profile analysis system (BPAS) and combined with historic profile data. Each profile was checked for proper juxtaposition and datum correction against previous profile data. Consistent with prior CSE reports (2011a, 2012, 2013a-b, 2014b, 2015, 2016b-c, 2017a-b), the November 2010 survey was used as the baseline condition to calculate volume changes. Overall volume changes by reach were computed by extrapolating unit volume changes over representative shore lengths.

### **4.1 Beach Volume Analysis Method**

Profile volumes are a convenient way to determine the condition of the beach and compare one area with another. They convert a two-dimensional measure of the beach to a "unit volume" measurement. Unit volume (given in cubic yards per linear foot) is a measure of the amount of sand contained in a 1-ft (unit) length of the beach as illustrated in Figure 4.1. Specific volumes reflect a quantity in a wedge of sand extending from the dune line or seawall to a particular depth offshore.

Unit volumes for each survey date and unit-volume changes between selected edates were calculated to determine the quantity of sand in one linear foot of beach at each station. These unit volumes were used to calculate the station-to-station net volumes, the net volumes of reaches, and finally the net volume for the entire project.

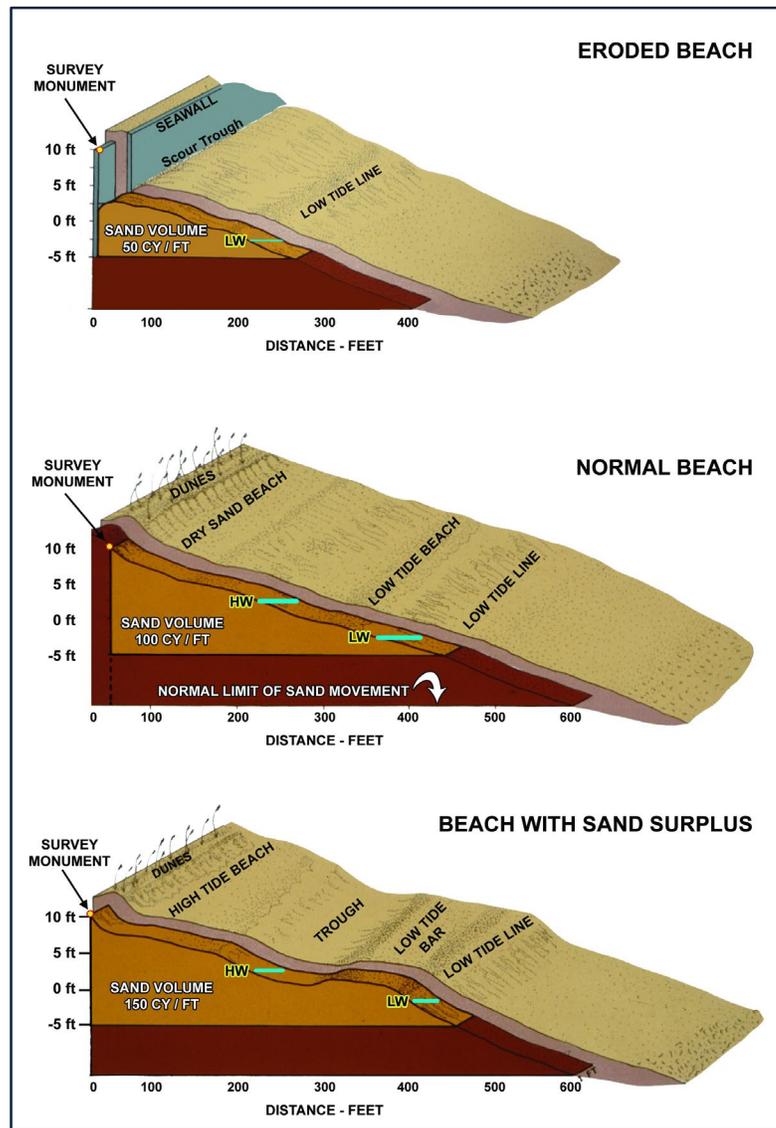
Changes in unit volume (or beach width, etc) can be determined by overlaying sequential profiles and computing the differences in the cross-sectional area. The two-dimensional change in a cross-section is extrapolated between adjacent profiles to yield net volume change (in cubic yards) in that particular section. Using standard statistical techniques (average end area method), the overall (net) change is computed by summing the changes from profile to profile for subreaches and total project reach.

Profile volumes integrate all the small-scale perturbations across the beach and provide a simple objective measure of beach condition (Kana 1993). They provide quantitative estimates of sand deficits or surpluses when compared against a target or desirable beach condition.

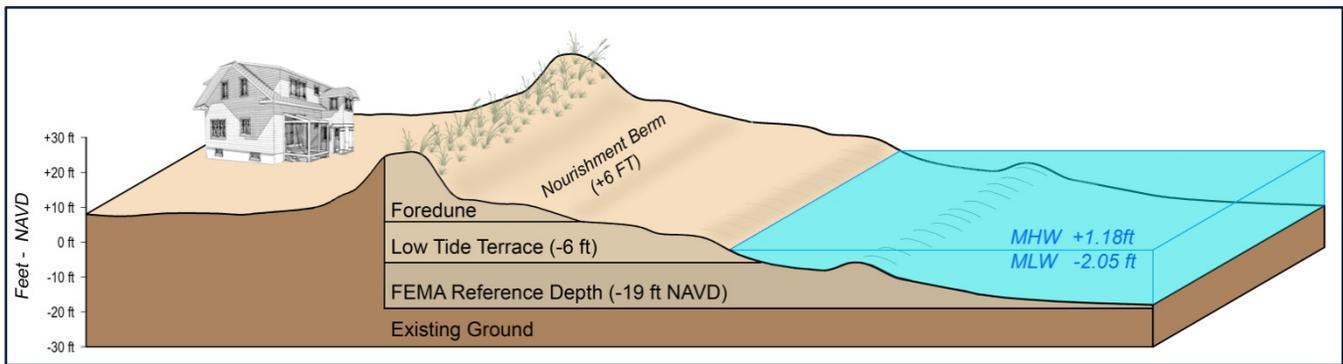
The examples of profile volumes in Figure 4.1 show a “normal beach” with a typical unit volume of 100 cy/ft measured to low-tide wading depth. The other profiles in the graphic illustrate values for an eroding beach (in this case, backed by a seawall) and a beach with a sand surplus.

The unit volume of the eroded profile is much lower than the normal beach. Beaches near inlets often incorporate wide, low-tide bars resulting in a surplus of sand relative to beaches away from inlets. The calculation limits can be arbitrary as long as they are consistently applied. Ideally, they should encompass the entire active zone of profile change for the time period(s) of interest.

Volume changes at Nags Head were estimated using standard methods (average-end-area method) and common cross-shore boundaries and contour datums. Per the Town’s request, three (3) lenses (ie – volumes between particular reference contours) were used in the present analysis to evaluate levels of dune protection, beach, and the underwater zone. Figure 4.2 illustrates the cross-sectional areas of these three lenses for Nags Head.



**FIGURE 4.1.** The concept of unit-width profile volumes for a series of beach profiles showing an eroded beach with a deficit, a normal beach, and a beach with a volume surplus. [After Kana 1990]



**FIGURE 4.2.** Illustration of the three (3) lenses used in the profile volume analysis for Nags Head. Lens 1 includes the dune and the upper portion of the beach above the 2011 project construction berm. Lens 2 represents the active beach to low-tide wading depth; and Lens 3 represents the outer surf zone extending to the FEMA depth limit.

**Lens 1) “Foredune”** — From the face of dune\* to +6 ft NAVD. The 2011 nourishment construction berm was designed at +6 ft with several areas up to +7 ft NAVD. The volume above the +6 ft elevation is a measure of the sand quantities shifted toward the dunes and upper beach. Therefore, this is a measure of storm and flood protection levels associated with the project or gains in dune volume due to post-project buildup above this contour.

**Lens 2) “Beach”** — Between +6 ft and -6 ft NAVD. It includes the dry-sand beach (“berm”) and the wet-sand beach extending to low-tide wading depth. The majority of the nourishment sand (~4.165 million cubic yards or 90 percent) was initially placed in this lens during the 2011 nourishment project for construction convenience. This is not only the primary recreational portion of the beach but also the inner surf zone where a significant proportion of wave-breaking and energy dissipation occurs.

**Lens 3) “Underwater”** — Between -6 ft and -19 ft NAVD. This represents the outer surf zone extending seaward from low-tide wading depth to the depth set forth for the FEMA post-storm restoration criteria (-19 ft NAVD).

*\*[CSE surveys the beach including the dune area to the landward back of the dune along each survey station. A landward starting point for volume analysis of each station was originally determined at the time of project planning (CSE 2011a). It is normally located landward of the crest of the dune as illustrated in Figure A. This landward starting point may vary from station to station but remains the same for a certain station unless significant changes occur landward of the station that prevents data collection. If the landward starting point of a station has to be changed, volumes at this station will be recalculated for all survey dates so that volume comparison can be based on the same boundaries of a sand box.]*

Unit volumes for Nags Head profiles were calculated to determine the quantity of sand in one linear foot of beach at each lens and at each survey line. These unit volumes were then used to calculate the line-to-line net volumes, the net volumes of each reach, and finally the net volume for the entire project. The line-to-line net volumes are proportional to the distance between lines and represent the alongshore distribution of sand volume in the project area. The net volumes by reach were subsequently divided by the applicable reach lengths to yield weighted average unit volumes, taking into account the variations in shoreline distances from line to line.

Conveniently, the stations for Nags Head are evenly spaced at 500 ft. If they are not evenly spaced, the station-to-station net volumes should be proportional to the distance between stations to represent the actual alongshore distribution of sand volume. Beach profiles at CSE survey stations are plotted in Appendix 3 along with the cumulative unit volumes of the three lenses at each survey date, which include:

- November 2010 for pre-project
- November 2011 for post-construction
- June 2012 for Year 1 post-project but before the hurricane season and November 2012 for Year 1 post-project but after the hurricane season
- June 2013 for Year 2 post-project and before the hurricane season
- June 2014 for Year 3 post-project and before the hurricane season
- June 2015 for Year 4 post-project and before the hurricane season
- June 2016 for Year 5 post-project and before the hurricane season
- July 2017 for Year 6 post-project and before the hurricane season
- May 2018 for Year 7 post-project and before the hurricane season

Unit volumes of representative lenses and cumulative lenses for July 2017 and May 2018 surveys (listed in Appendix 4) are discussed in detail within this section. Total volumes of these two recent surveys (listed in Appendix 5) will be reviewed in Section 5.

## **4.2 Unit Volume Results**

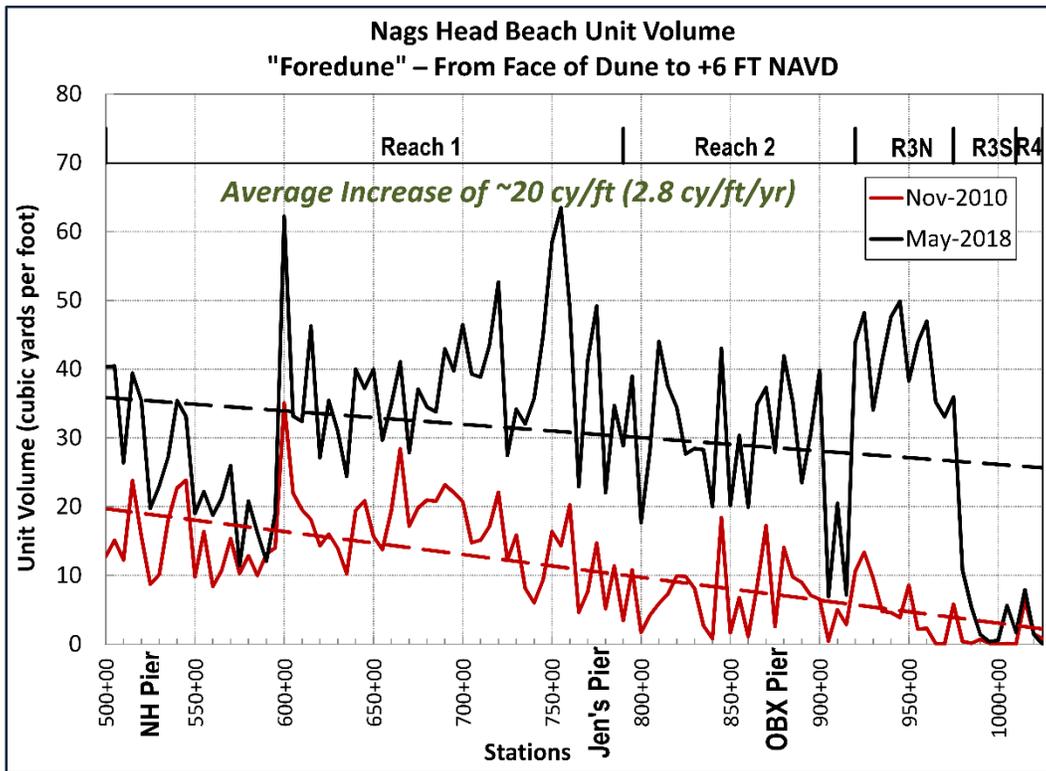
### **4.2.1 Foredune – Lens 1 (from Face of Dune to +6 ft NAVD)**

CSE expected the higher dry beach (formed by storm overwash and a landward shift of some sand after completion of the 2011 project) would remain dry most of the time and serve as a feeder for dune growth. Unit volumes of Lens 1 from the face of dune to +6 ft NAVD **by station** along Nags Head are shown in Figure 4.3. For graphic clarity, only unit volumes for May 2018 (black line in the graphic) are plotted against the pre-construction condition (red line in the graphic).

Before nourishment, north Nags Head had higher unit volumes than south Nags Head (red dashed line shows the linear trend), indicating the dune condition of the north was healthier and provided more storm protection than the south. Some portion of south Nags Head had zero or near-zero volume in this lens, indicating low dune (or no dune) and offered little protection before the project. The 2011 nourishment project placed higher fill density at the south and provided a wider beach for dune growth. As the nourishment berm has been a “feeder” for the upper beach and dune

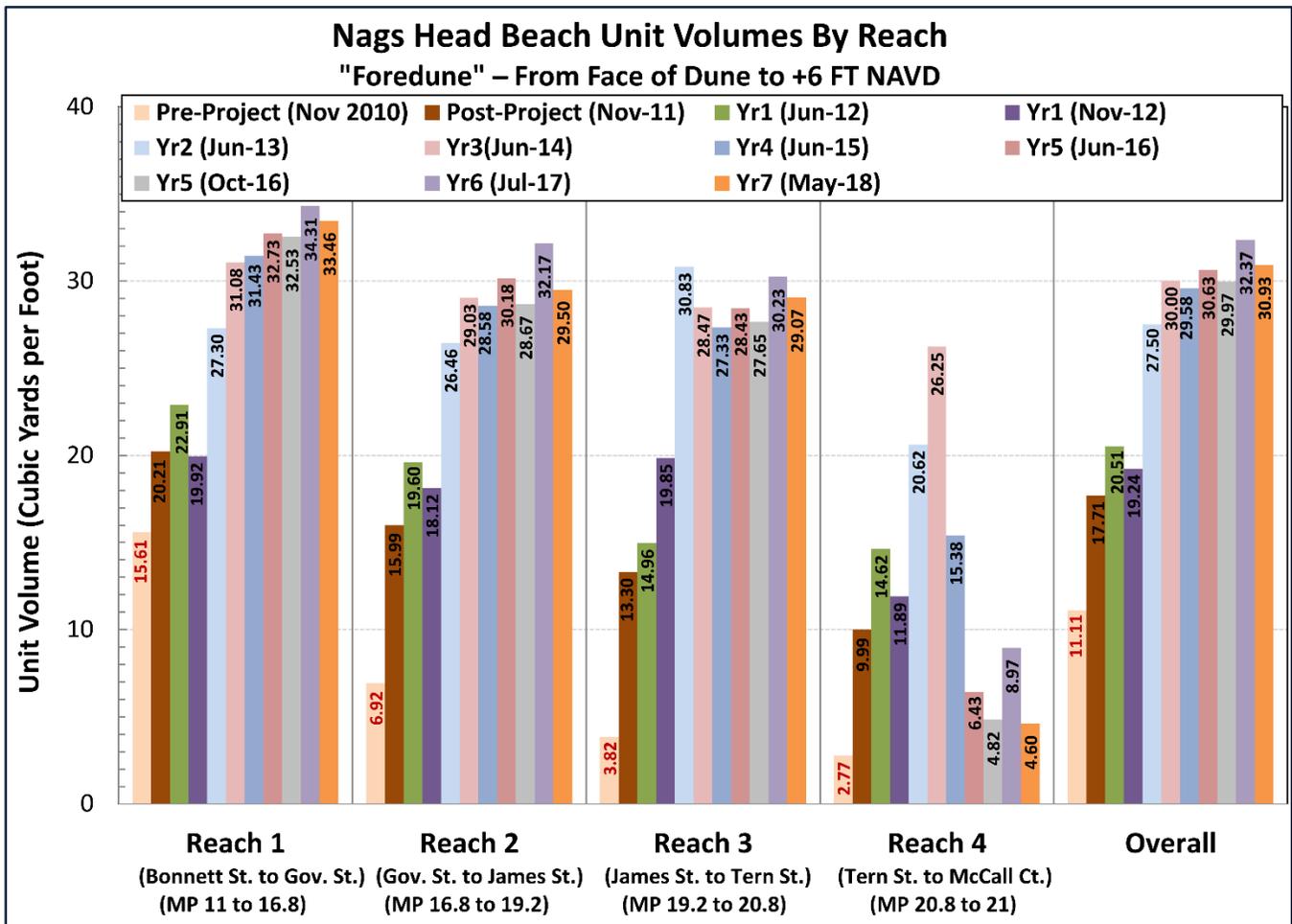
area, sand fencing installed by the Town following project completion helps trap sand moving toward the backshore into this lens.

By June 2013, survey results indicated that relatively similar dune protection existed from north to south along the entire project area (CSE 2013b). Beginning in June 2014, survey results showed that the south end of the project was losing sand and had lower unit volumes compared to the north end (CSE 2014b). The May 2018 results (black line in Fig 4.3) show a continuation of this trend (note the descending black dashed line which shows the linear trend).



**FIGURE 4.3.** Comparison of unit volumes along Nags Head from the face of dune to +6 ft NAVD contour before nourishment (November 2010) and the most recent survey condition (May 2018). This indicates a significant increase of unit volumes after the project at most stations. Unit volumes in previous surveys (November 2011, June 2012, November 2012, June 2013, June 2014, June 2015, June 2016, October 2016, and July 2017) are plotted in earlier reports by CSE (2013a,b / 2014b / 2015 / 2016b,c/2017a,c).

Figure 4.4 shows the average unit volume **by reach** in Lens 1 for all surveys since November 2010. These results indicate that unit volumes in this lens (ie – in the foredune) have overall steadily increased in all reaches following project completion. In contrast, May 2018 results show all reaches lost sand with Reach 4 losing the most compared to the previous years. As projected in the 2014 monitoring report, dune growth has declined as the dry-sand beach has narrowed by natural profile evolution.



