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FINAL DESIGN OF THE NAGS HEAD BEACH NOURISHMENT PROJECT USING A LONGSHORE NUMERICAL MODEL

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Nags Head, located at the northeastern part of North Carolina in the U.S., has sustained chronic erosion over the past 50 years. In 2005, Coastal Science & Engineering (CSE) was retained by the town of Nags Head to develop an interim beach restoration plan. Profile volume change was used in the planning and preliminary design of the project, and longshore and cross-shore numerical models were used in the final design to refine the preliminary nourishment plan and increase potential longevity of the project. This paper focuses on the key factors of the longshore numerical model setup for the project. These include model selection, input data and parameters, model calibration, and applications under different design alternatives. The Generalized Model for Simulating Shoreline Changes (GENESIS) was used in this study to evaluate shoreline evolution under normal wave conditions during various stages of the design life following the beach nourishment project. The model was used to identify the potential occurrence of erosional hotspots and to optimize the nourishment design so that the effects of such hotspots could be avoided or minimized where possible. Model results were also used to evaluate the impact of borrow area dredging on longshore transport in the project area and the impact of nourishment on shoaling in the adjacent inlet. The project encompasses 10.11 miles (mi) (16.28 kilometers-km) of ocean shoreline, and the design nourishment volume is based on the total permitted volume of 4 million cubic yards (cy) (3 million cubic meters-m³). [Note: As-built length was 10.0 mi and volume was 4.615 million cubic yards.] The final design has fill densities varying from north to south in relation to historical erosion rates and model projections. The average fill density is 75 cubic yards per foot (cy/ft) (188 m³/m) and ranges from 38 cy/ft to 150 cy/ft (95 m³/m to 375 m³/m). In conclusion, it is shown that the numerical model selected in this study was capable of predicting the overall performance of the large scale beach nourishment project in Nags Head as well as the performance at a particular location within or adjacent to the project, and its design methods can offer guidance to future projects.

Keywords: beach nourishment, shoreline evolution, longshore sediment transport, GENESIS, STWAVE, Nags Head NC

PROJECT SETTING AND MODEL INTRODUCTION

The Town of Nags Head encompasses ~11 miles (mi) (18 kilometers-km) of ocean shoreline on North Carolina's Outer Banks (OBX), a chain of barrier islands along the Atlantic Ocean, about 60 mi (100 km) south of the Chesapeake Bay entrance and about 20 mi (32 km) south of the U.S. Army Corps of Engineers (USACE) Field Research Facility (FRF) and pier at Duck, NC. The nearest inlet, Oregon Inlet, is located ~5 mi (~8 km) south of the south border of the Town (Fig 1). Details of the project setting, coastal processes, erosion history, sediment quality, project planning, and preliminary design are summarized in the Kana & Kaczkowski paper of this volume. English units are used in this paper to be consistent with the original source documents, and selected metric-unit equivalents are also given. *[Note: 1 ft ≈ 0.3 m, 1 mi ≈ 5,280 ft ≈ 1.6 km, 1 cy ≈ 0.76 m³, and 1 cy/ft ≈ 2.5 m³/m]*

The Generalized Model for Simulating Shoreline Changes (GENESIS) was used in this study to evaluate shoreline evolution under normal wave conditions during various stages of the design life following the beach nourishment project. The structure of GENESIS was originally developed by Hanson in 1987 in a joint research effort between the University of Lund (Sweden) and the Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES) (Hanson 1987, Hanson & Kraus 1989; Kraus et al 1988). It has been tested, revised, and upgraded since it was developed and has been widely used for predicting the behavior of shorelines and longshore transport. The project sites include stretches of coast in the United States such as Alaska, California, Louisiana, New Jersey, New York, Texas, Florida, and South Carolina, etc. Additionally there are applications on the coastlines outside of the United States to countries such as Sweden, Japan, Thailand, and China (Horikawa & Hattori 1987, Hanson & Kraus 1989, Beumel and Beachler 1994, Bodge et al 1996, Ebersole et al 1996, ERDC 2005, Ravens et al 2007, ACRE 2008, Juh 2008, Ekphisutsuntorn et al 2010, Kuang 2010.)

As concluded by Dean (2002) and also addressed in numerous articles in the coastal engineering literature, several things should be taken into consideration to have a successful application of the model. These key factors are listed below:

- Representative wave data or reliable hindcasts are available.
- Historical shoreline position and the longshore distribution of volume changes for substantial periods are available.
- Model is set up appropriately, including domain coverage, grid size, and bathymetry, etc.
- Model is properly calibrated and verified.
- An external wave transformation model which has the capability to transform the wave data from offshore to the nearshore reference point as required by the GENESIS model.

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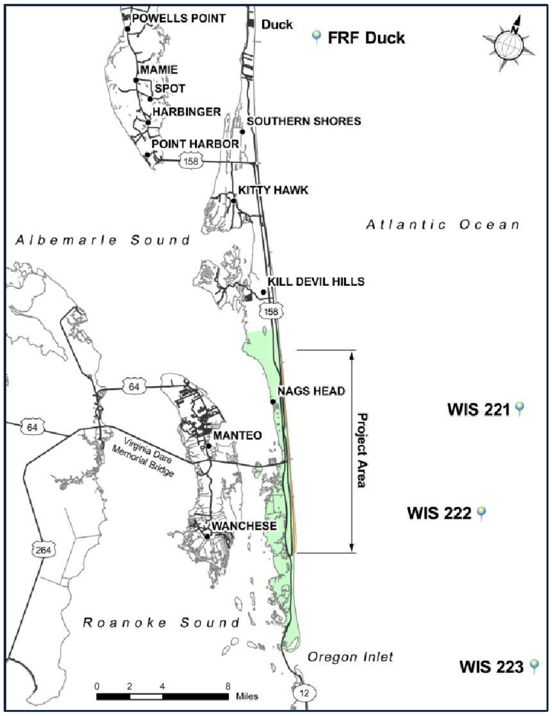

Figure 1. Project vicinity map and locations of wave stations. [FRF Duck and WIS Stations will be referred to in the later section.]

When the GENESIS model was used for the Nags Head project, the challenges included a lack of site-specific long-term wave data, and the highly variable annual longshore sediment transport (LST) rates of the project site ranging from accretion in some years to ~570,000 cy/yr erosion (CSE 2011). In addition, the official 50-year erosion rates of Nags Head and the adjacent downdrift shoreline varied significantly from north to south, ranging from 2 feet per year (ft/yr) to almost 10 ft/yr (0.6-3.0 m/yr) (NCDENR 1998, 2004). Therefore, calibration of the model to reasonably reproduce historic shoreline changes and LST rates was necessary before using the model to predict shoreline evolution after beach nourishment.

The wave-energy field required by the GENESIS model was generated by a numerical wave model, STWAVE (Steady-state spectral WAVE model). The STWAVE model was first applied to transform representative offshore waves to the reference point having a near-breaking depth. The internal wave transformation model within GENESIS was then used to mathematically model the wave propagation from the nearshore reference point to the breaking point and to the beach. This internal model determined the breaking wave characteristics which were used to calculate the actual longshore sediment transport.

The models (STWAVE and GENESIS) were executed within the Coastal Engineering Design & Analysis System (CEDAS) (V4.03, available from Veri-Tech Inc) software package. The CEDAS software allows direct coupling of the two models (ie – the wave energy field calculated from STWAVE was used directly by GENESIS for calculating shoreline changes).

In the following sections, the details of model setup, its calibration, applications for beach nourishment design templates, and the environmental impact of the proposed borrow area dredging and nourishment, as well as the project impact on the Oregon Inlet shoaling will be discussed. The conclusions of the engineering study will be given after the discussion.

