Coastal Dynamics 2017
Paper No. 242

BEACH-FILL EQUILIBRATION AND DUNE GROWTH AT TWO LARGE-SCALE NOURISHMENT SITES

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Abstract

Large-scale nourishment projects at Nags Head (North Carolina, USA) (completed in 2011) and Bridgehampton–Sagaponack (New York, USA) (completed in 2014) offer new insight regarding fill templates, natural dune growth, and cross-shore rates of equilibration under comparatively high-wave energy conditions. After nourishment, a natural beach and inshore morphology was produced with minimal formation of escarpments as the beach profile equilibrated. Net sand volume changes at both sites have been low since project completion. Both sites exhibited significant natural dune growth by aeolian transport after nourishment. The extra volume and elevation in the dunes has provided a higher level of storm protection and helped the sites avoid any major damage to the oceanfront properties during hurricanes or numerous severe winter storms.

Key words: beach nourishment, Nags Head (North Carolina), Bridgehampton–Sagaponack (New York), beach-fill equilibration, dune growth, aeolian transport

1. Introduction

Beach nourishment is the addition of quality sand from non-littoral sources for purposes of advancing the shoreline. It is an erosion solution increasingly embraced along developed coasts in the United States as well as in other countries. A nourishment project at Nags Head (NC), constructed in 2011, is the largest locally funded beach nourishment accomplished to date in the United States (Kaczkowski & Kana 2012). It used offshore borrow areas and placed ~3.5 million cubic meters along ~16 kilometers (km) at a fill density averaging ~215 cubic meters per meter of shoreline (m^3/m). The Bridgehampton–Sagaponack (NY) project was completed in 2014 and placed ~1.95 million cubic meters (~210 m^3/m) along ~9 km. It is nearly as large as all previous nourishments, combined, east of Shinnecock Inlet (NY) and is the first nourishment project east of Westhampton Dunes to utilize an offshore borrow area. As of Summer 2016, ~90 percent of the nourishment sand (~3.15 million m^3) remained within the Nags Head project limits, and ~100 percent of the nourishment sand remained within the Bridgehampton–Sagaponack project limits.

Long-term annual erosion rates for the two project sites were derived from historical beach condition surveys and aerial images. These erosion rates, especially the gradient of the rates from north to south, became a design guide for the nourishment projects (Kana & Kaczkowski 2012). Numerical models were used in the final design to refine the preliminary nourishment plan and evaluate the environmental impact to the adjacent areas. Beach condition surveys to −12 m NAVD* at ~150-m spacing before and after nourishment confirmed the volume placed during the projects. Semi-annual or annual surveys in the following years provided measures of nourishment volume remaining, beach-fill adjustment and equilibration, and natural dune growth. [**NAVD — North American Vertical Datum of 1988 which is 0.13 m above local mean sea level (MSL) for Nags Head and 0.23 m above MSL for Bridgehampton–Sagaponack. Source: NGS–NOAA*]

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2. Project Background

The two project sites are located along the East Coast of the United States (Fig 1), and they are exposed to comparatively high-wave energy conditions. Mean tide ranges are ~1.0 m and ~0.9 m for Nags Head and Bridgehampton (respectively)

2.1. *The 2011 Nags Head Beach Nourishment*

The Nags Head project encompasses ~10 miles (mi) (16 km) of ocean shoreline on North Carolina's Outer Banks, a chain of barrier islands along the Atlantic Ocean which define the central East Coast of the United States. It is about 32 km south of the U.S. Army Corps of Engineers (USACE) Field Research Facility (FRF) at Duck (NC). It is within the same NNW-SSE trending shoreline bight, with Oregon Inlet situated 8 km to the south and Chesapeake Bay entrance situated 100 km to the north.

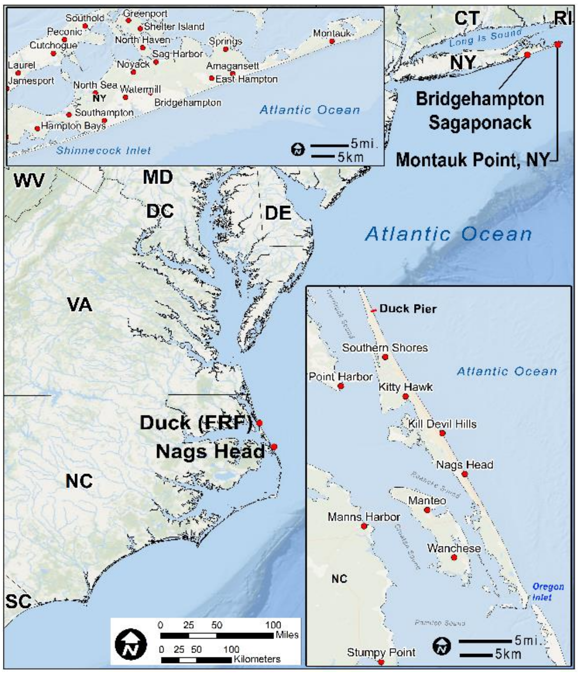

Figure 1. Vicinity map of the Nags Head and the Bridgehampton–Sagaponack beach nourishment projects. [FRF–Duck, a site familiar to many researchers, is located ~32 km north of the Nags Head project north boundary, and Oregon Inlet is located ~8 km south of the Nags Head south boundary.]