**FIGURE 4.4.** Comparison of unit volumes along Nags Head from the face of dune to +6-ft NAVD contour. It shows the general increase of volume after the project by comparing volumes by reach and year from November 2010 to May 2018.

The right group of bars in Figure 4.4 represents the overall performance to date along the project area illustrating that foredune volume increased from 11.1 cy/ft in November 2010 (before the project) to 17.7 cy/ft in November 2011 (following construction). After nourishment, the unit volume in the foredune continued to increase to 20.5 cy/ft in June 2012 and slightly dropped to 19.2 cy/ft in November 2012. Significant increases climbed to 27.5 cy/ft in June 2013 and steadily increased to 30 cy/ft in June 2014. The unit volume remained relatively stable at 29.6 cy/ft in June 2015 and slightly increased to 30.6 cy/ft in June 2016. Nags Head lost 0.7 cy/ft of sand in this portion of the beach after Hurricane *Matthew* in October 2016, regained ~2.4 cy/ft of sand nine months later in July 2017, but then lost ~1.4 cy/ft in May 2018. All reaches show sand loss over the past year at a rate ranging from 4.37 cy/ft (Reach 4), 2.67 cy/ft (Reach 2), 1.16 cy/ft (Reach 3), to 0.85 cy/ft (Reach 1).

The overall results indicate a **natural growth** of ~20 cy/ft (or ~2.8 cubic cy/ft/yr) through May 2018 compared to the pre-project condition in November 2010. The wider dry beach constructed by the 2011 nourishment (especially in Reaches 2 and 3 where fill density was higher) has provided an ample sand source for aeolian transport (ie – wind-generated sand transport). Post-project installation of sand fencing and vegetation planted by the Town have efficiently accumulated sand along the back beach, adding height and width to the dunes.

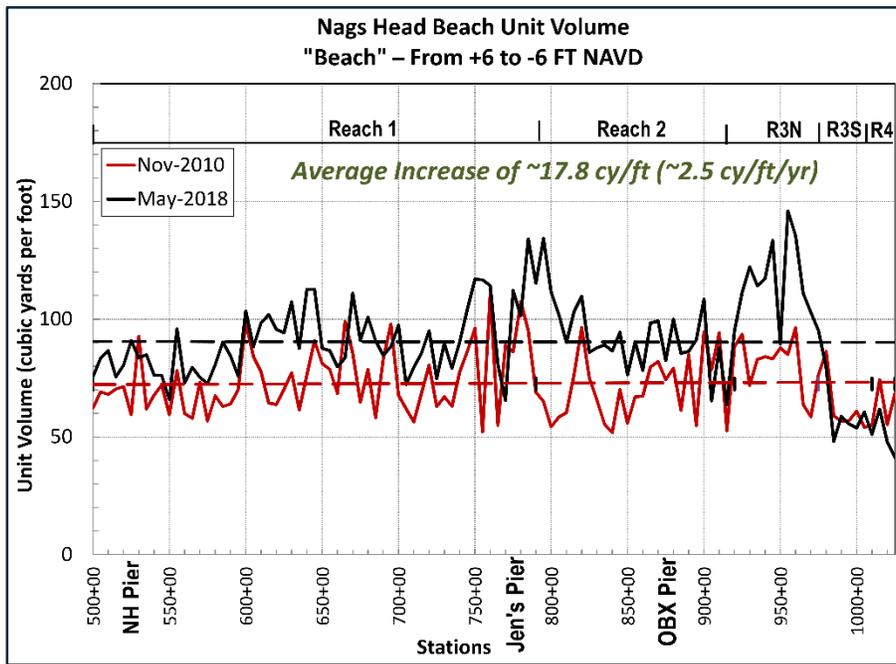
#### **4.2.2 Recreational Beach – Lens 2 (from +6 ft to –6 ft NAVD)**

Lens 2 represents the recreational beach to low-tide wading depth, and Figure 4.5 shows unit volume comparisons **by station** in November 2010 (pre-project) and May 2018 (most recent survey). Figure 4.6 illustrates the comparisons **by reach** for all surveys between November 2010 and May 2018. Preceding the nourishment project, average unit volume in this lens was 72.8 cy/ft and would be 83.9 cy/ft if the volume in Lens 1 is added. In this setting Lens 2 is considered to be an “eroded” beach (cf – Fig 5.1).

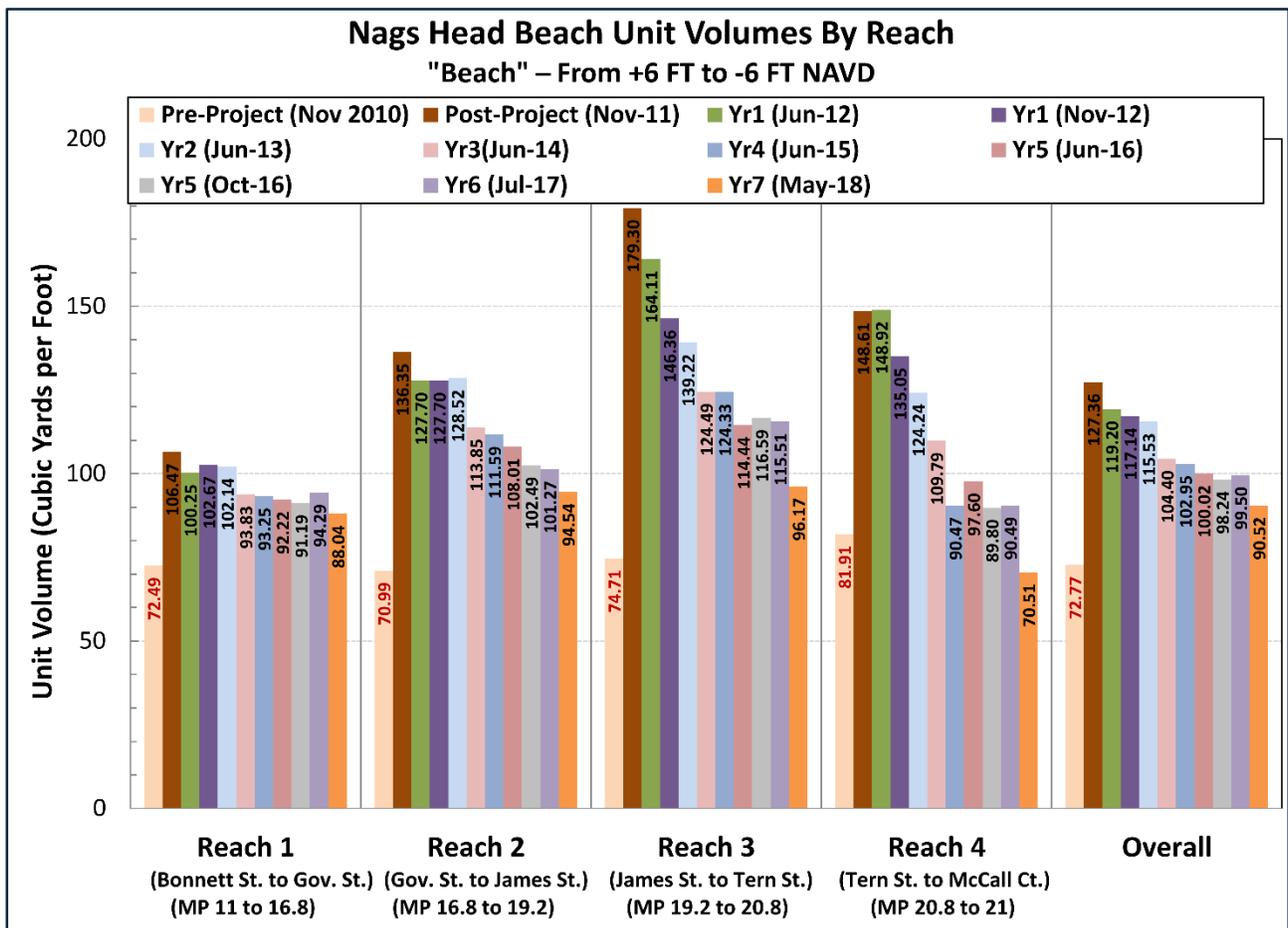
Unlike unit volumes in Lens 1, the trend of unit volumes in Lens 2 was flat from north to south, reflecting the general uniformity of recreational beach width along Nags Head before nourishment. After nourishment, Nags Head retains an average of ~18 cy/ft more sand in this lens as of May 2018 in comparison to the pre-nourishment condition (November 2010). The trend of unit volumes in the recreational part of the beach shows that south Nags Head contains slightly more volume (greater width) than north Nags Head.

The majority (~90 percent) of the 2011 nourishment sand volume was initially placed on the beach between the +6 ft and –6 ft contours for reasons of construction convenience. Nourishment sand shifted underwater by wave action, and the newly constructed beach gradually reshaped toward its equilibrium profile. Under normal conditions, nourishment profile adjustment generally occurs in 1–2 years after project completion. However, Hurricane *Irene* and subsequent fall storms accelerated the initial adjustment at Nags Head so that by November 2011, overall average unit volume was ~127.4 cy/ft (ie – about 55 cy/ft more than pre-project conditions). After further profile adjustment and exposure to storms over the past ~6.6 years, unit volumes in the recreational beach now average ~90 cy/ft, ~17.8 cy/ft more than the pre-project conditions (see the right group of bars in Fig 4.6).

Compared to the post-project condition (November 2011) in Figure 4.6, all reaches show similar trends, indicating profile adjustment occurred similarly from north to south. All reaches lost sand over the past year, and the average loss rate is ~9 cy/ft between July 2017 and May 2018. Specific sand lost rates ranged from 19.98 cy/ft (Reach 4), 19.34 cy/ft (Reach 3), 6.73 cy/ft (Reach 2), to 6.25 cy/ft (Reach 1).



**FIGURE 4.5.** Comparison of unit volumes on the “recreational beach” by station along Nags Head between +6 ft and -6 ft NAVD.



**FIGURE 4.6.** Comparison of unit volumes on the “recreational beach” by reach between +6 ft and -6 ft NAVD.

Two reasons for higher erosion rates at the south half of Nags Head (Reaches 3 and 4) include:

- 1) Long-term historical erosion rates exceed 10 ft/yr along the adjacent Cape Hatteras National Seashore, drawing off sand from Nags Head.
- 2) The nourishment project had to end in a long taper around McCall Court, thus leaving a bulge in the shoreline which became a focal point for wave attack and sand spreading.

Despite the higher erosion rate in the south, the placement of extra nourishment sand has provided a wider recreational beach to feed natural dune growth and increase overall longevity of the project.

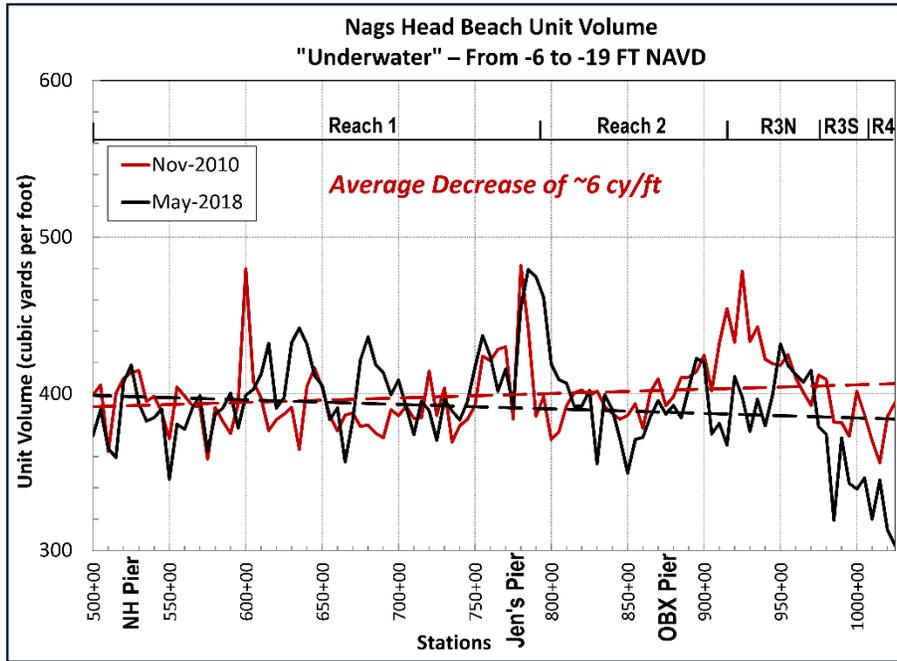
In summary, the project area has lost an average of 36.84 cy/ft on the “recreational beach” since project completion (May 2018 versus November 2011). Despite this loss, the average unit volume in Lens 2 is still ~18 cy/ft more than the pre-project condition, resulting in an overall “normal beach” if using the illustration in Figure 5.1.

#### **4.2.3 Underwater – Lens 3 (from –6 ft to –19 ft NAVD)**

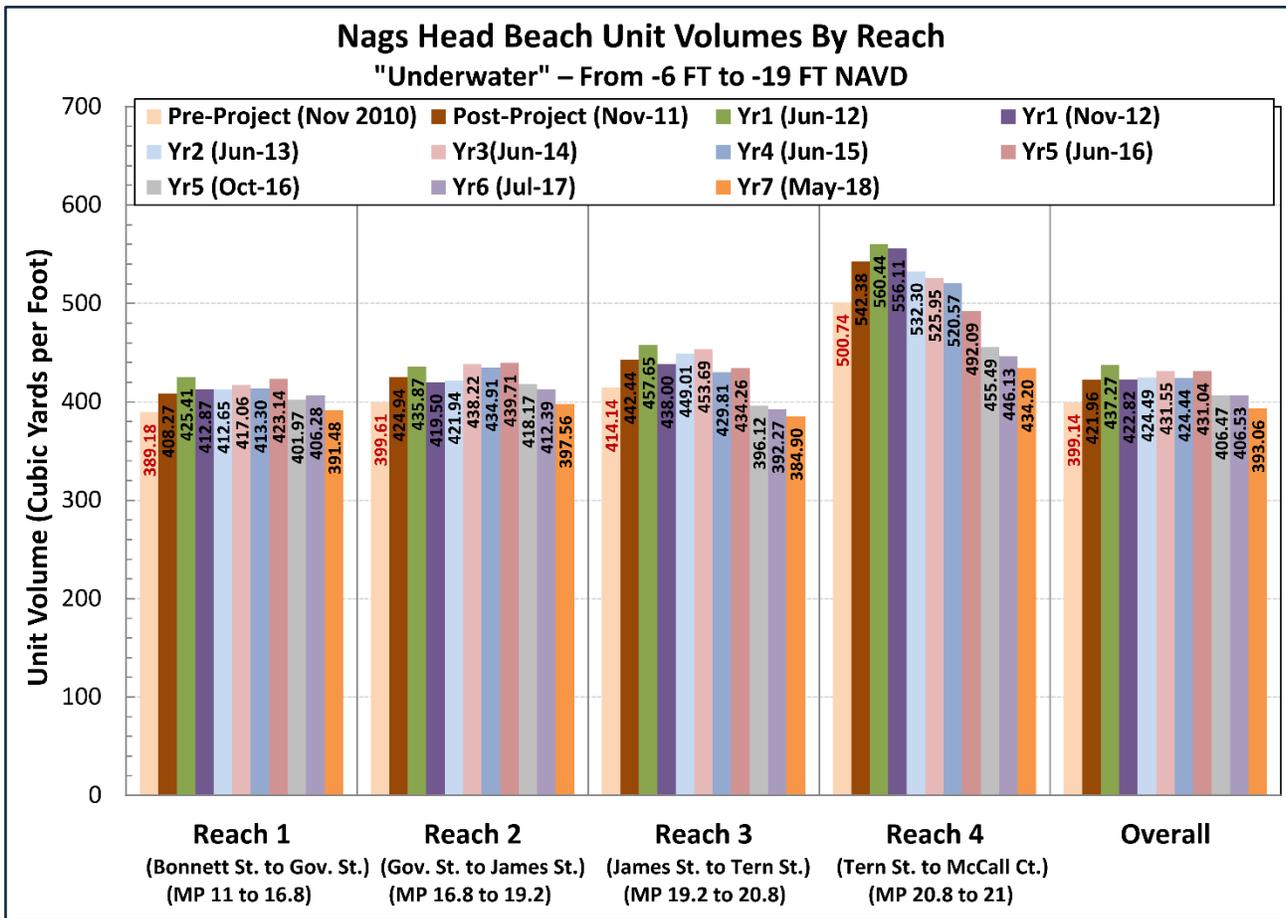
Lens 3 represents the underwater portion of the profile used for calculating volumes in the reference sand box. It includes inshore and offshore bars and extends to the FEMA depth limit of –19 ft NAVD. The profiles in Appendix 3 show a generally broad, longshore bar positioned ~1,200 ft to 2,000 ft offshore in the Lens 3 depth zone. Natural bars tend to develop over gentle slopes within this lens, and the bars tend to shift alongshore or cross-shore under varying waves. All nourishment sand was placed within or above this lens during the 2011 project, indicating this is the construction and initial adjustment limit of the nourishment.

Figure 4.7 shows unit volume comparisons **by station** in November 2010 (pre-project) and May 2018 (most recent survey). Unit volumes vary from station to station but do not change much from north to south along Nags Head in Lens 3 as shown in Figure 4.7. Nags Head had more sand in this lens after project completion until July 2017 (CSE 2017a,c). The most recent survey results indicate the same trend and there is ~6 cy/ft less sand in the underwater portion of the beach in May 2018 compared to pre-project conditions in November 2010.

Figure 4.8 shows comparisons **by reach** for all surveys between November 2010 and May 2018. At Year 6 following project completion, unit volume in July 2017 remained ~7 cy/ft higher than pre-project conditions (November 2010). However, the overall unit volume in May 2018 shows ~13 cy/ft of sand loss over the past year, yielding a lower unit volume in May 2018 than November 2010. The volume gain in the first six years is confirmation that some nourishment sand, placed mainly on the “recreational beach,” shifted underwater into this lens soon after construction. The volume loss in Lenses 2 and 3 in the recent year indicates a significant amount of sand has left the underwater portion of the beach shifting to deeper water, and may not fully return to the sand box. The Nags Head renourishment project was planned and permitted in time to replenish the sand losses due to chronic erosion and multiple storms since the completion of the 2011 project.



