Toward Predicting Barrier Island Vulnerability:

Simple Models for Dune Erosion

by

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Toward Predicting Barrier Island Vulnerability:  
Simple Models for Dune Erosion

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Abstract

The objective of this study is to quantify the accuracy of two engineering models for dune erosion (SBEACH and EDUNE), and to determine which of the two models is best suited for predicting barrier island vulnerability due to extreme storm events. The first model, SBEACH, computes sediment transport using empirically derived equations from two large wave tank experiments. The second model, EDUNE, theoretically relates excess wave energy dissipation in the surf zone to sediment transport. The first mechanism for model comparison is sensitivity testing, which describes the response of the model to empirical, physical, and hydrodynamic variables. Through sensitivity tests, it is possible to determine if responses to physical variables (e.g. grain size) and hydrodynamic variables (e.g. wave height) are consistent with theoretical expectations, and whether the function of each variable is properly specified within the governing equations. With respect to empirical parameters, model calibrations are performed on multiple study sites in order to determine whether or not the empirical parameters are properly constrained. Finally, error statistics are generated on four study sites in order to compare model accuracy.

Cross-shore profiles of dune elevation are extracted from coastal lidar (light detecting and ranging) surveys flown before and after the impact of major storm events. Three study sites are taken from 1998 lidar surveys of Assateague Island, MD in response to two large northeasters that produced significant erosion along the Assateague shoreline. Two additional study sites are
obtained from 2003 lidar surveys of Hatteras Island, NC in response to erosion caused by Hurricane Isabel. Error statistics generated on these study sites suggest that the models are statistically equivalent in their ability to hindcast dune erosion due to extreme storm events. However, observed inconsistencies in the performance of the EDUNE model undermines confidence in the model to correctly predict dune erosion. These inconsistencies include ill-constrained empirical parameters, as well as a flawed description of onshore transport that leads to anomalous accretionary features on the beach and dune. Therefore, SBEACH is viewed as the preferred model for future studies employing macroscale approaches to dune erosion modeling.
Chapter One

Introduction

Study Objective

Hazards posed by coastal change arise from many different environmental causes, including long-term coastal change due to sea level rise, and short-term events such as cliff failure and erosion caused by extreme weather conditions. This study focuses on coastal change that arises as a consequence of extreme storm events that often reshape entire beach environments and cause immense property damage. Tall sand dunes that line many beaches absorb wave energy produced by small storms, thereby protecting adjacent coastal properties. In fact, sand dunes are so effective at protecting coastal property that many state governments in the United States have paid millions of dollars to create, reinforce, and heighten coastal dunes. However, even tall and massive dunes cannot withstand the most severe storms, and when dunes fail, water and sand inundate entire coastal areas, destroying and damaging property.

The fallible nature of the dune system has led researchers to create predictive models to quantitatively describe dune response to extreme storm events. Two of these models are EDUNE, a first principles model that quantifies beach change based on the theory of an equilibrium beach profile, and SBEACH, an empirical model derived from observations of sediment transport in large wave tank studies. In order to predict coastal change in areas of special concern, both models have been used by government agencies including the Federal Emergency Management Agency and the U.S. Army Corps of Engineers. However, both models incorporate multiple empirical parameters to account for unknown physical processes, some of which are capable of drastically changing model results. Because calibration values tend to vary
widely between coastal areas, the models will remain questionable as predictive tools until all parameters are properly constrained. The limited availability of storm-related beach surveys has hampered this process, with reports of calibration values still ranging over an order of magnitude on different beaches (Larson and Kraus, 1989; Larson, Kraus, and Byrnes, 1990).

The advent of lidar (light detecting and ranging) mapping, an airplane based system for producing high-resolution elevation maps, now makes it possible to better constrain empirical parameters and to verify these models with an extensive number of beach profiles. In order to accomplish these goals, the models will first undergo sensitivity testing and calibration with a set of profiles from Assateague Island, MD, which were eroded as a result of two northeasters that traversed the Atlantic Ocean in early 1998. Sensitivity tests will first identify parameters that affect the accuracy of model results, and subsequent calibrations will constrain the parameters to values that minimize model RMS error. The calibrated models will then be verified with profiles from Hatteras Island, NC that experienced extensive erosion as a result of the passage of Hurricane Isabel in 2003. The verification process questions whether model error is minimized with the calibration values generated with the Assateague Island profiles, despite changes in dune morphology and storm characteristics. If the calibrated values are stationary between the two study areas, then the model is considered well constrained with respect to its empirical parameters.

Three additional study areas are selected from Assateague and Hatteras Islands for further testing, each exhibiting unique characteristics in dune morphology and storm-induced erosion. The first additional study area consists of a set of berm profiles on Assateague Island that lack the presence of a dune. As a result of the storms, these profiles experienced severe erosion on the foreshore, and the development of overwash deposits landward of the original berm location. The second additional site consists of tall dunes on Assateague Island that experienced great variability in dune response, from complete destruction of the dune, to mild beach erosion. The
variation in dune response does not exhibit a consistent longshore trend, and may be due to gradients in longshore forcing and sediment transport rates. Finally, the third additional site is a section of Hatteras Island coastline that was breached by storm surge and waves during Hurricane Isabel. This inlet is the first storm-related breaching event recorded by lidar, and creates an excellent case study for the models’ ability to predict extreme impacts. Because neither model has been tested with similar data sets in the past, this analysis will expand the potential applications of both models.

Model performance will be evaluated on two levels, including the qualitative ability to correctly predict ‘impact regime,’ as well as quantitative accuracy in reproducing the measured post-storm profile. First, impact regimes are qualitative descriptions of dune erosion that can be incorporated into maps that predict the vulnerability of the coastline to storm events. The four impact regimes utilized in this study were developed by Sallenger (2000), and include swash, collision, overwash, and inundation. Vulnerability maps have tremendous potential to identify weak sections of the dune system, and therefore, both models will be analyzed for their ability to correctly predict impact regime for vulnerability mapping applications. Secondly, two quantitative measures of error will be used to evaluate the accuracy of the models in predicting measured post-storm dune shape. Quantitative measures of accuracy will allow an assessment of model performance between study sites, and will facilitate a comparison of the two models.

This research is conducted as a part of the USGS National Assessment of Coastal Change Hazards program, a project of the USGS Coastal and Marine Geology program that seeks to create a better understanding of coastal processes of societal concern. The societal relevance of this research is threefold in that (1) because it seeks to predict the vulnerability of different coastal areas, it will serve as a planning tool for counties and states when creating zoning laws and construction setback limits, (2) this research will bring about a better understanding of the fundamental nature of nearshore hydrodynamics and sediment transport during storm events,
knowledge that can be applied to all coastlines affected by extreme weather events, and (3) the correct application of numerical models should provide improved real time predictions of beach change, comparable to the National Weather Service’s hurricane tracking system. Quantification of the vulnerability of U.S. coastlines to storm events has multiple scientific and societal impacts, all of which stem from the pressing need for comprehensive knowledge of the response of coastal geomorphology to physical forcing created by storms.

Background

Beginning in the 1940s, coastal scientists performing beach surveys observed a remarkably consistent seasonality in profile shape. During summer months when wave heights were small, the beach maintained a wide, flat berm, and in general the nearshore zone was void of sandbars. In winter months when wave heights increased, the berm narrowed and sandbars were formed. Shepard (1950) called these differing shapes “summer profiles” and “winter profiles” after documenting five years of this behavior at Scripps Pier in La Jolla, CA. Bascom (1953) also observed this cyclic behavior with two years of observations at Carmel, CA. Both assumed that the volume of sand was conserved between the berm and the sandbars over these seasonal cycles, although neither measured far enough offshore to confirm this hypothesis. Literature now commonly identifies the two profile shapes as “berm profiles” and “bar profiles” (Komar, 1998). While these differences have generally been observed on seasonal cycles, they also apply to changes that result from large storm events.

At first, attempts to delineate between the two cases were based on critical values of offshore wave steepness, \( H_\infty / L_\infty \), where \( H_\infty \) is the significant offshore wave height, and \( L_\infty \) is the associated wave period. Johnson (1949) reported that based on his data, values of wave steepness less than 0.025 always resulted in berm profiles, and steepness values greater than 0.03 always generated bar profiles. The critical wave steepness varied greatly between studies, and was given
by Rector (1954) to be 0.016. Rector remarked that differences in critical $H_c/L_c$ values could possibly be attributed to differences in grain size between beaches. This observation initiated a large number of studies attempting to incorporate grain size into the critical threshold for the occurrence of bar and berm profiles.

Most notably, Dean (1973) developed a critical relationship between wave steepness and the dimensionless fall velocity, $w_s/gT$, where $w_s$ is the fall speed of a specific grain size, $g$ is acceleration due to gravity, and $T$ is the wave period. Dean theorized that sediments are primarily suspended during the crest phase of a wave, when onshore horizontal velocities dominate. Therefore, if the time required for a grain to fall out of suspension is small compared to the wave period, the grain will move onshore. However, if the settling time is much greater than the wave period, the sediment is transported offshore into the bar. The equation developed by Dean as a critical boundary between bar and berm profiles based on small scale laboratory data is:

$$\frac{H_x}{L_x} = \frac{1.7\pi w_s}{gT}. \quad (1.1)$$

Several subsequent studies have attempted to revise this model, including Larson and Kraus (1989) who developed the relationship:

$$\frac{H_x}{L_x} = 0.00070\left(\frac{H_x}{w_s T}\right)^3. \quad (1.2)$$

based on observations from large wave tank studies. This equation is used by Larson and Kraus to predict the direction of sediment transport in the SBEACH model, the implications of which will be discussed in Chapter 3.

A more advanced approach to predicting profile evolution is the development of time dependent models that calculate profile change as a function of hydrodynamic forcing. Multiple process based models attempt to quantify profile change by developing governing equations for wave-sediment, current-sediment, and sediment-sediment interactions. These models often
incorporate internal modules for computing waves, currents, and sediment transport. Hedegaard, Deigaard, and Fredsøe (1991) present a deterministic model for predicting the morphology of nearshore profiles. The model focuses on the development of the wave-current boundary layer and the resultant transport of sediments. The hydrodynamic portion of the model accounts for wave heights across the profile, non-linear wave interactions in the turbulent wave boundary layer, wave drift, and mean flows. The sediment transport module is based on the channel flow approach of Engelund and Fredsøe (1976), which separates transport into bedload and suspended modes.

Nairn and Southgate (1993) and Southgate and Nairn (1993) also developed a process-based model for predicting sediment transport across the nearshore zone. This model also includes internal hydrodynamic modeling, including longshore processes such as the $S_{xy}$ radiation stress component. The specification of longshore forcing allows the model to predict longshore gradients in transport leading to profile change. The Nairn and Southgate sediment transport model is based on the classic energetics approach of Bagnold (1963), which states that a portion of wave and current produced energy is expended in transporting suspended sediment loads.

Several other deterministic profile change models have been developed, each employing different variations of several existing process-based sediment transport models, including those mentioned above, the Grant and Madsen (1979) model, and others. These process based models focus on the transport of sand in the nearshore zone, which is exceedingly important for predicting erosion on the beach and dune. However, no models to date have attempted to incorporate these deterministic models with descriptions of the swash and avalanching processes that define the basic mechanisms for subaerial profile erosion.

Several notable approaches to predicting dune erosion have focused on empirical considerations of wave runup created by storms. Fisher, Overton, and Chisholm (1986) constructed full-scale sand dunes in the swash zone at the FRF Pier, and videotaped the gradual
erosion process. Vertical stakes and capacitance wave gauges were used to characterize the specific force of each swash bore, and the videos were used to calculate the eroded volume of sand created by individual bores. The specific force was found to correlate linearly to the volume of sediment eroded from the dune. Overton, Fisher, and Fenaish (1987) then developed a two-dimensional momentum equation to predict the specific force created by each bore, and Overton et al. (1993) investigated the roles of grain size and dune density on the erosion of the dune by the individual bores.

Sallenger (2000) proposed a conceptual model that classifies interactions between runup and dune morphology into one of four impact regimes including swash, collision, overwash, and inundation. Lidar data were used to identify the elevations of the dune crest and dune base, denoted as ‘dhi’ and ‘dlo’ respectively. Holman’s (1986) equations for calculating runup based on offshore wave characteristics were used to calculate the high and low elevations of runup, named ‘rhi’ and ‘rlo.’ Comparisons of the runup and dune elevations place each dune into one of the four regimes. For example, if the high elevation of runup exceeds the dune crest, overwash is expected. This model does not have the capability to predict the volume of sediment eroded or the shape of the post-storm dune. Additionally, because the model is not time dependent, it neglects storm-induced changes in dune morphology that may affect the prediction of impact regime.

Edelman (1968, 1972) developed a simple geometric dune erosion model specific to the Dutch coastline, where a series of dikes and tall dunes protect the country from inundation by the North Sea. This model predicts the volume of eroded sediment and resulting post-storm profile shape based on the highest elevation of storm surge occurring during the storm. The profile shape is predicted by a single equation that relates the horizontal position of each contour to the maximum storm surge elevation. This model produces profiles in favorable agreement with
observed field data in the Netherlands, but does not perform satisfactorily on other coastlines because of its specific calibration to Dutch dunes.

More recent models have attempted to incorporate time dependence and additional hydrodynamic variables such as wave height and wave period. One such model under investigation in this study is SBEACH (Larson and Kraus, 1989). This model employs an internal wave model developed by Dally, Dean, and Dalrymple (1984, 1985), and empirical relationships that define sediment transport rates based on observations from two large wave tank studies. The large wave tank data revealed the existence of four cross-shore regions with unique sediment transport rate structures. This model makes use of excess energy dissipation as the main driving force behind sediment transport, a mechanism that is also derived from wave tank observations. The SBEACH model is described in more detail in the following section, and model results are presented in Chapter 3.

The second model explored in this study is EDUNE (Kriebel and Dean, 1985). This model is based on equilibrium beach profile theory developed by Dean (1976, 1977). Dean’s theory states that individual beach profiles should come into static equilibrium with constant waves and water levels. The profile maintains its equilibrium shape because waves generate uniform energy dissipation per unit volume across the profile. However, when water levels rise, wave shoal further inshore and dissipate excess energy over the shallow portions of the profile. Subsequently, the profile evolves toward equilibrium with the new hydrodynamic forcing. The EDUNE model is described later in this chapter, and model results are presented in Chapter 4.

**SBEACH Model Description**

In an attempt to quantitatively predict profile change, the SBEACH model was developed by a group of coastal engineers at the U.S. Army Corps of Engineers Waterways Experiment Station. Their primary objective was to develop a tool that could predict beach change in the vicinity of coastal engineering projects. The model takes a macroscale approach to predicting
beach change, invoking sediment transport over length scales of meters, and time scales of hours. This approach was preferred to a microscale sediment transport model, because at the time of development little was known about sediment-current, sediment-wave, and sediment-sediment interactions on the seafloor. Although these theories have been advanced in recent years, the computing time required to run these models is substantial, covering spatial scales limited to a few square meters rather than the hundreds of meters that a profile typically encompasses. Rather, the evolution of macroscale features such as berms and sandbars exhibit amazing regularity in time, and therefore the development of a macroscale model was prudent.

The numerical scheme makes two main assumptions about the nature of sediment transport in the coastal environment. First, the model assumes that over short time scales and under storm conditions, profile change is dominated by cross-shore transport, and therefore longshore sediment transport gradients can be excluded. Secondly, the developers assumed that sediment transport rates observed during two large wave tank experiments could be applied to the field environment. Initial tests of the model with field data showed that adjustments were required to correctly scale the model to real world beach environments. After these adjustments were made, favorable agreement was found between calculated and measured post-storm profiles for several beaches on the east and west coasts of the United States.

A full description of the large wave tank experiments, model development, and model tests can be found in a series of technical reports published by the USACE. The first report by Larson and Kraus (1989) describes the large wave tank experiments, as well as the data analysis techniques used to derive the fundamental equations implemented in the numerical model. A second report by Larson, Kraus, and Byrnes (1990) describes model development and the numerical scheme in greater detail. Wise, Smith, and Larson (1996) report verification tests and the development of an optional randomized wave model that can be implemented within the SBEACH program.
For each simulation, the user defines the shape of the pre-storm profile, which the model interpolates to the pre-defined grid spacing. The user also supplies time series of offshore significant wave height, period, angle, and water elevation, which are interpolated to the chosen time increment. At each time step, values from the time series are used to calculate the cross-shore wave height profile, by employing the wave model of Dally, Dean, and Dalrymple (1984, 1985). The wave heights are then used to calculate sediment transport rates, which are applied to the profile change module. The following paragraphs describe each step of the process in detail, including the method for calculating wave heights across the profile, the transport rate equations, and computations of profile change.