MODEL SETUP

The task of model setup includes determining the computational domain, building up the model grid, designating model parameters, and generating input data files. Input data of a typical GENESIS model and a STWAVE model include the wave field (wave height, wave period and wave direction), bathymetry over the model domain, initial shoreline position, measured shoreline position for calibration purposes, and coastal engineering activities (coastal structure positions or beach fill characteristics if applicable). The GENESIS model output includes the shoreline position and longshore transport rates at user-specified time steps.

Model Grid

STWAVE model grid

USACE-established stations were used in this project. These stations are developed from baseline control points, and the distance between two stations is calculated in feet by simply subtracting the station numbers. For example, there are 1,000 linear feet (lf) between stations 500+00 and 510+00. The project area during the planning and design phases starts from station 491+00 and extends southward to station 1025+00 (Fig. 2), therefore, it covers a total of 53,400 ft (10.11 mi or 16.28 km) from north to south.

The STWAVE grid for the model extends about 3 miles beyond the north end and 3 miles beyond the south end of the project. The model domain extended beyond the project area to minimize possible edge effects from the model boundary along the area of interest. Model sensitivity study confirmed that such extents yielded proper model function without edge effects.

The STWAVE model grid was also extended seaward from the shoreline to a distance of about 3 miles. The seaward boundary is parallel to the general shoreline trend with an azimuth of 245° as marked in Figure 2. The seaward boundary is defined as the y-axis of the STWAVE model, and the axis perpendicular to the y-axis pointing in the shoreline direction is denoted as the x-axis. The two axes are shown as black lines in Figure 2, and the south and onshore boundaries are marked with red lines in the same figure. Average water depth along the seaward boundary is 55 ft (17 m). The grid encompasses both the project area and the identified borrow areas S1[2] which is situated 1-3 miles offshore of Nags Head. The overall wave model grid dimensions are 18,900 × 90,000 ft (5,760 × 26,432 m), and are shaded with light reddish color in Figure 2.

[2]Borrow Area S1 - The federal project (USACE 2000) had identified a potential borrow area (S1) situated 1-3 miles (~1.5-5 km) off Nags Head with upward of 100 million cy (~76 million m^3) of beach-quality sand.

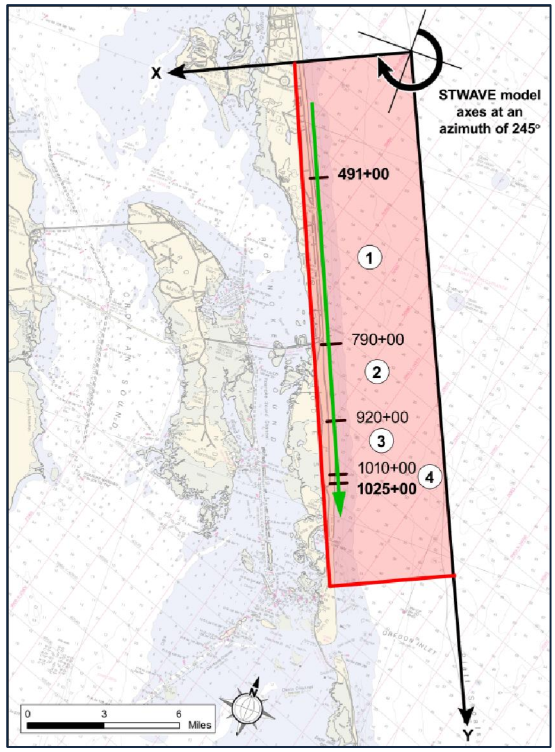

Figure 2. STWAVE and GENESIS model boundaries and grid coverage. Four reaches along Nags Head were delineated based on systematic variations in erosion rates (CSE 2005), and their boundary stations are shown herein. NOAA Navigation Chart No. 12204 is used as the background.

GENESIS model grid

The GENESIS model domain was nested within the coverage of STWAVE domain. The wave model domain was extended beyond the limits of the shoreline domain so that an adequate wave energy field can be generated by the wave model and passed to the shoreline model. The GENESIS model boundary is parallel to the y-axis of the STWAVE grid and is marked by a green line with an arrow pointing from north to south in Figure 2.

Ideally the GENESIS model boundary should not only cover the project area but also extend some distance beyond the north and south ends of the project to eliminate any possible boundary effects and to evaluate the shoreline performance of adjacent beaches. For the scenarios based on the 2005 or 2009 beach survey data, the model has ideal coverage starting from station 430+00 and extending to station 1160+00. However, there are no profile data available further to the south of station 990+00 for the 1994 data set. For the scenario based on the 1994 data set, the shoreline model coverage is only from station 430+00 to station 990+00.

Model grid size

Generally speaking, if the grid cell size is smaller, then the shoreline simulation model results are more detailed. However, reducing the grid size increases the STWAVE computation time. Model sensitivity studies with different spatial resolution ranging from 50 ft to 500 ft were conducted, and the optimum grid size determined for this project was 100 ft (30 m) for both STWAVE and GENESIS models.

Model Bathymetry

The setup of the STWAVE and GENESIS models requires the application of offshore and nearshore data to develop the bathymetry and topography in the model domain. A 1994 survey data by the USACE (2000) is believed to be the first complete profile data set for the project area, and was used in the model calibration process. In April 2005 and November 2009, CSE used a single-beam sensor with a linked Real-Time-Kinematic Global Positioning System (RTK-GPS) to conduct bathymetric surveys. Data collected by boat over water were combined with land portions to yield a comprehensive profile of the active littoral zone from foredune to deep water. The data were transformed to standard North Carolina State Plane coordinates (NAD'83) for the horizontal datum and National American Vertical Datum (NAVD[3]) for elevations. The shoreline used in this study is defined as the 0-ft contour line relative to NAVD datum.

[3]NAVD — North American Vertical Datum of 1988 which is ~0.5 ft (~0.15 m) above local mean sea level. [Source: National Oceanic and Atmospheric Administration-National Ocean Service, NOAA-NOS]

Additional bathymetric surveys were conducted at the proposed borrow area S1 in April 2005. There were no significant bathymetry changes recorded in this area from 2005 to 2009. Therefore, these survey data were added to the regular survey data for both 2005 and 2009 conditions.

CSE bathymetric surveys (excluding limited data in the borrow area) and the USACE 1994 profile data only extended from the shoreline seaward to a distance less than one mile. As discussed in the previous section, the model grid is extended seaward to 3 miles. Bathymetric data of the area between the survey limit and the grid boundary were obtained by digitizing NOAA Navigational Chart No. 12204.

The survey data coverage combined with the digitized chart data are shown in Figures 3 for 1994, 2005, and 2009 conditions. The intervals between nearshore survey transects are from 500 ft to 1000 ft. The dense offshore S-shaped data zones for 2005 and 2009 conditions are the additional survey data at the proposed borrow area. The other scattered points are digitized data from the navigational chart. These scattered data were then interpolated onto the model grid to be used in the simulations.