**FIGURE 4.7.** Comparison of unit volumes “underwater” by station along Nags Head between -6 ft and -19 ft NAVD.

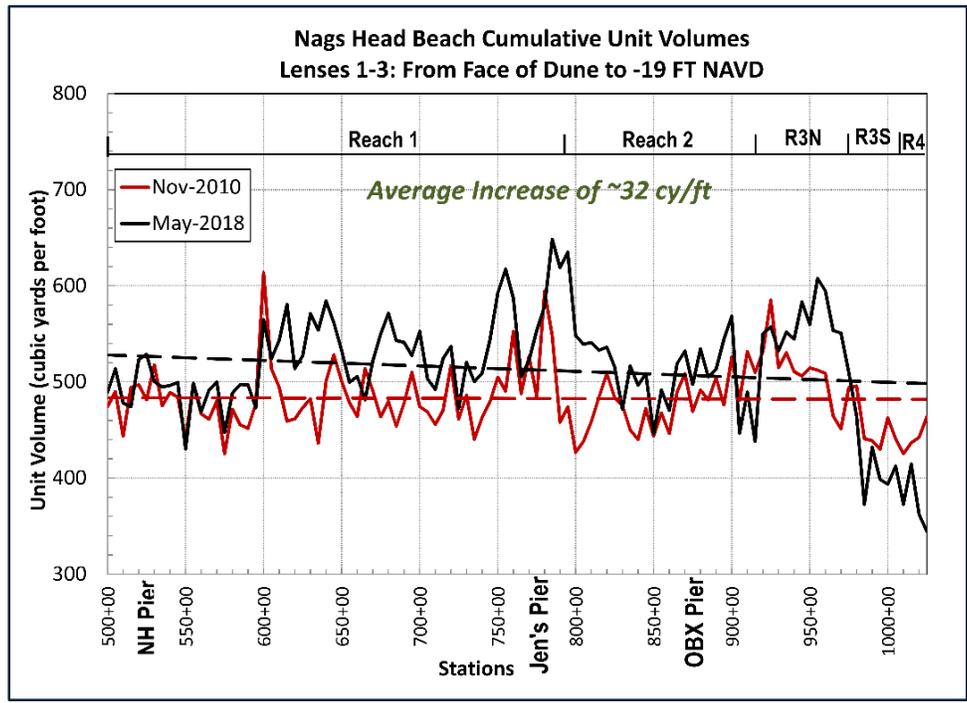


**FIGURE 4.8.** Comparison of unit volumes “underwater” by reach along Nags Head between -6 and -19 ft NAVD.

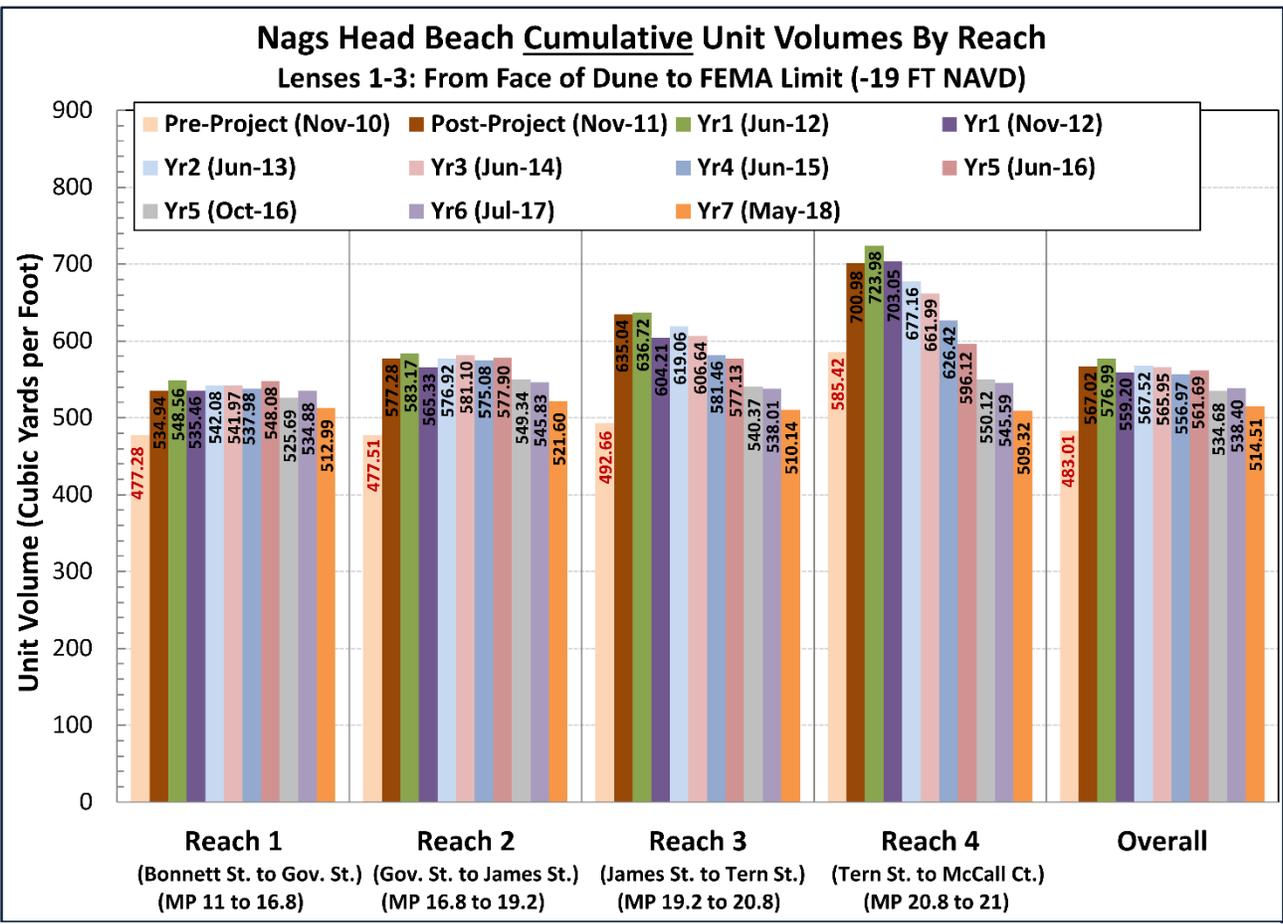
#### 4.2.4 Cumulative Unit Volumes – Lens 1-3 (from Face of Dune to -19 ft NAVD)

Figures 4.9 and 4.10 show the cumulative unit volumes by station along the beach and by reach from Lens 1 to Lens 3 (ie – from the face of dune to -19 ft NAVD—FEMA depth limit encompassing the entire sand box). Using the same layout as Figures 4.3, 4.5, and 4.7, the two dashed lines in Figure 4.9 represent the trend of volume variations for November 2010 (pre-project) and May 2018. The results indicate that despite local fluctuations between adjacent stations, average unit volumes in these lenses were generally uniform along Nags Head before the project. After the project, average volumes increased from north to south for the first five years resulting from the higher fill density placed in the south (CSE 2012, 2013, 2014, 2015, 2016, 2017), but decreased from north to south in July 2017 and May 2018 indicating higher erosion occurred in the south over the past two years.

Results in Figure 4.10 show that the cumulative unit volume has not changed significantly since project completion until October 2016 after Hurricane *Matthew*. Before the project, Nags Head had an average unit volume of ~483 cy/ft in November 2010. Following the project, average unit volume increased to ~567 cy/ft after project completion in November 2011 and decreased slightly to ~562 cy/ft as of June 2016. The ~5 cy/ft lower volume is equivalent to an ~1.2 cy/ft/yr erosion rate over the 4.6 years between November 2011 and June 2016. This loss rate is much lower than the historical erosion rate of ~5.2 cy/ft/yr adopted in the nourishment design (CSE 2011a). Hurricane *Matthew* (October 2016) caused an average loss of ~27 cy/ft along the 10-mile-long project area and brought the average annual erosion rate to ~6.5 cy/ft/yr between November 2011 and October 2016. Approximately 3.7 cy/ft of the *Matthew* loss recovered as of July 2017, however, ~24 cy/ft of sand was lost between July 2017 and May 2018. Due to the occurrence of significant erosion in Year 5 (2015–2016) and Year 7 (2017–2018), the average annual erosion rate has increased to ~7.8 cy/ft/yr since project completion, which is ~2.6 cy/ft higher than the 5.2 cy/ft/yr rate adopted in the 2011 nourishment design. As Figure 4.10 illustrates, the average unit volume of sand along each reach in May 2018 is remarkably similar ranging narrowly between ~509 cy/ft (Reach 4) and ~522 cy/ft (Reach 2). This result suggests the original plan to vary the fill sections in accordance with the variable erosion rates has been effective for ~7 years, now yielding comparable beach conditions over the length of Nags Head.



**FIGURE 4.9.** Comparison of cumulative unit volumes by station between the face of dune and -19 ft NAVD.



**FIGURE 4.10.** Comparison of cumulative unit volumes by reach between the face of dune and -19 ft NAVD.

## 5.0 TOTAL VOLUME CHANGES AND VOLUME REMAINING

### 5.1 Total Volume Summary Before and After Nourishment

The total beach volume was estimated by applying the unit volume calculated at each measured profile over an applicable shoreline distance. The method (known as the average-end-area method) uses the average unit volume of two adjacent profiles multiplied by the distance between the profile stations to estimate the volume of sand between the two profiles. The total volume of sand in the project area is simply the sum of the individual section volumes measured to common vertical datums.

Because Nags Head stations are evenly spaced, the trends in total volume along the project site are similar to results using unit volumes. The same seven lenses as the 2011 nourishment design (CSE 2011a) were used to estimate the total volume, and detailed numbers for each station are listed in Appendix 5.

Prior to nourishment in November 2010, the project area contained 41,695,693 cy of sand between the face of dune and -24 ft NAVD (Table 5.1). The contractor's construction survey showed that 4,615,126 cy of sand were placed along 10.0 miles of Nags Head between 24 May and 27 October 2011. Following project completion in November 2011, CSE's surveys confirmed the total volume within the project limit was 4,762,013 cy (estimated  $\pm 3$  percent survey error) more than the pre-project conditions (November 2010) (Table 5.2). CSE conducted two surveys in the first year after the project, one survey in May to July before the hurricane season each of the following years (2013–2018), and one additional survey in July 2017 after the passage of Hurricane *Matthew*. The volume changes relative to November 2010 (before the project) are listed in Tables 5.3 to 5.11. The three lenses used in this study are shaded in these tables.

**TABLE 5.1.** Total volume by reach in the seven lenses (CSE's survey in November 2010 before the nourishment project).

Reach	GLDD Reported Volume (cy)	Length (ft)	Total Volume (CY) Nov-2010						
			To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
<b>Reach 1 (495-790)</b>	1,619,172	29,500	460,353	1,229,793	1,603,262	2,598,903	5,881,865	14,079,811	22,766,566
<b>Reach 2 (790-920)</b>	1,361,165	13,000	89,909	357,170	513,340	1,012,731	2,576,143	6,207,611	10,140,563
<b>Reach 3 (920-1010)</b>	1,437,605	9,000	34,351	192,801	307,178	706,701	1,859,746	4,433,970	7,311,386
<b>Reach 4 (1010-1025)</b>	197,184	1,500	4,161	29,243	47,179	127,022	354,983	878,133	1,477,177
<b>Total (495-1025)</b>	4,615,126	53,000	588,773	1,809,007	2,470,960	4,445,358	10,672,737	25,599,524	41,695,693

**TABLE 5.2.** Total volume changes by reach between November 2010 and November 2011. These results reflect the direct impact of nourishment and Hurricane *Irene*.

Reach	Length (ft)	Volume Changes Between Nov-10 And Nov-11 (CY)						
		To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Reach 1 (495-790)	29,500	135,789	628,366	804,495	1,138,026	1,820,770	1,700,982	1,896,965
Reach 2 (790-920)	13,000	117,999	619,674	769,748	967,742	1,358,359	1,297,082	1,357,039
Reach 3 (920-1010)	9,000	85,345	586,855	736,277	1,026,681	1,377,313	1,281,379	1,332,193
Reach 4 (1010-1025)	1,500	10,824	70,687	90,237	110,880	158,723	173,344	175,816
<b>Total (495-1025)</b>	<b>53,000</b>	<b>349,957</b>	<b>1,905,582</b>	<b>2,400,757</b>	<b>3,243,329</b>	<b>4,715,165</b>	<b>4,452,787</b>	<b>4,762,013</b>

**TABLE 5.3.** Total volume changes by reach between November 2010 and June 2012.

Reach	Length (ft)	Volume Changes Between Nov-10 And Jun-12 (CY)						
		To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Reach 1 (495-790)	29,500	213,713	699,596	842,208	1,032,425	1,900,618	2,101,133	2,400,434
Reach 2 (790-920)	13,000	164,846	622,300	753,514	902,188	1,387,186	1,373,586	1,374,533
Reach 3 (920-1010)	9,000	100,273	576,284	707,895	904,870	1,264,045	1,296,493	1,346,085
Reach 4 (1010-1025)	1,500	17,767	78,229	96,829	118,284	184,993	207,830	207,538
<b>Total (495-1025)</b>	<b>53,000</b>	<b>496,599</b>	<b>1,976,409</b>	<b>2,400,445</b>	<b>2,957,766</b>	<b>4,736,841</b>	<b>4,979,042</b>	<b>5,328,590</b>

**TABLE 5.4.** Total volume changes by reach between November 2010 and November 2012. These results incorporate the impacts of Hurricanes *Irene* (August 2011) and *Sandy* (October 2012).

Reach	Length (ft)	Volume Changes Between Nov-10 And Nov-12 (CY)						
		To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Reach 1 (495-790)	29,500	124,589	397,135	597,102	1,014,648	1,517,204	1,713,410	1,842,395
Reach 2 (790-920)	13,000	145,705	535,471	687,337	883,008	1,151,399	1,141,685	1,142,648
Reach 3 (920-1010)	9,000	144,338	546,616	666,292	789,190	1,068,920	1,003,944	1,052,841
Reach 4 (1010-1025)	1,500	13,678	67,185	85,484	93,392	153,622	176,447	182,404
<b>Total (495-1025)</b>	<b>53,000</b>	<b>428,309</b>	<b>1,546,407</b>	<b>2,036,215</b>	<b>2,780,237</b>	<b>3,891,144</b>	<b>4,035,486</b>	<b>4,220,288</b>

**TABLE 5.5.** Total volume changes by reach between November 2010 and June 2013.

Reach	Length (ft)	Volume Changes Between Nov-10 And Jun-13 (CY)						
		To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Reach 1 (495-790)	29,500	344,963	709,240	829,877	1,219,411	1,251,419	1,911,609	2,426,419
Reach 2 (790-920)	13,000	254,009	626,918	768,321	1,002,007	859,510	1,292,398	1,402,892
Reach 3 (920-1010)	9,000	243,163	602,371	708,803	823,748	851,338	1,137,586	1,190,208
Reach 4 (1010-1025)	1,500	26,771	68,619	83,059	90,268	108,016	137,614	141,313
<b>Total (495-1025)</b>	<b>53,000</b>	<b>868,906</b>	<b>2,007,147</b>	<b>2,390,061</b>	<b>3,135,434</b>	<b>3,070,282</b>	<b>4,479,208</b>	<b>5,160,832</b>

**TABLE 5.6.** Total volume changes by reach between November 2010 and June 2014.

Reach	Length (ft)	Volume Changes Between Nov-10 And Jun-14 (CY)						
		To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Reach 1 (495-790)	29,500	456,407	743,325	805,974	1,085,981	1,321,751	1,908,360	2,428,109
Reach 2 (790-920)	13,000	287,513	590,206	685,370	844,702	899,942	1,346,691	1,452,637
Reach 3 (920-1010)	9,000	221,848	507,594	580,317	669,903	718,590	1,025,817	1,048,064
Reach 4 (1010-1025)	1,500	35,216	77,858	89,139	77,033	39,073	114,850	107,448
<b>Total (495-1025)</b>	<b>53,000</b>	<b>1,000,984</b>	<b>1,918,982</b>	<b>2,160,799</b>	<b>2,677,619</b>	<b>2,979,356</b>	<b>4,395,717</b>	<b>5,036,257</b>

**TABLE 5.7.** Total volume changes by reach between November 2010 and June 2015.

Reach	Length (ft)	Volume Changes Between Nov-10 And Jun-15 (CY)						
		To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Reach 1 (495-790)	29,500	466,904	811,279	888,989	1,079,356	1,346,970	1,790,705	2,682,009
Reach 2 (790-920)	13,000	281,663	641,470	734,960	809,453	763,863	1,268,412	1,495,487
Reach 3 (920-1010)	9,000	211,574	500,008	565,949	658,157	646,187	799,182	924,939
Reach 4 (1010-1025)	1,500	18,915	41,953	46,153	31,752	24,696	61,492	69,398
<b>Total (495-1025)</b>	<b>53,000</b>	<b>979,057</b>	<b>1,994,711</b>	<b>2,236,051</b>	<b>2,578,719</b>	<b>2,781,717</b>	<b>3,919,791</b>	<b>5,171,832</b>

**TABLE 5.8.** Total volume changes by reach between November 2010 and June 2016. These results are prior to Hurricane *Matthew* and reflect much better than expected performance during Years1–5 after nourishment.

Reach	Length (ft)	Volume Changes Between Nov-10 And Jun-16 (CY)						
		To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Reach 1 (495-790)	29,500	505,044	847,400	949,293	1,086,961	1,425,683	2,088,642	2,551,384
Reach 2 (790-920)	13,000	302,382	569,254	656,488	783,717	807,560	1,305,026	1,391,912
Reach 3 (920-1010)	9,000	221,481	470,829	516,565	579,130	617,606	760,191	801,539
Reach 4 (1010-1025)	1,500	5,486	25,964	29,270	29,024	42,620	16,051	3,098
<b>Total (495-1025)</b>	<b>53,000</b>	<b>1,034,393</b>	<b>1,913,447</b>	<b>2,151,617</b>	<b>2,478,832</b>	<b>2,893,469</b>	<b>4,169,910</b>	<b>4,747,932</b>

**TABLE 5.9.** Total volume changes by reach between November 2010 and October 2016. These results incorporate impacts of Hurricane *Matthew* (October 2016)

Reach	Length (ft)	Volume Changes Between Nov-10 And Oct-16 (CY)						
		To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Reach 1 (495-790)	29,500	499,174	738,834	819,256	1,050,876	1,065,152	1,428,101	2,003,509
Reach 2 (790-920)	13,000	282,830	494,219	556,427	692,436	668,184	933,764	1,104,287
Reach 3 (920-1010)	9,000	214,512	439,200	487,595	591,506	553,986	429,350	546,489
Reach 4 (1010-1025)	1,500	3,073	16,017	18,310	14,913	12,363	-52,959	-42,077
<b>Total (495-1025)</b>	<b>53,000</b>	<b>999,589</b>	<b>1,688,270</b>	<b>1,881,589</b>	<b>2,349,731</b>	<b>2,299,686</b>	<b>2,738,257</b>	<b>3,612,207</b>

**TABLE 5.10.** Total volume changes by reach between November 2010 and July 2017. These results reflect some recovery of sand within the Nags Head sand box ~9 months after Hurricane *Matthew*.