The predominant wave direction is northeast, exposing Nags Head to some of the highest wave energy along the US East Coast (Leffler et al 1996) with average deep-water wave heights exceeding 1.6 m every ten days (1942–1988—source Dolan et al 1988). Lowest wave energy occurs in June, July, and August when prevailing southwesterly winds are directed offshore. During fall and winter, upward of 20 percent of observed waves exceed 1.5 m.

Nags Head has sustained chronic erosion over the past 50 years due to storms and sand losses to Oregon Inlet. Erosion rates range from 0.6 meter per year (m/yr) to ~2.0 m/yr with a strong gradient from north to south (NCDENR 1998, 2004). Sustained erosion has forced abandonment of property and has left numerous buildings with no dune protection. Northern Nags Head has a history of moderate to low erosion rates in the range of 0.6–0.9 m/yr. The southernmost ~4 km experience higher recession of up to ~2 m/yr at the town line, 8 km from Oregon Inlet. This “signature of erosion” (Kana 1995) with large gradients of change along the updrift shoreline near tidal inlets is similar to other sites such as western Fire Island (NY).

The formulation for the 2011 nourishment project was based simply on the replacement volume of ten years of erosion losses at ~210,000 m^3/yr plus a safety factor. The final construction plan called for ~3.5 million cubic meters (m^3) with an average fill density of ~215 m^3/m. The project area was divided into four reaches, and the actual fill densities ranged from 110–430 m^3/m to account for the high gradients in volume losses from north to south as illustrated in Figure 2.

Nags Head native beach sediments have a composite, mean grain size of 0.31 millimeter (mm), but exhibit large variations between the subaerial beach (~0.4–0.5 mm typical), plunge point (>1.0 mm typical), and outer bar (~0.2 mm typical). Sediments are predominantly quartz with minor percentages of feldspar and heavy minerals (e.g. garnet) and <2 percent shell material ($CaCO_3$). Offshore borrow areas 2 and 3 (Fig 2) were delineated and used for excavation by dredge. Sediment compatibility determined by the James (1975) overfill factor (R_A) for these areas was close to 1.0, and composite mean grain sizes were 0.43 mm and 0.42 mm (respectively) for Areas 2 and 3. The overall quality of borrow sediments was a close match with the native beach in terms of sediment color, grain size, and concentration of gravel and shell. The fact that the nourishment sand was slightly coarser than the native beach increased the chance of the nourishment sand being stable and remaining within the project boundaries for the project life.

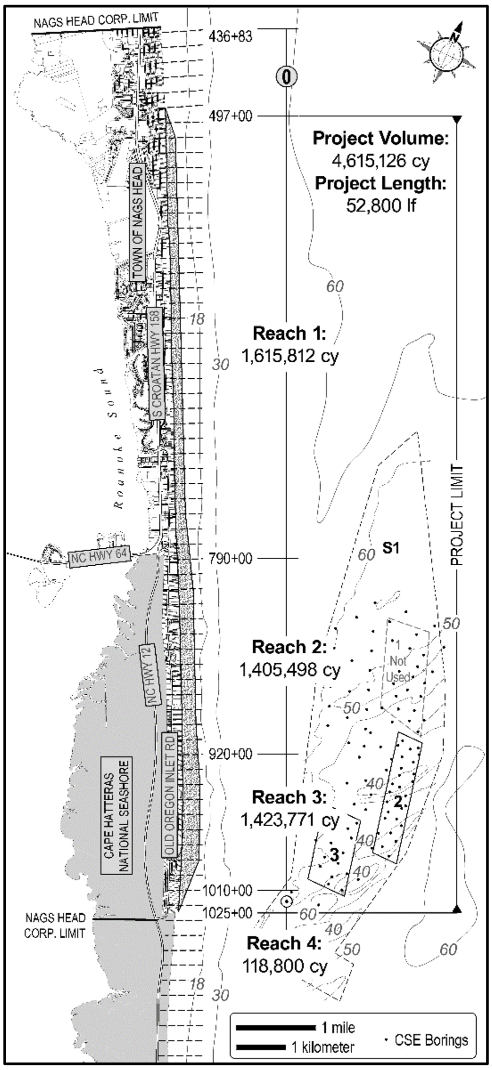

Figure 2. The 2011 Nags Head beach nourishment project map. The 16-km project area was divided into four reaches (i.e. Reach 1 to Reach 4). Offshore borrow areas 2 and 3 were excavated by one cutterhead suction dredge and three hopper dredges between 24 May and 27 October 2011. Volumes placed by reach are given in English units (cubic yards–cy) for consistency with project documents. [1 cy ≈ 0.76 m^3, 1 foot ≈ 0.3 m]

Construction started on 24 May 2011, and was successfully completed by 27 October 2011 without any environmental incident (CSE 2012a).