**Wave Height Module**

Beginning at the seaward-most grid cell, wave height is known from the input time series, and energy flux can be calculated with the following equation:

\[ F = EC_g \]  \hspace{1cm} (1.3)

where \( E \) is the wave energy density, and is defined as:

\[ E = \frac{1}{8} \rho g H^2, \]  \hspace{1cm} (1.4)

and \( C_g \) is the wave group speed defined as:

\[ C_g = nC. \]  \hspace{1cm} (1.5)

In the group speed equation, \( C \) is the wave phase speed and is equal to wavelength divided by period, where wavelength is determined from the full equations for linear wave theory. The quantity \( n \) is defined as:

\[ n = \frac{1}{2} \left[ 1 + \frac{2\kappa d}{\sinh(2\kappa d)} \right] \]  \hspace{1cm} (1.6)
where $\kappa$ is the wavenumber, and $d$ is the total depth defined by:

$$d = h + \eta. \quad (1.7)$$

where $\eta$ is setdown (or setup) caused by excess momentum flux due to waves. In the seaward most calculation cell, setdown is determined analytically with the equation:

$$\eta = \frac{\pi H^2}{4L \sinh(2\kappa d)}. \quad (1.8)$$

and is used to calculate total depth in Equation 1.7. Utilizing Equations 1.4 through 1.8, the energy flux at the seaward boundary of the profile can be calculated with Equation 1.3.

Once $F$ is calculated in the seaward-most cell, the model utilizes the conservation of energy flux equation developed by Dally, Dean, and Dalrymple (1984, 1985):

$$\frac{\partial}{\partial x} (F \cos \theta) + \frac{\partial}{\partial y} (F \sin \theta) = \frac{k}{d} (F - F_s) \quad (1.9)$$

where $F_s$ is the stable energy flux, $\theta$ is the wave angle with respect to the bottom contours, and $k$ is the wave decay coefficient. A convenient two-dimensional form of Equation 1.9 that assumes alongshore-uniform wave conditions and straight and parallel bottom contours is written as:

$$\frac{d}{dx} (F \cos \theta) = \frac{k}{d} (F - F_s). \quad (1.10)$$

A finite difference form of Equation 1.10 is used to calculate the value of $F$ at the adjacent landward cell.

To perform this calculation, the value $\theta$ is calculated from a finite difference form of the two-dimensional Snell’s Law equation that assumes straight and parallel bottom contours:

$$\frac{d}{dx} \left[ \sin \frac{\theta}{L} \right] = 0 \quad (1.11)$$

where $\theta$ is given at the seaward-most cell, and $L$ is calculated in both cells with the full linear wave theory equations. Before waves break, $k$ is set at a value of zero, indicating that the only
changes in energy flux are due to changes in wave angle as waves shoal over intermediate and shallow depths:

\[
\frac{d}{dx} (F \cos \theta) = 0.
\]  

(1.12)

After \(F\) is calculated at the adjacent grid cell, wave height is determined with Equations 1.3 through 1.7. Setdown (or setup) is determined from a finite difference form of the radiation stress equation:

\[
\frac{dS_{xx}}{dx} = -\rho g \frac{d\eta}{dx}
\]  

(1.13)

where \(S_{xx}\) is the x-directed flux of x-directed momentum given by the equation:

\[
S_{xx} = \frac{1}{8} \rho g H^2 \left[ n(\cos^2 \theta + 1) - \frac{1}{2} \right].
\]  

(1.14)

This process continues cell by cell, moving landward towards the shoreline.

After wave height is determined at each grid cell, the model checks for broken waves with the following empirical criterion:

\[
\frac{H_b}{h_b} = 1.14 \left( \tan \beta \left( \frac{H_{\infty}}{L_{\infty}} \right)^{1/2} \right)^{0.21}
\]  

(1.15)

where \(\tan \beta\) is the slope of the local profile. Breaking waves occur when the ratio of wave height to water depth meets or exceeds the condition specified by the right hand side of this equation.

When the first instance of breaking waves occurs, Equation 1.10 is modified so that \(k\) is set at a standard value of 0.15 determined by large and small wave tank experiments. This coefficient value determines the rate at which energy is dissipated as the waves break. The stable energy flux in Equation 1.10 \((F_s)\) is defined as the energy flux necessary for stable conditions to occur once the waves break, and is calculated by the equation:

\[
F_s = E_s C_g.
\]  

(1.16)
In this equation, $E_s$ is the stable wave energy density determined by:

$$E_s = \frac{1}{8} \rho g H_s^2$$

(1.17)

where $H_s$ is a function of water depth and the empirical parameter $\Gamma$:

$$H_s = \Gamma d.$$  

(1.18)

The value of $\Gamma$ is set at 0.40, which was also determined from large and small-scale wave tank experiments.

Finally, the model attempts to simulate wave reformation by identifying grid cells where $F=F_s$. When this condition is met, the wave is considered to reform, and $k$ is again set at a value of zero. The model then searches for the next break point using a new breaking criterion:

$$\frac{H_b}{h_b} = 1.$$  

(1.19)

This criterion for waves breaking after reformation is used in order to maintain numerical stability in the shallow region of the surf zone. The end result of this module is a cross-shore profile of wave heights calculated at the given time step. The wave heights are then fed into the sediment transport rate module, which is described in the following section.

**Sediment Transport Module**

The large wave tank experiments used to develop the SBEACH model revealed four distinct cross-shore regions, each defined by a unique sediment transport rate structure. The four zones are illustrated in Figure 1.1, and are referred to as (I) the prebreaking zone, (II) the breaker transition zone, (III) the broken wave zone, and (IV) the swash zone. The location of each region shifts landward and seaward in time with the break point, while Zones II and III often occur multiple times in the presence of wave reformation. Wave heights calculated by the methods described in the previous section are used to divide the profile into these four regions.
First, the boundary between Zones I and II is defined at the location of the break point. The breaking wave criterion establishing this location is defined in Equation 1.15, and is dependent on the ratio of wave height to water depth. The boundary between Zones II and III is located at the plunge point, a distance $3H_b$ landward of the break point. The distinct separation of the break point and the plunge point is based on observations that a certain distance is required after wave breaking before turbulent conditions become uniform. Finally, the boundary between Zones III and IV is dependent on an arbitrary depth $\alpha$ assigned by the user, which generally ranges between 0.1 and 0.5 meters. The effects of assigning different values of $\alpha$ on model results are explored in Chapter 3.

The transport rate equations derived from the large wave tank experiments are as follows:

**Zone I:**

$$Q_x = Q_b e^{-\lambda_b (x - x_b)}, \quad x_b < x$$  

**Zone II:**

$$Q_x = Q_p e^{-\lambda_p (x - x_p)}, \quad x_p < x < x_b$$  

**Zone III:**

$$Q_x = \begin{cases} K \left[ D - D_{eq} + \frac{\varepsilon}{K} \frac{dh}{dx} \right] & D > \left[ D_{eq} - \frac{\varepsilon}{K} \frac{dh}{dx} \right] \\ 0 & D < \left[ D_{eq} - \frac{\varepsilon}{K} \frac{dh}{dx} \right], \quad x_z < x \leq x_p \end{cases}$$  

**Zone IV:**

$$Q_x = Q_z \left[ \frac{x - x_r}{x_z - x_r} \right], \quad x_r < x < x_z$$

In these equations, each subscript refers to a specific location on the cross-shore profile, where $b$, $p$, $z$, and $r$ refer to the location of the break point, the plunge point, the landward edge of the surf zone, and the runup limit respectively.
Equation 1.22 defines the sediment transport rate $Q_s$ in the broken wave zone. The $D-D_{eq}$ term accounts for excess energy dissipation across the profile, which is the main mechanism driving sediment transport in this zone. This equation was derived from the large wave tank observation that excess wave energy dissipation accounted for 50 to 70% of the variability in transport rate, while the local profile slope accounted for an additional 10% of the variability. The term $D$ in this equation is the wave energy dissipation per unit volume, and is defined by the equation:

$$D = \frac{k}{d^2} (F - F_s) \ . \quad (1.24)$$

Equilibrium energy dissipation $D_{eq}$ is the energy density required to maintain the instantaneous profile form, and the equation for computing $D_{eq}$ is:

$$D_{eq} = \frac{5A^{3/2} \rho g^{3/2} \gamma^2}{24} \quad (1.25)$$
where \( \gamma \) is the ratio of wave height to water depth at breaking, and \( A \) is the profile shape parameter. The value of \( A \) is determined by the equation:

\[
h^{3/2} + \frac{\varepsilon}{K} \frac{24}{5 \rho g^{3/2} \gamma^2} = A^{3/2} \chi
\]

which is based on the equilibrium profile shape developed by Dean (1977).

Additional terms in Equation 1.22 are \( K \), the transport rate coefficient, an empirical coefficient that directly controls the magnitude of the sediment transport rate, and \( \varepsilon \), an empirical coefficient governing the slope dependent term. Values of \( K \) generally range between 2.5x10^{-7} and 2.5x10^{-6} m^4/N, and calibration values from previous studies have varied widely across this approximate range. Values of \( \varepsilon \) range between 5.0x10^{-4} and 5.0x10^{-3} m^2/s, although little calibration work has been done with this parameter. Chapter 3 discusses the effects of both empirical parameters on model results, and provides a calibration value for each.

Sediment transport rates in Zones I and II decrease exponentially moving away from the plunge point, and the rate decay coefficients are defined by:

\[
\lambda_1 = 0.4 \left( \frac{D_{50}}{H_b} \right)^{0.47}, \text{ and}
\]

\[
\lambda_2 = 0.2 \lambda_1.
\]

Subsequent versions since the original model release have turned \( \lambda_1 \) into an empirical coefficient defined by the user, which generally ranges between 0.1 and 0.5 m^{-1}. Chapter 3 will also discuss the effect of \( \lambda_1 \) on model accuracy. Once \( \lambda_1 \) and \( \lambda_2 \) are defined, sediment transport rates offshore of the breakpoint are computed with Equations 1.20 and 1.21.

Finally, sediment transport rates in Zone IV decrease linearly from the landward edge of the surf zone to the limit of runup. The limit of runup is defined as the ‘active subaerial profile height’ \( (z_r) \) developed from the large wave tank data:
\[ z_r = 1.47 \left( \frac{\tan \beta}{(H_w / L_w)^{1/2}} \right)^{0.79}. \] (1.29)

Once \( z_r \) is calculated, sediment transport rates in the swash zone are computed with Equation 1.23.

Once the transport rate magnitudes have been determined for the entire length of the profile, the model employs a final equation to determine the direction of transport:

\[ \frac{H_s}{L_n} = 0.00070 \left[ \frac{H_w}{w_s T} \right]^3. \] (1.30)

Both the large wave tank studies and field data show that this equation has good predictive skill in delineating between episodes of onshore and offshore transport. When the left hand side of the equation is larger (smaller) than the right hand side, onshore (offshore) transport takes place over the length of the profile.

Profile Change Model

Once sediment transport rates are calculated across the profile, a finite difference form of the conservation of mass equation is used to evolve the profile to its new form:

\[ \frac{\partial h}{\partial t} = \frac{\partial Q_s}{\partial x}. \] (1.31)

The model solves for profile change by adjusting the vertical elevation at fixed horizontal locations along the profile. The landward boundary for the application of this equation is the horizontal limit of runup, and the offshore boundary occurs where the sediment transport rate decreases to zero.

The profile change model also employs the concept of avalanching, which occurs when the slope between adjacent grid cells becomes overly steep. When the slope of the profile exceeds the angle of initial yield \( \phi \), avalanching occurs between neighboring grid cells, until the
residual angle $\phi$-10° is achieved. This mechanism safeguards the model from numerical instabilities that would occur with nearly vertical slopes. The large wave tank data suggests that the angle $\phi$ should be set at 28°, with a residual angle of 18°. The effects of assigning different values of $\phi$ on model results are discussed in Chapter 3.

**EDUNE Model Description**

In an attempt to predict the N-year frequency distribution of extreme coastal erosion events, coastal engineers at the University of Delaware’s Center for Applied Coastal Research developed the EDUNE model to quantitatively forecast the volume of erosion produced by a randomly generated storm. Existing Monte Carlo storm surge models were used to calculate storm surge from randomly selected meteorological parameters, and breaking wave heights were also estimated based on the parameters of the storm. A theoretical erosion model named EDUNE was then developed to incorporate storm surge and breaking wave height values. The model was used to calculate eroded volumes on simulated beach profiles, and these volumes were used to calculate the N-year frequency distribution of erosional events.

The development of the EDUNE model is documented in multiple papers, including the original report in the *Proceedings of the 19th Coastal Engineering Conference*, which details its development for calculating erosional frequency distributions (Kriebel and Dean, 1984). Improvements to the model are documented in a second report by Kriebel and Dean (1985), and two users manuals published as technical memos for the Beaches and Shores Resource Center at Florida State University (Kriebel, 1984(a); Kriebel, 1984(b)). Final improvements to the model are documented in the *Proceedings of the 22nd Coastal Engineering Conference* (Kriebel, 1990), and a users manual published by the University of Delaware’s Center for Applied Coastal Research (Kriebel, 1995).
Although EDUNE was developed as a first principles model with the goal of calculating eroded sediment volumes for frequency distributions, it was quickly popularized for a variety of coastal engineering tasks because it was the first quantitative model developed to predict sediment transport on the subaerial profile. Most notably, the U.S. Army Corps of Engineers and the Federal Emergency Management Agency used the model to predict the impact of storms on United States beaches. Several years later, EDUNE became outdated when the SBEACH model was developed and adopted by the USACE and FEMA. However, EDUNE remains a good case study of a predictive erosion model, because of its theoretical approach to beach erosion. The guiding principle of the equilibrium beach profile is incorporated into many models, and therefore it is important to understand the EDUNE model implicitly before attempting to create and understand more advanced models.

The first simplifying assumption made by EDUNE is that sediment transport gradients in the cross-shore dominate over short time scales and under storm conditions, and therefore longshore processes can be excluded from the model. As a consequence of this assumption, cross-shore forcing generates all change in the beach profile. The second assumption alleges that the energy dissipation per unit volume generated by constant wave heights and water levels produce a profile in static equilibrium with the forcing. The amount of energy dissipation required to maintain the shape of the profile is called the ‘equilibrium energy dissipation,’ and is a function of wave height, water level, and shape of the profile. The profile produced by constant waves and water levels is called the ‘equilibrium profile.’

Once a profile comes into equilibrium with hydrodynamic forcing, a rise in water level allows waves to shoal further inshore, increasing the energy dissipation per unit volume over the shallow profile. Because the actual energy dissipation is greater than the equilibrium value for the given profile shape, the profile must evolve in order to attain equilibrium with the new forcing. The evolution of the profile proceeds with the erosion of sediment from the beach and
surf zone, which translates the profile upward and landward. As water levels and wave heights fluctuate over time, a continual evolution of the profile takes place as the energy dissipation fluctuates at levels greater than equilibrium values. The profile will continue to evolve until wave heights and water levels are constant and the profile once again reaches equilibrium with the forcing.

For each simulation, the user defines the pre-storm profile shape, which must conform to the requirement that elevations decrease monotonically on either side of the dune crest. Because actual profiles seldom meet this requirement, a routine was developed to transform lidar profiles into this form, and is documented in detail in Chapter 2. The user also supplies time series of storm surge elevations, wave period, breaking wave heights, and runup elevations. Because breaking wave height is not recorded by any traditional observational methods, the SWAN model (Booj et al., 1999) is used to generate breaking wave heights from measured offshore wave parameters. At each time step, values from the breaking wave height time series are used to calculate the location of the surf zone, and subsequently, sediment transport rates are computed across the width of the active profile. Calculated sediment transport rates are then used to compute the evolution of the profile based on profile change equations. The following paragraphs describe each step of the process in detail, including calculations of sediment transport rates and the profile change module.

**Sediment Transport Module**

The first step in calculating sediment transport rates is defining horizontal boundaries on the surf zone. The seaward boundary is defined as the location of wave breaking, and is calculated from empirical evidence that suggests that the wave height is a fixed percentage of the water depth when it breaks (McCowan, 1894; Sverdrup and Munk, 1946):

\[ \gamma_b = \frac{H_b}{h_b} = 0.78 \quad (1.32) \]
At each time step, the breaking wave height \( H_b \) is known from the input time series, and the depth at breaking \( h_b \) can be calculated. The horizontal location of this depth defines the seaward boundary of the surf zone. The landward boundary is defined at the depth where the concave underwater beach profile is tangent to the equilibrium beach slope. This slope, named \( \text{etanb} \), is an empirical parameter that is defined by the user for each model run, and the horizontal location of this depth defines the landward boundary of the surf zone. The effects of assigning different values of \( \text{etanb} \) on model results are explored in Chapter 4.

The EDUNE model does not employ an internal wave module, and therefore, wave heights are not calculated at each grid cell within the surf zone. Rather, the authors developed a method to calculate sediment transport rates at each grid cell without knowledge of the local wave height. As stated in preceding paragraphs, sediment transport occurs when energy dissipation per unit volume exceeds the equilibrium energy dissipation specific to that profile. Therefore, it is only necessary to calculate equilibrium dissipation \( (D_{eq}) \) and actual dissipation \( (D) \) in order to compute sediment transport rates.