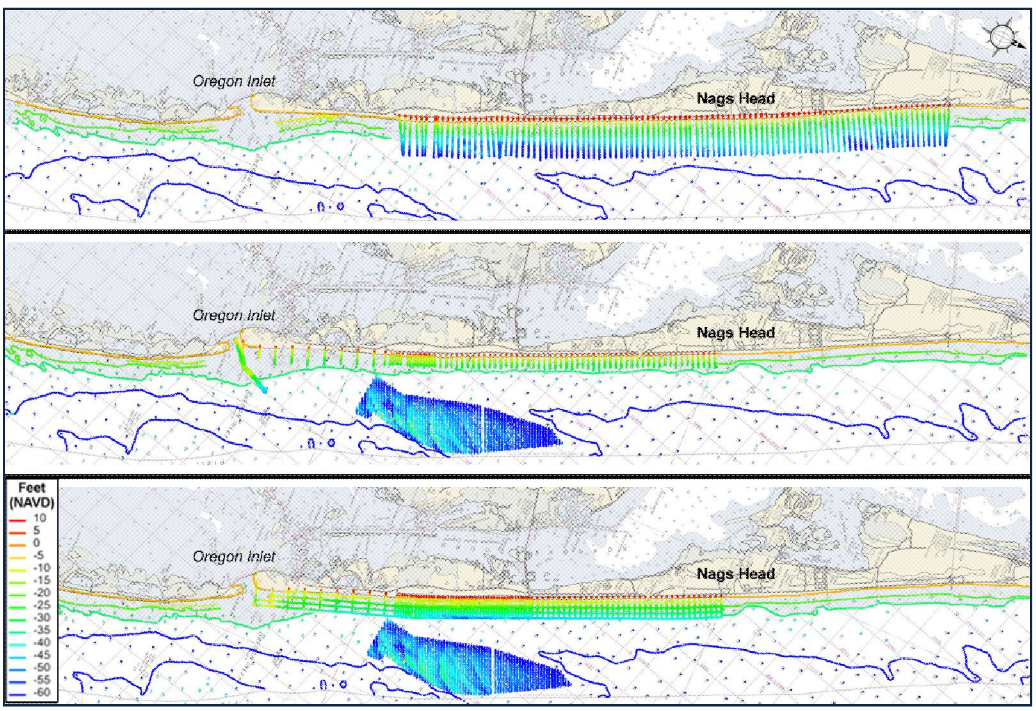

Figure 3. Bathymetric survey data points for: [UPPER] 1994; [MIDDLE] 2005; and [LOWER] 2009. NOAA Navigation Chart No. 12204 is used as the background.

Wave Climate Analysis

Obtaining satisfactory wave data is a necessary and crucial task in the preparation and execution of the GENESIS model. There are no site-specific and concurrent wave records for the period of evolution being modeled, and precise estimation of future wave conditions is not possible. However, a reasonable estimate of shoreline evolution can still be obtained based on the use of statistically representative offshore wave conditions together with the use of the STWAVE wave transformation model which has the capacity to take the nearshore bathymetry in consideration.

The area of interest in this study is over 10 miles long with a broad bulge in the shoreline along the south Reach 2 through Reach 3 (see Fig 2 for reach boundaries). Site exposure, and therefore wave climate, varies with location along the project range. There are several wave data sources near the

Table 1. Wave sources comparison. [Sources: USACE-FRF and USACE-WIS]						
Station Name	**Location**	**Relative Position**	**Water Depth (ft)**	**Available Time Period**	**Data Interval**	**Acquisition Method**
FRF Duck	36.20N, 75.71W	1.9 miles offshore	57	1987-present	34–44 min	measured
WIS 221	36.00N, 75.42W	12 miles offshore	56	1980-1999	1 hr	hindcast
WIS 222	35.92N, 75.42W	10 miles offshore	62	1980-1999	1 hr	hindcast
WIS 223	35.83N, 75.33W	12 miles offshore	98	1980-1999	1 hr	hindcast

project site, including the USACE Field Research Facility (FRF) Lab at Duck (NC) and at least three Wave Information Study (WIS) stations off Nags Head. The location map of these data sources is shown in Figure 1, and a comparison of data sources is listed in Table 1. Reviewing these wave data carefully and selecting the most representative wave climate for the wave and shoreline simulation studies is a crucial part of the calibration process, and also the key to the success of this study.

The USACE FRF at Duck (NC) is situated about 20 miles (~32 km) north of the center of the Town. Despite the fact that the FRF has real-time measurements in the nearshore area (only 1.9 miles offshore), these data were not used for the Nags Head study because the model results generated under the FRF inshore wave climate yielded a predominantly northerly net sediment transport, which is counter to the inferred pattern and gradients of longshore transport along Nags Head. Previous studies show that longshore sediment transport (LST) varies along the Chesapeake Bay entrance to Oregon Inlet bight with northerly transport occurring near the mouth of the Chesapeake, and predominantly southerly transport around Oregon Inlet (Inman and Dolan 1989). The FRF is situated close to the center of the Bight, and the orientation of the shoreline at this station and the complexity of its nearshore bathymetry may have significant impact on the wave climate and, therefore, may generate a different longshore transport pattern than the Nags Head area.

The three nearby WIS stations are all located 10-12 miles offshore of Nags Head; however, both the magnitude and pattern of longshore sediment transport generated by these stations are different from each other. After examining the results, station 222 was chosen because the net transport generated under the wave climate of this station agreed the best with historical observations.

The 20-year hindcast wave climatology for WIS station 222 cannot be used directly since the station is located 10 miles offshore, while the wave model boundary is only 3 miles offshore. Therefore, WIS Phase III transformation technique (WISPH3) in the CEDAS software was first used to transform time-series of wave height, period, and direction to coincide with the wave offshore boundary. The transformed wave data was then characterized by binning the significant wave heights, peak spectral wave periods, and vector mean wave directions at the peak spectral frequencies. The histogram of percent occurrence of these three wave parameters are graphed in Figure 4.

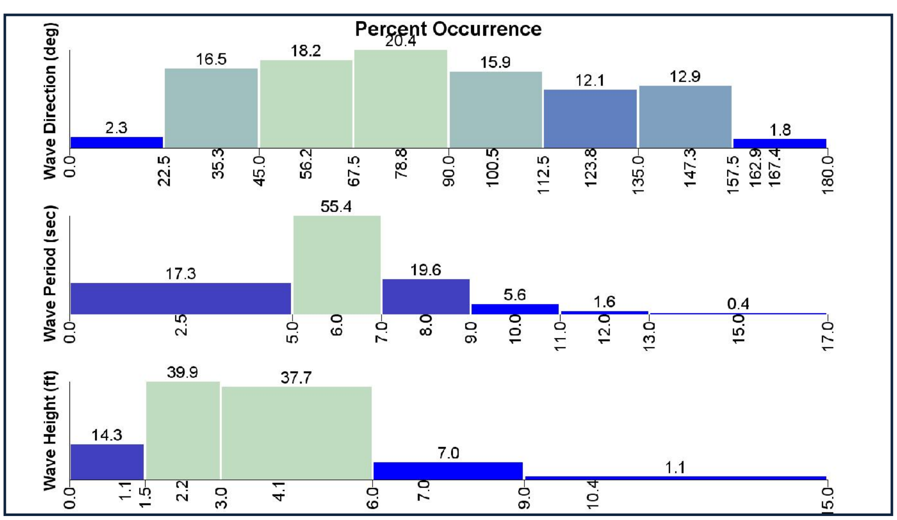

Figure 4. Histogram of percent occurrence of wave height, period, and direction.

Bright green bins correspond to events occurring most frequently, and bright blue bins correspond to events occurring least frequently. Wave direction in these figures uses meteorological convention (ie – a wave direction of 0° corresponds to a wave that is coming from due north, and 90° from due east). There are eight wave-direction bins, six wave-period bins, and five wave-height bins shown in Figure 4. The largest significant wave height identified in the 20-year WIS wave hindcast was 25 ft (7.7 m), and the mean significant wave height was 3.9 ft (1.2 m). The mean wave period for this data set was 7 seconds. Based on the statistical wave summary, ~57 percent of all deepwater waves approached the Nags Head shoreline from a northerly or northeasterly direction. The most predominant wave height fell within the 1.5–3.0 ft band and the 3.0–6.0 ft band. Approximately 77.6 percent of all waves have heights within these two bands. The 5–7 second wave-period band was the most dominant, containing 55.4 percent of all occurrences.