2.2 *The 2013-2014 Bridgehampton–Sagaponack Beach Nourishment*

Sagaponack and Bridgehampton are two adjacent erosion control districts (ECDs) located in the Town of Southampton in Suffolk County (NY). The 5.6-mile-long (~9 km) beach is a segment of a mainland bluff shoreline extending from Montauk Point to Shinnecock Inlet. Sagaponack Pond and Mecox Bay are located in the project area and are periodically flushed via intermittent inlets, causing interruptions to littoral transport. The project site has sustained moderate erosion over the past century through normal processes, and net sand transport is east to west along the south shore of Long Island (USACE 1958).

Best-available historic data indicate that the Sagaponack beach (Reaches 1 and 2 in Fig 3) has lost an average of 4.5 cy/ft/yr (11.3 m^3/m/yr) over the past 50 years and has a volume deficit of ~3.5 cy/ft (8.75 m^3/m) in the foredune with respect to FEMA 100-year protection criteria for the area. The Bridgehampton beach (Reaches 3 and 4 in Fig 3) has lost an average of 3.5 cy/ft/yr (8.75 m^3/m/yr) and has a dune volume deficit of ~12.8 cy/ft (32 m^3/m). The authors conducted detailed surveys of the littoral zone in July 2011 and calculated erosion rates, volume deficits, and nourishment requirements for a ten-year project (CSE 2012b).

While the project was under final design and permitting, the deadliest and most destructive Superstorm (*Sandy*) of the 2012 Atlantic hurricane season impacted the project area on 27 October. Superstorm *Sandy* passed New York during the full moon phase and was coincident with the highest tides of the month. The large diameter of the storm combined with slow forward movement produced long fetch lengths and generated extreme wave heights. The largest single wave that was recorded by a Datawell Waverider buoy at Block Island (Rhode Island), ~64 km northeast of the project site, was 14.35 m, and the highest significant wave was ~9.5 m.

The project area was surveyed after *Sandy* in November 2012 from the dune to about mean sea level, and a comprehensive condition survey was completed from the dune to deep water in April 2013. Survey results confirmed that *Sandy* and other 2013 winter storms caused extraordinary sand losses in the project area. An additional 380,000 m^3 of sand were added to the initial project plan volume to partially replace storm losses and maintain a projected design life of ten years under normal conditions. The final plan for construction called for placement of ~1.95 million cubic meters (~210 m^3/m) along the ~9 km project area (CSE 2014a).

The authors completed a sand search for potential borrow areas ~1.5–2 km offshore and confirmed sufficient deposits for the project (Fig 3). The strategic locations of the borrow areas made it possible for both cutter suction dredges and hopper dredges to perform the work. Sediment samples were collected and analyzed from the beach and offshore zone for purposes of determining the native sand distribution and confirming sand quality in borrow areas. The mean grain size of the native beach averaged 0.42 mm versus 0.44 mm for the borrow areas. Sediment sampling analysis during construction showed that the nourishment sand was slightly coarser but of similar texture as the native beach and, therefore, was expected to provide similar performance with respect to beach profile evolution and annual erosion losses. Construction started on 15 October 2013, and the project was successfully completed by one cutter suction dredge on 21 February 2014 (CSE 2014b). The actual project volume by reach is illustrated in Figure 3.

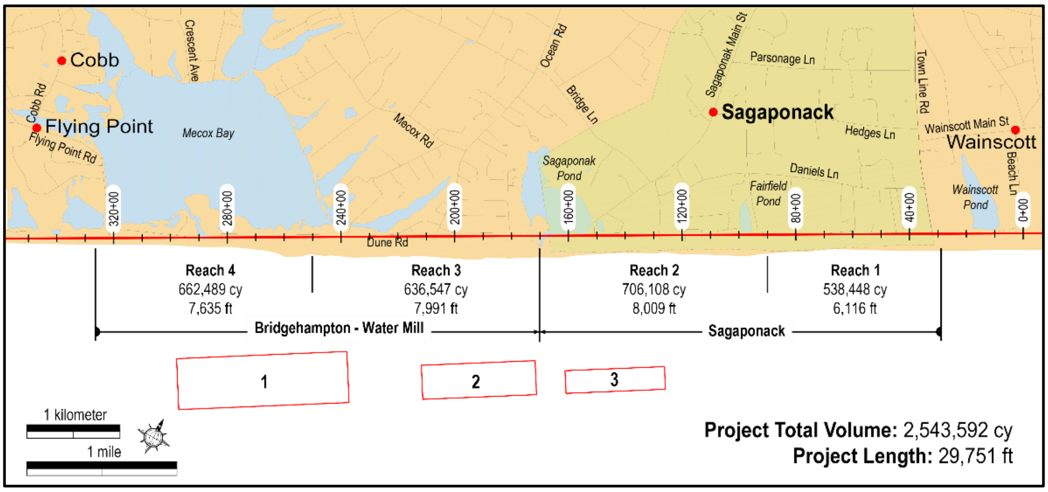

Figure 3. The 2013–2014 Bridgehampton–Sagaponack beach nourishment project map. The 9-km project area was divided into four reaches (i.e. Reach 1 to Reach 4). Offshore borrow areas 1, 2, and 3 were excavated by one cutterhead suction dredge between 15 October 2013 and 21 February 2014. Volumes placed by reach are given in English units (cy) for consistency with project documents. [1 cy ≈ 0.76 m^3, 1 foot ≈ 0.3 m]