To calculate \( D_{eq} \), the model utilizes Dean’s equilibrium profile theory, which states that equilibrium energy dissipation per unit volume exists for each profile, and is a function of profile shape, wave height, and water level. Equilibrium energy dissipation is calculated from Dean’s equation that relates \( D_{eq} \) to the shape parameter \( A \), wave height, and water depth:

\[
D_{eq} = \frac{5A^{1/2} \rho g^{3/2} H^2}{24h^2} .
\]  

(1.33)

An equation for determining \( A \) was derived by Moore (1982), and suggests that the shape parameter is a function of grain size:

\[
A = \begin{cases} 
10 & D_{50} < 0.262 \\
10^{\frac{\log D_{50} - 2.264}{3.30}} & D_{50} \geq 0.263 
\end{cases}
\]

(1.34)
where $D_{50}$ is the median grain diameter in millimeters. Because $H$ is not calculated at each grid cell, it must be removed from Equation 1.33 through theoretical principle. Assuming that the waves are spilling breakers, the value of $\gamma$ is set equal to $\gamma_b$ from Equation 1.32, indicating that wave height decreases proportionally as a function of water depth as waves break across the surf zone:

$$\gamma = \frac{H}{h} = 0.78 \quad (1.35)$$

This assumption allows Equation 1.33 to become independent of wave height:

$$D_{eq} = \frac{5A^{3/2}\rho g^{3/2}\gamma^{2}}{24} \quad (1.36)$$

In order to calculate sediment transport rates, it is then necessary to compare the value of $D_{eq}$ to the actual dissipation of energy per unit volume across the width of the surf zone.

The actual energy dissipation per unit volume ($D$) is calculated at each grid cell using the equation:

$$D = \frac{1}{h} \frac{dF}{dx} \quad (1.37)$$

where $F$ is the energy flux. The quantity $F$ is determined from the linear theory equation for waves propagating in shallow water:

$$F = EC_g \quad (1.38)$$

where $E$ is the energy density, and $C_g$ is the wave group speed. Energy density is defined as:

$$E = \frac{1}{8} \rho g H^2 \quad (1.39)$$

and the equation for wave group speed in shallow water is:

$$C_g = (gh)^{1/2} \quad (1.40)$$
Combining Equations 1.39 and 1.40, Equation 1.38 becomes:

\[ F = \frac{1}{8} \rho g^{3/2} H^{2} h^{1/2}. \]  

(1.41)

Spilling breaker theory from Equation 1.35 is again used to eliminate the dependence of \( F \) on wave height, and the equation becomes:

\[ F = \frac{1}{8} \rho g^{3/2} \gamma^{2} h^{5/2}. \]  

(1.42)

This value of \( F \) is used to compute \( D \) at each grid cell with Equation 1.37.

Once \( D \) and \( D_{eq} \) are calculated across the width of the surf zone, sediment transport rates are calculated as a function of the excess wave energy dissipation:

\[ Q_{x} = K(D - D_{eq}) \]  

(1.43)

where \( K \) is the transport rate coefficient that governs the magnitude of the sediment transport rate. The transport rate coefficient is a free parameter in the model formulation, and was found by Moore (1982) to be \( 2.2 \times 10^{-6} \) m\(^4\)/N. Later calibration by Kriebel (1986) with a large-scale laboratory experiment performed by Saville (1957) increased the best estimate of \( K \) to \( 8.7 \times 10^{-6} \) m\(^4\)/N. The effects of assigning different values of \( K \) on model results are discussed in Chapter 4.

The transport rate calculated at the landward edge of the surf zone is used as a boundary condition for calculating sediment transport rates in the swash zone. Sediment transport rates are computed according to geometric arguments rather than a physically based swash zone transport model. This process is described as the “potential erosion prism method,” and the numerical scheme aims to evolve the profile slope to match the equilibrium beach slope, \( \theta_{tanb} \). Figure 1.2 provides a schematic diagram of this method, which is described in detail by Kriebel (1990, 1995). If the equilibrium slope is steeper than the existing slope, the situation is defined as Case I, and the contours at the bottom of the prism have a greater erosional potential than those at the top. In Case II situations, the existing slope is steeper than the equilibrium slope, and correspondingly the top of the
prism has the greatest erosion potential. When the two slopes are identical, as shown by Case III, all contours erode uniformly.

![Diagram](image)

**Figure 1.2** Illustration of the “potential erosion prism method” used to calculate sediment transport rates between the landward edge of the surf zone and the edge of runup. This figure is taken from Kriebel (1990).

One serious limitation found in the model’s numerical scheme is the inability to simulate overwash processes when water levels overtop the existing dune crest. The imposed continuity requirement states that sediment must be conserved between the active dune crest and the most seaward grid cell, and therefore sediment cannot be transported outside of this zone (i.e. landward). A second limitation of the model is that onshore transport is simulated only when water levels fall and the quantity \( D-D_{eq} \) becomes negative. This condition for onshore transport is not physically based, but rather a by-product of the numerical scheme. No attempts have been made to determine the validity of this representation of the recovery process, although it has been
suggested that it produces much quicker recovery than is experienced in nature (Larson and Kraus, 1989). Larson and Kraus (1989) also noted that maximum onshore transport rates are simulated when energy dissipation reaches a minimum at zero. Previous studies have shown that a cutoff energy dissipation exists under which no transport occurs, suggesting that this process is an inaccurate description of system dynamics.

Profile Change Module

Once sediment transport rates are calculated for each grid cell between wave breaking and the landward edge of runup, the profile change module employs a finite difference form of the continuity equation:

\[
\frac{\partial h}{\partial t} = \frac{\partial Q}{\partial x} . \tag{1.44}
\]

The EDUNE model solves this equation for profile change by calculating the horizontal location of fixed vertical contours. The equation is solved in the form of a tridiagonal matrix relating three adjacent contours, and a recursion formula that is employed in a double-sweep procedure to determine the change in the position of each contour over time. The specifics of this process are described in detail by Kriebel and Dean (1985).

After Equation 1.44 is utilized to compute the resulting profile, the numerical scheme checks the slope between adjacent grid cells to assure that the profile has not become overly steep at any location. The maximum allowable slope between any two adjacent contours depends on their position across the profile. The empirical parameters tanoff, tanrep, and etand are defined as the maximum allowable slopes seaward of the break point, along the active profile, and between the edge of runup and the dune crest, respectively. If the slope between adjacent contours exceeds the corresponding critical value, the horizontal distance between the fixed vertical contours is adjusted to meet the critical value, and eroded sediment is redistributed to neighboring contours. The slope above the runup limit is a special case, in which sand that is eroded from the
dune as a result of oversteepening is redistributed on the beach face until the slope there becomes uniform. Additional sand is distributed in a non-uniform manner across the active profile, decreasing in thickness moving offshore. Each of these three slope values is defined by the user, and the effects of each value on model results will be explored in Chapter 4.

Assateague Island Study Site

Assateague Island is an unpopulated barrier island encompassing approximately 57 kilometers of Maryland and Virginia coastline. The island hosts two national wildlife refuges, Assateague NWR in the north and Chincoteague NWR in the south, and is undeveloped except for a state highway that runs along the coastline. A map detailing the location of Assateague Island and the three local study areas is provided in Figure 1.3. The first study area, Assateague North, is used for sensitivity testing and calibration with respect to empirical, physical, and hydrological parameters. The second and third sites, Assateague South and Chincoteague, are used to investigate model accuracy, and to confirm empirical parameters calibrated with Assateague North data.

In October 1997, a cooperative program between the USGS, NASA, and NOAA produced detailed elevation maps of the island using lidar mapping techniques. The data gathered by this system are spatially dense, rendering approximately one elevation measurement per square meter, and providing an excellent snapshot of the instantaneous topography of this transient system. These data were gathered as part of the “lower 48” mapping project aiming to characterize the barrier island system. Soon after the data were collected, a large storm system moved north along the Atlantic Coast, causing extensive beach and dune erosion. This event provided an excellent opportunity for mapping the post-storm island topography, creating one of the first highly dense sets of pre and post-storm beach profiles. The following paragraphs describe these storms in more detail.
On January 26, 1998, a low pressure cell originating in Texas migrated quickly across the southern United States, turning northeast and crossing into the Atlantic Ocean over the mouth of the Chesapeake Bay around 19:00 EST on January 28th. The storm system moved north along the Atlantic Coast, buffeting the shoreline with winds exceeding 80 km/hour, and generating offshore significant wave heights exceeding 7 m. The storm system moved north, with wind speeds decreasing by 19:00 on January 29th. Several days later on February 3rd, a second low pressure cell originating in the Gulf of Mexico migrated north across the coastal states, entering the Atlantic Ocean over the North Carolina-Virginia border at 19:00 on February 4th. This storm was stronger than the previous system, producing wind speeds exceeding 95 km/hr, and offshore significant wave heights again in excess of 7 m. This storm lasted approximately 24 hours before fading offshore of the Maine coastline. A more detailed description of the storm system is provided by Ramsey et al. (1998).

Figure 1.4 displays storm data local to Assateague Island beginning at 08:00 on January 27th, and ending at 10:00 on February 13th. Water level elevations (\(\eta\)) were obtained from NOAA
Tide Gauge 8570283 at Ocean City Inlet, MD, and are referenced to mean sea level. Wave data were gathered from NDBC Buoy 44009 in Delaware Bay, including significant offshore wave height ($H_\infty$), peak period ($T_p$), and wave angle ($\theta$). The wave angle measurements in this figure have been transformed from the true north orientation recorded by the buoy into the convention used by the SBEACH model, where $0^\circ$ indicates waves approaching the beach shore normal, positive angles indicate waves approaching from the northeast, and negative angles denote waves approaching from the southeast. This transformation was made with the first order approximation that the Assateague Island coastline runs directly north to south. These data are used to simulate the storm system in both models, for all locations along Assateague Island.

![Figure 1.4](image)

**Figure 1.4** Storm characteristics of the two northeasters that affected Assateague Island during January and February 1998. These time series were used as input data into both models. Time 0 corresponds to 08:00 EST on January 27th, 1998.
For both models, the absolute timing of the events is not as important as an accurate representation of the water levels and wave heights, with particular importance assigned to keeping the relative timing of the waves and water levels as accurate as possible. The relative proximity of the tide gauge and buoy to one another provides data that are well synchronized in time, when compared to other possible combinations of offshore buoys and coastal tide gauges that were operational during this time period. Additionally, the large extent of the storm system compensates for the distance between the instruments and the study sites. Unlike the compact nature of a hurricane, northeasters tend to affect large areas of coastline in a relatively uniform manner.

Figure 1.5 plots dune elevation as a function of latitude for the length of Assateague Island. The top plot shows pre-storm dune elevations gathered in 1997, and the bottom plot displays post-storm dune elevations collected in 1998. As this figure indicates, significant losses in dune crest elevation occurred around a few hotspots, while the majority of dunes maintained their pre-storm dune elevations. The locations of the three study sites, including two from Assateague Island NWR in Maryland, and one from Chincoteague NWR in Virginia, are highlighted in yellow. Each site is approximately three kilometers long, encompassing 300 cross-shore profiles. Because of limitations on computing time, 30 evenly spaced profiles from each area were chosen for the study.
Figure 1.5  Dune crest elevations are plotted as a function of latitude along Assateague Island. The top graph displays pre-storm elevations, and the bottom graph presents post-storm elevations.

The Assateague North study area is situated at the north end of the island, and is composed of high dunes averaging 6.5 m in elevation at the crest. Over the course of the storm, these dunes experienced erosion on the beach and dune face. Figure 1.6 plots the observed gross volume change for each of the 30 profiles as a function of latitude, indicating that erosion in this area was relatively constant, increasing slightly moving to the north. This figure also plots three profiles from this study area in order to demonstrate several examples of observed profile change. Towards the south, the profiles experienced little change, with small volumes of sediment eroded from the beach. Along the northern end of the study area, the dune face was consistently eroded back from its original location, although never beyond the location of the dune crest.
Figure 1.6 Observed values of gross volume change are plotted as a function of latitude for the Assateague North study site, and three example profiles display the varying impacts of the storm on dune erosion. In each figure the blue profile represents the pre-storm profile, and red represents the post-storm profile.

The Assateague South study area is composed mainly of “berm type profiles” averaging 2.8 meters in elevation at the berm crest. Figure 1.7 plots observed gross volume change on this section of island as a function of latitude, along with three profiles demonstrating the typical response of the beach and berm to the storms. On most profiles, the storm eroded sediment from the top of the berm, and transported a portion of the sand landward to form thin overwash deposits. Profiles of this nature are ubiquitous along the U.S. Atlantic and Gulf Coasts, and therefore, it is essential to understand the behavior of both models on this study site.
Figure 1.7 Observed values of gross volume change are plotted as a function of latitude for the Assateague South study site, and three example profiles display the varying impacts of the storm on dune erosion. In each figure the blue profile represents the pre-storm profile, and red represents the post-storm profile.

Finally, the Chincoteague study area is situated on the south end of the island, and is composed of high dunes with a mean elevation of 5.8 meters at the dune crest. From Figure 1.5, it is apparent that this is an area of high longshore variability in dune response, with some dune crest heights changing by more than three meters, while others experience no change at all. Figure 1.8 displays the observed gross volume change for each of the 30 profiles as a function of latitude, along with three corresponding profiles. The longshore variability is even more expressed in this figure, with some dunes experiencing total erosion and overwash, while others experienced only mild beach erosion. There is no discernable pattern to the erosion, suggesting that longshore gradients in local hydrodynamic forcing may have caused these variations in dune response.
Figure 1.8  Observed values of gross volume change are plotted as a function of latitude for the Chincoteague study site, and three example profiles display the varying impacts of the storm on dune erosion. In each figure the blue profile represents the pre-storm profile, and red represents the post-storm profile.

Hatteras Island Study Site

Hatteras Island is a narrow barrier island that encompasses more than 80 kilometers of North Carolina coastline. The northern portion extends from Oregon Inlet in the north to Cape Hatteras in the south, and includes Pea Island Wildlife Refuge and several small village communities. At Cape Hatteras the island turns to the southwest, ending approximately 20 km away at Hatteras Inlet. This section of the island encompasses the small town of Hatteras Village at its southwestern edge. The entire island is included in the Cape Hatteras National Seashore, and therefore developments are small and growth is highly restricted. The two Hatteras Island study areas both lie on the southwest to northeast trending portion of the island, displayed in Figure 1.9. The first, Hatteras North, is used for model verification after the models are
calibrated to Assateague Island profiles. The second site, Hatteras Breach, is the site of island breaching that took place during Hurricane Isabel.

![Figure 1.9](image)

**Figure 1.9** Maps showing the location of the two Hatteras Island study areas, the location of NDBC Buoy 41025 at Diamond Shoals, and NOAA Tide Gauge 8654400 at the Hatteras Island Fishing Pier.

Hurricane Isabel developed as a tropical wave off the western coast of Africa on September 1, 2003. The system moved slowly westward, and was given hurricane status on September 7th. The storm intensified over the following days, and was classified as a Category 5 hurricane on September 11th, with maximum sustained winds in excess of 260 km/hr. On September 15th, the system turned north-northwest and encountered increased vertical wind shear, which weakened the storm to a Category 3 hurricane.

On September 18th, Hurricane Isabel made landfall at Drum Inlet, North Carolina as a Category 2 storm, with maximum sustained surface winds of 128 km/hr recorded near Cape Hatteras. The location of landfall was approximately 45 kilometers to the southwest of the study sites on Hatteras Island. As the storm passed over the Outer Banks, significant wave heights at the location of the Diamond Shoals buoy reached 15 m, as predicted by the WaveWatch3 model. Storm surge along the coast was consistently greater than 2 meters for locations lying to the
northeast of landfall. A NASA true color satellite image of the storm is presented in Figure 1.10. Additional details and descriptions of Hurricane Isabel are available in the National Hurricane Center’s Tropical Cyclone Report (Beven and Cobb, 2004).

![Figure 1.10](image) A true color image of Hurricane Isabel taken by NASA’s Terra satellite at 11:50 EST on September 18th, 2003.

As Isabel slowly advanced on the east coast of the United States, lidar surveys were flown over much of the coastline on September 16th, just as waves from the storm began to approach the shore. This is the first lidar data set flown immediately before the strike of the storm, eliminating questions of profile change between the first flight and storm impact. Lidar surveys were gathered post-impact on September 21st, providing an ideal snapshot of beach change caused by the hurricane. Although the data coverage extends the entire length of the Outer Banks, the quality of the pre-storm profiles in some areas is compromised because of the hurried nature of the flights prior to the arrival of the storm. Because it was difficult to identify a
long stretch of coastline without gaps in high quality coverage, the study areas were narrowed to 300 meters, with profiles spaced approximately 10 meters apart in the longshore.

The intensity of the hurricane caused many observational instruments to fail near the peak of the storm. For this reason, the data used for model runs combine observed and modeled storm characteristics from a variety of sources. Figure 1.11 plots the storm characteristics as a function of time, beginning at 00:00 EST on September 16th. Water level information is derived from two NOAA tide gauges, 8651370 at the Duck FRF Pier, and 8654400 at the Cape Hatteras Fishing Pier. Although the Cape Hatteras tide gauge is perfectly positioned in relationship to the study areas (Figure 1.9), it failed prior to the peak of the storm on September 18th. Data recorded prior to gauge failure were compared to several other coastal tide gauges in the area, and were found to best match the record at the Duck Pier, more than 100 km to the north. Because of a lack of alternatives, the Duck record was used as a best estimate of conditions at the study site. Because the Duck gauge was significantly further from landfall than the study site, the two records begin to diverge immediately before the Hatteras tide gauge failed. For this reason, data at the peak of the storm is replaced with water level predictions from the National Hurricane Center’s SLOSH model, which estimates that water levels reached 2.2 meters at the height of the storm.