A group of 126 representative wave events was selected from all possible combinations of wave angle, period, and height bins and was used in STWAVE model as the input wave parameters.

Model Parameters

The parameters used in the GENESIS model include sand and beach data, and longshore sand transport calibration coefficients. The grain size and beach fill data were determined by geotechnical and engineering studies in the planning and preliminary design phases (CSE 2005 and 2011), and are listed as follows:

- Effective grain size = 0.306 millimeter-mm
- Average berm height = 6 ft (relative to NAVD)
- Closure depth = 24 ft (relative to NAVD)

Historic volumetric studies at Nags Head show that ~272,000 cy of sand has been lost per year during the period of 1994 to 2005 (CSE 2005). Such background erosion can have a significant effect on the performance of a beach nourishment project. Therefore, superposition of transport rates due to background erosion is considered in the model to incorporate the effects of background erosion in the design and prediction process. Such approach was achieved in the model calibration process by adjusting the transport parameters, K_1 and K_2, to obtain the best fit of simulated volumetric transport rate with historical data.

GENESIS MODEL CALIBRATION

Proper operation of the GENESIS model requires calibration by adjusting the various model parameters until the model can reasonably reproduce historical shoreline change over a given time interval. If calibration is successful, the model can then be used as a predictive tool for the project area.

It is important to recognize in applying shoreline changes that the reference contour (0-ft NAVD in this case) can advance or retreat without a change of profile volume. Thus when calibrating against shoreline changes, a sufficient length of time should be selected to ensure that the established shoreline trend is truly representative of volume changes and not simply the result of a volumetric redistribution across the profile.

Since the 1994 survey data is the first comprehensive survey record for the project site, a period of 11 years (ie – from 1994 to 2005) was selected for the purpose of calibration. The STWAVE and GENESIS models were set up based on the bathymetry of 1994, and the GENESIS model domain ended at station 990+00 according to the data coverage.

STWAVE Model Results

The STWAVE model results for one of the 126 wave events (where H = 4.4 ft or 1.35 m, T = 7.69 seconds, Theta = 40.56°) are shown as an example in Figure 5. The contour represents the wave height distribution, and the vectors represent the wave direction. [Note the orientation of the x and y axes are related to the geography in Figure 2.]

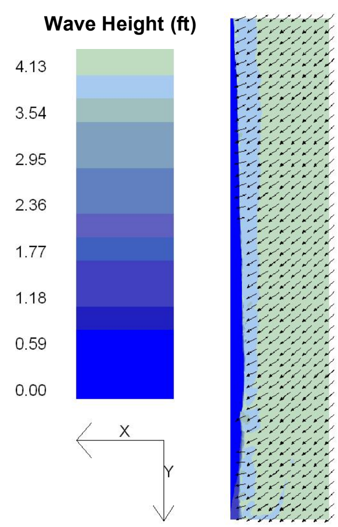

Figure 5. STWAVE simulated wave heights and directions for the calibration period.

Shoreline Changes

Simulated and measured shoreline positions over the calibration period were represented by the group of colorful lines at the middle to top of Figure 6, and shoreline changes were represented by solid and dotted black lines at the bottom of the same figure. Positive changes mean that the shoreline accreted seaward, while negative changes mean that the shoreline encountered erosion

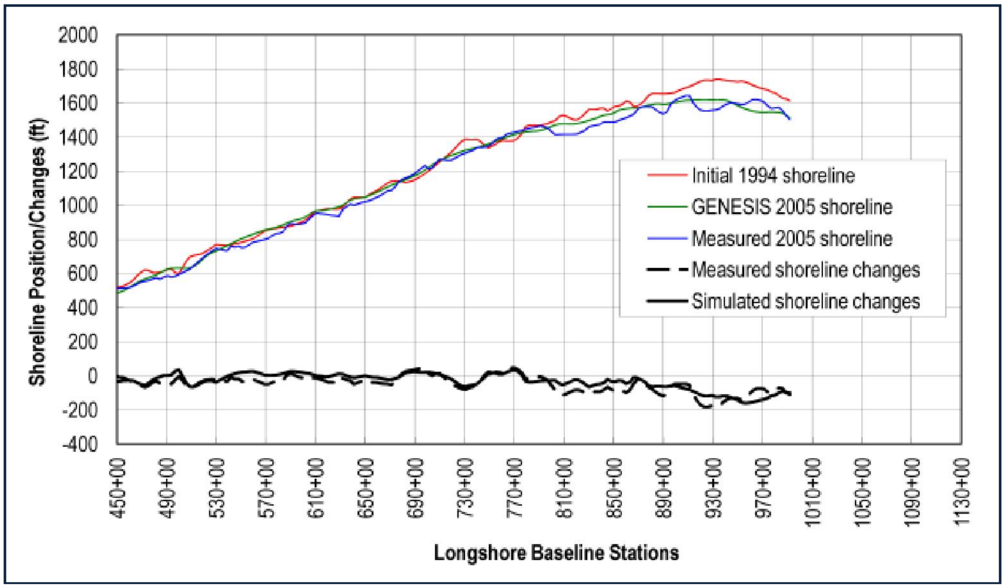

Figure 6. Comparison of model simulated and measured shoreline changes for the calibration period of 1994 to 2005.

over this period. From the relative position of these two lines, it can be determined whether the model underestimated or overestimated shoreline changes.

Measured data show that most of the project site had erosion and that the shoreline retreated between 1994 and 2005. Additionally, the magnitude of shoreline changes increased from north to south. It means that south Nags Head sustained higher erosion rates than north Nags Head. The model captured these trends very well, and yielded excellent agreement with the measurements over 10,000 ft (~3 km) of the project area from station 680+00 to station 780+00. The average difference between simulated and measured shoreline changes within the project area is +1.5 ft/yr, which means the model underestimated the shoreline erosion by a magnitude of 1.5 ft/yr. However, there are some places where differences between simulated and measured data were as high as 50-70 ft for 11 years (or 4.5-6.4 ft/yr). Largest differences were mostly at south Nags Head where erosion rates were up to 18 ft/yr at some stations during this time.

In addition to the direct comparison between simulated and measured shoreline changes, it is desirable to define a meaningful measure of the degree of agreement for purposes of assessing the confidence merited by the calibration. The following equation (Dean 2002) provides a measure (ε) for the accuracy of shoreline changes Δy .

$$\varepsilon = \frac{\sum_i \left(\Delta y_{m_i} - \Delta y_{p_i}\right)^2}{\sum_i \Delta y_{m_i}^{\ 2}} \qquad (1)$$

where the subscript "*i*" denotes the longshore position of the shoreline change and the subscripts "*m*" and "*p*" denote measured and predicted (respectively). If the values of ε are smaller than 0.4 for the calibration phases, and if the nourishment sand is reasonably compatible with the native, the design phase should warrant a high level of confidence.

The ε value for the Nags Head calibration period is 0.24, almost one half of the above-stated criteria of 0.4, suggesting the model can provide reliable simulation for assessing shoreline evolution. Overall, the GENESIS model was able to capture the shoreline change pattern for most of the project area, and simulated changes agreed reasonably well with measurements for the 1994-2005 calibration period.