3. Beach-Fill Equilibration

Beach nourishment projects are usually placed at slopes steeper than equilibrium for convenience of confirming pay quantities and because of the time lag between initial placement and profile adjustment. This creates a protuberance or "bulge" in the subaerial planform, which represents disequilibrium to the pre-nourished system (Dean 2012). Equilibration in cross-shore and longshore directions occur simultaneously in nature, but for many projects the time scales associated with the cross-shore (i.e. beach profile) equilibration are believed to be relatively short compared with those for the planform. Therefore, it is customary and convenient to discuss the profile and planform equilibrations separately with the profile equilibration being the main focus of this paper.

Fill templates at both sites utilized an average berm elevation matching the pre-nourishment berm with the expectation that minor storm events would produce wave overtopping and washover development. The authors favor this approach because it appears to produce a natural beach and inshore morphology with minimal formation of escarpments as the fill equilibrates. Berm washovers lead to natural formation of storm berms and create an upper beach reservoir of dry sand to feed the foredune. Cross-shore transport shifts substantial nourishment volume to the longshore bar (well beyond the fill template), helping to stabilize fill losses. Rhythmic variations in beach width were characteristic of both sites before nourishment. Initial fill produced a relatively uniform berm width over long reaches, but both projects exhibited similar rhythmic topography (berm width) at ~1 km spacing two years or more after initial fill placement. The oblique aerial images in Figure 4 show the rhythmic topography along the project areas, indicating the planform equilibration after nourishment.

Figure 4. Oblique aerial photos showing the rhythmic topography of both project sites after nourishment, a similar feature to the pre-nourishment condition indicating beach fill equilibration in the longshore direction. [LEFT] Photo taken on 28 June 2015 at Nags Head looking southwest. [RIGHT] Photo taken on 30 June 2016 at Bridgehampton looking east.

3.1 Beach Profile Equilibration of the 2011 Nags Head Beach Nourishment

All beaches experience profile adjustment, which is simply the response of the beach to changing wave heights and water levels. Beaches absorb and dissipate wave energy with the universal response being a flattening of the profile as wave energy increases (Komar 1998). A flatter profile provides a broader wet-sand beach over which waves lose their energy. The initial adjustment of the Nags Head beach nourishment project was a combination of offshore movement due to the inherently unstable configuration of sand upon placement and the adjustment due to storms.

During each survey at Nags Head, the authors measure 106 profiles within the 16-km project area. Each profile represents the unique condition of that location and varies from place to place. To simplify the present profile analysis, all profiles are juxtaposed morphologically and averaged along Nags Head. The average profile represents the overall condition of the entire beach at the time of the survey.

Figure 5 shows the average profiles before nourishment (November 2010) and the first five years after nourishment from June 2012 to June 2016. Average profiles at Nags Head exhibited strong similarity to pre-

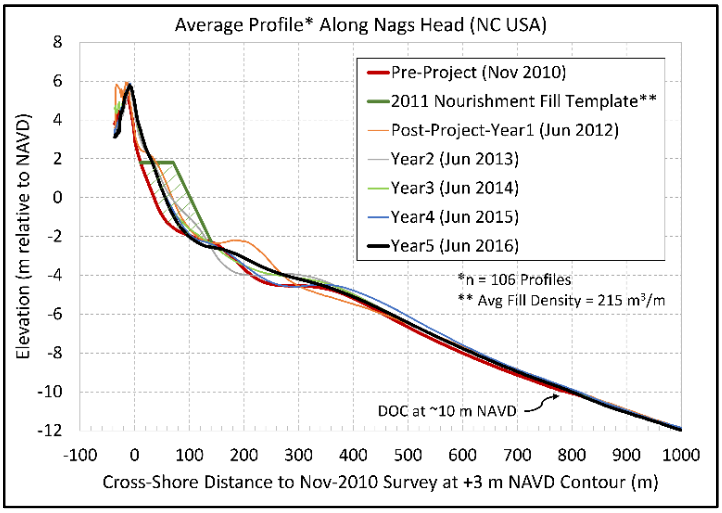

Figure 5. Composite average pre-nourishment profile, fill template (assumed 1 on 17 slope), and post-nourishment profiles during the first five years after project at Nags Head (NC USA). [DOC = depth of closure]

nourishment profiles by Year 5 after nourishment. The dry-sand beach widths (i.e. width between the toe of dune at +3 m NAVD and the approximate seaward edge of the dry-sand beach at +1.5 m NAVD) before and after nourishment are listed in Table 1 along with the wet-sand beach slope (i.e. slope of the beach face between +1.5 m and −1.8 m NAVD).