Reach	Length (ft)	Volume Changes Between Nov-10 And Jul-17 (CY)						
		To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Reach 1 (495-790)	29,500	551,781	913,183	1,018,833	1,194,858	1,544,218	1,699,296	2,198,184
Reach 2 (790-920)	13,000	328,262	603,387	672,761	721,915	761,814	888,118	1,023,462
Reach 3 (920-1010)	9,000	237,733	502,459	562,972	604,978	525,785	408,100	488,514
Reach 4 (1010-1025)	1,500	9,292	34,897	40,474	22,168	15,337	-59,743	-59,602
<b>Total (495-1025)</b>	<b>53,000</b>	<b>1,127,069</b>	<b>2,053,926</b>	<b>2,295,040</b>	<b>2,543,919</b>	<b>2,847,154</b>	<b>2,935,772</b>	<b>3,650,557</b>

**TABLE 5.11.** Total volume changes by reach between November 2010 and May 2018. These results incorporate major sand losses along the Nags Head project area due to 2017 hurricanes and northeasters.

Reach	Length (ft)	Volume Changes Between Nov-10 And May-18 (CY)						
		To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
<b>Reach 1 (495-790)</b>	29,500	526,825	822,998	898,143	985,588	756,102	1,053,383	1,767,609
<b>Reach 2 (790-920)</b>	13,000	293,650	530,354	588,392	599,858	362,270	573,200	754,012
<b>Reach 3 (920-1010)</b>	9,000	227,253	421,340	452,868	420,428	422,142	157,253	295,564
<b>Reach 4 (1010-1025)</b>	1,500	2,746	12,788	12,959	-14,344	-9,012	-114,154	-118,527
<b>Total (495-1025)</b>	53,000	1,050,473	1,787,480	1,952,361	1,991,530	1,531,503	1,669,682	2,698,657

Figure 5.1 plots the overall volume changes compared to November 2010 (before nourishment) in the 10-mile-long project area between the foredune and the three depth contours used in this study. The tan bars show the nourishment volume placed within the various beach areas during the dredging operations, whereas the brown bars indicate the sand remaining in November 2011 after project completion, Hurricane *Irene*, and the fall 2011 northeasters. The green bars represent the results of the June 2012 survey before the 2012 hurricane season, and the deeper purple bars illustrate the results of the November 2012 survey after Hurricane *Sandy*.

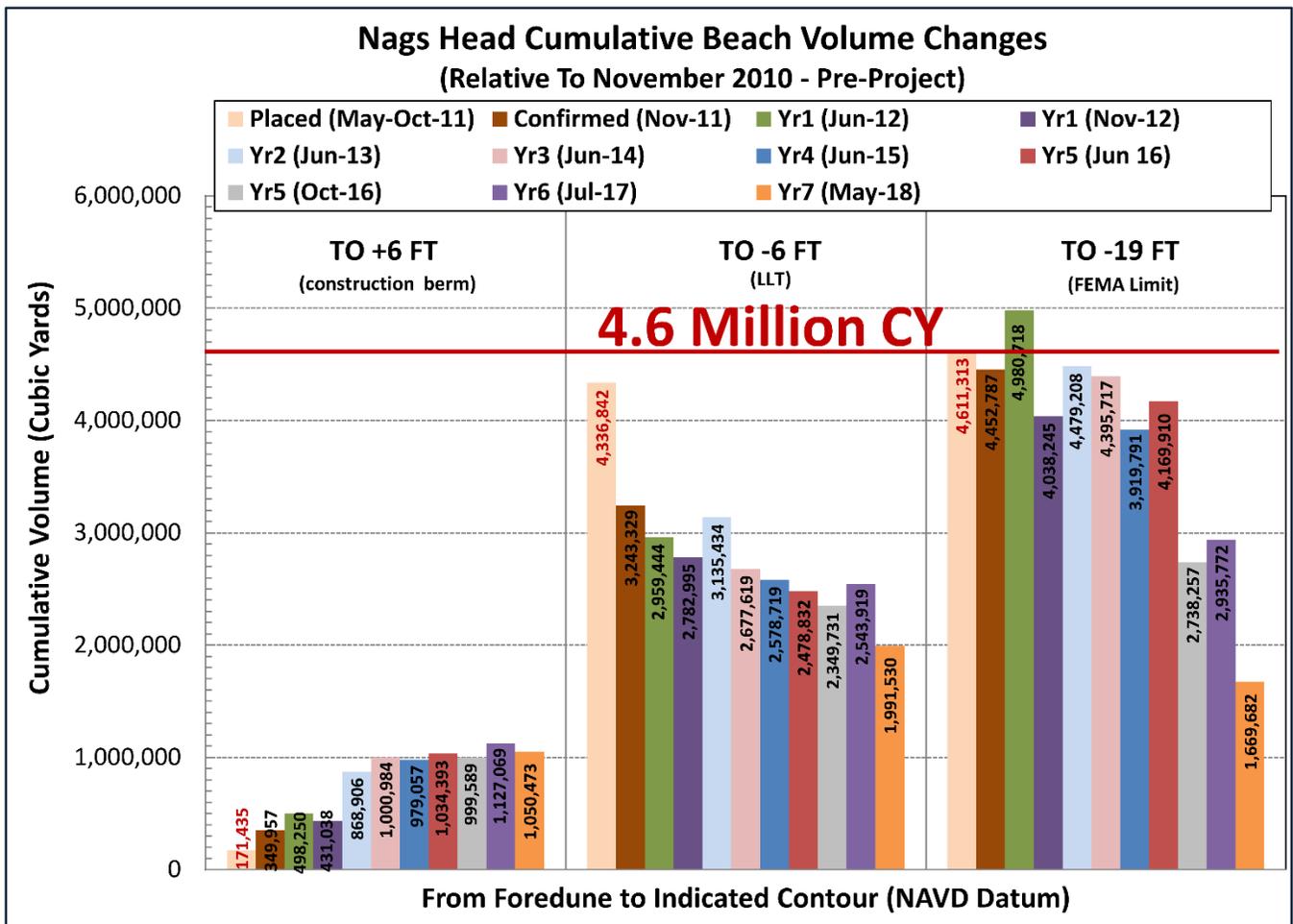
The deeper purple bars also show a same-season comparison with the baseline (November 2010) and the condition upon project completion (November 2011). The light blue bars indicate the results of the June 2013 survey, the pink bars represent the results of the June 2014 survey, and the dark blue bars illustrate the results of the June 2015 survey. The beige bars show the results of the June 2016 survey, and the gray bars indicate the results of the same year but after Hurricane *Matthew*. The light purple bars indicate the results of last year in July 2017, and the most recent survey in May 2018 is represented by the orange bars in the graphic.

The first set of bars in Figure 5.1 represent net volume changes in the foredune (ie – Lens 1); the second set of bars show net volume changes along foredune and beach (ie – Lenses 1&2); and the third set of bars indicate net volume changes from foredune to beach and underwater (ie – the FEMA reference sand box or Lenses 1, 2 and 3).

**Foredune (Lens 1)** — As of May 2018, the foredune areas (the first set of bars in Fig 5.1) have accumulated over 1 million cubic yards more sand than the condition before nourishment. This is equivalent to a gain of ~20 cy/ft (~3 cy/ft/yr) above +6 ft NAVD (nourishment berm elevation) since

pre-project conditions in November 2010, and a gain of ~13.3 cy/ft (~2.3 cy/ft/yr) since project completion in November 2011. Such gain is considered significant for Nags Head because before nourishment between 1994 and 2010, Nags Head experienced dune losses averaging ~1 cy/ft/yr along this portion of the beach.

**Foredune and Beach (Lenses 1 & 2)** — The second set of bars in Figure 5.1 show the total volume changes from the face of dune to low-tide wading depth (-6 ft NAVD). After the initial sand adjustment occurred in the first year following project completion, the beach volume had been relatively stable until this past year. The May 2018 survey shows 552,389 cy of sand loss over the past year (equivalent to over 10 cy/ft loss rate).



**FIGURE 5.1.** Cumulative, overall beach-volume changes relative to November 2010 survey results between the foredune and indicated contours.

**Foredune, Beach, and Underwater (Lenses 1, 2 & 3)** — The third set of bars in Figure 5.1 show the cumulative volume change from the face of dune to -19 ft (FEMA depth limit). The results of the June 2016 survey (Year 5 post-project) indicated that ~10 percent of the nourishment sand had shifted away from the sand box due to the chronic erosion at Nags Head, resulting in an average loss of ~90,000 cy/yr (1.6 cy/ft/yr) between project completion (November 2011) and June 2016. This average erosion rate was much lower than the 275,000 cy/yr (5.2 cy/ft/yr) historical erosion rate between 1994 and 2005 which was adopted in the 2011 project formulation (CSE 2011a).

Nags Head then lost ~1.43 million cubic yards of sand after Hurricane *Matthew* (October 2016) compared to the condition of June 2016. Due to the significant losses caused by *Matthew*, the average annual erosion rate increased to ~360,000 cy/yr (~6.8 cy/ft/yr). A portion of the *Matthew* volume losses returned to the project area as confirmed by the July 2017 survey. However, the most recent survey in May 2018 indicates another ~1.27 million cy of sand was lost over the past year.

**As of the most recent survey in May 2018, the Nags Head project area retains 1,669,682 cy of the nourishment sand at Year 7 post-project completion, which is equivalent to ~36 percent of the volume placed during construction.**

The average annual erosion rate has increased to ~440,000 cy/yr if averaged between November 2011 and May 2018. This is nearly 60% higher than the design erosion rate. Under normal wave conditions, this higher rate would be expected to decline in the next couple of years bringing the net volume losses closer to long-term averages.

## 5.2 Total Volume Changes by Reach and Subreach

Two analyses are developed to evaluate the total volume changes in the sand box\* by reach and subreach:

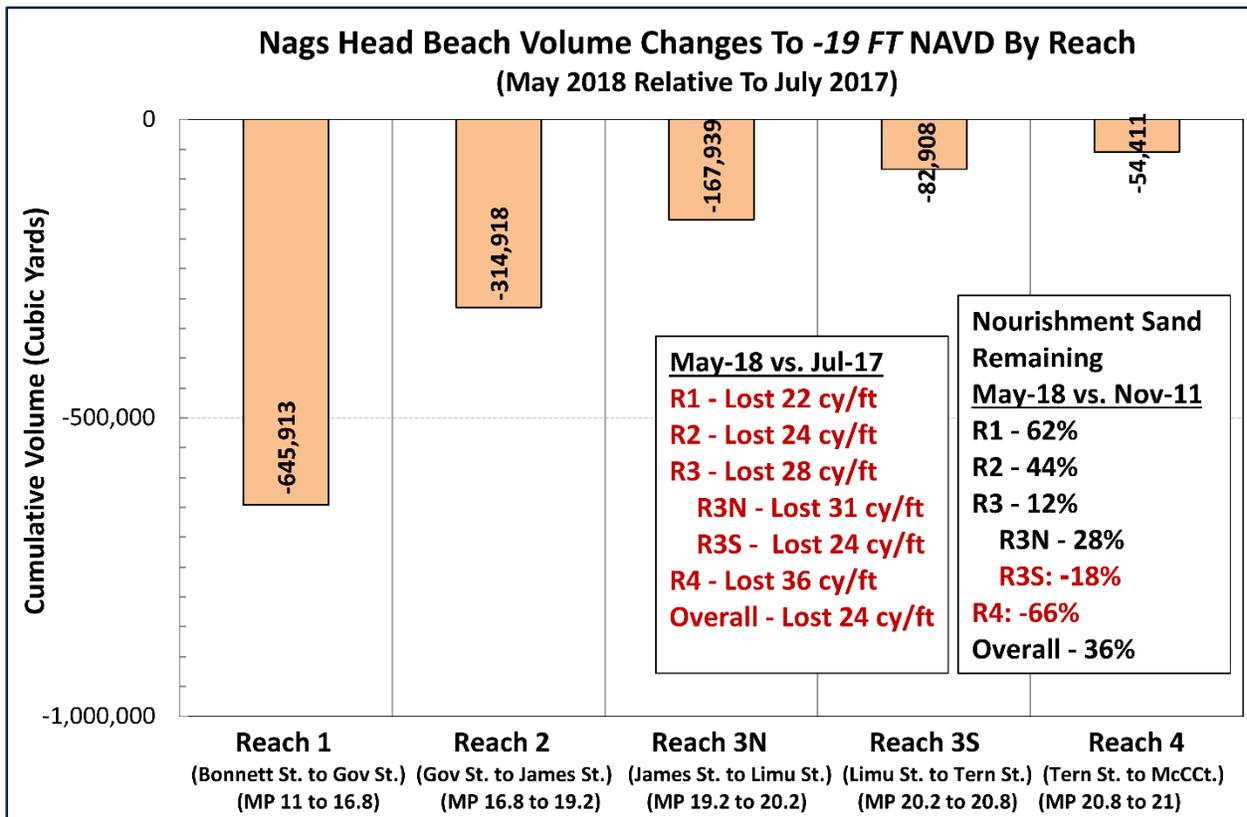
- (1) Volume changes over the present monitoring period, ie – May 2018 compared to July 2017, in relation to changes associated with Hurricane *Matthew*.
- (2) Volume changes since project completion, ie – May 2018 compared to November 2011

\*[Unless otherwise specified, volumes in this section are measured within the sand box, ie – from the foredune to the FEMA reference depth of -19 ft NAVD.]

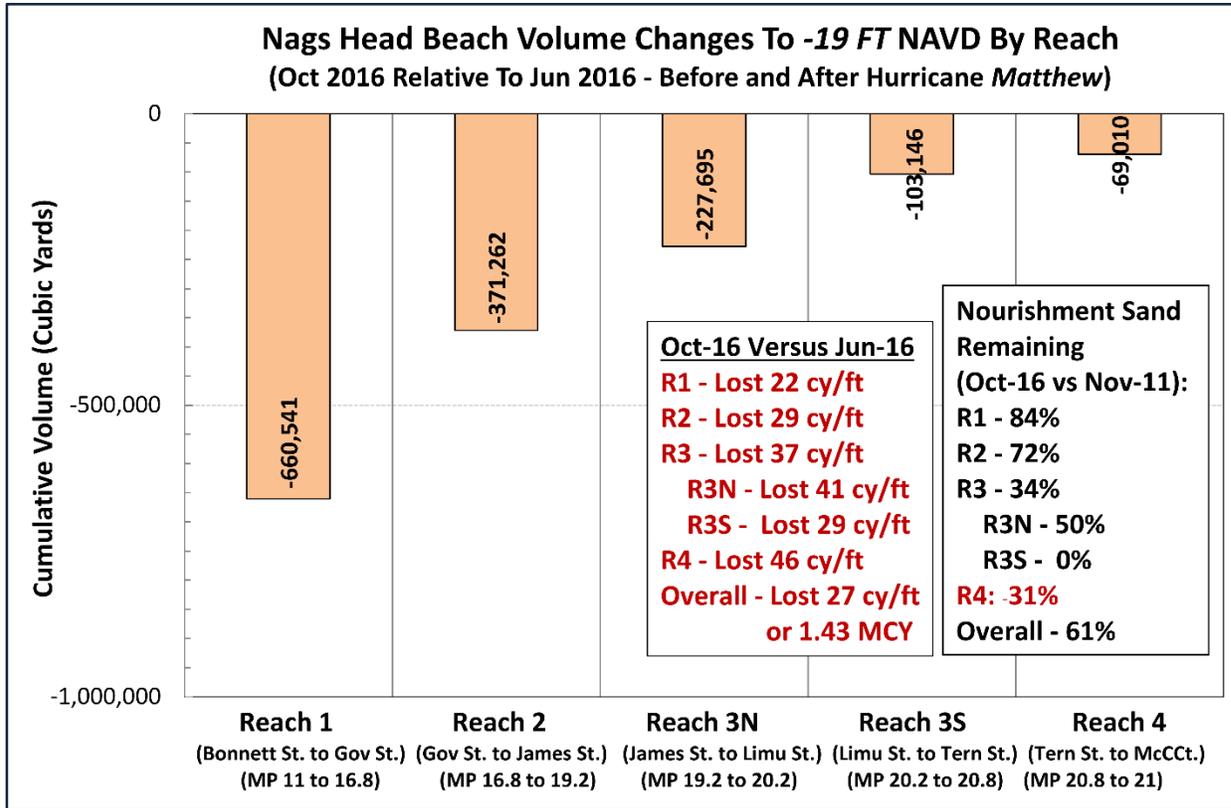
**5.2.1 May 2018 Compared to July 2017 (Volume Changes over Present Monitoring Period)**

To better document the nourishment performance and delineate erosion variations along south Nags Head, Reach 3 is further divided into two subreaches in the following analysis. All reaches and subreaches lost a significant amount of sand over the past 11 months with results indicating that the 10-mile-long Nags Head project area has lost 1,266,090 cy of sand. This loss represents ~28 percent of the 2011 nourishment volume and is in a similar magnitude of the amount lost during Hurricane *Matthew* (a total of 1,431,653 cy as aggregated by reach and subreach shown in Figure 5.3).

Lost	645,913 cy	in Reach 1
Lost	314,918 cy	in Reach 2
Lost	167,939 cy	in Reach 3N
Lost	82,908 cy	in Reach 3S
Lost	54,411 cy	in Reach 4
<hr/>		
Lost	1,266,090 cy	total (for the five reaches and subreaches)



**FIGURE 5.2.** Beach volume changes along the Nags Head project area by reach and subreach from the foredune to -19 ft NAVD during the present monitoring period between July 2017 and May 2018.



**FIGURE 5.3.** Beach volume changes by reach and subreach (after CSE 2016c) before and after Hurricane *Matthew* between June and October 2016. Results are calculated from the face of dune to -19 ft NAVD.

### 5.2.2 May 2018 Compared to Project Completion (November 2011)

Figure 5.4 shows the volumes (relative to the pre-project condition in November 2010) measured from the foredune to -19 ft NAVD along the reaches and subreaches. Reach 1 (northern half of the project) retained over 60 percent of the nourishment volume at Year 7 after project completion, and Reach 2 (the center to southern ~2.5 miles of the project) retained a little less than half of the nourishment volume. At Year 7 following project completion, Reach 1 lost ~22 cy/ft (~3.3 cy/ft/yr), Reach 2 lost ~56 cy/ft (~8.4 cy/ft/yr), Reach 3N lost ~112 cy/ft (~17 cy/ft/yr), Reach 3S lost ~145 cy/ft (~21.9 cy/ft/yr), and Reach 4 lost ~192 cy/ft (~29 cy/ft/yr). Despite the significant losses, all reaches (except for the southernmost ~1 mile of Reaches 3S and 4) have more volume in 2018 than the pre-project condition. The systematic increases in volume losses from north south confirms the long-term trend for Nags Head and affirms the basic requirement for variable fill sections to achieve the goals and objectives of nourishment (ie - to provide uniform protection for the life of each nourishment). This year's results are summarized as follows and compared with the sand loss due to Hurricane *Matthew*.