Net Transport Rates and Volumetric Changes

In addition to shoreline changes, the net longshore sediment transport rates and total volumetric erosion rates were also evaluated to confirm historical shoreline change patterns. Figure 7 shows calculated, net annual longshore sediment transport rates along the modeled shoreline. Positive rates denote net sand movement to the south. The graph shows that the sediment transport rate varied only in a small range at Reach 1 (stations 491+00 to 790+00), but started increasing rapidly from north to south over Reach 2 (stations 790+00 to 920+00) . It continued to increase at a steeper rate from

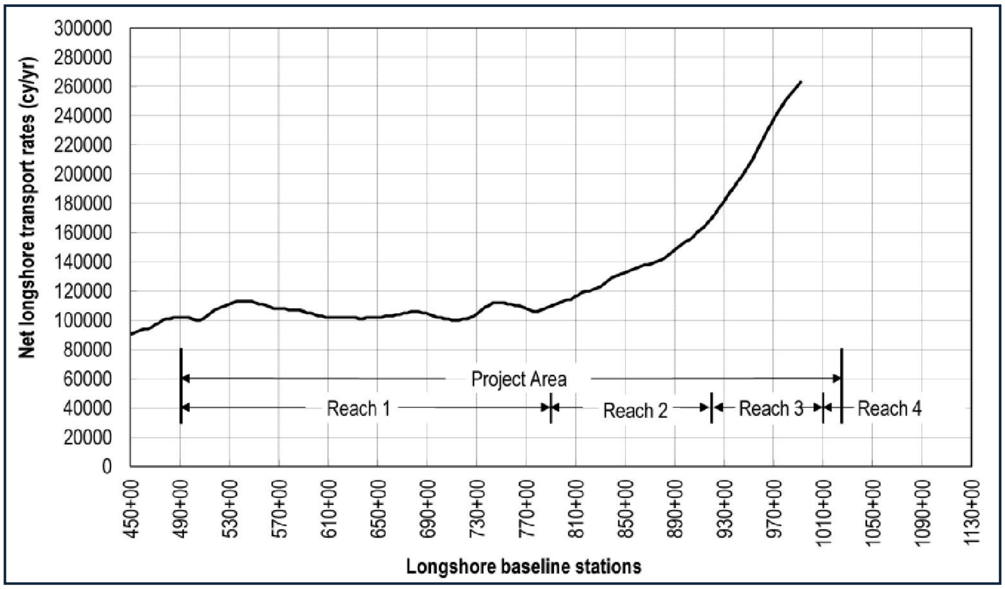

Figure 7. Longshore net sediment transport rates for the calibration period.

stations 920+00 to 990+00 of Reach 3. The increasing transport rate explains the higher erosion observed along south Nags Head (NCDENR 1998, 2004).

The simulated volumetric erosion rate for the area of the model coverage (from station 491+00 to station 990+00) for the calibration period is 162,000 cubic yards per year (cy/yr). If historic data at the model coverage for different periods are examined, annual erosion rates can vary from 109,000 cy/yr to 260,000 cy/yr (as listed in Table 2). Therefore, the erosion rate of 162,000 cy/yr predicted by the model is within the range of available data.

Table 2. Volumetric erosion rates over different periods. [1 cy ≈ 0.76 m^3]

	Aug-94	Aug-04	Apr-05	May-06*	Oct-06*	Nov-06*	Mar-09
Volume from Station 491+00 to Station 990+00 (1000 cy)	39,773	38,064	36,913	38,047	38,470	37,939	38,100
Volume relative to 1994 (1000 cy)		-1,709	-2,860	-1,726	-1,303	-1,834	-1,672
Annual rate (1000 cy/yr)		-171	-260	-144	-109	-153	-111

*Note: Additional survey data obtained by USACE.

MODEL SIMULATION OF BEACH NOURISHMENT PLANS

Using the calibrated shoreline model, shoreline position after a beach nourishment project can be predicted. The model results were used to refine the preliminary nourishment plan (Kana & Kaczkowski, this volume) and increase potential longevity of the project. According to the federal and state permits for the project, up to 4.6 million cubic yards (that is 4 million cubic yards ±15% yielding 3.4-4.6 million cy or 2.7-3.5 million m^3) of beach fill are permitted to be placed along the 10.11 miles of project shoreline. Therefore, the beach fill quantity was designed to be a limiting factor. Different beach-fill templates were studied, and all had a total volume of ~4 million cubic yards. It was assumed that the fill activity would be completed over a construction period of about four months.

While this numerical study was performed, the design profile was based on the 2009 survey beach profiles. (The final design for construction was based on a more recent survey of November 2010.) The new beach after the fill is expected to achieve the same profile after being acted on by storms and waves due to the assumption that the nourishment and native sands are compatible in terms of their grain-size distributions. The offshore segment of the nourished profile at equilibrium is simply displaced the same distance seaward over the vertical active dimension of the profile. After the desired volume of sand has been placed, the nourished beach would be shaped into its original profile with a closure depth of -24 ft NAVD and a dry beach with an average berm height of +6 ft NAVD, which is the same as the 2009 average height of the natural berm along the project area. The equilibrium shoreline advancement (Dean 2002), Δy_0, is given by:

$$\Delta y_0 = \frac{\forall}{h_* + B} \quad (2)$$

where $\forall$ is sand volume per unit length, h_* is the depth of closure, and B is the berm height. Based on the 2009 profile, every 1.11 cy/ft of fill density will yield 1 ft of shoreline advancement (ie – dry beach).

The Nags Head project has a target design life of ~ten years. Therefore, shoreline evolution of 1 year, 5 years, and 10 years after the beginning of dredging and filling was examined to evaluate the project performance, representing shoreline stages shortly after construction, mid-term, and the end of the project design life.

Prior to the evaluation of different beach-fill templates, a scenario without any beach nourishment was first simulated to obtain a better understanding of shoreline performance over times under typical wave conditions. Different fill sceneries were then studied to refine the nourishment design and to select the optimal fill template. All scenarios were set up with 2009 bathymetry and shoreline position as derived from the survey shown in the lower panel of Figure 3. Model parameters are the same as those calibrated in the previous section. Shoreline changes of selected scenarios will be discussed in detail in the following section.

Shoreline Changes Without A Beach Nourishment

It is important to first evaluate the natural shoreline performance under typical wave conditions without any human activities. This no-action analysis helps predict future erosion trends along the project area. It also can help identify erosional hot spots which tend to be the focus of significant engineering interest and public scrutiny. If they can be identified, possibilities exist of designing proper beach-fill density from place to place to avoid or minimize the hot spots and achieve improved beach performance during the life of the project.

Shorelines can change from year to year as well as from season to season. But historic shoreline analysis showed some common trends along the project reaches. The highest shoreline erosion always occurred along Reach 3 (stations 920+00 to 1010+00). There was an average 18 ft of shoreline retreat per year from station 950+00 to station 990+00 and 10 ft/yr around station 910+00 based on 1994 to 2005 data. Other hot spots observed in the historic shoreline analysis occurred between stations 610+00 and 670+00 and between stations 750+00 and 790+00.

Model simulation without nourishment showed that hot spots would occur at locations close to those identified in the historical data. If no nourishment plan is put in place, the model predicted that the shoreline along most of Reach 3 would retreat an average of 50 ft to 100 ft within the next ten years, and the development in this area would be impacted (Fig 8).