Table 1. Nags Head dry-sand beach width and wet beach slope before and after the 2011 beach nourishment project.

	Nov-2010 (Pre-Project)	Jun-2012 (Year 1)	Jun-2013 (Year 2)	Jun-2014 (Year 3)	Jun-2015 (Year 4)	Jun-2016 (Year 5)
Dry-sand beach width (m) (+3 m to +1.5 m NAVD)	15	41	28	26	25	24
Wet-sand beach slope (+1.5 m to −1.8 m NAVD)	1 on 22	1 on 18	1 on 25	1 on 22	1 on 18	1 on 17

The results show the foredunes average 0.6 m taller and 12 m wider in 2016 than before nourishment (red line versus black line in Fig 5), equilvalent to over 760,000 m^3 of sand gain in this portion of beach (discussed in Section 4). Average profiles also confirm the beach face shifted seaward by ~20 m, and the underwater portion had more volume in 2016 than in 2010.

Dry-sand beach width (Table 1) more than doubled after the 2011 project and increased from 15 m in November 2010 to 41 m in June 2012. Beach width gradually narrowed in the following four years, mainly due to fill adjustment and sand redistribution, but there was still 9 m more beach width in 2016 than the condition before nourishment. Fill templates for the 2011 project were designed assuming a 1 on 17 slope. The wet beach slope of June 2012 was close to the construction beach slope, but the beach face became gentler in the next two years (2013 and 2014) with slopes similar to the pre-project condition. The gentler slopes in those two years reflected post-storm recovery after Superstorm *Sandy* impacted Nags Head on 27 October 2012.

3.2 Beach Profile Equilibration of the 2013-2014 Bridgehampton–Sagaponack Beach Nourishment

The Bridgehampton–Sagaponack site was nourished about one year after Superstorm *Sandy* impacted the area, and therefore, its equilibration occurred in conjunction with post-storm beach recovery. Composite (i.e. mean) profiles at this site do not yet exhibit comparable similarity with pre-nourishment profiles, but the additional volume along the profile after nourishment is as obvious as the Nags Head project (Fig 6). There is evidence from the Bridgehampton–Sagaponack site that the offshore transfer of sand after nourishment has been augmented by onshore transport from deeper water in conjunction with post-hurricane recovery.

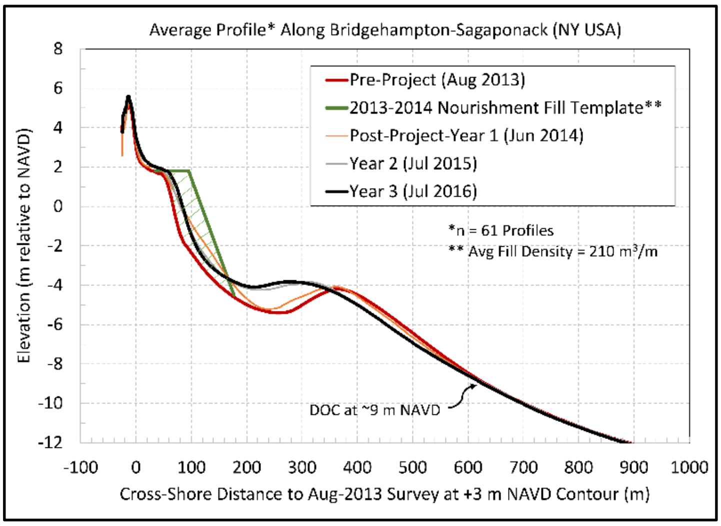

Figure 6. Composite average pre-nourishment profile fill templates (assumed 1 on 13 slope), and post-nourishment profiles during the three years after the Bridgehampton–Sagaponack (NY USA) project. [DOC = depth of closure]

During each survey at Bridgehampton–Sagaponack, the authors measure 61 profiles within the 9-km project area. Figure 6 shows the average profiles before nourishment (August 2013) and the first three years after nourishment from June 2014 to July 2016. The dry-sand beach widths (i.e. width between the toe of dune at +3 m NAVD and the approximate seaward edge of the dry-sand beach at +1.5 m NAVD)

before- and after-nourishment are listed in Table 2 along with the wet sand beach slope (i.e. slope of the beach face between +1.5 m and −1.8 m NAVD).
Similar to Nags Head after nourishment, the foredunes average ~0.5-m taller and 5-m wider in 2016 than before nourishment (red line versus black line in Fig 6), equilvalent to over 236,000 m^3 of sand gain in this portion of beach (discussed in Section 4). It can also be seen from the composite profiles that the beach face has shifted seaward by ~20 m.