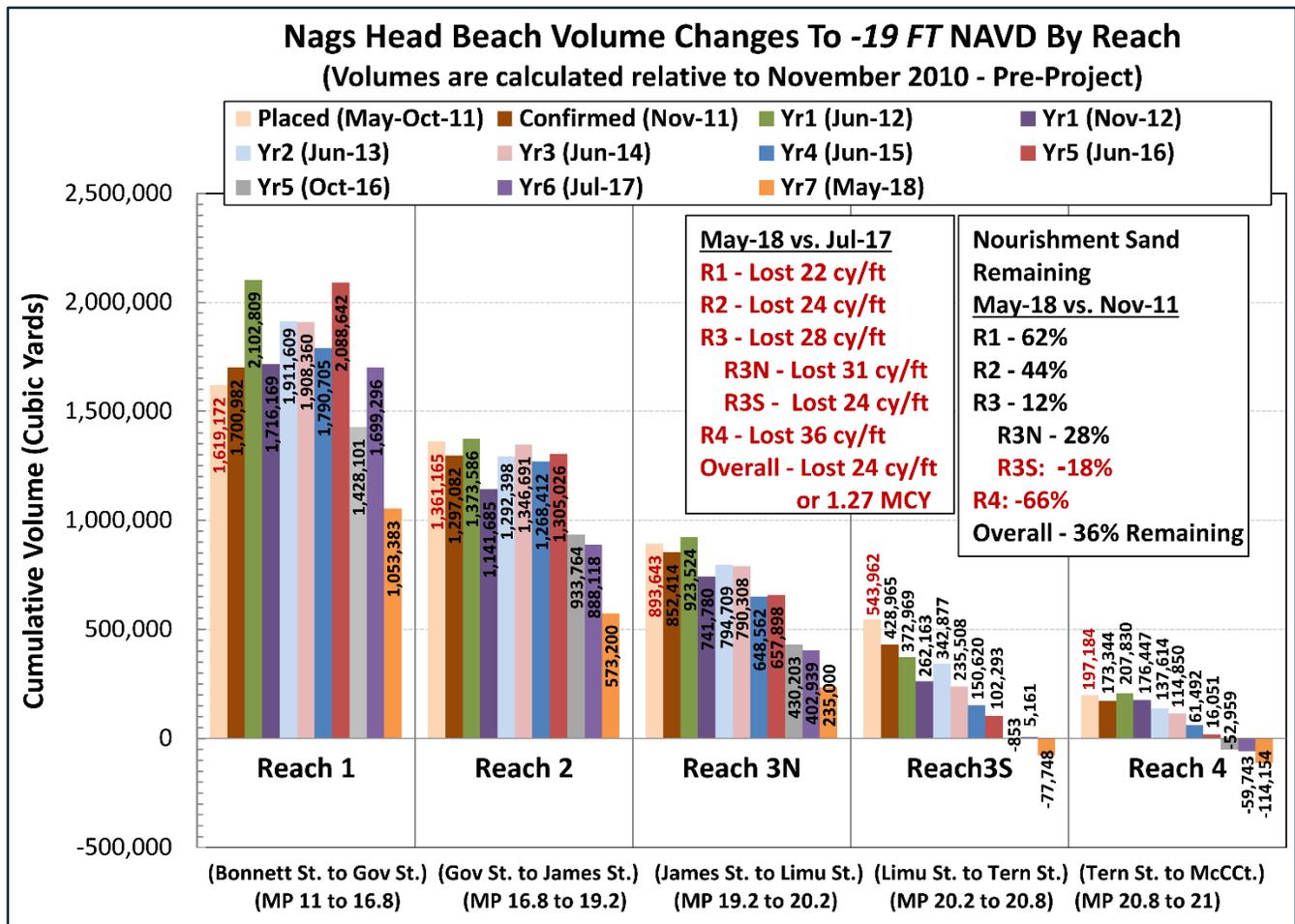


FIGURE 5.4. Beach volume changes by reach and subreach relative to November 2010 survey results from the foredune to -19 ft NAVD.

**Reach 1 (R1)** — The northern ~5.5 miles of beach from Mile Posts 11 to 16.8 (CSE stations 497+00 to 790+00) lost 660,541 cy between June and October 2016 mainly due to Hurricane *Matthew*, and lost 645,913 cy over the past year primarily due to the close passage of several hurricanes in September 2017 and a series of northeasters in March 2018. Compared to the condition after project completion in November 2011, Reach 1 contains ~60 percent of the nourishment volume as of May 2018, resulting in an annual erosion rate of ~3.3 cy/ft/yr.

**Reach 2 (R2)** — The center to southern ~2.5 miles of beach from Mile Posts 16.8 to 19.2 (CSE stations 790+00 to 920+00) lost ~371,262 cy during Hurricane *Matthew* and another ~314,918 cy over the past year, and has lost 723,882 cy (55.7 cy/ft or 8.4 cy/ft/yr) since project completion (November 2011) which is about the same magnitude as the loss rate of the entire project. The total loss as of May 2018 is equivalent to ~56 percent of the nourishment volume in this reach.

**Reach 3 (R3)** — The southern ~1.7 miles of beach from Mile Posts 19.2 to 20.8 (CSE stations 920+00 to 1010+00) lost ~330,841 cy during Hurricane *Matthew* and another 250,847 cy over the past year, and has lost 1,124,126 cy (~125 cy/ft or ~18.9 cy/ft/yr) between November 2011 and May 2018. The erosion rate is over two times higher than the erosion rate for Reach 2 or the entire project.

**Subreach 3N (R3N)** — The northern two-thirds of Reach 3 from Mile Posts 19.2 to 20.2 (CSE stations 920+00 to 975+00) lost ~227,695 cy over the past survey year, reflecting the impact of September hurricanes and March northeasters. Compared to the condition after project completion in November 2011, Subreach 3N has lost 617,414 cy (~112 cy/ft or ~17 cy/ft/yr), which is equivalent to ~72 percent of the nourishment sand placed there. This rate is lower than the volume loss rate of 88 percent for the entire Reach 3.

**Subreach 3S (R3S)** — The southern one-third of Reach 3 from Mile Posts 20.2 to 20.8 (CSE stations 975+00 to 1010+00) lost 82,908 cy over the past survey year between July 2017 and May 2018. Since project completion, Subreach 3S has lost 506,713 cy (~145 cy/ft or ~22 cy/ft/yr), which is 18 percent more than the nourishment volume placed.

**Reach 4** — The southernmost ~0.2 mile of beach from Mile Posts 20.8 to 21 (CSE stations 1010+00 to 1025+00) lost 54,411 cy over the past year. Compared to conditions after project completion, Reach 4 has lost 166 percent of the nourishment volume indicating that the average erosion rate is as high as ~192 cy/ft (~29 cy/ft/yr) which is even higher than Subreach 3S. The beach condition since June 2016 along this 1,500-ft-long end of the project area has returned to conditions prior to nourishment based on the volume analysis.

Sand losses were projected to be higher along south Nags Head than north Nags Head based on historical trends, but the erosion rates of the last three years in these two reaches are significantly higher than CSE's original design estimate. This difference is likely related to the shoreline offset produced by placing a higher fill density at the south portion of the project to account for higher erosion rates.

In conclusion, **the total volume remaining after nourishment to -19 ft NAVD (FEMA depth limit) in May 2018 is ~1,669,682 cy (~36 percent of the nourishment volume placed).** The overall annual erosion rate since nourishment is ~440,000 cy/yr (~8.4 cy/ft/yr), which is ~60 percent higher than the historical erosion rate of 275,000 cy/yr (~5.2 cy/ft/yr) that was adopted in the 2011 project planning and design.

## 6.0 DUNE GROWTH, EROSION, AND ESCARPMENTS

---

Natural dune growth by aeolian transport (ie – wind-generated transport) after the 2011 nourishment has been observed and measured along Nags Head. The extra volume and elevation in the dunes have provided a higher level of storm protection and have helped the Town avoid any major damage to oceanfront properties during hurricanes and numerous severe winter storms. CSE initiated a comprehensive dune study in 2014, and the results were compared with the Bagnold (1941) analytical model predictions of dune growth (CSE 2014b). Volumetric dune growth results have been updated and documented in monitoring reports following each annual survey (CSE 2015, 2016b, 2017c). This section includes the most recent survey data for 2018. As stated in previous annual monitoring reports, dune growth rates are highly impacted by storm events and are shown to correlate and decay closely with dry-sand beach width as the nourished profile equilibrates.

Although incipient dunes started forming in many places along Nags Head oceanfront, they haven't developed into established dunes due to the short period of time since formation. Lack of dunes or low incipient dunes makes certain portions of beach vulnerable to dune overtopping and wave overwash into streets through beach accesses. Areas with high established dunes but a narrow dry-sand beach instead lead to dune escarpments after hurricanes or winter storms. Rhythmic variations in beach width have been a characteristic along the project area both before and after nourishment likely because of variations in the longshore bar offshore of Nags Head. Variable conditions alongshore result in localized “erosional hotspots” on the beach and will be evaluated in this section.

### 6.1 Overall Dune Growth After Nourishment

As discussed in Sections 4 and 5 and shown in Figures 4.3–4.4 and 5.1, an important feature of beach profile equilibration experienced in Nags Head post-nourishment is dune growth via natural wind forces known as aeolian transport. The original beach fill did not incorporate a protective dune (CSE 2012), but Nags Head exhibited rapid adjustment of the upper beach with sand shifting landward producing high rates of natural dune growth the first few years after nourishment. The wide dry beach constructed by nourishment provided a new sand source for aeolian transport making natural dune growth possible. Sand-fencing installed after the project helped concentrate sand along the back beach thereby enhancing the foredune. Dune growth initially occurred at >7 cy/ft in the seven months between November 2012 and June 2013 along Nags Head, but as the berm width equilibrated and narrowed, dune accretion rates declined. At Nags Head, over one million cubic yards of sand (~22 percent of the total nourishment volume) shifted into the foredune within the first three years post-nourishment, equivalent to ~5 cy/ft/yr of accretion during this period (as of June 2014). Since 2014, sand volume in the foredune area of the beach has remained relatively stable with a declining trend over the last two years.

Wind-generated aeolian transport is the most common process occurring along the visible beach, and is known to be the primary reason for dune growth. It is believed that when sufficient (onshore) wind occurs and there is available sediment for transport, it will move from the beach toward the dunes, leading to an increase of dune volume. Dunes are affected by other factors including marine processes (eg – storm waves) if water levels, including wave runup, are high enough to reach the dunes, and wave conditions are strong enough to erode them. Although quantitative knowledge of dune-building processes is limited due to the problem’s complexity and limited field data, classical studies of dune mechanics and sand transport, particularly the pioneering work of Bagnold, exist (1941).

### 6.1.1 Dune Growth Mechanics–Aeolian Transport

Bagnold (1941) identified the main factors influencing aeolian transport rates,  $q$ , (in kilograms per meter per second—kg/m/s), as the local grain-size diameter ( $d$ ) relative to a reference grain-size diameter ( $D$ ) (a standard grain-size diameter 0.25 mm), the air density ( $\rho = 1.22 \text{ kg/m}^3$ ), the gravitational acceleration ( $g = 9.81 \text{ m/s}^2$ ), the shear velocity ( $u_*$  in m/s), and an empirical coefficient ( $C_b$ ).

$$q = C_b \frac{\rho}{g} \sqrt{\frac{d}{D}} (u_*)^3 \quad (1)$$

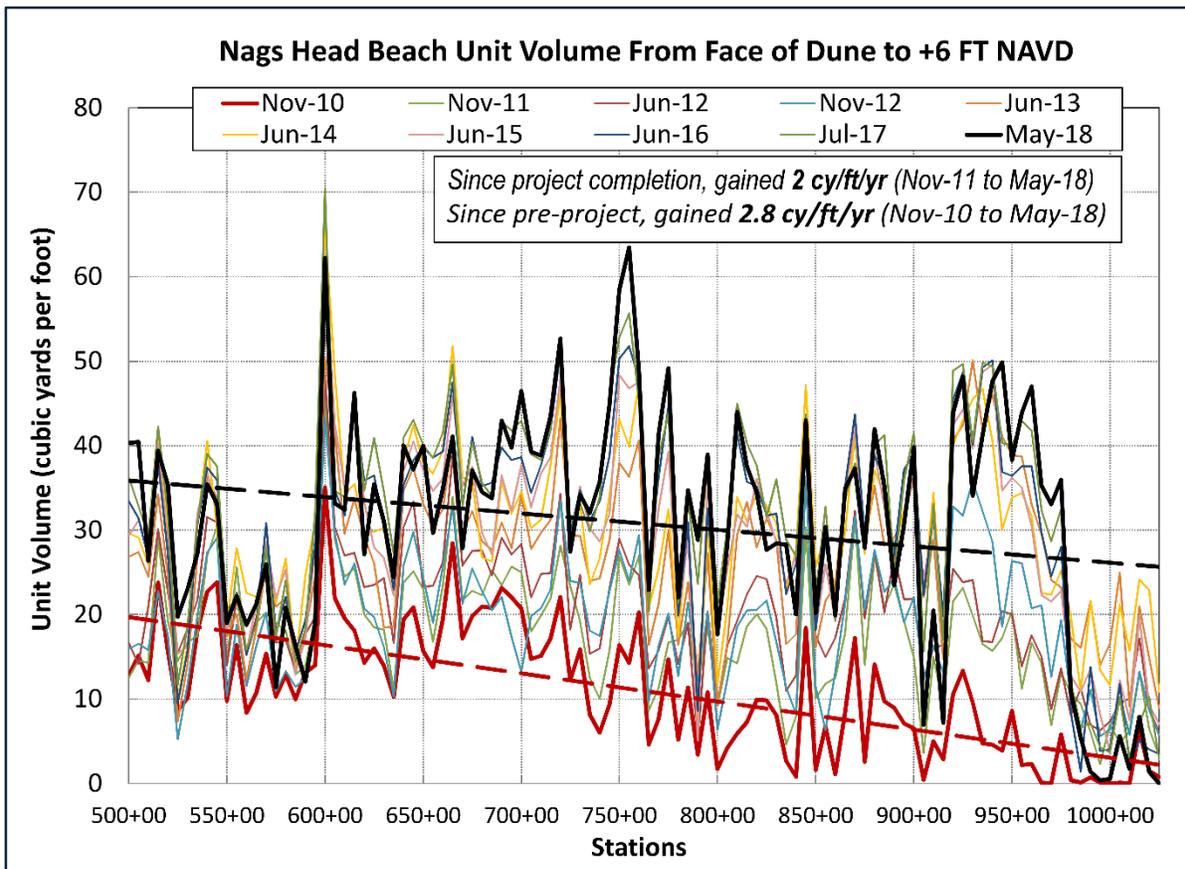
The shear velocity is a measure of the velocity gradient of the wind, and its threshold  $u_{*t}$  is dependent on the grain-size diameter ( $d$ ), the gravitational acceleration ( $g$ ), the density of the sand grains ( $\rho_s$ ), the density of the air ( $\rho$ ), and an empirical coefficient ( $A$ ).

$$u_{*t} = A \sqrt{dg (\rho_s - \rho) / \rho} \quad (2)$$

Over the years, these principles have been applied by many researchers for measuring, deriving, and defining appropriate  $C_b$  and  $A$  values for various conditions of interest. Almost all aeolian sand transport equations consider the sediment transport rate proportional to the shear velocity cubed:  $q \propto u_*^3$ . This implies that once sediment is moving, a small increase in the wind velocity causes a large increase in the sediment transport rate. For example, only a 25 percent increase in the wind speed will induce a doubling of the sediment transport rate.

Apparently not all winds can generate aeolian transport. Coastal dunes made up of fine to medium sand (size range ~0.2–0.5 mm) are characterized by a threshold wind velocity of 4–8 meters per second (m/s) (or 9–18 miles per hour, mph) (Masselink & Hughes 2003). Arens (1996) estimated that sufficient winds needed for sediment transport are typically in the order of >5–10 m/s (11–22 mph), which frequently occur during moderate conditions. Extreme conditions with greater wind speeds often coincide with precipitation, which inhibits aeolian transport because the sand surface becomes wet and more cohesive. Therefore, the cumulative effect of aeolian sediment transport is mainly governed by relatively mild conditions instead of rare extreme conditions.

Equations (1) and (2) imply the assumption that there is an unlimited sand source for aeolian transport. This is a good assumption in a desert environment, but it is not always applicable on the beach (especially for a narrow beach like Nags Head). Before nourishment, the beach was too narrow for a stable dune, and actual measurements proved losses averaging ~1 cy/ft/yr between 1994 and 2010 (Kaczkowski et al 2018). Figure 6.1 plots the linear trend lines for 2010 and 2018 datasets as red and black dashed lines in the graphic. The distance between these two trend lines indicates the ~20 cy/ft (~2.8 cy/ft/yr) dune growth compared between pre-project conditions (Nov 2010) through May 2018.



**FIGURE 6.1.** Comparison of unit volumes along Nags Head from the face of the dune to +6 ft NAVD contour before and after nourishment. This shows a significant gain in volume at most stations following project completion. Linear trend lines 2010 and 2018 are plotted as red and black dashed lines. Note: the +6 ft NAVD is the elevation of the nourishment berm located shoreward of the dune.

## **6.1.2 Main Factors Affecting Aeolian Transport in the Beach Environment**

Most sediment transport formulations suggest that wind velocity is the most important governing parameter for aeolian dune growth. However, several coastal studies (particularly in the Nags Head study) show wind-driven sediment transport may reach limiting conditions regardless of the wind velocity. Important factors that limit wind-driven sediment transport include beach geometry, sediment properties, moisture, vegetation, and storms (de Vries et al 2012).

### **6.1.2.1 Beach Width and Fetch Length**

Of particular relevance to coastal environments is the fact that beaches are often too narrow for winds to become fully saturated with sand (Nordstrom & Jackson 1993), and therefore, dunes do not always grow naturally. The sediment transport can then be said to be “fetch-limited.” The fetch effect states that longer fetch lengths lead to higher transport under given wind conditions until a certain limit is reached. This limit is known as the “critical fetch” where wind reaches transport saturation. While winds are directly or obliquely onshore at a beach, the maximum available fetch distance is limited by beach width. When the maximum available fetch is smaller than the critical fetch, aeolian sediment transport toward the dunes is limited due to beach width.

Therefore, variable beach width might induce variable sediment transport rates toward the dunes if the beach width is less than the critical fetch. Values of critical fetch measured in the field vary from 30 ft to 130 ft (Davidson-Arnott & Law 1990) up to over 600 ft (Davidson-Arnott et al 2008). The magnitude of the critical fetch length on the process scale has proven to be highly variable and dependent on wind speed, wind direction, surface moisture content, and the presence of lag-specific conditions.

Sand volume in Lenses 1 and 2 (from the face of the dune to low-tide wading depth at -6 ft NAVD) can be used to indicate beach width. As shown in Figure 5.1, overall sand volume has reduced in this portion of the beach since project completion. The total volume in May 2018 is only ~50 percent of the volume in November 2011 following project completion. As a nourished beach profile equilibrates, beach width is expected to decrease (as confirmed in Table 6.1 for Nags Head), and natural dune growth rates will decline.

### **6.1.2.2 Beach Slope**

Surface slope affects wind or shear velocity because changes in slope can produce wind-velocity acceleration or deceleration, promote turbulence, and potentially act to create the development of internal boundary layers and even flow separation. Furthermore, increasing slope angles tend to enhance the effect of gravity which potentially reduces sand-transport rates.