Wave heights and periods were recorded offshore at NDBC Buoy 41025 at Diamond Shoals until several hours before the peak of the storm. For model runs, predictions from NOAA’s WaveWatch3 model extracted at the location of the Diamond Shoals buoy were substituted for observed data. The model also provides peak periods and wave angles, which are illustrated in Figure 1.11. The wave angles in this figure have been transformed to the conventions used by SBEACH, where 0° indicates a wave approaching shore normal, positive angles indicate waves arriving from the east, and negative angles indicate waves arriving from the
south. This transformation relies on the approximation that the southern portion of Hatteras Island trends exactly southwest to northeast.

**Figure 1.11** Storm characteristics for Hurricane Isabel that affected Hatteras Island during September 2003. These time series were used as input data into the models. Time 0 corresponds to 00:00 EST on September 18th, 2003.

In Figure 1.12, dune crest elevations from Hatteras Inlet to Cape Hatteras are plotted as a function of longshore distance, and the two study areas are highlighted in yellow. As mentioned previously, the two study areas identified as Hatteras North and Hatteras Breach both encompass a longshore extent of 300 m, consisting of 30 profiles spaced approximately 10 m apart in the longshore. The average pre-storm dune crest elevation on this stretch of beach was 4.5 meters, with a standard deviation of 1.8 meters. As this figure indicates, significant losses in dune crest elevation were recorded along the southwestern section of the island that was closest to landfall.
The Hatteras North study area is composed of tall dunes averaging 6.5 m in elevation at the dune crest. The storm caused extensive damage on this study site, lowering the mean dune crest elevation to 5.3 m. Observed erosion on this site is confined mostly to the dune face and crest. These observations are captured in Figure 1.13, which plots observed gross volume change as a function of latitude, and three pre- and post-storm profiles from this area. On these profiles, erosion is observed at the top of the dune, while the beach appears to have accreted through deposition of the eroded sand.
Figure 1.13 Observed values of gross volume change are plotted as a function of latitude for the Hatteras North study site, and three example profiles display the varying impacts of the storm on dune erosion. In each figure the blue profile represents the pre-storm profile, and red represents the post-storm profile.

The Hatteras Breach study site consists of shorter dunes averaging 4.5 m in elevation at the dune crest. As seen in Figure 1.14, the post-storm profiles clearly show that the dune and beach were completely destroyed as a consequence of the storm. However, because lidar cannot penetrate water, the post-storm profiles are only reflections off the water’s surface, and do not measure the depth of the channel scoured by currents moving over the island. Because lidar cannot capture the true post-storm bathymetry, calculations of eroded volumes are not practical. The extreme nature of the impact along this section of coastline may be due to a number of factors, including extreme local water levels and wave heights, short and narrow dunes, the narrowing of the island at this location, and transport by currents flowing over the island.
Figure 1.14 Three profiles displaying dune change at the Hatteras Breach study site. In each figure the blue profile represents the pre-storm profile, and red represents the post-storm profile.
Chapter Two

Methods

Description of Lidar Data Sets

Topographic data sets were obtained from airborne topographic lidar (Light Detection and Ranging) surveys. Lidar technology is a laser mapping technique with numerous remote-sensing applications, which in recent years has been adapted for coastal applications including the rapid surveying of narrow strips of beach and barrier island environments. The rapid nature of the surveying method makes lidar ideal for collecting storm related beach change data sets. Descriptions of coastal lidar theory and methods are presented in Brock et al. (2002), and are briefly summarized here.

Analogous to radar theory, lidar systems emit laser pulses that reflect off the earth’s surface, allowing the computation of elevation from the two-way transmission time. These high frequency laser pulses are emitted from NASA’s airborne topographic mapper (ATM), a light-transmitting device that is mounted on a small twin-engine aircraft that flies at an altitude of approximately 700 meters. The ATM emits laser pulses at a frequency of 20,000 Hz in an elliptical scanning pattern as the aircraft flies overlapping flight lines over the survey site. The pulses are emitted with a near step function shape, and return time measurements are referenced to a pre-defined amplitude on the leading edge of the pulse. The return time, or two-way transmission time, is used to calculate the distance between the airplane and the earth’s surface, a measurement that is also known as range. An illustration of the lidar system is provided in Figure 2.1.
Additionally, the aircraft is fitted with an Inertial Navigation System (INS), which records pitch, roll, and heading of the plane at a frequency of 64 Hz and an accuracy of 0.1 degrees. Measurements from the INS are used to correct range measurements from simple return time calculations. The aircraft is also equipped with Global Positioning Systems (GPS), which records the location of the plane with an accuracy of 5 centimeters when operated in conjunction with a GPS ground station. The ground station is usually located at the airport where the local aircraft operations are based. The raw data including range measurements and GPS locations are converted to latitudes and longitudes in NAD83 and elevations in NAVD88. Post-processed data sets consist of approximately one elevation measurement per square meter.

In order to investigate storm-induced beach change, the post-processed data are utilized to construct a series of cross-shore elevation profiles spaced approximately ten meters apart in the longshore direction. Elevation points lying within +/- 1 meter of a pre-defined profile line are incorporated into each cross-shore profile. Each profile encompasses several hundred meters of beach and dune morphology, from landward of the frontal dune, to seaward of the beach/water.
interface. Lidar data gathered either from the “lower 48” mapping project conducted in the mid to late 1990s (Assateague Island study areas), or from immediately before the storm event (Hatteras Island study areas) are utilized in constructing pre-storm profile lines. Lidar surveys are flown within several days of the passage of major storm events, and cross-shore profiles are extracted at longshore locations matching those of the pre-storm profiles.

The vertical accuracy of ATM survey data was investigated as part of the 1997 nearshore field experiment “Sandy Duck” held at the U.S. Army Corps of Engineers Field Research Facility (FRF) in Duck, North Carolina. Field methods and an in-depth statistical analysis from this study are presented in Sallenger et al. (2003), and are summarized here. On September 26th, seven overlapping ATM surveys were conducted over a 70-km stretch of beach encompassing Bodie Island from Corolla to Oregon Inlet. On the same day, three distinct ground surveying methods were used to conduct surveys of three regions of Bodie Island encompassed by the ATM surveys. The ground surveys were carried out to allow a statistical determination of the vertical accuracy of the ATM data.

The first ground surveying method, the “long transect buggy,” consisted of a single transect line along the beach from Corolla to Oregon Inlet, obtained from an Ashtec GPS receiver mounted on an ATV. The second method, the “local transect buggy,” gathered multiple cross-shore survey lines from the region of runup to the dune base over a longshore distance of 3 km in the vicinity of the FRF, and consisted of a Trimble GPS mounted on an ATV. The final ground surveying method, the “GPS rod survey,” consisted of a series of beach transects from the region of swash to the dune base over a 100-meter longshore stretch near Corolla. This survey was conducted manually with an Ashtec GPS mounted on a stadia rod. It is important to note that each of the ground surveys encompassed only the beach region, so that error estimates obtained from this study can only be applied to the beach, and not to the steeply sloping face of the frontal dune.
Statistical analysis of the data included intercomparisons of the seven overlapping ATM surveys, as well as comparisons between the ATM and ground-based surveys. The study shows that the vertical accuracy of individual elevation measurements obtained by ATM surveys is $\cong 15$ cm. While this error estimate may not be acceptable for some applications, 15 cm is a reasonable instrument error relative to vertical beach change recorded during storm events. Sallenger et al. cite the 1998 Assateague Island storms, and note that for the profiles investigated in their study, maximum vertical beach change was approximately 2 meters, and maximum vertical dune change was approximately 3 meters.

SBEACH Program Interface

The SBEACH program (Version 3.01G, released 2003) was purchased through Veri-Tech Inc., a coastal science and engineering software company. Publications documenting model theory consist of five Army Corps of Engineers technical reports, including Larson and Kraus (1989), which discusses the model’s empirical foundation, and Larson et al. (1990), which introduces the numerical scheme. The three additional manuals include Rosati et al. (1993) which is a users manual for an early DOS version of SBEACH, Wise et al. (1996) which discusses a random wave model that the user can choose to incorporate in model runs, and Larson and Kraus (1998) which discusses modifications to the model that allow nonerodible hard bottoms. SBEACH runs on a Microsoft Windows interface, and the code is not available to the user for modification. Therefore, all work done with the SBEACH model was performed within the user interface developed by Veri-Tech Inc.

Profiles are compiled in Matlab, and transferred individually into the SBEACH user interface in tabular format. The subaerial profile consists of the exact lidar profile bounded on the seaward edge by the horizontal location of mean sea level. The subaqueous profile is calculated with Dean’s $h=Ax^{2/3}$ equilibrium equation and Moore’s equation for $A$ (Equation 1.34), and is fitted to the subaerial profile at the location of mean sea level. Time series of water
level, offshore significant wave height, wave angle, and peak period are also transferred into SBEACH in tabular format. Various windows within the program allow the user to define physical variables and empirical parameters. Following each model run, final profile data is saved in tab delimited data files with the help of an automated keyboard software program. A Matlab program then converts the tab-delimited data into Matlab .mat files in a format suitable for statistical analysis programs.

EDUNE Program Interface

The EDUNE model is available online through the University of Delaware’s Center for Applied Coastal Research (CACR, 1994). The CACR website provides code for EDUNE in the Fortran programming language, as well as example data files for two profiles and their corresponding storms, profile R-41 from a Hurricane Eloise data set, and profile F-9 from a Hurricane Frederic data set. A users manual written by Kriebel (1995) describes program variables, as well as the individual algorithms that complete the framework of the program. The following paragraphs describe how this information was utilized and implemented in the current study.

Before EDUNE was utilized for the current study, the model was translated from its original Fortran to the Matlab programming language, in order to allow faster computing times and convenient storage of output data. The Matlab version was verified with the example data files provided on the CACR website. When running EDUNE in Matlab, the user must first create an input file defining physical variables and empirical parameters. The program prompts the user for profile numbers, which are identical to USGS profile numbers extracted from lidar data sets. The program also prompts the user for a number assigned to the storm event of interest. The program extracts profile data and time series data of storm surge, peak period, offshore significant wave height, and breaking wave heights from corresponding data folders. Following each model run, output data including the final profile is automatically saved in a separate file folder.
One significant limitation of EDUNE is that input profiles must monotonically decrease in elevation both seaward and landward of the dune crest. Profiles of this form are seldom observed in lidar surveys, and cannot encompass backbarrier dunes, nor accurately represent elevated berms that occur seaward of the dune crest. In order to transform each lidar profile to meet this requirement, a Matlab program was developed to convert measured elevations into the correct monotonic form while maintaining as much of the original profile shape as possible. Within this program, if the original lidar profile does not decrease monotonically in elevation on both sides of the dune crest, the program performs a three point moving average across the profile and then assesses the averaged profile for the same monotonic criterion. The program continues this process using progressively larger moving average windows until the criterion is met. The subaqueous profile is calculated from Dean’s $h=Ax^{2/3}$ equilibrium equation and Moore’s equation for $A$ (Equation 1.34), and is fitted to the subaerial profile at the location of mean sea level.

Modified profiles show only small departures from the original lidar measurements, except in cases where elevated berms are present. Figure 2.3 illustrates the differences between the lidar and modified profiles for two cases on Assateague North, one with and one without a significantly elevated berm. Gross volume errors (GVE) and root-mean-square (RMS) errors (both statistical measures are described in more detail later in this chapter) between the original lidar profiles and the modified profiles are presented in Table 2.1 for each of the five study areas. The mean RMS error for all 150 profiles is 15 cm, with a standard deviation of 5 cm. This error is the same magnitude as the rms error of the lidar measurements themselves.
Figure 2.2  Original lidar profile and modified profile that conforms to EDUNE program requirements for (a) a profile with a significantly elevated berm, and (b) a profile without a significantly elevated berm. EDUNE profiles must decrease monotonically in elevation both landward and seaward of the dune crest. Both profiles are from the Assateague North study area.

<table>
<thead>
<tr>
<th>Study Area</th>
<th># of Profiles</th>
<th>Mean GVE</th>
<th>Standard Deviation GVE</th>
<th>Mean RMS Error</th>
<th>Standard Deviation RMS Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assateague North</td>
<td>30</td>
<td>0.09 m$^3$/m</td>
<td>0.02 m$^3$/m</td>
<td>0.13 m</td>
<td>0.04 m</td>
</tr>
<tr>
<td>Assateague South</td>
<td>30</td>
<td>0.12 m$^3$/m</td>
<td>0.03 m$^3$/m</td>
<td>0.18 m</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Chincoteague</td>
<td>30</td>
<td>0.08 m$^3$/m</td>
<td>0.01 m$^3$/m</td>
<td>0.12 m</td>
<td>0.02 m</td>
</tr>
<tr>
<td>Hatteras North</td>
<td>30</td>
<td>0.10 m$^3$/m</td>
<td>0.05 m$^3$/m</td>
<td>0.15 m</td>
<td>0.07 m</td>
</tr>
<tr>
<td>Hatteras Breach</td>
<td>30</td>
<td>0.10 m$^3$/m</td>
<td>0.04 m$^3$/m</td>
<td>0.15 m</td>
<td>0.05 m</td>
</tr>
<tr>
<td>All Study Sites</td>
<td>150</td>
<td>0.10 m$^3$/m</td>
<td>0.04 m$^3$/m</td>
<td>0.15 m</td>
<td>0.05 m</td>
</tr>
</tbody>
</table>

Table 2.1 Mean and standard deviations of both gross volume error (GVE) and root-mean-square (RMS) errors between original lidar profiles and modified EDUNE profiles for each of the five study sites.
Statistical Analysis

Statistical tests performed in this study serve two purposes: (1) defining the sensitivity of the models to changing input variables, and (2) determining the accuracy of the models for both model tests and calibration purposes. Three statistical measures will be discussed, including gross volume change (GVC), gross volume error (GVE), and root-mean-square (RMS) error. First, calculations of GVC are used to measure the sensitivity of the models to changing values of input parameters. GVC is a quantitative measure of the normalized gross change in volume between the measured pre-storm profile and the model predicted post-storm profile. Secondly, both RMS error and GVE are used as quantitative measures of model accuracy. Both calculations measure differences between the surveyed post-storm profile and the model prediction of the post-storm profile. GVE quantifies the normalized gross difference in volume between the two profiles, while RMS error is the root-mean-square error in elevation measurements. A model prediction that matches the measured profile exactly will have both a GVE and an RMS error equal to zero. The following paragraphs discuss the numerical methods used to calculate these three statistical measurements.

The area of interest for the present study is the subaerial profile including the dune and the beach. Therefore, the horizontal boundaries for statistical calculations are defined to encompass only on the subaerial profile. The landward boundary is chosen at the landward edge of the dune and is user defined. The seaward boundary is chosen at the location of mean high water on the post-storm profile, and is determined with a Matlab program developed specifically for this application. MHW is defined on the post-storm profile because it eliminates contamination of the profile by waves. The selection of horizontal boundaries is illustrated in Figure 2.3.
Figure 2.3 Horizontal boundaries on the subaerial profile are chosen at the landward dune base and mean high water. Example profile is 4342 from Assateague North. (a) The shaded area indicates the portion of the profile included in statistical analysis. The landward boundary is chosen manually on the pre-storm profile, and the seaward boundary is chosen by a mean high water crossing method on the post-storm profile. (b) An enlarged view of the subaerial profile.

\[
\text{GVC is calculated as:}
\]

\[
GVC = \frac{1}{L} \sum_{i=1}^{N} (\hat{z}_i - z_{i,\text{pre}})dx
\]

where \(L\) is the length of the profile, \(\hat{z}\) is the predicted elevation, \(z_{\text{pre}}\) is the measured pre-storm elevation, the subscript \(i\) refers to the series of interpolated elevations points, \(N\) is the total number of elevation points, and \(dx\) is the horizontal distance between elevation points.

Measurements of GVC are used in sensitivity tests to describe the response of model results to empirical, physical, and hydrodynamic variables. The calculation of GVE is similarly specified by:

\[
GVE = \frac{1}{L} \sum_{i=1}^{N} (\hat{z}_i - z_{i,\text{post}})dx
\]
where $z_{post}$ is the post-storm dune elevation. Figure 2.4 illustrates the method for calculating GVE with an example profile from Assateague North. Additionally, RMS error calculations make use of the interpolated elevations along the horizontal extent of the subaerial profile:

$$RMS = \left[ \frac{1}{N} \sum_{i=1}^{N} (\hat{z}_i - z_{i,post})^2 \right]^{1/2}.$$  \hspace{1cm} (2.3)

Both GVE and RMS error are used in calibration tests to confirm calibration values of empirical coefficients and to describe the accuracy of the calculated profile.

Figure 2.5 demonstrates how GVE and RMS error change as a function of horizontal spacing between elevation points for five different profiles from Assateague North. A value of $dx=0.1$m is chosen because while smaller intervals allow error statistics to converge to a limiting value, they utilize excessive computation time for the corresponding increase in accuracy. Conversely, greater values of $dx$ cause both error statistics to diverge from the limiting value.
Figure 2.5 GVE and RMS error are plotted as a function of $dx$. As $dx$ decreases, both error statistics converge to a limiting value. For the current study, $dx$ was set at 0.1 m for both calculations. Data is compiled from an SBEACH run on five profiles on Assateague North.