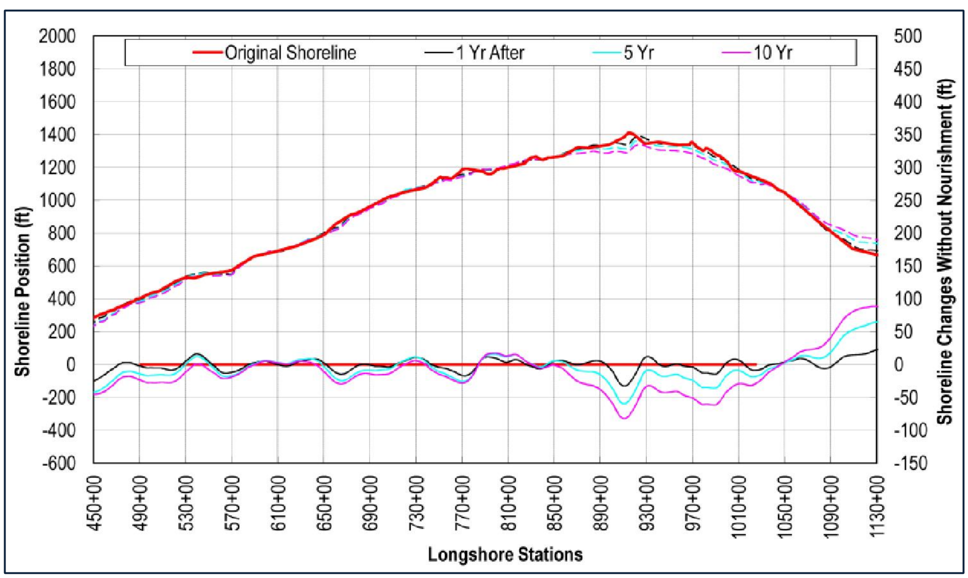

Figure 8. Predicted shoreline positions and changes in 1 year, 5 years, and 10 years without nourishment. [Note: The upper group of lines represent shoreline positions at various run times, and the lower group of lines represent corresponding shoreline changes relative to the original shoreline position (ie — 2009 shoreline).]

Other hot spots predicted by the model are shown in Figure 8. These hot spots occurred mainly as a result of non-uniform wave-focusing conditions due to offshore bathymetry and shoreline orientation. There were usually one or two adjacent erosional cold spots where advancement or accretion of the shoreline was evident. For example, the model results show that a hot spot occurred near station 770+00, while a cold spot occurred at an adjacent station (790+00).

Beach Nourishment – Uniform Width of Fill

If fill was placed uniformly, then 4 million cubic yards of permitted sand would have an average fill density of ~75 cy/ft (188 m^3/m) over the 53,400-ft project length. Since the equilibrium beach profile is assumed to have an average berm height of +6 ft NAVD and a closure depth of -24 ft NAVD, the actual dry beach added everywhere is about 67.5 ft (~20.5 m). Shoreline positions of this scenario for different run times are shown in Figure 9. Note that these shoreline changes have the same pattern as those shown in Figure 8. At the end of ten years, there will be dry beach at most portions of the project site except for a couple of locations predicted and shown in Figure 9. Although 67.5 ft dry beach have been added, shoreline in the areas around stations 900+00 to 920+00 and 980+00 to 1000+00 will still retreat by about 30 ft (9 m) from the existing shoreline in ten years.

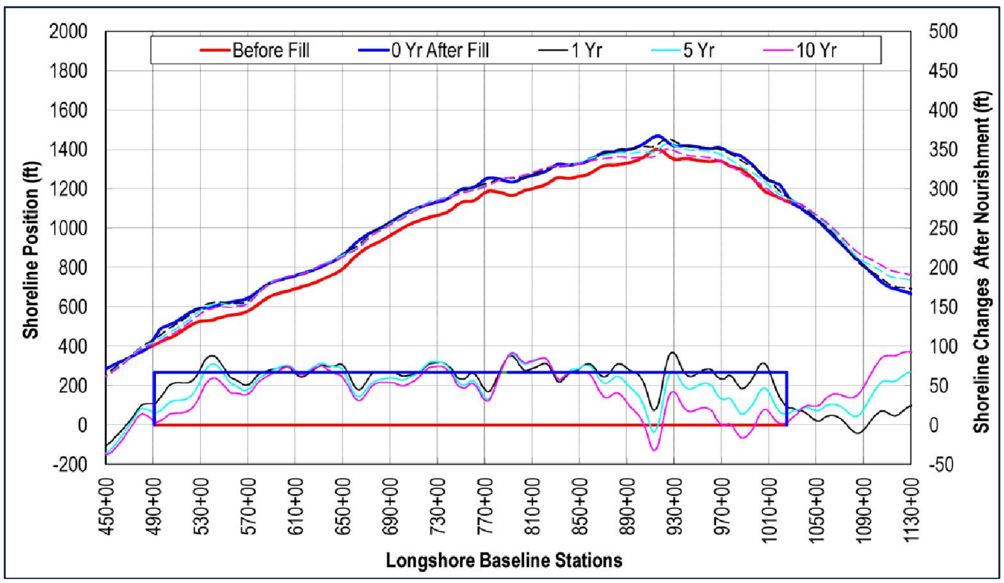

Figure 9. Predicted shoreline positions and changes in 1 year, 5 years, and 10 years with uniform nourishment.

Beach Nourishment – Variable Fill at Hot Spots Only

Simulations of shoreline evolution without any beach nourishment provide a better understanding of shoreline performance and the potential location of hot spots. A question to be investigated is what if only the hot spots are nourished and the no-problem area is left unnourished. CSE simulated selective nourishment of hot spots (Fig 10). The model results indicated the fluctuation in shoreline positions during the first year after the project would not be acceptable, and ten years after the completion of the nourishment the shoreline at certain areas would return to the condition before the nourishment.

Beach Nourishment – Recommended Plan

Based on the results of the previous scenarios, the authors recommended the nourishment plan listed in Table 3. It had the permitted total volume of ~4 million cubic yards and different fill densities from place to place, not necessarily following the exact division from reach to reach. The fill placement of this plan was designed in such a manner that:

1) The greatest benefit is provided to the overall project area.
2) Potential hot spots are avoided or minimized.
3) Variations in fill density are gradual such that construction can proceed efficiently.
4) Shoreline fluctuation after nourishment is minimal.

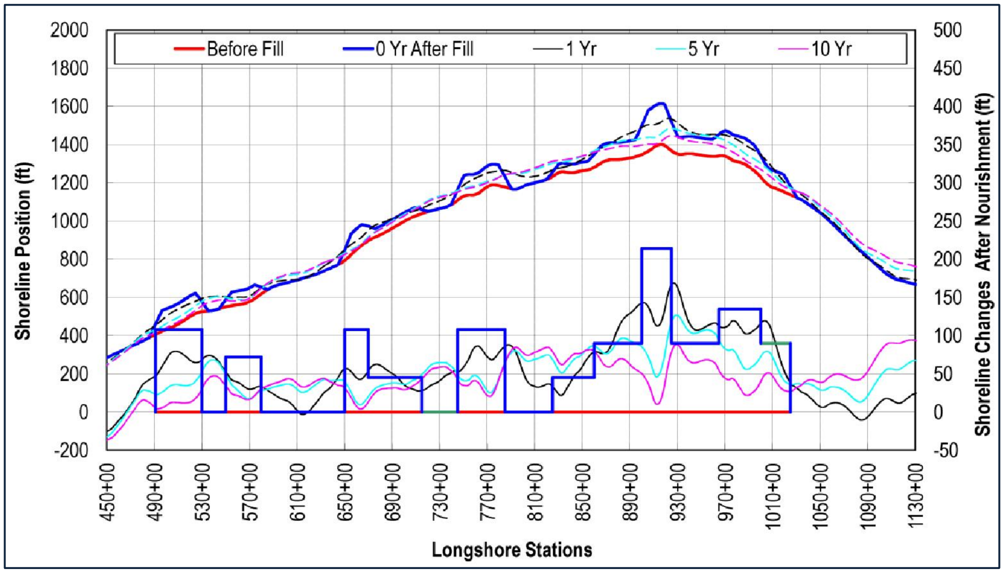

Figure 10. Predicted shoreline positions and changes in 1 year, 5 years, and 10 years with variable fill at hot spots only.