Dry-sand beach width (ie – width between the toe of dune at +10 ft NAVD and the approximate seaward edge of the dry-sand beach at +5 ft NAVD) and wet beach slope (ie – slope of the beach face between +5 ft and –6 ft NAVD) of representative profiles at different survey dates are compared in Table 6.1 as an example for different sections of Nags Head from north to south. The results indicate that beach width increased significantly in June 2012 due to the 2011 nourishment, gradually adjusted, and has decreased overall since then. Three main reasons for such decrease include: (1) nourishment profile adjustment post-construction; (2) as dune volumes increase, the dune line or the edge of vegetation shifts seaward (in other words, beach width decrease is a “trade-in” of dune growth); and (3) chronic erosion. All of these reasons have been confirmed and documented in CSE’s annual monitoring reports (CSE 2012–2017).

**TABLE 6.1.** Nags Head dry-sand beach width and wet beach slope before and after the 2011 beach nourishment project. (Refer to Figure 1.3 for station locations.)

<b>Dry-Sand Beach Width (m) (+10 to +5 ft NAVD)</b>	<b>Nov-2010 (Pre-Project)</b>	<b>Jun-2012 (Year 1)</b>	<b>Jun-2013 (Year 2)</b>	<b>Jun-2014 (Year 3)</b>	<b>Jun-2015 (Year 4)</b>	<b>Jun-2016 (Year 5)</b>	<b>Jul-2017 (Year 6)</b>	<b>May-2018 (Year 7)</b>
Station 710+00 (Reach 1)	40	89	113	49	89	64	84	61
Station 810+00 (Reach 2)	56	190	170	91	82	133	86	59
Station 960+00 (Reach 3)	50	359	156	163	146	168	144	111
Station 1005+00 (Reach 4)	27	201	96	83	43	69	99	81
<b>Wet-Sand Beach Slope (+5 to –6 ft NAVD)</b>	<b>Nov-2010 (Pre-Project)</b>	<b>Jun-2012 (Year 1)</b>	<b>Jun-2013 (Year 2)</b>	<b>Jun-2014 (Year 3)</b>	<b>Jun-2015 (Year 4)</b>	<b>Jun-2016 (Year 5)</b>	<b>Jul-2017 (Year 6)</b>	<b>May-2018 (Year 7)</b>
Station 710+00 (Reach 1)	1 on 10	1 on 12	1 on 22	1 on 24	1 on 18	1 on 9	1 on 18	1 on 20
Station 810+00 (Reach 2)	1 on 12	1 on 25	1 on 18	1 on 20	1 on 14	1 on 20	1 on 19	1 on 18
Station 960+00 (Reach 3)	1 on 22	1 on 25	1 on 15	1 on 26	1 on 26	1 on 28	1 on 19	1 on 27
Station 1005+00 (Reach 4)	1 on 30	1 on 18	1 on 25	1 on 10	1 on 19	1 on 30	1 on 23	1 on 21

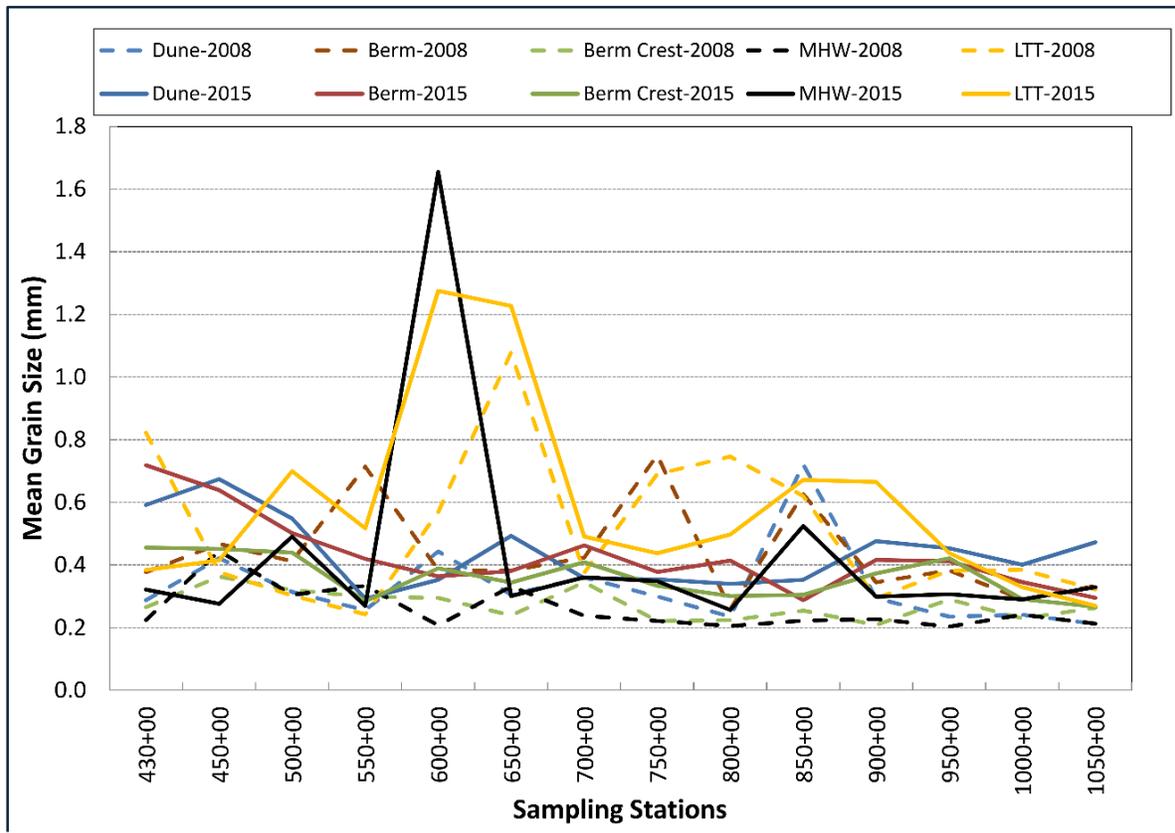
**6.1.2.3 Sand Moisture**

Wet surface and pore water act to increase the threshold drag velocity required to initiate aeolian sediment movement. Hotta (1988) shows that up to water content (w) of 10 percent, the threshold wind velocity increases linearly with increasing water content of the sand surface and also with increasing sediment size. On average, the shear velocity required to initiate transport on a surface with a moisture content of 5 percent is about twice that when the sand is dry (Sherman & Lyons 1994).

#### 6.1.2.4 Grain Size and Distribution

Sediment properties influence aeolian transport by changing the sediment transport capacity and sediment availability. The speed and distance the grain will be transported are determined by grain properties on the visible beach including grain size, shape, and density. The local grain-size diameter and its corresponding bed shear stress are two main factors in Bagnold equations (1) and (2).

Sediment samples at the visible beach [ie – toe of the dune, the berm, berm crest, mean high water (MHW), and low-tide terrace (LTT)] at representative stations were collected at Nags Head before the 2011 nourishment (November 2008) and after the nourishment (June 2013 and June 2015). Beach sediments in June 2015 were 0.066 mm coarser than the pre-project condition (0.385 mm for the 2008 condition versus 0.410 mm for the 2015 condition). Size distributions along the length of the beach in June 2015 were slightly more uniform than before the project (Fig 6.2).



**FIGURE 6.2.** Alongshore sediment distribution of average grain size at specific cross-shore locations on the visible beach at Nags Head in June 2015 compared to the pre-project conditions in November 2008. Refer to Figure 1.3 for locations of the sampling stations.

#### **6.1.2.5 Storm Impact**

Storm activity inevitably results in elevated water levels and causes dune and beach erosion. However, a well-developed dune system dissipates wave energy and protects the backshore area. The sand eroded from the dune system will be transported offshore, but much of it will eventually return to the beach under fair-weather conditions. As sediment is returned to the beach, aeolian processes lead to renewed dune development. Nags Head lost ~1 cy/ft of sand in the dune area after Superstorm *Sandy* but gained ~8 cy/ft of sand in the same portion of beach seven months following *Sandy* at a much faster rate than in other years (CSE 2013). Nags Head lost ~0.7 cy/ft after Hurricane *Matthew* but regained it back as of May 2018.

#### **6.1.2.6 Vegetation**

Naturally formed dunes (especially those with vegetation roots entangled throughout the sand) provide erosion resistance against a minor storm. When attacked by waves, dune vegetation helps hold sand in place as escarpments form. At both project sites, sand fencing and vegetation added post-nourishment have efficiently accumulated sand along the back beach increasing protection. The wide, dry-sand beach provided by nourishment made it possible for vegetation to grow in some areas previously impacted by waves and tides.

#### **6.1.3 Dune growth After the 2011 Nourishment**

As discussed in Section 1.1, the 2011 Nags Head nourishment added ~4.6 million cubic yards of sand along the 10-mile beach, and ~3.2 million cubic yards (~70 percent) of sand was placed between +6 ft NAVD and mean low water (MLW) at -2.05 ft NAVD, forming a steeper-than-natural beach slope. Profile adjustment after the project was expected (ie – some of the sand placed above MLW shifted underwater and the active beach equilibrated to a natural slope). Before some of the sand shifted underwater, it was blown across the upper beach and carried into the dunes via aeolian transport, gradually adding volume and yielding a total of ~150,000 cy of extra sand to this section of beach over the first ~7 months after the project (as of June 2012). Unit volumes from the face of dune to +6 ft NAVD contour along Nags Head post-nourishment were plotted in Figure 6.1 along with the historical dataset of 1994.

Because nourishment added a wide dry-sand beach and provided an ample source of sand, the implicit assumptions of Equations 1 and 2 are applicable. A Nags Head post-project sediment analysis in June 2013 determined that the mean grain size of the nourished beach was 0.402 mm. If  $C_b = 1.8$ ,  $A = 0.1$  (Masselink & Huges 2003), and the sand density  $\rho_s$  is 1,600 kg/m<sup>3</sup>, then the threshold shear velocity  $u_{*t}$  is ~0.23 m/s and the aeolian sediment transport rate is ~3.3 grams/m/s (grams per meter per second). Using the *Law of the Wall* and assuming a value for the roughness length  $z_0 = D/30$ , the threshold wind velocity at 2 m above the sand surface as a function of sediment size can be derived using Equation (3):

$$u = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \quad (3)$$

where  $k$  is von Karmen’s constant (equal to 0.4),  $z$  is elevation above the bed, and  $z_0$  is the hydraulic bed roughness length.

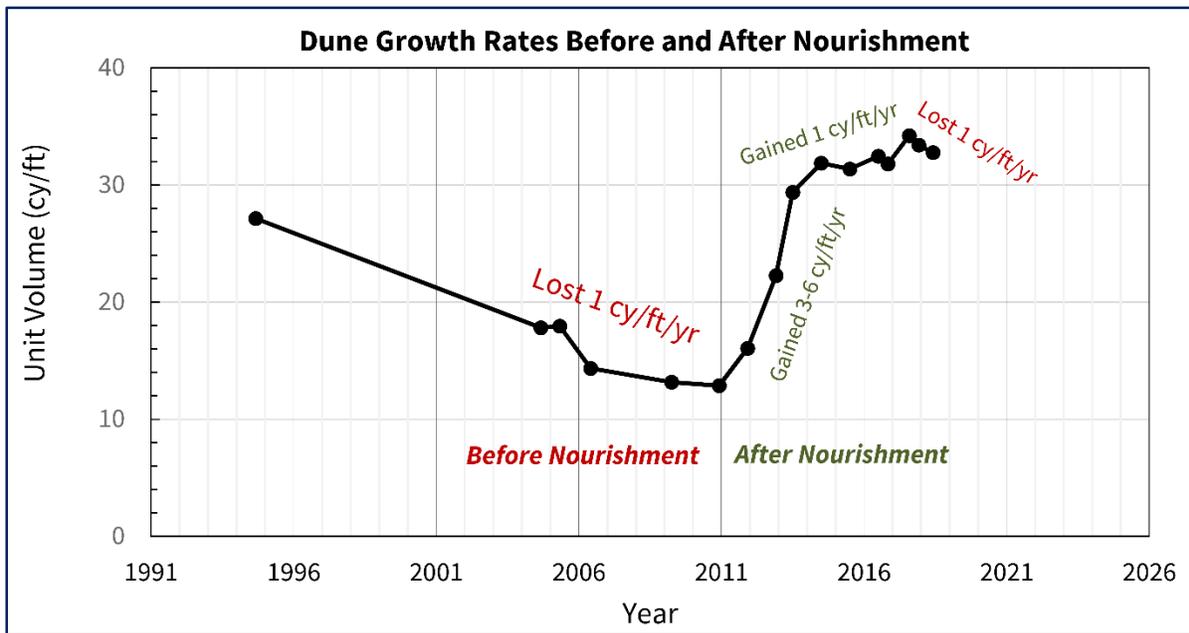
For Nags Head, the threshold wind velocity is around ~6.8 m/s, which means no sediment is expected to be transported for wind speeds less than 6.8 m/s (ie ~15 mph). The azimuth of the Nags Head coastline is 158° true north (ie – only wind coming from an arc between 338° and 158° will have a positive impact on aeolian transport and dune accumulation).

Based on the time-series wind-speed analysis available for station DUKN7-8651370 at FRF–Duck (NC) from 2008 to 2013, the probabilities of wind speeds exceeding 6.8 m/s between 2008 and 2013 were between 14 and 23 percent (Table 6.2) with an average of 18.7 percent. Therefore, the yearly average aeolian sediment transport rate derived from the above-stated equations and parameters is 19,460 kg/m/yr (or 12.2 m<sup>3</sup>/m/yr), which is remarkably coincident with the actual measured dune growth rate of 4.7 cy/ft/yr for the first three years following project completion as of June 2014. After that, the Bagnold analytical model is no longer applicable for Nags Head as dry-sand beach is reduced and the assumption of the formula (ie – unlimited sand source) is invalid. Also, other factors (ie – storms) discussed in section 6.1.2 started playing more important roles in dune mechanics.

**TABLE 6.2.** Probabilities of onshore wind speed exceeding the threshold wind speed at Nags Head between 2008 and 2013. [Source: National Data Buoy Center (NDBC) database]

Year	2008	2009	2010	2011	2012	2013	Average
Probabilities (%)	22.7	19.7	14.3	17.1	18.8	19.5	18.7

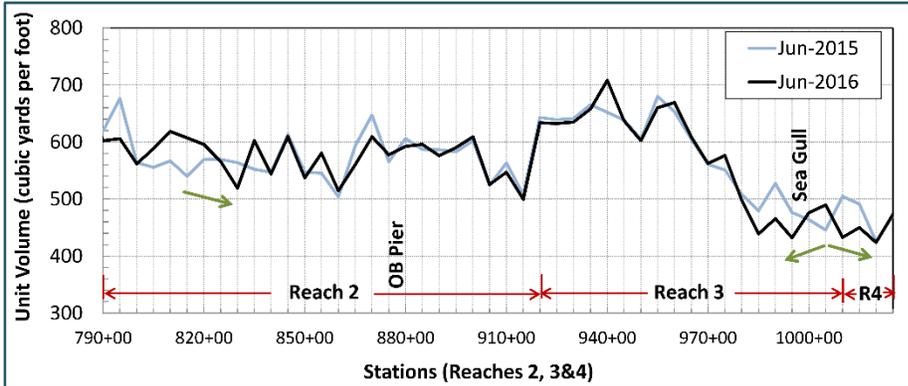
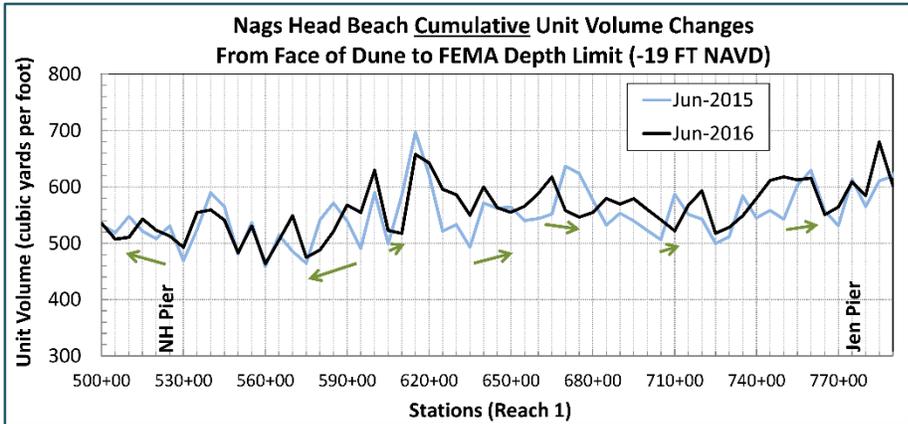
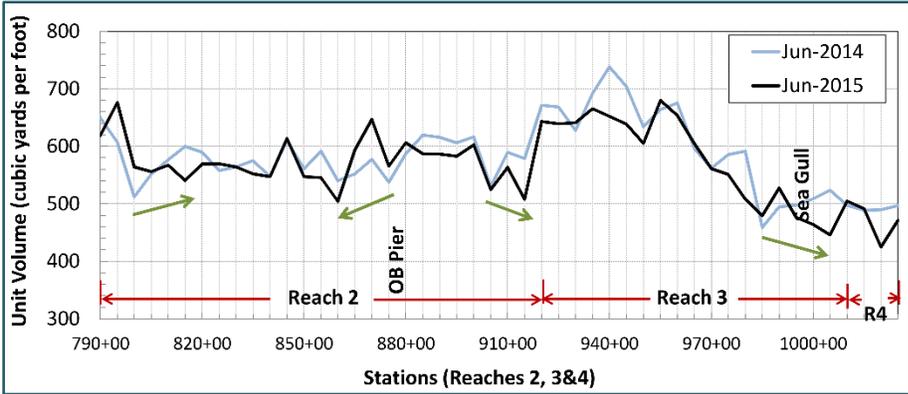
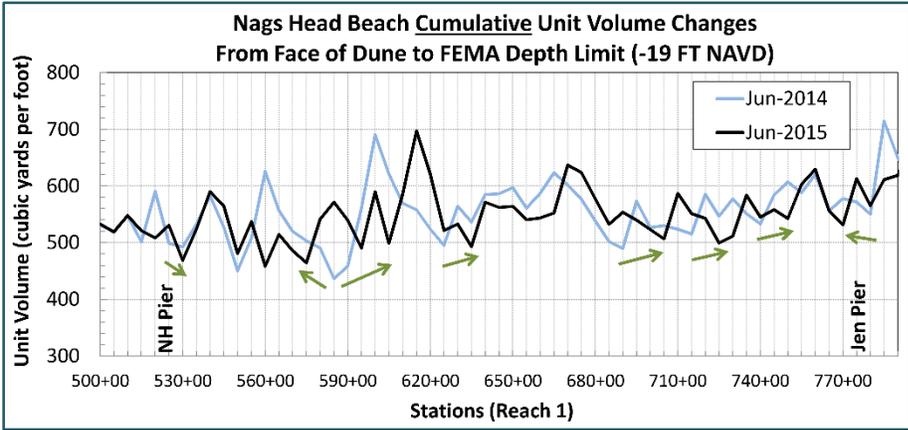
As described in previous sections, dune growth is related to the width of the dry-sand beach (“critical fetch”). Since 2014, aeolian transport rates have declined because the dry-sand beach narrowed by the natural evolution of the profile post-nourishment. Annual surveys in the subsequent years showed that dune volumes have been stable, which reduced the average dune growth rate for the first seven years following project completion to ~2 cy/ft/yr. Average dune growth rates before and after nourishment are plotted in Figure 6.3. Despite the decline of the dune growth rates in the past four years, Nags Head has over 13 cy/ft more sand in the dune and upper beach above +6 ft NAVD contour compared to the as-built condition (November 2011). The extra volume and elevation in the dunes since project completion, has provided a higher level of storm protection, helping Nags Head avoid significant damage to oceanfront properties during Superstorm *Sandy* (27 October 2012), Hurricane *Matthew* (8 October 2016), or during numerous severe winter storms.