Two additional statistical measures were investigated, but their values were determined to be of limited use for the current study. First, net volume error (NVE) was investigated because it calculates the net positive or negative error associated with the model fit, whereas this information is lost in the calculation of GVE. The NVE calculation is similar to GVE:

$$
NVE = \frac{1}{L} \sum_{i=1}^{N} (\hat{z}_i - z_{i, \text{post}})dx.
$$

This statistical measure had no value as a measure of accuracy, due to local positive and negative errors canceling out over the length of the subaerial profile. NVE calculations often resulted in error estimates near zero when the true model fit was poor, such as the example provided in Figure 2.6. Additionally, contour retreat errors were measured at the mean sea level contour, the 3-meter contour, and the 5-meter contour. These measurements proved problematic, as the mean
sea level contour was often obscured by waves, and as the post-storm dune often did not exceed 3 meters. In some cases of low berm profiles, the 3 and 5 meter contours did not exist on the pre-storm profile. Although these statistical measures have been used in previous studies, their value for this study was limited.

Figure 2.6 Net volume error (NVE) calculations were not used as a measure of accuracy, because local positive and negative errors often canceled over the length of the profile. In this example, NVE is near zero, while the true model fit is poor. In this case, GVE and RMS error provide a better measure of accuracy. For illustrative purposes, $dx=1.0$ m in this graphic. Example data is from an EDUNE model run for profile 4352 from Assateague North.
Chapter Three
SBEACH Results

Introduction

The objective of this chapter is to quantify the accuracy of calculated SBEACH profiles for a variety of model tests, and to identify parameters that influence the magnitude of model error. Sensitivity tests are performed for a wide variety of variables, in order to determine the relative effect of each variable on model results. The first section in this chapter examines the sensitivity and calibration of the model to empirical parameters (e.g. K, the transport rate coefficient), while the second section examines the sensitivity of the model to physical and hydrodynamic variables (e.g. grain size, time series of water levels). All sensitivity and calibration runs are calculated with lidar data from the Assateague North study area.

In the third section, model results and error calculations are presented for the three Assateague Island study sites. Analysis presented in this section confirms the robust nature of the calibrated transport rate coefficient between study sites on the same island. The fourth and final section discusses results from the Hatteras North and Hatteras Breach study areas. Hatteras North data are used to produce a site-specific calibration value for the transport rate coefficient, which is determined to be the same as the calibrated Assateague value. This section also briefly proposes two transport mechanisms that may account for the model’s inability to reproduce the breach.

Model Sensitivity and Calibration: Empirical Parameters

The results of sensitivity tests performed on the SBEACH model are important for two reasons. First, all previous publications about SBEACH have commented on model parameters
in terms of their effects on the development and movement of the sandbar. Because this study seeks to use SBEACH to hindcast the post-storm subaerial profile, it is important to examine sensitivity relative to the dune rather than the bar system. It is imperative to understand these differences in light of the fact that many engineering firms and governmental agencies now use SBEACH to predict dune erosion. Secondly, several recent changes to the SBEACH model have gone unnoted in the literature, most recognizably, the addition of several empirical and physical parameters. The user now defines variables such as the landward edge of the surf zone, the transport rate decay coefficient, and water temperature. The effect of these parameters on model results must be fully understood before SBEACH can be considered a viable predictive tool.

K, the Transport Rate Coefficient

The first empirical parameter inherent to the SBEACH model is K, the transport rate coefficient, which enters the SBEACH model formulation through Equation 1.22:

\[
Q_s = \begin{cases} 
K \left[ D - D_{eq} + \frac{\varepsilon}{K} \frac{dh}{dx} \right] & D > \left[ D_{eq} - \frac{\varepsilon}{K} \frac{dh}{dx} \right] \\
0 & D < \left[ D_{eq} - \frac{\varepsilon}{K} \frac{dh}{dx} \right]
\end{cases}
\]  

(3.1)

K governs the magnitude of the sediment transport rate \(Q_s\), when excess wave energy dissipation is present. As values of K increase, gross volume change is expected to increase proportionally, as large values of K should increase transport rates across the entire profile. Previous studies have found best-fit K-values ranging from 7.0x10^{-7} to 2.0x10^{-6} m^4/N. A range of 2.5x10^{-7} to 2.5x10^{-6} m^4/N is chosen for sensitivity analysis in order explore model results over an order of magnitude, while incorporating the previous calibration values.

Model results for each value of K are presented in Figure 3.1 for an example profile from Assateague North. As predicted, the shape of the calculated profile varies widely, simulating too little erosion for small values of K, and producing excessive erosion for large values of K.
Results of the sensitivity tests for K are shown in Figure 3.2(a). In this figure, the predicted gross volume change is reported as a mean value for the 30 Assateague North profiles, with each error bar representing the 95% confidence interval on the mean value. The apparent trend reveals a statistically significant increase in mean GVC with increasing K. The change in the mean value is 369% across this one order of magnitude of K-values, and is significant at the 95% confidence level.

At the smallest value of K tested, mean gross volume change is 0.47 m³/m, which is evident as a deficiency in erosion on both the beach and dune. Conversely, the entire dune is erroneously eroded at the greatest value of K, with mean gross volume change equaling 2.2 m³/m. Figure 3.2 indicates that among the five empirical parameters, model results are most sensitive to K. For this reason, it is essential to establish an accepted K-value that can be transferred between study areas and storms, if SBEACH is to be used in the future as a predictive tool.

Calibration tests were performed to determine the best-fit K-value through minimization of both RMS error and GVE. Calibration curves are presented in Figure 3.3, indicating that error statistics are minimized at values of 5.0x10⁻⁷ and 7.5x10⁻⁷ m⁴/N. Tests of the equality of means and variances indicate that there is no statistical difference between the errors produced at these two values. The value of K=5.0x10⁻⁷ m⁴/N is chosen as the best-fit K value for Assateague Island, minimizing mean RMS error at 39 cm, and mean GVE at 0.27 m³/m. The sizeable error bars that are observed at large K-values are due to numerical instabilities that occur when transport rates become large. In these cases, excessive sediment is transported in and out of single grid cells, which results in calculated profiles containing numerous jagged peaks and valleys often ranging several meters in amplitude.
Figure 3.1 Profile 4362 from Assateague North is used as an example of SBEACH model response to changing values of $K$ (m$^3$/N). In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Figure 3.2 SBEACH sensitivity to (a) $K$, the transport rate coefficient, (b) $\varepsilon$, the slope coefficient, (c) $\theta$, the maximum local slope before avalanching, (d) $\alpha$, the landward surf zone depth, and (e) $\lambda_1$, the transport rate decay coefficient. Sensitivity is evaluated through a mean calculation of predicted gross volume change ($m^3/m$) for the 30 Assateague North profiles. Each error bar represents the 95% confidence interval on the mean value.
This calibration value is appreciably lower than K-values chosen in previous SBEACH studies, including K=1.6x10^{-6} \text{ m}^4/\text{N} from the original large wave tank studies, K=7.0x10^{-7} \text{ m}^4/\text{N} from the Duck, NC field study, K=1.4x10^{-6} \text{ m}^4/\text{N} from the Torrey Pines Beach, CA field site, and K=2.0x10^{-6} \text{ m}^4/\text{N} from the New Jersey beach field sites (Larson and Kraus, 1989; Larson et al., 1990). Figure 3.3 indicates that any of these previously determined values would produce large errors on the Assateague North study site. However, each of the four previous calibration values was generated by minimizing an error statistic that considered the entire length of the profile, of which the subaqueous profile was the dominant portion. For this reason, the new Assateague Island calibration value is important for model tests that focus on the accuracy of the model on the subaerial portion of the profile. Further testing will investigate whether this calibration value remains constant between different field sites.

Figure 3.3 SBEACH calibration curves for values of K, the transport rate coefficient on the Assateague North study site. Each error bar represents the 95% confidence interval on the mean value. The large error bars seen at large K values are a result of model instabilities that occur with high sediment transport rates.
\( \varepsilon \), the Slope Coefficient

The empirical parameter \( \varepsilon \) is found in the sediment transport rate calculation in Equation 3.1, where it acts as a coefficient for the local slope term. Large values of \( \varepsilon \) are expected to smooth locally steep slopes occurring in the broken wave zone, enhancing offshore transport and sandbar formation in the offshore region. In theory then, because waves break over much of the beach during storms, increasing values of \( \varepsilon \) should increase GVC on the subaerial profile by smoothing beach slopes and transporting sand seaward. However, because transport is affected only through the slope term, the consequences of changing values of \( \varepsilon \) are expected to be small. A calibration value of \( 2.0 \times 10^{-3} \text{ m}^2/\text{s} \) is reported for Torrey Pines Beach, CA, and therefore, the limits for sensitivity tests are set at \( 5.0 \times 10^{-4} \) and \( 5.0 \times 10^{-3} \text{ m}^2/\text{s} \) in order to encompass one order of magnitude surrounding the previously reported value.

Model results for each value of \( \varepsilon \) are presented in Figure 3.4 for an example profile from Assateague North. The observed differences in model results are much more subtle than those observed for changing values of the empirical coefficient \( K \). However, careful inspection shows that as the value of \( \varepsilon \) increases, subaerial erosion increases through the flattening of the beach. Figure 3.2(b) indicates that SBEACH is most sensitive to changes in the slope coefficient \( \varepsilon \) in the lower range of values. The observed trend suggests that as hypothesized, total erosion on the subaerial profile increases with increasing values of \( \varepsilon \). The change in the mean value of predicted gross profile change across one order of magnitude of \( \varepsilon \)-values is 102%, and is statistically significant with 95% confidence.

Calibration plots are shown in Figure 3.5, indicating that neither error statistic changes appreciably for \( \varepsilon \) values greater than \( 2.0 \times 10^{-3} \text{ m}^2/\text{s} \). The mean error statistics reported for \( \varepsilon \)-values in the range of \( 1.5 \times 10^{-3} \) to \( 4.5 \times 10^{-3} \text{ m}^2/\text{s} \) are not statistically different from one another at the 95% confidence level. As a result, any \( \varepsilon \)-value between \( 1.5 \times 10^{-3} \) and \( 4.5 \times 10^{-3} \text{ m}^2/\text{s} \) can be
Figure 3.4 Profile 4362 from Assateague North is used as an example of SBEACH model response to changing values of $\varepsilon$ (m$^2$/s). In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
viewed as a valid for calibration purposes. Larson et al. (1990) calibrate SBEACH to Torrey Pines Beach, CA field data, and report $\varepsilon=2.0\times10^{-3}$ m$^2$/s as the best-fit value. The error statistic used to generate this calibration value is dominated by the subaqueous portion of the profile including multiple sandbars, and therefore $\varepsilon=2.0\times10^{-3}$ m$^2$/s can be used as a robust value that minimizes error on both the subaerial and subaqueous portions of the profile.

![Figure 3.5](image)

**Figure 3.5** SBEACH calibration curves for values of $\varepsilon$, the slope coefficient on the Assateague North study site. Each error bar represents the 95% confidence interval on the mean value.

$\phi$, the Maximum Local Slope Before Avalanching

The third empirical parameter inherent to the SBEACH model is $\phi$, the maximum slope that can exist between adjacent grid cells. When the model detects a slope that exceeds the angle $\phi$, avalanching occurs until the slope stabilizes at a residual angle of $\phi-10^\circ$. Small values of $\phi$ cause frequent small avalanches on the dune face as the slope of the dune base steepens due to transport by swash and breaking waves. The sediment that is eroded during avalanching will ultimately be carried into the surf zone, and will migrate further offshore under high wave conditions. Large values of $\phi$ reduce the sediment transport on the dune by allowing the dune
base to achieve steeper angles before avalanching occurs. Therefore, gross profile change calculated by SBEACH should exhibit an inverse dependence on \( \phi \), with erosion on the subaerial profile decreasing with increasing \( \phi \).

A preliminary value used by Larson and Kraus (1989) and Larson et al. (1990) of 28° is based on observations from the large wave tank studies. For the purpose of sensitivity tests, \( \phi \) is varied between 24° and 42°, in order to accommodate this value and initial observations that the optimal value of \( \phi \) for Assateague Island may be larger than 28°. Contrary to the original hypothesis, Figure 3.2(c) indicates that the model is insensitive to \( \phi \), with virtually no change occurring in predicted gross volume change across the test range of \( \phi \)-values. Tests of the equality of means and variances confirm that none of the mean values of GVC are statistically different from one another at the 95% confidence level, signifying that erosion on the subaerial extent of the model is insensitive to \( \phi \)-values in the given range.

Despite this result, a visual inspection of the 30 profiles from Assateague North indicates that an optimum value of \( \phi \) does exist for this study area. A \( \phi \)-value of 38° allows the model to most accurately reproduce the slope of the post-storm dune. These optimal slopes are achieved through the avalanching of small volumes of sand off the dune face and stabilizing at the residual angle of 28°. This observation suggests that the optimal value of \( \phi \) should be chosen based upon the slope of the post-storm dune and the residual angle after avalanching. Knowledge of post-storm dune shape from prior storms will facilitate the user in choosing the correct value of \( \phi \) for any study area.

\( \alpha \), the Landward Surf Zone Depth

One fundamental principle of the SBEACH model is the existence of distinct cross-shore transport regions, between which the structure of the sediment transport rate equations vary significantly. The rate equations for each of the four regions were developed with data from two
large wave tank experiments, and are given in Equations 1.20 to 1.23. Naturally, the successful use of these equations is in part dependent on the correct placement of horizontal boundaries between the zones. Unfortunately, the exact criterion for the placement of boundaries is unknown, and the task is left to the best scientific judgment of the user.

The horizontal boundary between transport rates in the broken wave zone (Zone III) and the swash zone (Zone IV) is marked at an arbitrary depth $\alpha$, generally ranging from 0.1 to 0.5 meters. When the location of the boundary occurs at shallow depths, the width of the broken wave zone increases, and waves expend energy over a greater width of the profile. In theory, as $\alpha$ increases, predicted gross volume change should decrease as waves dissipate energy over a shorter distance.

Model results for each value of $\alpha$ are presented in Figure 3.6 for an example profile from Assateague North. At values of $\alpha$ greater than 0.15 m, the profiles often exhibit sharp peaks and valleys on the beach. These instabilities occur when Zones III and Zones IV exist on the subaerial profile during the storm, and a portion of this profile is excluded from the smoothing effects of changing wave heights due to large $\alpha$-values. When waves are allowed to expend energy closer to shore with smaller values of $\alpha$, local spikes in the profile are smoothed as energy dissipation over that portion of the profile fluctuates with time. Figure 3.2(d) indicates that the mean value of GVC remains constant as $\alpha$-values increase over one order of magnitude, from 0.05 to 0.5 m. The means and variances of predicted GVC values are statistically equivalent at the 95% confidence level, indicating that the subaerial model results are insensitive to $\alpha$. Therefore, a fixed value of $\alpha=0.1$ m is chosen for all SBEACH runs, in order to avoid the jagged profiles that occurs for greater values of $\alpha$. 

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Figure 3.6 Profile 4362 from Assateague North is used as an example of SBEACH model response to changing values of $\alpha$ (meters). In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
\( \lambda_{1} \), the Transport Rate Decay Coefficient

The sediment transport rate decays exponentially offshore of the broken wave zone. The rate of decay is controlled by \( \lambda_{1} \), the transport rate decay coefficient, which is found in Equation 1.20:

\[
Q_x = Q_0 e^{-\lambda_1 (x - x_b)}
\]  

(3.2)

Large values of \( \lambda_{1} \) create sharp gradients in the transport rate, and facilitate the development of slowly moving sandbars in the offshore region. Smaller values of \( \lambda_{1} \) do not encourage the accumulation of sand in any single area, and allow uniform sheets of sediment to move slowly offshore. Because \( \lambda_{1} \) controls the shape of the offshore profile, it should have little effect on model results on the subaerial profile.

Initial versions of SBEACH calculated the value of \( \lambda_{1} \) at every time step with the equation:

\[
\lambda_{1} = 0.4 \left( \frac{D_{sb}}{H_b} \right)^{0.47}
\]  

(3.3)

where \( H_b \) is the breaking wave height. Subsequent versions abandoned this time-dependent version of \( \lambda_{1} \) for a constant value defined by the user. For sensitivity testing, \( \lambda_{1} \) was varied between values of 0.1 and 0.5 m\(^{-1}\), which correspond to breaking wave heights of 6.2 and 0.2 meters respectively from Equation 3.3. Figure 3.2(e) displays mean values of GVC for the test range of \( \lambda_{1} \) values. The means and variances for the GVC values are not statistically different from one another at the 95% confidence level, confirming that the subaerial model results are insensitive to \( \lambda_{1} \). A visual inspection of the 30 profiles from Assateague North displays no bias towards any specific value, and therefore, an arbitrary fixed value of \( \lambda_{1} = 0.2 \) m\(^{-1}\) is chosen for all SBEACH model runs.
Model Sensitivity: Physical and Hydrodynamic Variables

\(D_{50}\), Median Grain Diameter

Median grain diameter, given the notation \(D_{50}\), plays two distinct roles in the SBEACH model. First, \(D_{50}\) influences the shape of the offshore profile calculated with Dean’s \(h = Ax^{2/3}\) equilibrium profile equation, where \(A\) is a function of grain size. It is important to note that the representation of the offshore profile by Dean’s equation is not standard to SBEACH, but was chosen for lidar data sets that do not include subaqueous data. As grain size increases the profile steepens, allowing waves to shoal further inshore before breaking. When the waves break further inshore, the energy dissipated over the shallow depths increases and causes an increase in total transport. Therefore, this cause-and-effect relationship implies that an increase in grain size should increase total sediment transport.