Dry-sand beach width (Table 2) doubled after the 2013–2014 project and increased from 26 m in August 2013 to 54 m in June 2014. The width reduced in the following two years but still provided a wider dry beach to sustain natural dune growth. In July 2016, beach width was 22 m greater than the condition before nourishment. Fill templates for the 2013–2014 project assumed a 1 on 13 slope. The wet-beach slopes of 2014 and 2015 were much gentler, reflecting a higher-than-normal winter storm in those years (CSE 2015a, 2015b). Beach slope in 2016 was closer to the pre-nourishment profile, but does not appear to be fully equilibrated three years after construction.

Table 2. Bridgehampton–Sagaponack dry-sand beach width and wet beach slope before and after the 2013–2014 beach nourishment project.

	Aug-2013 (Pre-Project)	Jun-2014 (Year 1)	Jul-2015 (Year 2)	Jul-2016 (Year 5)
Dry-sand beach width (m) (+3 m to +1.5 m NAVD)	26	54	45	48
Wet-sand beach slope (+1.5 m to −1.8 m NAVD)	1 on 11	1 on 20	1 on 18	1 on 15

4. Natural Dune Growth after Nourishment

As shown in Figures 5 and 6 and briefly discussed in Section 3, an important feature of beach profile equilibration experienced in the Nags Head and the New York sites is the dune growth through natural wind forces—aeolian transport. Neither project incorporated a protective dune with the beach fill (see the fill template illustrated in Figures 5 and 6), but both sites exhibited rapid adjustment of the upper foreshore and had high rates of natural dune growth after nourishment. 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 projects has concentrated sand along the back beach, enhancing the foredune. Dune growth initially occurred at >23 m^3/m in the first seven months after nourishment along Nags Head, and as berm width equilibrated, dune accretion rates declined. At Nags Head, ~22 percent of the initial nourishment volume shifted into the foredune within the first five years. At Bridgehampton–Sagaponack, ~12 percent of the nourishment volume shifted to the foredune within the first three years.

Dunes grow mainly due to wind-generated aeolian transport, the most common process occurring in the subaerial environment on backshores. It is believed that when sufficient (onshore) wind occurs and sediment is available for transport, sediment is transported from the beach toward the dunes, leading to an increase of dune volume. Dunes are affected by marine processes (e.g. storm waves) if water levels are high enough to reach the dunes and wave conditions are strong enough to erode the dunes. Although quantitative knowledge of dune-building processes is limited due to the complicated nature of the problem as well as limited field data, there are classical studies of dune mechanics and sand transport, particularly the pioneering work of Bagnold (1941).

4.1 Dune Growth Mechanics–Aeolian Transport

Bagnold (1941) identified the main factors influencing aeolian transport rates (q in kg/m/s) as the local grain diameter (d) relative to a reference grain diameter (D) (a standard grain-size diameter 0.25 mm), the air density (ρ = 1.22 kg/m^3), the gravitational acceleration (g = 9.81 m/s^2), the shear velocity ($\boldsymbol{u}_*$ 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 $\boldsymbol{u_{*t}}$ is dependent on the grain diameter (d), the gravitational acceleration (g), the density of the sand grains ($\boldsymbol{\rho_s}$), the density of the air ($\boldsymbol{\rho}$), 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 purposes of measuring, deriving, and defining appropriate C_b and A values for various conditions of interest. Practically all aeolian sand transport equations consider the sediment transport rate proportional to the shear velocity cubed: $\boldsymbol{q} \propto \boldsymbol{u_*^3}$. 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) (Masselink & Hughes 2003). Arens (1996) estimated that sufficient winds needed for sediment transport are typically of the order >5−10 m/s, 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 unlimited sand source for aeolian transport. This is a good assumption in a desert environment, but 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 a <u>*loss*</u> of ~2.5 m^3/m/yr between 1994 and 2010 [note red (1994) and burgundy (2010) lines in Figure 7]. Linear trend lines for 1994 and 2010 datasets are plotted as red- and burgundy-dashed lines in the graphic.

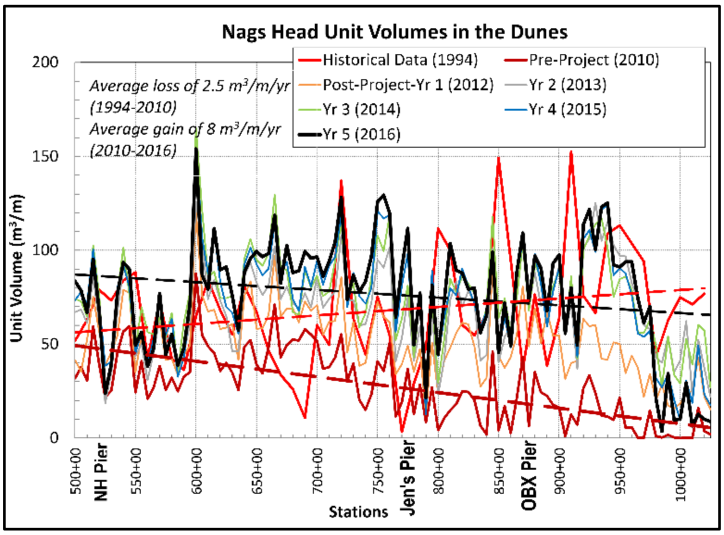

Figure 7. Comparison of unit volumes along Nags Head from the face of the dune to +1.8 m NAVD contour before and after nourishment. This shows a volume loss before nourishment between 1994 and 2010 but a significant volume gain after the project at most stations. Linear trend lines for 1994, 2010, and 2016 are plotted as dashed lines.