**FIGURE 6.3.** Dune growth rates before and after the Nags Head nourishment project. Nourishment occurred between May and October 2011.

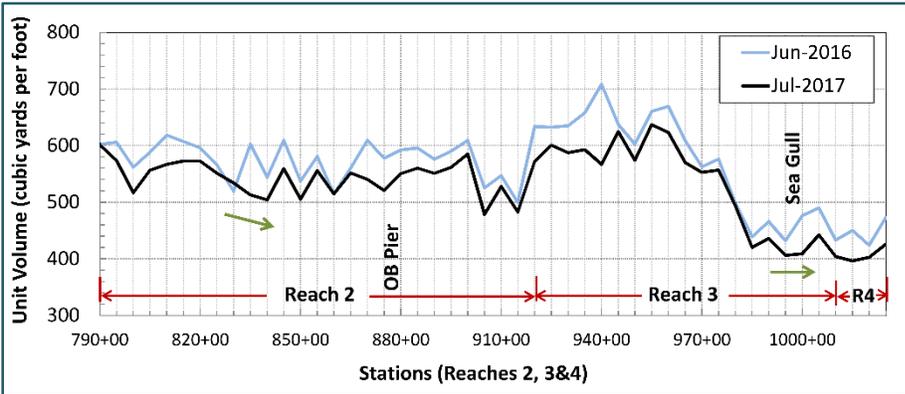
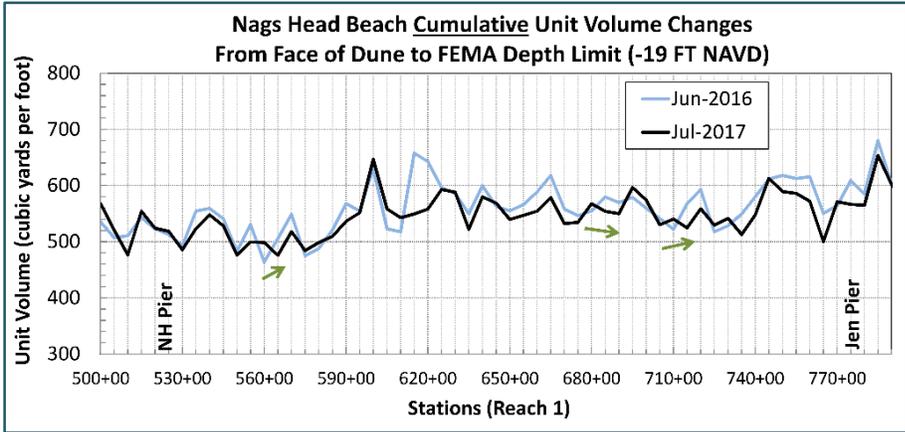
## 6.2 Erosional Hotspots and Dune Escarpments

Beaches exhibiting anomalously high erosion rates relative to the surrounding beach are defined as erosional hotspots. It is common for a nourishment project to show spatially uneven behavior at different times in its life cycle and for erosional hotspots to occur within the project area. For Nags Head, historical erosion rates have increased several degrees from north to south. Large variations observed from station to station have been documented by annual profile surveys at 500-ft intervals. The differences in sand volume reflect the dynamic nature of beaches and underwater topography which accounts for some of the natural waviness of the shoreline. As shown in the series plots in Figure 6.4, tracking these specific “erosion hotspot” areas over the past few years show these areas tend to move alongshore from year to year. Some hotspots, however, become more persistent at specific locations indicating the beach in that location has become more vulnerable than others.

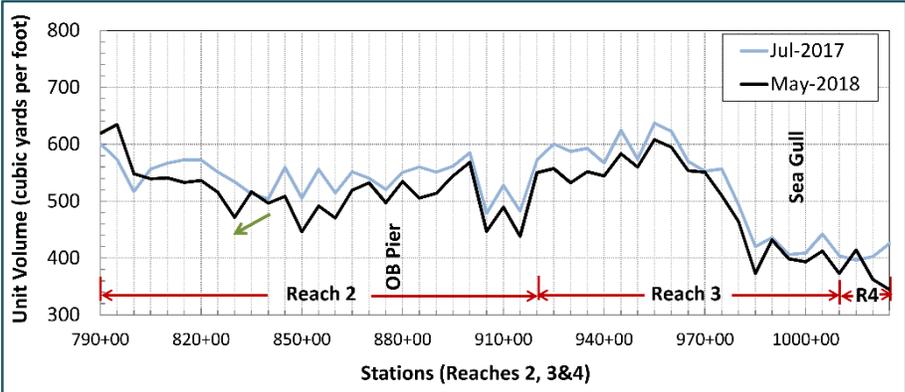
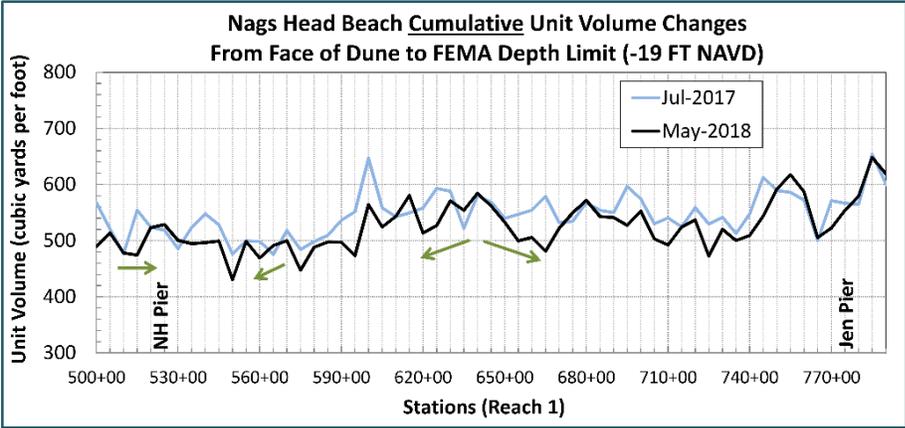


**FIGURE 6.4 (a).** Yearly shift in volume among adjacent stations over recent years between 2014 and 2015.

**FIGURE 6.4 (b).** Yearly shift in volume among adjacent stations over recent years between 2015 and 2016.

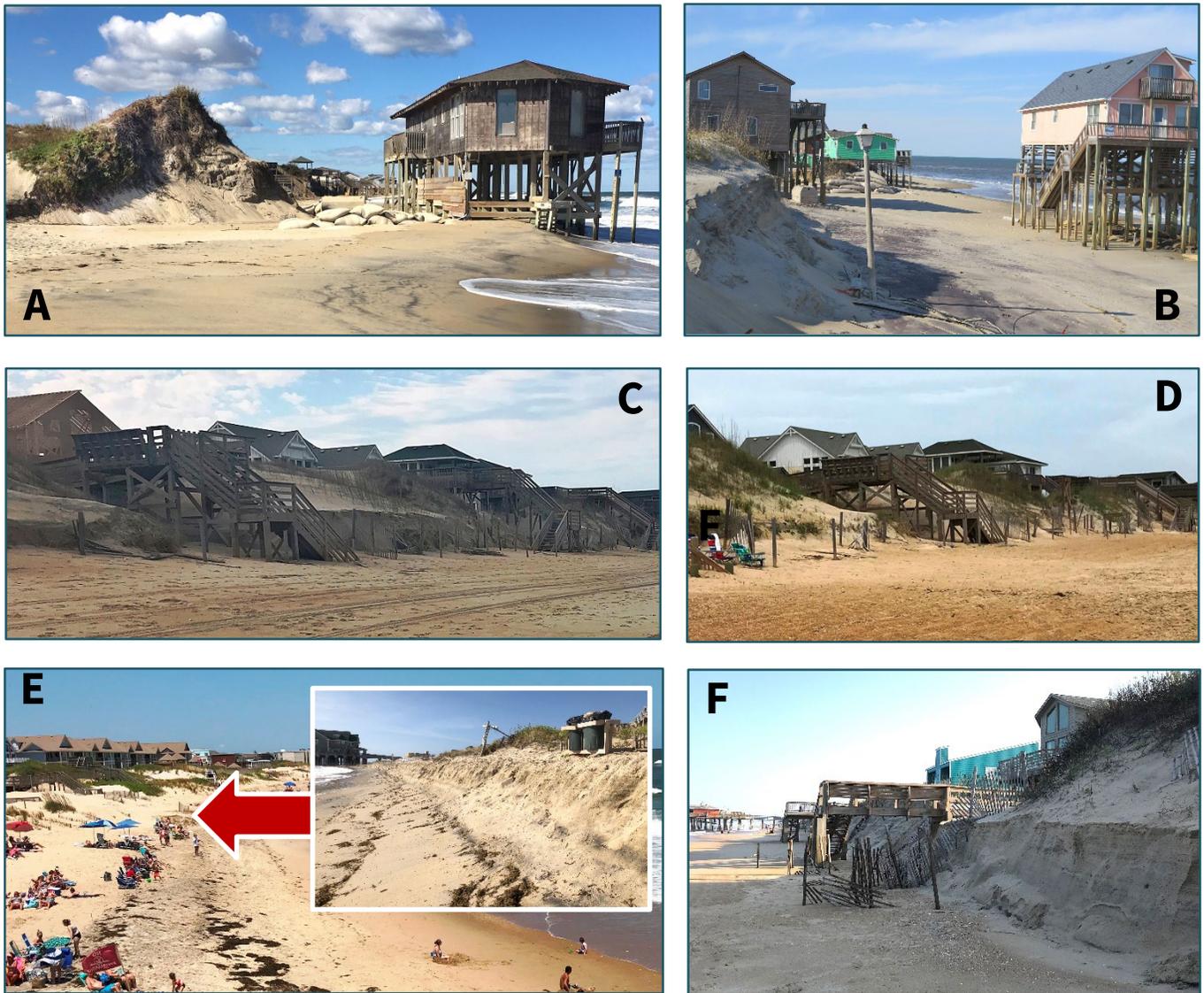


**FIGURE 6.4 (c).** Yearly shift in volume among adjacent stations over recent years between 2016 and 2017.



**FIGURE 6.4 (d).** Yearly shift in volume among adjacent stations over recent years between 2017 and 2018.

Incipient dune overtopping and established dune escarpment are the two common pieces of evidence associated with erosional hotspots. Figure 6.5 shows the high escarpments that had developed along Nags Head under different weather events with the most recent one created in July 2018 when a strong northeasterly wind was coincident with spring tides and in September 2018 after Hurricane *Florence*.



**FIGURE 6.5.** Photos taken in Nags Head following recent weather events. (a) On 22 October 2016 after Hurricane *Matthew* near the south end of the project at E McCall Ct. A huge dune escarpment was formed and sandbags became exposed following the storm (b) On 15 March 2018 after northeasters at E Seagull Dr. (c) On 15 March 2018 at E Conch St. The March 2018 northeasters not only left a dune escarpment at the south end of Nags Head (where erosion rates are several times higher than the other areas) but also at the north portion of Nags Head (where established dunes existed). (d) On 5 May 2018 at E Conch St at the same location as photo (c). Beach conditions were relatively healthy at that locality and the dune recovered naturally and vegetation sprouted on the dune face. (e) On 15 July 2018 at Jennette's Pier looking northeast. Inset photo was taken on the same day in the morning around high tide showing the escarpment at Gray Eagle St. (Inset photo was provided by D. Ryan, Town of Nags Head). (f) On 22 September 2018 after Hurricane *Florence* just north of the Outer Banks Pier. Hurricanes and winter storms in recent years have taken away most of the sand volume that naturally accumulated on the dune face and under the walkovers after project completion. Further south of the Pier, the dry-sand beach becomes very narrow in some areas and is barely passable during high tides.

As the back beach and the dune have built up over the past seven years following project completion, escarpments tend to appear higher than normal because of the extra sand that accumulated along the back beach and toe of the foredune. Escarpments most commonly occur where an erosional arc or rhythmic topography is propagating through the area. Some of them recover naturally when the wind shifts directions and the astronomical tides wane down from spring tides to neap tides (see Figure 6.5 Photo C and Photo D). Despite the escarpments and loss of sand fencing and vegetation, no ocean overwash penetrated the dunes and damaged developed properties along the project area. The upcoming 2019 beach renourishment project will replenish the sand deficit along the entire 10-mile project area, and restart a new cycle of profile changes and evolution. The next project incorporates an initial dune feature in the design. CSE will revise the final design at the time of construction and address the erosional hotspots in order to increase the longevity of renourishment.

— *THIS PAGE INTENTIONALLY LEFT BLANK* —

## 7.0 UPFOAST AND DOWNFOAST CHANGES

---

As part of the annual condition surveys, CSE obtained profiles upcoast and downcoast of the project area. The upcoast dataset covers station 430+00 (inside Kill Devil Hills town line) to station 495+00 (near the Nags Head project limit). The Nags Head town line is around station 436+83 (see Fig 1.2). Data are available for November 2010 and 2011, June and November 2012, June 2013, June 2014, June 2015, June and October 2016, July 2017, and May 2018. Downcoast of the project, CSE obtained profile data between station 1025+00 (project limit) and station 1080+00 (~1 mile south of the project and ~4 miles north of Oregon Inlet along the Cape Hatteras National Seashore). Data are available for November 2010, June and November 2012, June 2013, June 2014, June 2015, June and October 2016, July 2017, and May 2018.

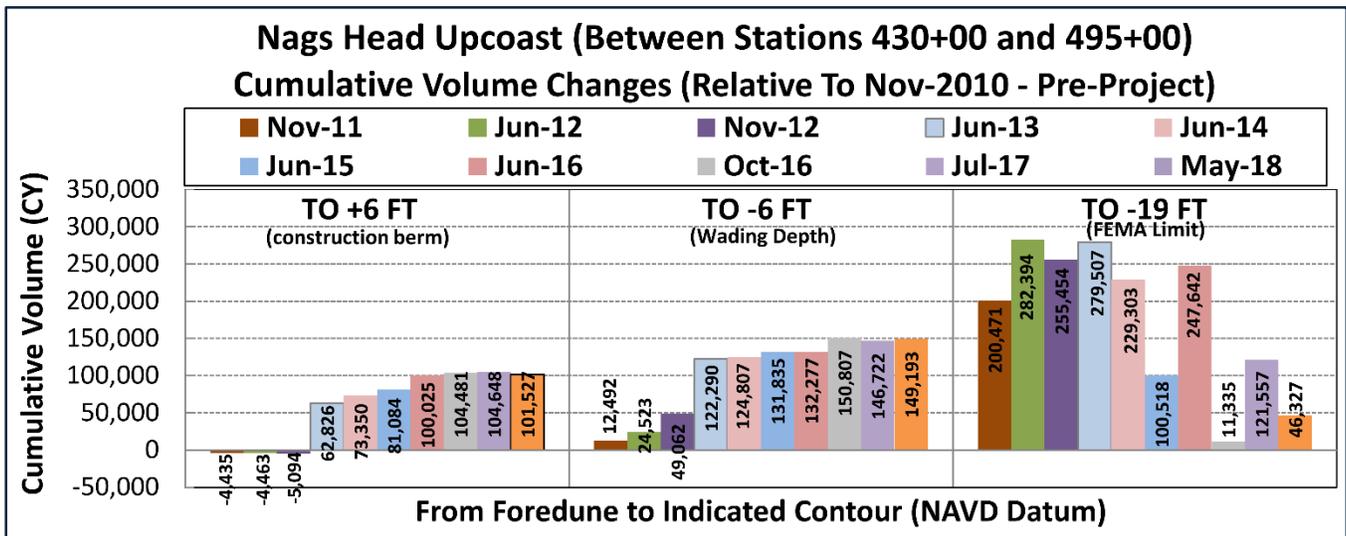
Changes in the downcoast and upcoast beaches partly reflect spreading of nourishment volume away from the project while some changes are associated with onshore and offshore transport. The available profiles are included in Appendix 3, unit volumes are shown in Appendix 4, and total volumes are represented in Appendix 5.

### 7.1 Upcoast Reach

Figure 7.1 and Table 7.1 show the cumulative volume changes relative to the November 2010 condition for the upcoast area. As the brown bars (November 2011) indicate, there was a gain of ~12,492 cy (to -6 ft) and ~200,471 cy (to -19 ft) relative to the November 2010 condition. This initial gain, soon after nourishment completion mainly indicates that sand is spreading to the un-nourished area.

The October 2016 survey (gray bars in the graphic) showed significant volume loss (~36 cy/ft) to the -19 ft NAVD contour after Hurricane *Matthew*. The May 2018 survey (orange bars in the graphic) represented another ~12 cy/ft of volume loss north of the project to the -19 ft NAVD contour, indicating similar erosion trends as the Nags Head project area.

Measured to -6 ft NAVD and compared to the pre-nourishment condition in November 2010, the ~1.2-mile upcoast area has gained ~149,193 cy by sand spreading and natural accretion as of May 2018, resulting in a healthier condition along the visible beach. Measured to -19 ft NAVD, the upcoast reach has retained much less sand compared to the post-project condition (November 2011), but still contained 46,327 cy (~7 cy/ft) more sand in May 2018 than in November 2010 before nourishment. The volume change trends to -19 ft are similar to the trends that were observed along Reach 1 and Reach 2 in Nags Head. The erosion rate to -19 ft for the upcoast reach is equivalent to ~23.7 cy/ft or 3.6 cy/ft/yr since November 2011.



**FIGURE 7.1.** Cumulative volume changes from the foredune to the indicated contour relative to the November 2010 condition along upcoast stations outside the project area.

**TABLE 7.1.** Cumulative volumes and volume changes relative to November 2010 for upcoast stations. The north town line is near station 436+83. [The three lenses discussed in this study are highlighted in the table.]