However, well-known sediment transport theory states that greater energy is required to entrain larger grains in the flow, and that these large grains settle out of the water column quickly after initial suspension. This concept is incorporated into the SBEACH model through the sediment fall speed, \(w_s\). Grain size directly influences the sediment fall speed, with larger grains settling at greater velocities than their smaller counterparts. Fall speed enters the numerical formulation in Equation 1.30:

\[
\frac{H_s}{L_s} = 0.00070 \left( \frac{H_s}{w_s T} \right)^3.
\] (3.4)

The exact equations for fall speed have not been published, making this an important test for users who wish to know how grain size effects model results. This equation is calculated at each time step, and acts as the defining condition between onshore and offshore-directed transport. Onshore transport occurs when the left hand side of the equation is greater than the right hand side, so an increase in grain size (and hence fall speed) allows the right hand side of this equation to decrease rapidly with the cubed term. Therefore, as grain size increases, total onshore-directed
transport will increase over the duration of the simulated storm. Paired with the effect of increased total transport due to shoaling over a steeper profile, a large amount of sand is expected to move onshore, causing a significant decrease in erosion with increasing grain size.

The ‘true’ value of $D_{50}$ is 0.33 mm, which is the average median grain size from multiple sediment samples taken during a 1995 U.S. Army Corps of Engineers study along Assateague Island (USACE, 1998). For sensitivity tests, $D_{50}$ is varied about this value at intervals of 0.1 mm, ranging from 0.13 to 0.93 mm, corresponding roughly to the lower boundary of fine sand (0.125 mm) and to the upper boundary of coarse sand (1.0 mm). Model results for each value of $D_{50}$ are presented in Figure 3.7 for an example profile from Assateague North. Additionally, Figure 3.8(a) presents results of the sensitivity tests, displaying mean values of predicted GVC for all grain sizes.

An interesting trend is illustrated in these two figures, as mean GVC does not strictly increase or decrease as grain size increases, but rather reaches a maximum value at $D_{50} = 0.23$ mm. Most likely, transport on the upper profile is suppressed when $D_{50} = 0.13$ mm, because the corresponding offshore profile is exceedingly shallow, confining the dissipation of energy to the offshore region. When $D_{50}$ increases to 0.23 mm, the profile steepens slightly, allowing waves shoal further inshore. This increases overall transport, and therefore, predicted GVC increases. However, as grain size increases beyond this point, an increasing proportion of the total transport is directed onshore, decreasing GVC via Equation 3.4. In simpler terms, even as wave energy increases, large grain sizes do not erode as easily as small grain sizes, and when they do, they settle quickly before being transported away from their original location.

Encouragingly, Figure 3.9 indicates that both error statistics are minimized at the ‘true’ median grain diameter of 0.33 mm. Error measurements increase rapidly for values of $D_{50}$ greater and less than 0.33 mm, suggesting that a small measurement error or bad judgment in choosing this value could cause significant errors in model results. Background literature does not provide
Figure 3.7 Profile 4362 from Assateague North is used as an example of SBEACH model response to changing values of $D_{50}$ (millimeters). In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Figure 3.8 SBEACH sensitivity to (a) $D_{50}$, median grain diameter and (b) water temperature. Sensitivity is evaluated through a mean calculation of predicted gross volume change ($m^3/m$) for the 30 Assateague North profiles. Each error bar represents the 95% confidence interval on the mean value.

Figure 3.9 SBEACH calibration curves for values of $D_{50}$, the median grain diameter on the Assateague North study site. Each error bar represents the 95% confidence interval on the mean value.
recommendations for choosing the correct value of $D_{50}$, and therefore these results validate the choice of median grain diameter taken from mean high water to mean low water and averaged over multiple profiles (USACE, 1998). Because recent sediment surveys will not always be available for each study site, the user must use their best scientific judgment when choosing an appropriate value of $D_{50}$.

**Water Temperature**

Like median grain diameter, water temperature also enters the model formulation through sediment fall speed in Equation 3.4. As temperatures increase, the viscosity of the water decreases and sediments to settle with a greater velocity. Increasing fall speeds allow the right hand side of Equation 3.4 to decrease rapidly, therefore increasing total onshore-directed transport over the duration of the storm. Therefore, in theory, increasing water temperatures will impede profile change because of faster settling velocities.

The ‘true’ water temperature of 6.5°C was obtained from NDBC Buoy 44009, as a mean of hourly sea surface temperatures. Because the surf zone is a well-mixed environment, sea surface temperature should accurately approximate the temperature of the entire water column. However, because the measurement is taken offshore of the surf zone, an error of several degrees is quite possible. Therefore, sensitivity tests are performed with temperatures ranging from 1.5°C to 11.5°C. Greater differences in temperature that could potentially occur only on seasonal scales can be excluded from the possible range of measurement error. Figure 3.8(b) presents sensitivity test results for temperatures varying about the ‘true’ temperature of 6.5°C. Changes in the mean value of predicted GVC are not discernable, and none of the means or variances are statistically different from one another at the 95% confidence level. The model results are therefore insensitive to changes in water temperature within a reasonable range of the measured value. Although the original hypothesis states that GVC should decrease with increasing temperatures,
this result is not surprising. The influence of water temperature on the settling velocity is very small over a 10°C range, and consequently is undetectable in the results.

In Figure 3.10, model sensitivity is explored over a wider range of water temperatures. This graph shows that the model results change slightly as temperatures rise above 15°C. As temperatures increase, the mean value of predicted GVC decreases, confirming the original hypothesis that increased temperatures will decrease total erosion. A statistically significant change in mean GVC of -31% is recorded between 15°C and 40°C. This result indicates that the accuracy of the temperature measurement becomes increasingly important at higher temperatures. Therefore, it is more important to have an accurate measure of temperature for a hurricane that occurs in August, than for a northeaster that strikes during the winter months.

Figure 3.10 SBEACH sensitivity to water temperatures ranging from 0°C to 40°C. Sensitivity is evaluated through a mean calculation of predicted gross volume change (m³/m) for the 30 Assateague North profiles. Each error bar represents the 95% confidence interval on the mean value.

Wave Height

In order to investigate the effect of wave height on model results, the original time series of significant offshore wave heights (Hₙ) from NDBC Buoy 44009 was modified to vary between 0.5Hₙ and 1.5Hₙ. These values correspond roughly to mean and maximum wave height (0.60Hₙ and 1.57Hₙ respectively) from a Rayleigh distribution of wave heights for broad-spectrum hurricane waves (Goodknight and Russell, 1963). The original time series, as well as the extreme time series records used in the sensitivity tests are shown in
Figure 3.11. In theory, larger wave heights should increase energy dissipation across the length of the surf zone, and therefore, greater erosion across the entire profile. However, a greater wave height also causes the waves to break further offshore, dissipating some of the excess energy at greater depths, and therefore damping the effect of increasing energy dissipation on the subaerial profile.

Figure 3.12(a) shows the sensitivity test results for the modified wave height time series. The observed trend exhibits a slight increase in mean GVC with increasing wave height. The total change in the mean value of predicted GVC over the entire range of wave heights is 148%, which is statistically significant with 95% confidence. The small signal in model sensitivity is not only due to the dissipation of energy at greater depths, but also to the nature of the sensitivity measurement. GVC measurements are calculated on the subaerial profile, while wave heights dissipate energy that transports sediment in the surf zone. Therefore, if GVC were calculated over the entire profile length, sensitivity would increase dramatically. Because the study is focused on the dune and beach, sensitivity to wave height is less what is intuitively expected.

![Wave Height Time Series](image)

**Figure 3.11** Example time series of wave heights utilized to test SBEACH model sensitivity. The $H_\infty$ record was taken from NDBC Buoy 44009 in Delaware Bay. Time 0 corresponds to 08:00 EST on January 27, 1998.
Figure 3.12 SBEACH sensitivity to (a) wave height ($H_\infty$), (b) water elevation ($\eta$), (c) wave period ($T$), and (d) wave angle ($\theta$). Each error bar represents the 95% confidence interval on the mean value.
Figure 3.13 presents error statistics over the range of modified wave height time series. Interestingly, both mean RMS error and mean GVE are minimized at $1.3H_\infty$, a value that roughly corresponds to the calculation of $H_{1/10}=1.25H_\infty$ given by Goodknight and Russell (1963). However, the means and variances of the GVE and RMS error statistics for wave height time series ranging from $H_\infty$ to $1.3H_\infty$ are not statistically different from one another at the 95% confidence level. Therefore, this result does not justify running the model with wave heights of $1.3H_\infty$ without additional confirmation. Model results for each value wave height time series are presented in Figure 3.14 for an example profile from Assateague North.

Figure 3.13 SBEACH calibration curves for modified time series of wave height on the Assateague North study site. Each error bar represents the 95% confidence interval on the mean value.
Figure 3.14 Profile 4362 from Assateague North is used as an example of SBEACH model response to modified time series of wave height. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Water Elevation

The original time series of water elevations ($\eta$) was obtained from NOAA Tide Gauge 8570283 at Ocean City Inlet, MD. In order to investigate the sensitivity of the model to variations in $\eta$, the entire time series is shifted vertically by a fixed amount ranging from 1 m to –1 m. Example time series from the sensitivity tests are given in Figure 3.15. In theory, elevated water levels allows waves to break closer to the beach, which should cause increased erosion on the subaerial profile. Figure 3.12(b) confirms this expectation, with the mean value of predicted GVC increasing consistently over this range of $\eta$, with a statistically significant increase of 265%.

Figure 3.16 presents model results for an example profile for Assateague North, indicating that the model performs most accurately with a water elevation time series that is elevated above the original tide gauge data. This suggestion is supported by Figure 3.17, which plots mean error statistics for the different time series. Mean error is minimized at a $\eta+0.2$, which indicates that the original time series does not allow waves to shoal close enough to shore to produce observed levels of erosion. The variances of GVE and RMS error calculated at $\eta$ and $\eta+0.2$ are statistically different from one another at the 95% confidence level, suggesting that a greater level of accuracy is achieved with the modified time series. However, there is no reasonable justification in recommending that the water level time series should always be elevated above the observed values. Water levels are known to fluctuate along the shoreline, and may be smaller or larger than the measured values at a local tide gauge depending on the location of the shoreline relative to the storm.

The significance of this finding lies in the nature of storm surge along the coast. Water levels vary significantly in the longshore direction, depending on the location of the storm relative to the coastline. As a result, the use of a single water level time series for a long stretch of coast may cause varying degrees of model error at each location. This effect will become
increasingly important when modeling hurricane events, as water levels are elevated on one side of the eye, and depressed on the other. For example, for a hurricane on the east coast of the U.S., utilizing a tide gauge to the north of landfall for a section of coastline that lies south of landfall could potentially lead to an error in water levels of several meters. However, an error of several meters in water level could also occur in less extreme situations, making it important for future research to attempt to incorporate longshore variable time series of water levels from models such as NOAA’s SLOSH or DELFT-3D.

Figure 3.15 Example time series of water elevations utilized to test SBEACH model sensitivity. The \( \eta \) record was taken from NDBC Tide Gauge 8570283 at Ocean City Inlet, MD. Time 0 corresponds to 08:00 EST on January 27, 1998.
Figure 3.16 Profile 4362 from Assateague North is used as an example of SBEACH model response to modified time series of water elevation. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Wave Period

Wave period (T) plays two distinct and opposing roles in the SBEACH model formulation. First, period appears in Equation 3.4, which acts as the defining condition between onshore and offshore transport. Increases in wave period cause the right hand side of the equation to decrease rapidly, increasing total onshore transport over the duration of the simulated storm. However, increasing wave period also leads to an increase in wavelength, which according to SBEACH equations, allows waves to shoal closer to shore before breaking. This theoretical statement is represented numerically in Equation 1.15, which defines the depth at breaking with the breaking wave criterion:

\[
\frac{H_b}{h_b} = 1.14 \left[ \frac{\tan \beta}{\left( \frac{H_\infty}{L_\infty} \right)^{1/2}} \right]^{0.21}.
\] (3.5)

As waves break closer to shore, greater amounts of energy are dissipated over shallow depths, increasing erosion on the upper extent of the profile. These two opposing roles of wave period should act to offset any trend in profile change that either might produce individually.
To investigate the effect of wave period on model results, the original time series from NDBC Buoy 44009 was modified by shifting the entire series by a fixed amount, ranging from a decrease of four seconds to an increase of six seconds. The variation in period for this test was asymmetric in order to avoid negative periods, but to allow testing over a ten second range. Figure 3.12(c) shows evidence that the model is relatively insensitive to changes in wave period, with the mean value of GVC increasing by only 28% over the entire range of wave period records. Because the increase in mean GVC is statistically significant with 95% confidence, we can conclude that period is most influential through its effect on wavelength, allowing waves to shoal further inshore with increasing period. When compared to the sensitivity of the model to both wave height and water level, variations in model results with period are relatively insignificant.

**Wave Angle**

Wave angle is incorporated into the model through Equation 1.11, a one-dimensional form of Snell’s Law that assumes straight and parallel bottom contours:

\[
\frac{d}{dx} \left( \frac{\sin \theta}{L} \right) = 0.
\] (3.6)

Snell’s Law allows the computation of refraction as waves travel across the surf zone. The wave angles calculated from Equation 3.6 are incorporated into the conservation of energy flux equation (1.10):

\[
\frac{d}{dx} \left( F \cos \theta \right) = \frac{k}{d} \left( F - F_c \right)
\] (3.7)

where \( \cos \theta \) determines the proportion of total energy flux moving in the cross-shore direction. When waves arrive in the surf zone at low angles, the majority of total energy flux is available in the cross-shore over the entire length of the surf zone. However, when waves arrive at high angles, the available cross-shore energy flux is only a small percentage of the total. Cross-shore
flux then increases as waves refract and $\theta$ changes with decreasing depth, but the total energy expended in the cross-shore is appreciably less than for waves approaching at low angles. Therefore, the expectation arises that waves with high offshore angles will cause less erosion because of the decreased amount of energy dissipated across the width of the profile.

In order to test the sensitivity of the model to wave angle, the original time series from NDBC Buoy 44009 was modified to vary between $\theta$-50° to $\theta$+50°. An angle of 0° is shore normal, positive angles indicate waves arriving from the northeast, and negative angles denote waves arriving from the southeast. Relative frequency histograms of the original time series and the two extremes are shown in Figure 3.18. The original time series is skewed towards waves arriving at low angles from the southeast, but is essentially centered at shore normal. The extreme cases cause waves to approach at higher angles from both the northeast and the southeast. Therefore, erosion should be highest with the original time series, and should decrease as wave angles increase in both directions.

Figure 3.12(d) indicates that the model is essentially insensitive to changes in wave angle, with no discernable trend in calculated GVC as $\theta$ changes across the given range. A statistically significant decrease in GVC of 20% is recorded between the original time series, and $\theta$-50°, but no significant changes occur between the original time series and $\theta$+50°. Because of the relative insensitivity of the model to wave angle, a greater level of measurement error is acceptable than would be the case for wave heights and water levels. Additionally, if wave angle information is unavailable, SBEACH assumes a constant shore normal approach over the duration of the simulated storm. This method does not significantly change the results at the 95% confidence level, and therefore, SBEACH can be operated without wave angle input without losing accuracy in model results.
Model Results: Assateague Island

Calibration Site: Assateague North

The Assateague North study area is comprised of 30 profiles characterized by high dunes, with elevations at the dune crest ranging between 5 and 8 meters. Dune scarping is observed on the northern end of the site, while only beach erosion is observed in the south. Figure 3.19 plots SBEACH model results for ten Assateague North profiles spaced approximately 300 meters apart in the longshore. These results were calculated using calibrated values of empirical parameters from the previous section, including a K-value of 5.0x10^{-7} m^4/N. The model displays an exceptional ability to reproduce the basic shape of the beach, although the vertical placement often varies slightly from the measured post-storm location. Additionally, the model reproduces the slope of the dune well, even though the exact location of the sloping dune face is not always correct. These results indicate that the transport mechanisms (wave energy dissipation on the beach, and avalanching on the dune face) are empirically correct, despite errors in the magnitude of their effects.

Figure 3.20 presents RMS error and GVE as a function of latitude. From this plot it is apparent that RMS error is small and relatively constant for profiles that experience only beach erosion, and that the error increases significantly for those profiles that experience dune scarping.
Mean RMS error for the entire study site was 0.39 m, with a standard deviation of 0.19 m. In comparison, the eighteen ‘beach erosion’ profiles had a mean RMS error of 0.30 m, while the twelve ‘dune scarping’ profiles had a mean RMS error of 0.53 m. The two means are statistically different from one another at the 95% confidence level, suggesting an inverse relationship between erosion and model accuracy on the subaerial profile. The most important observation from this site is that the model correctly delineates between beach erosion and dune scarping in all 30 cases. Because the accurate prediction of impact regime has been a recent subject of study, the ability of SBEACH to differentiate between beach and dune erosion is a promising result.
Figure 3.19  Ten profiles selected from Assateague North and the predicted SBEACH results. The first profile (4122) is the southernmost profile in the study area, and the last profile (4392) is the third northernmost profile. The profiles are spaced approximately 300 meters apart in the longshore direction. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Figure 3.20  RMS error and GVE as a function of latitude for SBEACH model results on the Assateague North study site. The north end of the island is characterized by dune scarping, and the south end of the island is characterized by beach erosion.