Table 3. Nourishment plan for recommended fill.

Reach #	Limits	Linear feet	Unit Volume (cy/ft)	Reach Volume (cy)
1 - 2	491+00 to 640+00	14,900	38	570,000
	640+00 to 740+00	10,000	50	500,000
2	740+00 to 860+00	12,000	65	780,000
	860+00 to 900+00	4,000	100	400,000
2 - 3	900+00 to 1000+00	10,000	150	1,500,000
3 - 4	1000+00 to 1025+00	2,500	100	250,000
Totals	491+00 to 1025+00	53,400	75	4,000,000

Note: 1 ft ≈ 0.3 m, 1 cy ≈ 0.76 m³, and 1 cy/ft ≈ 2.5 m³/m

According to the recommended nourishment plan (Fig 11), fill densities increase from north to south to provide the highest fill density at the south part of project area. Reach 3 (stations 920+00 to 1010+00) has higher fill density to compensate for the anticipated higher erosion rate. Although the model predicts that a hot spot will likely occur near station 910+00, historic data indicates that it has happened at different places along Reach 3. To be conservative, the recommended fill plan has a density of 150 cy/ft over 10,000 linear feet of shoreline for most of Reach 3. This density is twice as high as the average fill density of 75 cy/ft. On each side of the high-density fill area, a fill density of 100 cy/ft is proposed so that the beach fill will not change suddenly and cause large fluctuations and shoreline instabilities in these areas. A beach segment of 24,900 ft (47 percent of total) will have a lower than average fill density of 38-50 cy/ft.

The shoreline changes in Figure 11 show that although the hot spot at station 910+00 is expected to have the highest erosion rate, overall performance of the nourishment is acceptable. There will be reasonable fluctuation of shoreline position over time, since nature will try to bring the added material into the original natural profile and form a dune on the back of the beach.

Overall, the model results show that there will be 68 ft of dry beach remaining one year after the project, 57 ft after five years, and 23 ft after ten years from the completion of the nourishment. The Nags Head shoreline is therefore, expected to recede by an average of ~ 5 ft/yr, which is in line with the historic erosion rate in the project area.

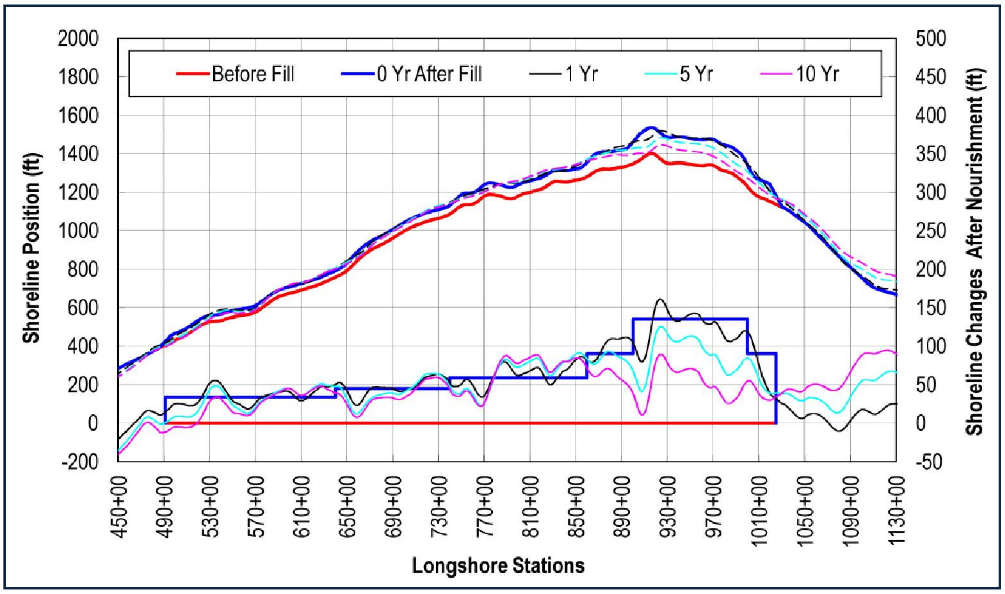

Figure 11. Predicted shoreline changes in 1 year, 5 years and 10 years with CSE recommended fill density.

PROJECT IMPACT

Impact of Borrow Area Dredging on Longshore Sediment Transport

Prior to nourishment, shorelines are in quasi-equilibrium with the waves and offshore bathymetry. Offshore borrow pits from which sand is removed for nourishment can represent substantial perturbations to the nearshore bathymetry. Through wave modification, this depth perturbation has the potential to cause a modified equilibrium planform with shoreline recession in some areas and shoreline advancement in others.

The proposed borrow areas for the Nags Head nourishment project are located 1-3 mi (~1.5-5 km) off Nags Head, and have an average depth of -53 ft NAVD and a total area of 575 acres (Kana & Kaczkowski, this volume). They are located considerably outside the depth limits of significant motion of the sediments. Sediment removal from the borrow sites will result in offshore depressions possibly up to 8 ft (maximum permitted) below the present bottom. To determine if the total removal of the sediment from the borrow sites would have any impact on the concentration of longshore wave energy and littoral sediment transport potential, wave transformation over the borrow sites was analyzed by comparing conditions before and after dredging.

Results from representative wave-incoming directions show that the wave height difference before and after dredging is less than 4 cm. Such difference would cause negligible impact on the annual, net longshore sediment transport as shown in Figure 12. Model results suggest that the borrow area is sufficiently offshore beyond the normal zone of sand transport along the beach, and longshore sediment transport along Nags Head should not be significant modified by the presence of the borrow area pit.

Impact of the Nourishment Project on Oregon Inlet Shoaling

Possible shoaling at Oregon Inlet after the beach nourishment project is a concern of the USACE charged with maintaining the navigation channel as well as the resource agencies. Annual net longshore sand transport rate before and after the project was evaluated and plotted in Figure 13. The results showed that the project impact on the sand transport rate is limited to the project site and its adjacent area. Reach 1 and Reach 2 will experience lower net sand transport rate, and Reach 3 will have a 13 percent higher rate. Locations 9,500 ft (1.8 mi or 2.9 km) south of the south end of project will experience almost no impact on the rate.

Due to the fact that Oregon Inlet is located ~5 mi (~8 km) south of the south end of the project, no adverse impact is detected by the model, and net longshore transport downcoast of Nags Head is expected to remain relatively constant after the project. This has implications for Oregon Inlet dredging because the results indicate the project is not expected to measurably impact shoaling of the channel.