4.2 Factors Affecting Aeolian Transport in Beach Environment

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

<u>*4.2.1 Beach Width and Fetch Length*</u>

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). 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 the critical fetch where wind reaches transport saturation. While winds are directly or obliquely onshore on 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 10 m to 40 m (Davidson-Arnott & Law 1990) up to over 200 m (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.

4.2.2 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. In addition, increasing slope angles tend to enhance the effect of gravity, potentially reducing sand-transport rates.

4.2.3 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 a 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).

4.3 *Dune growth after Nags Head nourishment*

The 2011 Nags Head nourishment added ~3.5 million cubic meters of sand along the 16-km beach, and ~2.5 million cubic meters (~70 percent) of the nourishment sand were placed between +1.8 m NAVD and mean low water (MLW) at −0.62 m NAVD, forming a steeper-than-natural beach slope (see the fill template shown in Fig 5). Profile adjustment after the project was expected (i.e. 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 under aeolian transport, gradually adding volume and yielding a total of ~380,000 m^3 of extra sand to this section of beach as of June 2012, ~7 months after the project. Unit volumes from the face of dune to +1.8 m NAVD contour along Nags Head before and after nourishment were plotted in Figure 7 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. Nags Head post-project sediment analysis in June 2013 determined that the mean grain size of the nourished beach was 0.402 mm (CSE 2013). If $\boldsymbol{C_b}$ = 1.8, A = 0.1 (Masselink & Huges 2003), and the sand density $\boldsymbol{\rho_s}$ is 1,600 kg/m^3, then the threshold shear velocity $\boldsymbol{u_{*t}}$ 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 $\boldsymbol{z_0 = D/30}$, the threshold wind velocity at 2 m above the sand surface as a function of sediment size can be derived using Equation (3):

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

where k is von Karmen's constant (equal to 0.4), $\boldsymbol{z}$ is elevation above the bed, and $\boldsymbol{z_0}$ 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. The azimuth of the Nags Head coastline is 158° true north (i.e. only wind coming from an arc between 338° and 158° will have a positive impact on aeolian transport and dune accumulation).

Based on the wind speed analysis available for station DUKN7-8651370 at FRF–Duck (NC USA), the probabilities of wind speeds exceeding 6.8 m/s between 2008 and 2013 were between 14 and 23 percent (Table 3) 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^3/m/yr, which is remarkably coincident with the actual measured dune growth rate of 11.8 m^3/m/yr for the first 3 years after project completion as of June 2014 (CSE 2014c).

Table 3. Probabilities of onshore wind speed exceeding the threshold wind speed at Nags Head between 2008 and 2013. (Source: 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 the previous sections have described, dune growth is related to the width of dry-sand beach ("critical fetch"). Since 2014, aeolian transport rates have declined because the dry-sand beach narrowed by natural evolution of the profile after nourishment (see Table 1). Annual surveys in June 2015 and June 2016 showed that the dune volumes have been stable, which reduced the average dune growth rate for the first five years after project completion to ~8 m^3/m/yr. Despite the decline of the dune grow rates in the recent two years, Nags Head has ~50 m^3/m more sand in the dune and upper beach above +1.8 m NAVD contour compared to the pre-nourishment condition (CSE 2016a). The extra volume and elevation in the dunes has provided a higher level of storm protection, helping Nags Head avoid any major damage to the oceanfront properties during Superstorm *Sandy* (27 October 2012) or during numerous severe winter storms since project completion.

4.4 *Dune growth after Bridgehampton–Sagaponack nourishment*

Additions of nourishment sand increase beach width (see Table 2), at least for some time, and are likely to result in increased volume in the dunes. If nourishment is large scale and the dry beach persists for several years without any major recession, as the case of this site, the dune line usually grows seaward of the prior dune line (see Fig 6).

Unit volumes from the face of dune to +1.8 m NAVD contour along Bridgehampton–Sagaponack before and after nourishment are plotted in Figure 8. Linear trend lines for August 2013 (before nourishment) and July 2016 (Year 3 after nourishment) datasets are plotted as burgundy- and black-dashed lines in the graphic.