Berm Profiles: Assateague South

The Assateague South study area is characterized by berm profiles whose elevations at the berm crest seldom exceed three meters. The storm system caused extensive erosion on these low lying profiles, resulting in thin deposits of sand occurring landward of the original berm location. These deposits are akin to overwash that occurs for profiles with high dunes, and therefore, they will be referred to as overwash deposits from this point on. Figure 3.21 displays model results for ten profiles from Assateague South, moving from south to north with a constant spacing of 300 meters between profiles. The calculated profiles exhibit a noticeable trend from south to north, simulating too much erosion on the southern profiles, and insufficient erosion on the northern profiles. Any unaccounted for longshore gradient in either wave height or water level could produce this type of trend. Additionally, this figure reveals that in general, the calculated results do not accurately reproduce the elevation or location of the overwash deposits.

Figure 3.22 plots GVE and RMS error measurements on Assateague South as a function of latitude. The south to north trend observed in the profiles themselves is absent from these
plots, because the net profile change signal is not present in either error statistic. Both error statistics are relatively low and constant across the study area, with a mean RMS error of 0.37 m, and a mean GVE of 0.30 m$^3$/m. The mean RMS error is statistically lower than the value calculated on Assateague North at the 95% confidence level, while mean GVE is not statistically different.

Additionally, because the model is highly sensitive to the empirical parameter K, it is important to confirm that the calibration value of 5.0x10$^{-7}$ m$^4$/N calculated with Assateague North data is appropriate for the given study area. Encouragingly, Figures 3.23 shows that calibration curves for the transport rate coefficient are comparable between Assateague South and Assateague North, and that both error statistics are minimized in the range of 5.0x10$^{-7}$ to 7.5x10$^{-7}$ m$^4$/N. Larger values of K create large instabilities in the profile, with occurrences of jagged peaks and valleys, and severe erosion on the beach and berm portions of the profile.
Figure 3.21 Ten profiles selected from Assateague South and the predicted SBEACH results. The first profile (3692) is the southernmost profile in the study area, and the last profile (3962) is the third northernmost profile. The profiles are spaced approximately 300 meters apart in the longshore direction. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Figure 3.22 RMS error and GVE as a function of latitude for SBEACH model results on the Assateague South study site.

Figure 3.23 SBEACH calibration curves for increasing values of K, the transport rate coefficient on the Assateague South study site. Each error bar represents the 95% confidence interval on the mean value.

Extreme Longshore Variability: Chincoteague

The Chincoteague study area profiles are characterized by high dunes that display immense longshore variability in profile response, ranging from beach erosion to a complete loss of the dune and the development of thin overwash deposits. Figure 3.24 presents SBEACH
results for ten profiles from this site, spaced evenly in the longshore by a distance of approximately 300 meters. As this figure shows, the model results were highly variable, with a general trend towards overpredicting erosion in cases of beach erosion and dune scarping, and underpredicting erosion for more severe cases when the dune lost elevation or overwash occurred. Figure 3.25 plots the mean error statistics as a function of latitude, with a mean RMS error of 0.77 m and mean GVE of 0.59 m³/m. Both error statistics are significantly greater than those recorded on both Assateague North and Assateague South with 95% confidence.

Interestingly, SBEACH results are accurate in predicting the general cases of beach erosion and dune scarping, with no instances of the model erroneously flattening the dune. Conversely, and more problematic, is the fact that in several instances the model predicts that the dune remains standing after the storm, when in reality it suffered severe erosion and was either lowered or overwashed. This observation has serious consequences in the engineering and emergency management aspects of this subject, where it is highly undesirable for a model to underpredict the storm’s true impact.

However, if the goal of the modeling effort is not to predict impact regime on individual profiles but rather over longer spatial scales, the SBEACH model can be seen as an appropriate modeling tool. For example, vulnerability mapping seeks to predict the most extreme impact over a binned section of coastline, which would be overwash in the case of the Chincoteague study area. The SBEACH model does correctly predict overwash on several profiles (not pictured in Figure 3.24), and therefore would produce accurate results for vulnerability mapping purposes.
Figure 3.24  Ten profiles selected from Chincoteague and the predicted SBEACH results. The first profile (550) is the southernmost profile in the study area, and the last profile (840) is the third northernmost profile. The profiles are spaced approximately 300 meters apart in the longshore direction. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Because the pre-storm dunes were fairly uniform in shape and elevation along the study area, longshore gradients in forcing must have existed in order to produce the extreme variability observed in profile response. The buoy record of wave height and the tide gauge record of water level utilized to produce results for the length of Assateague Island cannot account for potential longshore variability in these processes. Additionally, many processes that act in the longshore direction are not included in model formulation, including wave refraction, circulation cells and rip currents, and currents induced by longshore pressure gradients. Consequently, the model’s inability to hindcast extreme local variability in profile response is reflected in the model error. The implications of gradients in longshore forcing are discussed in more detail in Chapter 5.

Figure 3.25 presents error statistics as a function of K, the transport rate coefficient, for this length of coastline. Both RMS error and GVE are minimized between K-values of $5.0 \times 10^{-7}$ and $7.5 \times 10^{-7}$ m$/N$, the same as the Assateague North calibration. Once again, large values of K result in instabilities in the calculated profiles, with occurrences of jagged peaks and valleys, which are denoted by the larger error bars about the mean as K increases. This observation has been constant across all Assateague study sites, suggesting that the utility of setting K at a low value may be more closely related to avoiding profile instability than to finding a coefficient to predict the correct sediment transport rate.
Figure 3.25  RMS error and GVE as a function of latitude for SBEACH model results on the Chincoteague study site.

Figure 3.26  SBEACH calibration curves for increasing values of K, the transport rate coefficient on the Chincoteague study site. Each error bar represents the 95% confidence interval on the mean value.
Model Results: Hatteras Island

Verification Site: Hatteras North

Verification tests of the calibrated SBEACH model are performed with lidar data from the Hatteras North study area taken before and after Hurricane Isabel. This section of coastline is characterized by high dunes that are eroded beyond the dune crest, with a small portion of the dune remaining intact and preventing overwash. The model is run with the Assateague North calibration value for K, and with storm data from Hurricane Isabel, which is described in Chapter 1. Figure 3.27 presents model results for ten profiles from the study area, spaced evenly in the longshore direction by approximately 45 meters.

This series of plots indicates that the model produces profile shapes that are significantly different from the observed post-storm profiles. The model produces rounded, convex dunes, while lidar data indicates that the post-storm profiles are narrow and peaked, with a concave profile leading from the dune crest to the beach. The rounded profile form predicted by SBEACH is the result of the storm-specific water level and wave height time series that were observed during Hurricane Isabel, and their combined interaction in the SBEACH model. The consequence of oscillating water levels paired with extreme wave heights is to rapidly move shallow sandbars offshore, allowing waves to shoal further inshore before breaking. The excess energy dissipated on the profile lowers the dune so that runup overtops the profile and creates the calculated rounded shape. However, despite the model’s inability to predict the correct profile shape, it consistently predicts the lowering of the dune crest for all profiles.
Figure 3.27  Ten profiles selected from Hatteras North and the predicted SBEACH results. The first profile (17790) is situated on the southwest end of the study site, and the last profile (17817) is positioned at the northeast end of the study area. The profiles are spaced approximately 45 meters apart in the longshore direction. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Figure 3.28 presents RMS error and gross volume error as a function of longshore distance. A slight trend suggests that model error decreases moving to the northeast away from the location of the breach. Quite obviously, extreme forcing was present at the breach, and the effect of this forcing most likely reaches hundreds of meters in either direction. These effects are unaccounted for in the model runs, and may explain the trend in error moving away from the breach. Mean RMS error for the 30 profiles is 0.54 m, and GVE is 0.41 m³/m, both of which are significantly greater than the Assateague North value at the 95% confidence level.

Model error is plotted as a function of K, the transport rate coefficient, in Figure 3.29. Once again, model results indicate that for higher values of K, the model become unstable. Both error statistics are minimized in the range of 5.0x10⁻⁷ to 1.0x10⁻⁶ m³/N, which encompasses the previous calibration value of 5.0x10⁻⁷ m³/N. This test confirms that the calibration value is transferable between locations and storms, and allows the calibration value of K to be utilized when testing the extreme impact that is observed in the Hatteras Breach site.

![Figure 3.28](image.png)

**Figure 3.28** RMS error and GVE as a function of longshore distance for SBEACH model results on the Hatteras North study site.
Figure 3.29 SBEACH calibration curves for increasing values of $K$, the transport rate coefficient on the Hatteras North study site. Each error bar represents the 95% confidence interval on the mean value.

Extreme Impacts: Hatteras Breach

Although the occurrence of a breach is rare, the ability to predict this type of event is highly desirable from a coastal planning perspective. Figure 3.30 presents model results for ten profiles evenly spaced along this section of coastline by a distance of approximately 45 meters. The first profile presented in this figure is situated immediately to the southwest of the breach, and the last profile is situated to the northeast of the breach. Inspection of these results shows that the model calculated a consistent response among profiles, with the dune fully flattened and a rounded volume of sand approximately two meters high remaining in its place. Qualitatively, it is obvious that the model does not have the capability to reproduce breaching scenarios. Because the true profile response (channel formation) is not captured in the lidar profiles, it is impractical to calculate error statistics for this section of coastline.

Transport mechanisms not included in the model formulation may be responsible for the lack of skill in predicting breaches. First, the breach occurred at the narrowest section of the island, indicating that transport due to longshore funnelling of water may have initiated an
erosional hotspot and inundation of the island by storm surge and waves. Once inundation occurs and water flows freely over the island, the pressure gradient formed between the ocean and the estuary allows currents to scour the island. In this situation, transport by currents becomes the most important mechanism for moving sand into the estuary. The assumption of longshore homogeneity in hydrodynamics does not allow for the funneling of water to the narrowest sections of the island, nor does the model include any calculations of current velocities or transport by currents. Therefore, it is possible to identify at least two transport mechanisms that may be incorporated into future versions of the model in order to more accurately hindcast breaches. An in-depth discussion of breaching processes and model implications is presented in Chapter 5.
Figure 3.30 Ten profiles selected from Hatteras Breach and the predicted SBEACH results. The first profile (17736) is situated on the southwest edge of the breach, and the last profile (17763) is positioned at the northeast edge of the breach. The profiles are spaced approximately 45 meters apart in the longshore direction. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
The three main objectives of this chapter are to explore several simplifying assumptions inherent to the EDUNE model, to test the sensitivity of model results to a variety of parameters, and to quantify and discuss model accuracy. The first section explores three processes that are considerably simplified by model assumptions, including runup, tides, and the breaking wave criterion. First among these processes is runup, which the original model treats as a constant input value that is to be estimated based on previous knowledge of the field site. However, measurements of runup during storms are rare, and measurements from one storm are not directly applicable to another storm because of their dependence on wave height characteristics and the slope of the beach. Multiple field studies have concentrated on developing equations describing runup as a function of waves and beach slope (Hunt, 1959; Guza and Thornton, 1982; Holman and Sallenger, 1985; Holman, 1986), and therefore, several time-dependent runup equations are tested as an alternative to a constant value.

The second process explored in this section is the treatment of storm surge as a proxy for observed water levels. While this substitution allows the model to avoid onshore transport produced in shallow water, it also assumes that storm surge alone can account for erosion due to elevated water levels. Erosion of the profile should be implicitly linked to time-varying water levels produced by tidal cycles, and therefore it is important to quantify differences in model outcome that result from this substitution. Therefore, the model is tested with both time series,
and error statistics are examined in order to determine if storm surge is indeed an appropriate proxy.

The third process explored in this section is the simplified breaking criterion $H_b/h_b=0.78$, which defines the seaward boundary of the surf zone. Breaking wave heights are input from the SWAN model, and are compared with water depths until the specified ratio of 0.78 is met or exceeded. The input wave height statistic for this process is the rms breaking wave height, as recommended by Kriebel (1995). However, several field studies have established that rms breaking wave heights correspond to much lower values of $\gamma$ than 0.78 (Thornton and Guza, 1983; Sallenger and Holman, 1985). Therefore, values of $\gamma_b$ resulting from these field studies are tested as alternatives.

The second section of this chapter explores the sensitivity of model results to various several empirical parameters, and develops calibration values for $K$, the transport rate coefficient, and $\eta_b$, the equilibrium beach slope. In the third section, model results are found to be sensitive to each of the four hydrodynamic variables, although the magnitude of the sensitivity varies widely. EDUNE is most sensitive to changes in the storm surge elevation time series, a result that is expected based on the ability of storm surge to shift the surf zone landward. The final two sections test the accuracy of the model on the five study sites, using calibration values developed on Assateague North. Calibration curves for $K$ and $\eta_b$ are calculated at each site, to determine if the values remain constant between study sites.

_Simplifying Assumptions_

_Runup Equations_

Maximum runup elevations generated by storms can exceed several meters, and depend mainly on wave heights and beach slope. The landward extent of wave runup defines the edge of the swash zone, and hence the boundary for the application of swash zone sediment transport
processes. The original EDUNE model is formulated to operate with a constant runup value, which is not a realistic representation of a process that is highly dependent on wave characteristics and beach slope, both of which change constantly over the duration of the storm.

The three primary components of runup include setup, which is the change in mean water level due to momentum flux gradients associated with wave breaking, fluctuations about mean setup due to incident waves (incident swash), and fluctuations due to infragravity waves (infragravity swash). The resulting runup elevations can be calculated from equations based on field observations. Holman (1986) determined that the maximum 2% of all runup elevations exceed the value predicted by the formula:

$$R_{2\%} = H_\infty (0.83\xi_\infty + 0.2)$$  \hspace{1cm} (4.1)

where $\xi_\infty$ is the deepwater Iribarren number, which is defined as:

$$\xi_\infty = \frac{\tan \beta}{(H_\infty / L_\infty)^{1/2}}.$$  \hspace{1cm} (4.2)

where $\tan \beta$ is the beach slope. The 2% exceedence value of runup will be tested as a possible representation of runup in the EDUNE model. Because $R_{2\%}$ is an extreme value, it is also prudent to test two moderate representations of runup as well. Assuming a Rayleigh distribution of runup elevations, these $R_{2\%}$ values can be transformed to rms runup and significant runup with the formulas:

$$R_{rms} = R_{2\%} / 1.9779,$$  \hspace{1cm} (4.3)

$$R_s = 1.4142R_{rms}.$$  \hspace{1cm} (4.4)

These three representations of runup, $R_{2\%}$, $R_s$, and $R_{rms}$ are tested with the 30 Assateague North profiles and EDUNE calibration values from published literature, including a K-value of $8.7 \times 10^{-6}$ m$^4$/N.
In order to implement these equations in the model, the slope of the beach is calculated at each time step, at the location of mean high water +/- 0.5 vertical meters. Additionally, wave heights and periods are taken from buoy measurements, and wavelengths are calculated with the deep-water linear wave equations. Figure 4.1 displays the three time series of runup specific to Profile 4362 on Assateague North, and the corresponding model results. The $R_{2\%}$ record produces excessive erosion on the dune, as does the $R_s$ time series. The model results corresponding to $R_{rms}$ provide the best fit for all 30 Assateague North profiles, with a mean GVC value of 0.48 m$^3$/m, and mean RMS error of 0.63 m. Both error statistics are statistically smaller than those calculated with $R_{2\%}$ and $R_s$ representations of runup at the 95% confidence level. Based on these test results, $R_{rms}$ is chosen as the preferred representation of runup elevations for all EDUNE model runs.

![Figure 4.1](image.png)

**Figure 4.1** Three representations of time varying runup elevations specific to Profile 4362 from Assateague North, and corresponding EDUNE model results. Blue profiles represent the pre-storm profile, red profiles indicate the post-storm profile, and black represents the model results.
Tides

Water levels affect energy dissipation per unit volume in the surf zone, via Equations 1.42:

\[
F = \frac{1}{8} \rho g \frac{3}{2} \gamma^2 h^{5/2}.
\]  

(4.5)

Kriebel (1995) notes that when water levels are extremely low, actual energy dissipation can fall below equilibrium energy dissipation, generating onshore transport over the shallow portions of the profile:

\[
Q_s = K (D - D_{eq}).
\]  

(4.6)

This process is a by-product of the numerical scheme rather than theory or observation. In order to avoid extremely low water levels due to the fluctuations of tides, and therefore minimize the occurrences of onshore transport, Kriebel recommends using storm surge elevations as a proxy for observed water levels. As mentioned previously, water elevation is important in determining the cross-shore location of the surf zone, and therefore this substitution will impede the movement of the surf zone back and forth across the profile. Therefore, the model is also tested with the observed water level time series (tides plus storm surge), in order to determine if significant differences are observed in model accuracy.