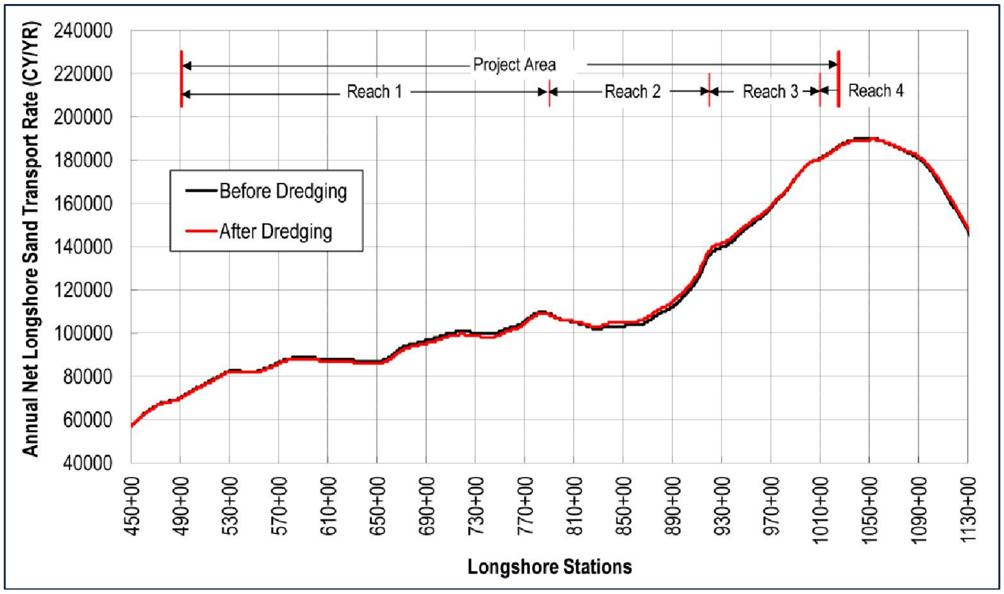

Figure 12. Comparison of annual, net longshore sediment transport rate before and after borrow area dredging.

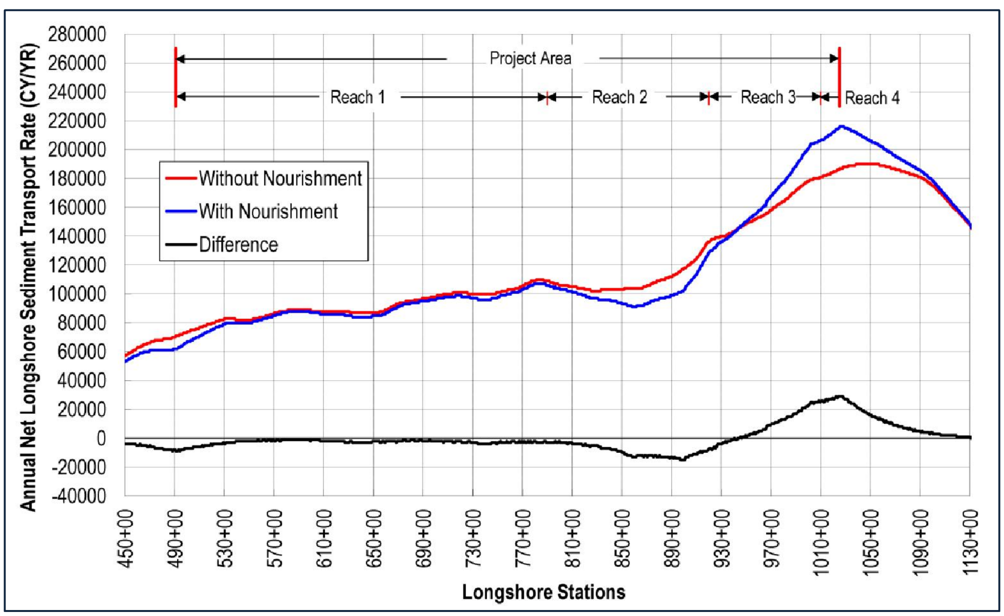

Figure 13. Comparison of annual, net longshore sediment transport rate before and after the nourishment project.

CONCLUSIONS

The Generalized Model for Simulating Shoreline Change (GENESIS) has been widely used to predict the behavior of shorelines and longshore transport. It was used in this study to evaluate shoreline evolution during various stages of the design life following the Nags Head beach nourishment project. Results were used to determine an optimal nourishment plan and to increase potential longevity of the project. The results were also used to evaluate the impact of borrow area dredging on longshore transport and the impact of nourishment on shoaling in Oregon Inlet.

The wave-energy field required by the GENESIS model was provided by a numerical wave model, STWAVE (Steady-state spectral WAVE model). STWAVE and GENESIS were coupled and executed within the Coastal Engineering Design & Analysis System (CEDAS) software package.

The GENESIS model was first calibrated over a period of 11 years from 1994 to 2005 to predict measured shoreline changes and longshore sediment transport rates. The 162,000 cy/yr annual net sediment transport rate obtained from the model was deemed to be within the range of the available data over different periods of time.

Calibration results show that the model is able to capture the shoreline change pattern under typical conditions. However, the model demonstrates that it cannot predict shoreline performance under extreme wind and wave conditions. When a storm occurs, the cross-shore sand transport process will play an important role in shoreline evolution, but such extreme conditions cannot be simulated in the GENESIS model. The cross-shore model SBEACH is applicable for predicting storm-induced beach erosion and post-storm recovery. SBEACH was utilized for the Nags Head project (CSE 2011), but is not included in this paper.

After the calibration was successful, GENESIS was then used as a predictive tool for the project area. A beach fill quantity of 4 million cubic yards (3 million cubic meters) was utilized for different fill configurations. Prior to the evaluation of various beach-fill templates, a scenario without any beach nourishment was first simulated to obtain a better understanding of shoreline performance over time under typical wave conditions. After evaluating different fill schedules, the authors proposed a nourishment plan which is aimed at providing better shoreline performance and longevity after the project.

The recommended nourishment plan calls for increasing fill densities from north to south to compensate for the anticipated gradients in the erosion rate. Reach 3 (stations 920+00 to 1010+00) has a density of 150 cy/ft (375 m^3/s) over 10,000 linear feet of shoreline. This density is twice as high as the average fill density of ~75 cy/ft (188 m^3/m). On each side of the high-density fill area, a fill density of 100 cy/ft (250 m^3/m) is proposed so that the beach fill will not change suddenly and cause large fluctuations and shoreline instabilities in these areas. A beach segment of 24,900 ft (47 percent of total) will have a lower than average fill density of 38-50 cy/ft (95-125 m^3/m).

The predicted shoreline changes show that although a chronic hot spot around station 910+00 is expected to have the highest erosion rate, overall performance of the nourishment is acceptable. There will be continued recession of shoreline position over time; for example, 68 ft of dry beach remaining 1 year after the project, 57 ft after 5 years, and 23 ft after 10 years according to the model simulation results. This equates to average recession rates of ~5 ft/yr which is close to the 50-year average rate for the ~10 mile project area.

The model predicted that the proposed nourishment project at Nags Head will restore a protective beach for a minimum of ten years. Regular monitoring of beach and offshore profiles will be a key component of the project. Model-predicted erosional hot spots are likely to occur, despite variations in the fill density to mitigate them. Although these areas may occupy a relatively small percentage of the total project length, they will likely receive a disproportionate amount of attention and exposure in the media. In addition to monitoring along the project area to document the impacts of the project, surveys will extend to beaches adjacent to the project.

The environmental impact of the borrow area dredging on the project area and possible shoaling at Oregon Inlet after the beach nourishment project is a concern of regulatory and the resource agencies. The model results show that the wave height difference before and after borrow area dredging is <4 centimeters. Such a difference is expected to cause negligible impact on the annual net longshore sediment transport along the project area. Net longshore transport downcoast of Nags Head was found to remain relatively constant after the project based on the model predications. This has implications for Oregon Inlet dredging, because the results indicate the project should not materially impact shoaling of the channel.

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