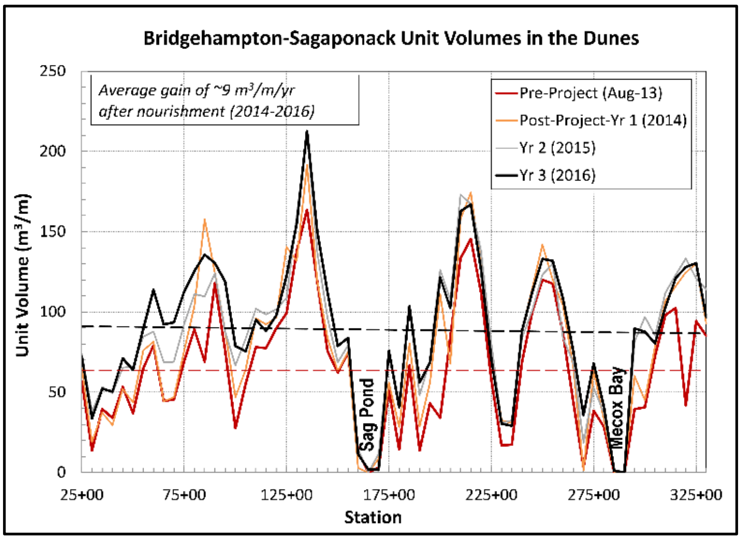

Figure 8. Comparison of unit volumes along Bridgehampton–Sagaponack from the face of the dune to +1.8 m NAVD contour before and after nourishment. It shows significant increase of unit volumes after the project at most stations. Linear trend lines for 2013 and 2016 datasets are plotted as dashed lines.

Bridgehampton–Sagaponack post-project sediment analysis in July 2016 determined that the mean grain size of the nourished beach was 0.466 mm (CSE 2016b). Following the same approach as described in Section 4.3, the threshold shear velocity is ~0.24 m/s, and the aeolian sediment transport rate is ~4.5 grams/m/s. The threshold wind velocity is around ~7.1 m/s, which means for wind speeds less than 7.1 m/s, no sediment is expected to be transported. The azimuth of the Bridgehampton–Sagaponack coastline is 62° true north (i.e. only wind coming from an arc between 62° and 242° will have a positive impact on aeolian transport and dune accumulation).

Based on the wind speed analysis available for a NDBC station at Central Long Island Sound (NY USA), directly landward of the project site, the probabilities of wind speeds exceeding 7.1 m/s between 2014 and 2016 were between 7 and 10 percent (Table 4) with an average of ~9 percent. Therefore, the yearly average aeolian sediment transport rate derived from the above equations and parameters is ~12,200 kg/m/yr, or ~7.6 m^3/m/yr, which is consistent with the actual measured dune growth rate of 8.8 m^3/m/yr for the first three years after project completion as of June 2016. Although the dune growth rate is slower than Nags Head due to the milder wind force at this site, the natural volume increase in the dune areas along Bridgehampton–Sagaponack yields 26 m^3/m more sand in 2016 than in 2013 before nourishment (CSE 2016b).

Table 4. Probabilities of onshore wind speed exceeding the threshold wind speed near Bridgehampton–Sagaponack between 2014 and 2016. (Source: NDBC database)

Year	2014	2015	2016	Average
Probabilities (%)	10.1	7.0	10.4	9.2

5. Conclusions

Beach-fill equilibration occurs simultaneously in cross-shore and longshore directions. The main focus of this paper is the cross-shore (beach profile) equilibration following two large-scale beach nourishment projects along the East Coast of the United States. These two project sites are exposed to comparatively high-wave energy conditions and received nourishment sand 3–5 years ago with similar fill density. Net sand volume changes at both sites have been low since fill placement with Nags Head averaging losses of ~2 percent per year measured to DOC (~10 m NAVD) through 2016. The New York project exhibited negligible loss measured to DOC (~9 m NAVD) through 2016. Composite (i.e. mean) profiles at Nags Head exhibit strong similarity to pre-nourishment profiles by Year 5 after nourishment. Profiles at the New York site do not yet exhibit comparable similarity with pre-nourishment profiles by Year 3 after nourishment.

An important feature of beach profile equilibration is that both sites exhibited significant natural dune growth after nourishment via aeolian transport. When sufficient onshore wind occurs and sediment is available for transport, sediment is transported from the beach toward the dunes, leading to an increase of dune volume. Nags Head has ~50 m^3/m more sand in the dune areas five years after nourishment while Bridgehampton–Sagaponack has ~26 m^3/m more sand in the dune areas three years after nourishment. The extra volume and elevation in the dunes has provided a higher level of storm protection and helped both sites avoid any major damage to the oceanfront properties during hurricanes or severe winter storms since project completion. The projection of dune growth rates estimated by Bagnold's equations can be used as guidance for future dune management plans.

Acknowledgements

This research was sponsored by the Town of Nags Head (NC USA) and the Town of Southampton (NY USA) as part of the annual monitoring of each project. All data collection was by CSE staff scientists and technicians, including Drew Giles and Luke Fleniken. The manuscript was prepared with assistance of Trey Hair and Diana Sangster.

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