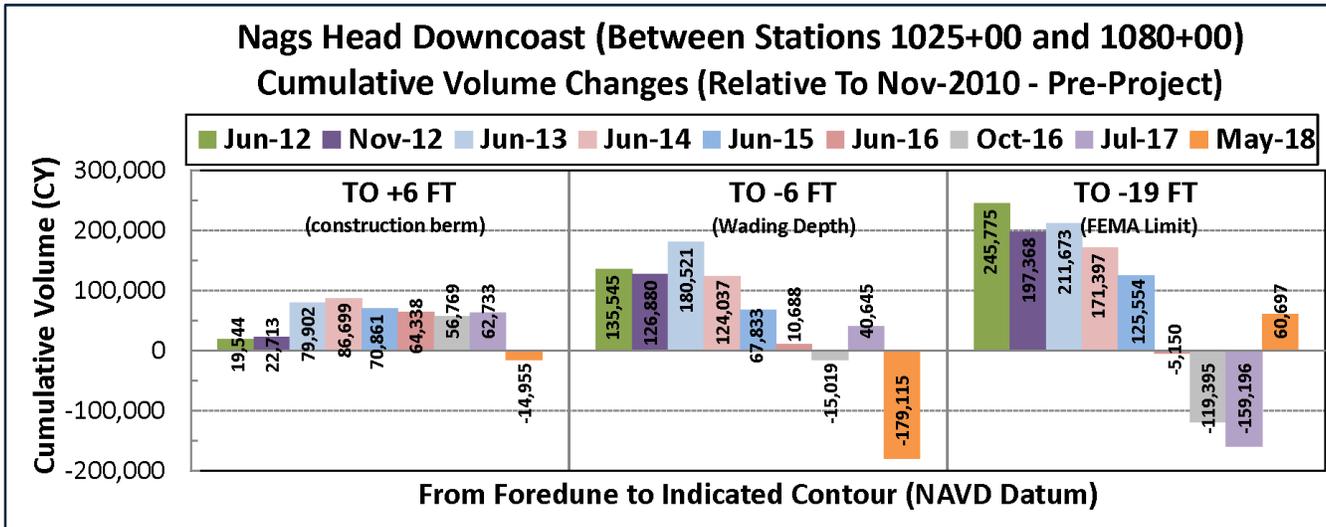
Survey Date	Accumulated Total Volume Between Stations 430+00 and 495+00 (CY)						
	To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Nov-10	188,552	393,413	485,402	717,713	1,457,903	3,303,789	5,325,401
Nov-11	184,117	394,245	491,605	730,205	1,592,815	3,504,260	5,575,476
Jun-12	184,089	409,282	506,847	742,237	1,592,444	3,586,183	5,669,514
Nov-12	183,458	373,066	481,599	766,775	1,553,377	3,559,243	5,597,602
Jun-13	251,377	485,736	584,105	840,003	1,629,315	3,583,296	5,741,959
Jun-14	261,902	490,759	583,541	842,520	1,593,835	3,533,092	5,668,875
Jun-15	269,636	502,457	595,064	849,548	1,577,677	3,404,307	5,573,375
Jun-16	288,577	521,035	617,730	849,990	1,646,946	3,551,431	5,654,875
Oct-16	293,032	521,692	617,355	868,521	1,577,235	3,315,124	5,407,425
Jul-17	293,200	522,502	618,411	864,435	1,621,210	3,425,346	5,525,050
May-18	290,079	530,483	628,329	866,906	1,573,879	3,350,116	5,430,950
Survey Date	Total Volume Changes Relative to Nov-2010 (CY)						
	To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Nov-11	-4,435	832	6,203	12,492	134,912	200,471	250,075
Jun-12	-4,463	15,868	21,445	24,523	134,541	282,394	344,113
Nov-12	-5,094	-20,348	-3,803	49,062	95,474	255,454	272,201
Jun-13	62,826	92,323	98,703	122,290	171,412	279,507	416,558
Jun-14	73,350	97,345	98,139	124,807	135,932	229,303	343,474
Jun-15	81,084	109,044	109,663	131,835	119,774	100,518	247,974
Jun-16	100,025	127,621	132,328	132,277	189,043	247,642	329,474
Oct-16	104,481	128,278	131,953	150,807	119,332	11,335	82,024
Jul-17	104,648	129,088	133,009	146,722	163,307	121,557	199,649
May-18	101,527	137,069	142,927	149,193	115,976	46,327	105,549

## 7.2 Downcoast Reach

Similar to the upcoast and Nags Head project area, the ~1-mile-long downcoast reach between station 1025+00 and station 1080+00 lost a significant amount of sand (~21 cy/ft) after Hurricane *Matthew* (CSE 2017) but regained this volume back over the past survey year. As of May 2018, there is 60,697 cy (~11 cy/ft) more sand compared to the pre-project conditions in November 2010.

There had been extra volumes in the downcoast reach between November 2011 and June 2015 relative to November 2010 conditions, measured from the face of dune to the -19 ft depth contour. However, the downcoast reach lost all the extra volume in 2016 and 2017, and its beach condition returned to the pre-project condition in those years. The high erosion rate (~53 cy/ft between June 2012 and July 2017 or ~11 cy/ft/yr) is comparable to the sand loss rate observed along the southern end of the project area with an offshore shift of the outer bar to deeper water (CSE 2017).

It is likely the downcoast 1-mile area would have sustained losses averaging ~80,000 cy/yr (~15 cy/ft) based on pre-nourishment erosion rates (CSE 2011a). The recent sand gain (~220,000 cy) over the past survey year could be caused by volume passed downcoast from Reach 3 and Reach 4 due to the southerly longshore sediment transport. As a result of the time it takes for sand to move downcoast and the relatively small amount, shoaling in Oregon Inlet in recent years has been principally related to erosion along the National Seashore.



**FIGURE 7.2.** Cumulative volume changes from the foredune to the indicated contour relative to the November 2010 condition along downcoast stations outside the project area.

**TABLE 7.2.** Cumulative volumes and volume changes relative to November 2010 for downcoast stations. The south town line is near station 1025+00. The three lenses used in this study are highlighted in the table.

Survey Date	Accumulated Total Volume Between Stations 1025+00 and 1080+00 (CY)						
	To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Nov-10	38,193	174,326	262,701	545,196	1,236,126	2,938,097	4,769,783
Jun-12	57,737	308,036	416,536	680,741	1,557,880	3,183,872	4,965,775
Nov-12	60,906	278,340	391,103	672,076	1,482,467	3,135,464	4,931,230
Jun-13	118,095	376,022	483,202	725,717	1,407,959	3,149,770	4,970,939
Jun-14	124,892	344,686	435,738	669,233	1,328,651	3,109,494	4,881,475
Jun-15	109,054	322,919	410,960	613,029	1,282,624	3,063,650	4,934,400
Jun-16	102,531	272,325	350,925	555,884	1,262,548	2,932,947	4,753,875
Oct-16	94,962	256,223	332,499	530,176	1,184,616	2,818,701	4,701,050
Jul-17	100,926	288,964	371,651	585,841	1,273,434	2,778,900	4,637,625
May-18	23,238	146,465	206,654	366,081	1,485,156	2,998,794	4,933,400
Survey Date	Total Volume Changes Relative to Nov-2010 (CY)						
	To +6 ft	To 0 ft	To -2.05 ft	To -6 ft	To -12 ft	To -19 ft	To -24 ft
Jun-12	19,544	133,711	153,835	135,545	321,753	245,775	195,992
Nov-12	22,713	104,014	128,402	126,880	246,341	197,368	161,446
Jun-13	79,902	201,696	220,501	180,521	171,833	211,673	201,155
Jun-14	86,699	170,360	173,037	124,037	92,524	171,397	111,692
Jun-15	70,861	148,594	148,259	67,833	46,497	125,554	164,617
Jun-16	64,338	97,999	88,224	10,688	26,421	-5,150	-15,908
Oct-16	56,769	81,897	69,798	-15,019	-51,510	-119,395	-68,733
Jul-17	62,733	114,638	108,950	40,645	37,307	-159,196	-132,158
May-18	-14,955	-27,861	-56,047	-179,115	249,030	60,697	163,617

## 8.0 MONITORING AND MAINTENANCE RECOMMENDATIONS

---

In accordance with FEMA Publication 321 and Code of Federal Regulations 44 CFR 206.226(j), a maintenance program involving periodic renourishment of sand must be established and adhered to by the Town of Nags Head to qualify for FEMA post-disaster assistance. The purpose of this program is to track the physical condition of the beach after nourishment, quantify sand-volume changes, and determine whether the project qualifies for emergency renourishment following declared disasters. It is also intended to identify erosion hotspots and recommend small-scale maintenance renourishment, placement of sand fencing, and/or sand scraping to increase the life of the project.

CSE recommends the Town of Nags Head continue to conduct an annual assessment of the physical condition of the nourished shoreline. The beach should be surveyed annually using the transect plan initiated by the USACE and CSE. Such surveys will give the Town an annual assessment of the beach condition and will reveal problem areas or erosion hotspots requiring attention. Annual surveys should be conducted in May to July before the hurricane season and will serve as documentation of the beach condition before the occurrence of a major erosion event, such as Hurricane *Matthew* in October 2016.

In accordance with the Nags Head *Maintenance and Monitoring Plan* (Ogburn 2011, Appendix 1), thresholds for future maintenance efforts are as follows:

- The Town will renourish the beach every six years unless ~50 percent or more of the initial nourishment sand remains on the beach and within the project boundaries calculated to -18 ft NGVD or -19 ft NAVD.
- If 50 percent or more of the sand remains on the beach at six years' post-initial project, then renourishment would commence when 50 percent or more is lost.

The Town of Nags Head has planned for a beach renourishment project to restore sand losses that have occurred since the 2011 nourishment project, and the state and federal permits have been received by March 2018. The renourishment project is expected to commence in spring 2019 by the successful bidder, Great Lakes Dredge and Dock, Inc (GLDD). The final agreement between the Town and GLDD calls for ~3.73 million cubic yards of beach-quality sand to be dredged from offshore borrow areas and placed along the previously nourished 10-mile-long shoreline. The renourishment project will integrate a dune management plan including initial dune construction along south Nags Head, installation of sand fencing, and planting of vegetation along the entire project area following construction.

The overall purpose and goals of the renourishment project are as follows.

- 1) Restore sand losses due to chronic erosion and Hurricane *Matthew* (2016)
- 2) Provide a higher level of storm protection
- 3) Provide wider recreational beach and create habitat for wildlife
- 4) Address high erosion rates at the south end of Nags Head
- 5) Integrate a dune management plan into the renourishment design
- 6) Maintain Nags Head's eligibility for future FEMA community assistance funds

The project will also incorporate a sand relocation plan along the areas where nourishment sand migrates landward and causes encroachment onto existing structures.

The Year 8 (2019) annual beach condition survey will take the renourishment project into account and will likely be conducted before the commencement of construction in spring 2019.

## REFERENCES

---

- Arens, SM. 1996. Rates of aeolian transport on a beach in a temperate humid climate. *Geomorphology*, Vol 17(1-3), pp 3-18.
- Bagnold, RA. 1941. *The Physics of Blown Sand and Desert Dunes*. Chapman and Hall, London, UK, 265 pp.
- CSE. 2005 (August). Preliminary coastal engineering analyses for large-scale beach restoration at Nags Head. Technical Report for Town of Nags Head (NC). CSE, Columbia, SC, 88 pp + three appendices.
- CSE. 2007a. Biological assessment for Nags Head beach restoration project, Dare County, North Carolina (submitted in conjunction with EIS for Action ID SAW 2006-40282-128). Appendix H, Draft EIS for US Army Corps of Engineers, Washington Regulatory Field Office, NC. CSE, Columbia (SC), 104 pp + 13 attachments.
- CSE. 2007b. Survey report 2007, Bogue Banks, North Carolina. Monitoring Report for Carteret County Shore Protection Office, Emerald Isle, North Carolina; Coastal Science & Engineering (CSE), Columbia (SC), 69 pp + 4 appendices.
- CSE. 2008. Final environmental impact statement, Nags Head emergency beach nourishment, Dare County, North Carolina. EIS for US Army Corps of Engineers, Wilmington District, NC (Action ID SAW-2006-40282-182). CSE, Columbia (SC), 126 pp + appendices.
- CSE. 2011a. Coastal engineering & geotechnical analyses for beach nourishment, Nags Head, North Carolina. Final Design Report for Town of Nags Head, NC. CSE, Columbia (SC), 163 pp + appendices.
- CSE. 2011b. Final project manual for construction, Nags Head beach nourishment, Dare County, North Carolina. Town of Nags Head, NC. CSE, Columbia (SC).
- CSE. 2012. Final Report for the 2011 Nags Head beach nourishment project, Volumes 1 and 2. CSE, Columbia (SC), 101 pp + 10 appendices.
- CSE. 2013a. Monitoring and analyses of the 2011 Nags Head beach nourishment project – 2012 Beach monitoring. Year 1 monitoring report for Town of Nags Head, NC. CSE, Columbia (SC), 81 pp + appendices.
- CSE. 2013b. Monitoring and analyses of the 2011 Nags Head beach nourishment project: 2013 beach nourishment monitoring. Prepared for the Town of Nags Head, North Carolina. CSE, Columbia (SC), 83 pp + 8 appendices.
- CSE. 2014a. Memorandum: 2011 Nags Head beach nourishment project – post-project monitoring Year 3 (2014) sediment compaction results. Prepared for USFWS. CSE, Columbia (SC), dated 13 March 2014, 16 pp.
- CSE. 2014b. Monitoring and analyses of the 2011 Nags Head beach nourishment project: 2014 beach nourishment monitoring. Prepared for the Town of Nags Head, North Carolina. CSE, Columbia (SC), 114 pp + 9 appendices.
- CSE. 2015. Monitoring and analyses of the 2011 Nags Head beach nourishment project. Year 4 (2015) beach monitoring report for Town of Nags Head, NC. CSE, Columbia (SC), 97 pp + appendices (2387).
- CSE. 2016a (August). Annual beach condition survey (June 2016) – preliminary results. Memorandum for Year 5 beach monitoring for Town of Nags Head, NC. CSE, Columbia (SC), 5 pp.
- CSE. 2016b (September). Monitoring and analyses of the 2011 Nags Head beach nourishment project. Year 5 (2016) beach monitoring report for Town of Nags Head, NC. CSE, Columbia (SC), 93 pp + appendices (2387).
- CSE. 2016c (November). Nags Head post-Matthew beach condition survey—preliminary results. Memo for Town of Nags Head, NC. CSE, Columbia, SC, 8 pp.
- CSE. 2017a (October). Nags Head post-project monitoring—annual beach condition survey (July 2017)—preliminary results (Year 6 after the 2011 project). Memo for Town of Nags Head, NC. CSE, Columbia, SC, 5 pp.
- CSE. 2017b (October). Environmental assessment for Nags Head beach renourishment, Town of Nags Head, NC. Prepared for USACE–Wilmington District, Washington Regulatory Field Office, Washington, NC. CSE, Columbia, SC, 197 pp + 8 appendices
- CSE. 2017c (December). Monitoring and analyses of the 2011 Nags Head beach nourishment project. Year 6 (2017) beach monitoring report for Town of Nags Head, NC. CSE, Columbia (SC), 50 pp + appendices (2458).
- Davidson-Arnott, RGD and MN Law. 1990. Seasonal patterns and control on sediment supply to coastal foredunes, Long Point, Lake Erie. In KF Nordstrom, NP Psuty, and RWG Carter (eds), *Coastal Dunes: Form and Process*. John Wiley & Sons, Chichester, UK, pp 177-200.
- Davidson-Arnott, RGD, Y Yang, J Ollerhead, PA Hesp, and IJ Walker. 2008. The effects of surface moisture on aeolian sediment transport threshold and mass flux on a beach. *Earth Surface Processes & Landforms*, Vol 33(1), pp 55-74.
- de Vries, S, HN Southgate, W Kanning, and R Ranasinghe. 2012. Dune behavior and aeolian transport on decadal time scales. In *Coastal Engineering* 67, pp 41-53.

- Hotta, S. 1988. Sand transport by wind. In K Horikawa (ed), *Nearshore Dynamics and Coastal Processes: Theory, Measurement and Predictive Models*, University of Tokyo Press, Japan, pp 218-238.
- Kaczkowski, HL, and TW Kana. 2012. Final design of the Nags Head beach nourishment project using a long shore numerical model, International Conference on Coastal Engineering 2012 (Santander, Spain), ASCE, New York.
- Kaczkowski, HL, TW Kana, SB Traynum, and R Visser. 2018. Beach-fill equilibration and dune growth at two large-scale nourishment sites. *Ocean Dynamics*, Vol 68, pp 1191-1206 (<https://doi.org/10.1007/s10236-018-1176-2>).
- Kana, TW. 1990. Conserving South Carolina Beaches Through the 1990s: A Case for Beach Nourishment. South Carolina Coastal Council (now OCRM), Charleston, SC, 33 pp.
- Kana, TW. 1993. The profile volume approach to beach nourishment. In DK Stauble and NC Kraus (eds), *Beach Nourishment Engineering and Management Considerations*, ASCE, New York, NY, pp 176-190.
- Kana, TW, HL Kaczkowski, SB Traynum, and PA McKee. 2012. Impact of Hurricane Irene during the Nags Head beach nourishment project. *Shore & Beach*, Vol 80(2), pp 6-18.
- Kana, TW, and HL Kaczkowski. 2012. Planning, preliminary design, and initial performance of the Nags Head beach nourishment project, International Conference on Coastal Engineering 2012 (Santander, Spain), ASCE, New York.
- Komar, PD. 1998. *Beach Processes and Sedimentation*. Second Edition, Prentice-Hall, Inc, Simon & Schuster, Upper Saddle River, NJ, 544 pp.
- Masselink, G, and MG Hughes. 2003. *Introduction to Coastal Processes & Geomorphology*, Oxford University Press Inc, New York, NY, 354 pp.
- McNinch, JE, KL Brodie, HM Wadman, KK Hathaway, RK Slocum, RP Mulligan, JL Hanson, and WA Birkemeier. 2012. Observations of wave runup, shoreline hotspot erosion, and sound-side seiching during Hurricane Irene at the Field Research Facility. *Shore & Beach*, Vol 80(2), pp 19-37.
- Nordstrom, KF, and NL Jackson. 1993. The role of wind direction in aeolian transport on a narrow sandy beach. *Earth Surface Processes and Landforms*, Vol 18, pp 675-685.
- Ogburn, C. 2011. Beach monitoring and maintenance plan for Town of Nags Head, Dare County, North Carolina. Adopted by Town of Nags Head Board of Commissioners, August 2011, 6 pp plus 4 attachments.
- Sherman, DJ, and W Lyons. 1994. Beach-state controls on aeolian sand delivery to coastal dunes. *Physical Geography*, Vol 15, pp 381-395.
- Stewart, SR. 2017. Hurricane *Matthew* (AL142016), 28 September — 9 October 2016. National Hurricane Center Tropical Cyclone Report, NOAA, NWS, 96 pp.
- USACE. 2010 (May). Final environmental impact statement, beach nourishment project, Town of Nags Head, North Carolina. US Army Corps of Engineers, Wilmington District, Washington Regulatory Field Office, NC (Action ID SAW-2006-40282-182), 164 pp+ executive summary, references, and appendices.
- USFWS. 2008. Biological opinion and take statement for Nags Head emergency beach nourishment project (Action ID SAW 2006-40282-128). US Fish & Wildlife Service, Raleigh, NC, 43 pp.