Figure 4.2 displays the two water level time series, and corresponding model results for Profile 4632 on Assateague North. Little difference is observed in the results produced by the two methods, and the mean error statistics for all 30 profiles are not significantly different from one another at the 95% confidence level. This observation suggests that storm surge is an appropriate proxy for observed water level. The lack of change in model results may be due to a high dependence on water levels at the height of the storm, which both time series represent accurately. Additionally, when results are generated with the observed water level time series, the model’s interpolation scheme shortens the time increment significantly due to the rapidly
fluctuating water levels, which increases computation time by 400%. Based on these results, all EDUNE runs are performed with storm surge records rather than observed water level time series.

Figure 4.2 Two representations of time varying water levels, and corresponding EDUNE model results for Profile 4362 from Assateague North. Blue profiles represent the pre-storm profile, red profiles indicate the post-storm profile, and black represents the model results.

Breaking Wave Criterion

The width of the surf zone is primarily determined by the breaking wave criterion, which defines the depth at breaking through the wave height to water depth ratio. The seaward edge of the surf zone is defined by the criterion for spilling breaking waves found in Equation 1.32:

\[ \gamma_b = \frac{H_b}{h_b} = 0.78. \]  

(4.7)
The value of 0.78 is also used in the definitions of equilibrium and actual energy dissipation in Equations 1.36 and 1.42, in order to eliminate the dependence of the model on the cross-shore wave height profile. Initial EDUNE tests showed that the combination of $\gamma_b=0.78$ and rms breaking wave height input from the SWAN model allowed small waves to break landward of the swash zone boundary. The model compensated for this instability by setting the landward and seaward boundaries of the surf zone at the same location, eliminating the presence of the surf zone altogether. Figure 4.3 plots three profiles and corresponding EDUNE model results, along with pdfs depicting the width of the surf zone over the duration of the storm. These pdfs show that the surf zone went undefined for a majority of time steps.

Because the surf zone did not exist in the presence of small waves, the entire profile seaward of the swash zone was defined as a part of the offshore region. This region was governed by the critical slope tanoff, and evolved in a linear fashion towards this empirical slope value. These linear slopes can be seen in the predicted profiles in Figure 4.3, which depart significantly from the observed concave shape of the post-storm profile. Additionally, model results were only moderately sensitive to changing values of $K$, the transport rate coefficient, which governs sediment transport rates in the surf zone. Figure 4.4 shows that calculated mean GVC increased by only 68% over one order of magnitude of $K$-values, which is small compared to the SBEACH sensitivity value of 369%.

Both Thornton and Guza (1983) and Sallenger and Holman (1985) found that the value of $\gamma_{rms}$ ($\gamma$ based on rms breaking waves) is much less than the 0.78 value used by EDUNE. Thornton and Guza found a value of $\gamma_{rms}=0.42$ based on field data from Torrey Pines Beach, CA, and Sallenger and Holman found $\gamma_{rms}=0.32$ based on data from Duck, NC. The model was tested with $\gamma_b$ values of 0.32 and 0.42, and as predicted these smaller values allowed the rms breaking wave heights to break further offshore, creating a wide surf zone over which the transport rate equations were employed. Figure 4.5 displays model results for three profiles from Assateague
North and corresponding relative frequency histograms of surf zone width when $\gamma_b$ is set at 0.32. This figure shows that while the surf zone is often narrow in the presence of small waves, the effective width is never zero. The beach profiles now display a concave shape similar to that of the observed profiles.

Figure 4.3 Vertical RMS error is plotted as a function of latitude on the Assateague North study site when $\gamma_b=0.78$. Also plotted are three EDUNE model results, and corresponding relative frequency histograms of surf zone width.
Figure 4.4 Sensitivity of the EDUNE model to K, the transport rate coefficient when $\gamma_b=0.78$. Sensitivity is evaluated through a mean calculation of predicted gross volume change (m$^3$/m) for the 30 Assateague North profiles. Each error bar represents the 95% confidence interval on the mean GVC value.

Figure 4.5 Vertical RMS error is plotted as a function of latitude on the Assateague North study site when $\gamma_b=0.32$. Also plotted are three EDUNE model results, and corresponding relative frequency histograms of surf zone width.
With $\gamma_b=0.32$, sensitivity to $K$ increases to an expected level, with mean GVC changing by 207% over one order of magnitude of $K$-values as shown in Figure 4.6. It is important to note that by decreasing the value of $\gamma_b$, the value of $K$ must increase in order to produce the correct volume of sediment transport in the surf zone. This implies that the calibration value of $K$ has a dependence on the value of $\gamma_b$. The model was calibrated to a best-fit $K$-value with both $\gamma_b=0.32$ ($K=2.0\times10^{-5}$ m$^4$/N) and $\gamma_b=0.42$ ($K=1.5\times10^{-5}$ m$^4$/N). Error statistics for model runs with $\gamma_b=0.32$ were significantly smaller than errors produced with $\gamma_b=0.42$ at the 95% confidence level. For this reason, $\gamma_b$ is set at a value of 0.32 for all model runs.

![Figure 4.6](image)

**Figure 4.6** Sensitivity of the EDUNE model to $K$, the transport rate coefficient when $\gamma_b=0.32$. Sensitivity is evaluated through a mean calculation of predicted gross volume change (m$^3$/m) for the 30 Assateague North profiles. Each error bar represents the 95% confidence interval on the mean value.

**Model Sensitivity and Calibration: Empirical Parameters**

The EDUNE model employs five empirical parameters, among which only the transport rate coefficient appears in the model’s governing equations. The remaining empirical parameters each describe the critical slope assigned to one of four distinct regions of the profile, including the dune face, swash zone, surf zone, and the offshore region. Because the location of each region fluctuates with breaking wave height and water level, each grid cell may be subject to two or three different critical angles over the duration of the storm. This confounds the true effect of
each parameter on model results, and limits interpretation of the sensitivity of the model to each slope parameter. The following subsections explore model sensitivity to K, as well as the four critical slope values.

K, the Transport Rate Coefficient

The function of K in the EDUNE model is the same as in SBEACH, directly influencing the magnitude of the sediment transport rate in the surf zone. Sediment transport rates should increase linearly as the value of K increases, as described in Equation 4.6. Therefore, eroded sediment volumes should increase as the value of K increases. Moore (1982) calibrated the EDUNE model and found a best-fit K-value of 2.2x10^{-6} m^4/N. Later, Kriebel (1986) performed a second calibration with laboratory data, and revised the best estimate of K to 8.7x10^{-6} m^4/N. However, both of these calibration values were determined with a $\gamma_b$ value of 0.78. Using the new $\gamma_b$ value of 0.32, neither calibration value produces sufficient erosion in the surf zone to minimize model error. Values of K used for sensitivity testing are therefore larger than the previously determined values, ranging over an order of magnitude from 5.0x10^{-6} to 5.0x10^{-5} m/N.

Figure 4.7 plots the results of sensitivity tests for a single profile from Assateague North. As hypothesized, erosion on the dune increases as the value of K increases. Differences in erosion are seen mostly on the dune, while the shape and elevation of the beach exhibit little change with increasing values of K. Figure 4.8(a) shows that mean calculated GVC increases by 207% over one order of magnitude of K-values, which is statistically significant at the 95% confidence level. This figure also indicates that among the five empirical parameters, the model is most sensitive to K. Calibration curves are presented in Figure 4.6, indicating that the best-fit value of K falls in the range of 2.0x10^{-5} to 3.0x10^{-5} m^4/N. A value of K=2.0x10^{-5} m^4/N is chosen for all subsequent model runs, minimizing mean RMS error at 0.51 m, and mean GVE at 0.38 m^3/m. As discussed in the previous section, this calibration value of K is specific to $\gamma_b=0.32$. 
Figure 4.7 Profile 4362 from Assateague North is used as an example of model response to changing values of K (m³/N). In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Figure 4.8 EDUNE sensitivity to (a) $K$, the transport rate coefficient, (b) $\eta_{\text{tanb}}$, the equilibrium beach slope, (c) $\eta_{\text{etand}}$, the equilibrium dune slope, (d) $\tan_{\text{rep}}$, the active profile critical angle, and (e) $\tan_{\text{off}}$, the offshore critical angle. Sensitivity is evaluated through a mean calculation of predicted gross volume change (m$^3$/m) for the 30 Assateague North profiles. Each error bar represents the 95% confidence interval on the mean value.
etanb, the Equilibrium Beach Slope

The equilibrium beach slope, etanb, performs two roles within the model’s numerical scheme. First and foremost, the landward boundary of the surf zone is defined at the location where the concave underwater profile is tangent to the slope value defined by etanb. As the value of etanb increases, the boundary moves landward, increasing the width of the surf zone. This landward shift of the surf zone boundary should increase erosion on the subaerial profile, and based on this particular role of etanb in the numerical scheme, GVC should increase with increasing values of etanb. Secondly, the ‘potential erosion prism method’ illustrated in Figure 1.2 generates sediment transport rates that evolve the swash zone towards the slope defined by etanb. Because the volume of the erosional prism does not change as a function of the target slope, this role of etanb should have little effect on total eroded volume. Therefore, eroded volumes should increase as etanb increases, due to the widening of the surf zone.

For sensitivity testing, the value of etanb is varied from 1.5° to 6°, encompassing slope values for a variety of beach types. Figure 4.10 presents the results of sensitivity tests for an individual profile from Assateague North. Contrary to the previously stated hypothesis, erosion on the dune and beach decreases significantly as values of etanb increase. This observation is
Figure 4.10  Profile 4362 from Assateague North is used as an example of model response to changing values of etanb (°). In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
confirmed in Figure 4.8(b), which shows that mean calculated GVC decreases for values of etanb greater than 2°. The change in mean GVC between etanb values of 2° and 6° is -65%, which is statistically significant at the 95% confidence level. Calibration plots are given in Figure 4.11, which indicate that both error statistics are minimized and statistically equivalent at etanb values of 2° and 2.5°. A best-fit value of 2.5° is chosen for all subsequent model runs.

One possible explanation for the unexpected inverse relationship between etanb and GVC lies within the undercutting and avalanching mechanisms that shape the face of the dune. At the height of the storm, the swash zone impinges on the steep dune face, and the volume of sediment defined by the erosional prism is eroded from the dune base. When etanb is small, the dune is undercut at the dune base, which initiates a significant redistribution of sand onto the active profile due to avalanching of the dune face. Conversely, if etanb is large, the undercutting of the dune will not be as dramatic and will result in less erosion.

![Figure 4.11](image_url)

**Figure 4.11** EDUNE calibration curves for values of etanb, the equilibrium beach slope on the Assateague North study site. Each error bar represents the 95% confidence interval on the mean value.

etand, the Equilibrium Dune Slope

The equilibrium dune slope, etand, defines the critical angle assigned to the portion of the profile lying between the dune crest and the landward edge of the swash zone. When the slope
between any two grid cells in this region exceeds etand, avalanching occurs until the residual slope matches the empirical value of etand. Sediment eroded by this process is redistributed across the swash and surf zones. Large values of etand impede the avalanching process and hinder erosion on the subaerial profile. Therefore, GVC should be inversely dependent on etand, decreasing with increasing values of the critical slope.

For sensitivity testing purposes, values of etand are varied over a wide range from 25° to 70°. Figure 4.8(c) shows that mean GVC is insensitive to changing values of etand, as opposed to the hypothesized inverse dependence between the two values. None of the means or variances are statistically different from one another at the 95% confidence level, confirming that the model is insensitive to etand. However, like the SBEACH model, a visual inspection of model results shows a slight variation in profile shape with changing values of etand. While this change is not large enough to make a significant impact on the mean GVC value, an etand value of 60° best allows the model to reproduce the post-storm dune slope, and therefore is used for all model runs.

tanrep, the Active Profile Critical Angle

The empirical parameter tanrep is the critical angle assigned to the surf and swash zones. Within both regions, if the slope between grid cells exceeds tanrep, spacing between contours is adjusted until the critical angle is established. Sediment that erodes as a result of this adjustment is redistributed to neighboring cells. Because the evolution of the swash zone is first governed by the parameter etanb, tanrep only serves as a second check on slopes in order to prevent instabilities in this region of the profile. Conversely, tanrep is the governing value that prevents oversteepening of the surf zone profile. As with etand, large values of tanrep impede the redistribution of sediment in the surf zone, and therefore reduce erosion on the subaerial profile. This implies that an inverse relationship between tanrep and erosion should exist, with GVC decreasing as the value of tanrep increases.
For sensitivity testing purposes, tanrep was varied from 2° to 20°. Figure 4.8(d) shows that GVC is insensitive to values of tanrep ranging between 4° and 20°, and are not statistically different from one another at the 95% confidence level. An arbitrary tanrep value of 10° is therefore chosen for all EDUNE model runs. Another noticeable trend in Figure 4.8(d), is that the mean GVC value calculated with a critical angle of 2° is substantially higher than for the rest of the range. The higher GVC value occurs because the value of tanrep is less than the calibrated etanb value of 2.5°. At each time step, the ‘potential erosion prism method’ attempts to establish a slope of 2.5°, and subsequently the tanrep mechanism redistributes sediment in order to establish a flatter slope of 2°. As a result, the competing processes generate excessive erosion on the subaerial profile. Therefore, it is recommended that the value of tanrep should always exceed the value of etanb.

tanoff, the Offshore Critical Angle

The offshore critical angle, tanoff, is the critical angle established for grid cells seaward of the surf zone. If any slope value in this region exceeds tanoff, spacing between contours is adjusted until the critical angle is reached, and eroded sand is redistributed among neighboring cells. Because this readjustment does not affect the subaerial profile in any way, eroded volume on the dune and beach should not be affected by differing values of tanoff. Proving the hypothesis, Figure 4.8(e) shows that model results are insensitive to values of tanoff ranging from 2.5° to 8.5°. The means and variances reported for each value of tanoff are not statistically different from one another at the 95% confidence level. An arbitrary tanoff value of 4.5° is used for all model runs.
Model Sensitivity: Physical and Hydrodynamic Variables

The EDUNE model inherently relies on one physical and two hydrodynamic variables. The physical parameter found in the model’s numerical formulation is $D_{50}$, the median grain diameter. This value affects the shape parameter $A$, which influences the equilibrium energy dissipation per unit volume and the slope of the initial offshore profile. The two hydrodynamic variables are $S$, the storm surge elevation, and $H_{b,\text{rms}}$ the rms breaking wave height. The storm surge time series directly influences the cross-shore location of the surf zone, while the breaking wave height time series affects surf zone width. The addition of time dependent runup equations introduced earlier in the chapter produces a model dependence on two additional hydrodynamic variables, $H_{\infty}$, the offshore significant wave height, and $L_{\infty}$, the corresponding offshore wavelength. Both of these values are utilized to calculate the elevation of runup, which in turn determines the width of the swash zone.

$D_{50}$, the Median Grain Diameter

The physical setting of the dune environment is described by a single parameter, $D_{50}$. Median grain diameter plays two opposing roles within the model formulation, both through calculations of the shape parameter $A$. The first role of $D_{50}$ is defined in Equation 1.34:

$$A = \begin{cases} 10^{\left(\frac{\log D_{50} - 0.237}{0.924}\right)} & D_{50} < 0.262 \\ 10^{\left(\frac{\log D_{50} - 2.264}{3.30}\right)} & D_{50} \geq 0.263 \end{cases} \quad (4.8)$$

Through this equation, $A$ increases nonlinearly as $D_{50}$ increases. Subsequently, equilibrium energy dissipation defined Equation 1.36 increases:

$$D_{eq} = \frac{5A^{3/2} \rho g^{1/2} T^2}{24}. \quad (4.9)$$
Increased values of $D_{eq}$ decrease sediment transport rates in the surf zone (Equation 4.6) and limit erosion of the subaerial profile. Therefore, an increase in $D_{50}$ should bring about a corresponding decrease in GVC. This relationship is conceptually correct, as research has shown that energy required for transport increases as grain size increases.

The second effect of $D_{50}$ on model results is due to the dependence of the initial offshore profile slope on the shape parameter. Because lidar does not penetrate water to record bathymetric data, the shape of the initial offshore profile is calculated with Dean’s $h=Ax^{2/3}$ equilibrium profile. As $D_{50}$ increases the profile steepens, which allows waves to shoal further inshore before breaking. This effect should cause GVC to increase as $D_{50}$ increases. Therefore, any observed trend in GVC will be the net result of the two opposing processes.

Figure 4.12(a) shows that the mean calculated GVC value decreases by 40% as $D_{50}$ increases from 0.13 to 0.93 mm. This change is statistically significant at the 95% confidence level. This observation implies that the increase in $D_{eq}$ with increasing $D_{50}$ is the dominant process, the magnitude of which cannot be fully discerned due to the simultaneous steepening of the initial profile. Figure 4.13 presents calibration curves for $D_{50}$, implying that error is not minimized at the ‘true’ value of 0.33 mm. Instead, both error statistics are smallest at 0.13 mm, and are statistically different from the other mean error statistics at the 95% confidence level. This observation suggests that model accuracy can be improved by decreasing the values of $D_{eq}$ calculated in Equation 4.9, and that the function of $D_{50}$ is not correctly defined within the numerical scheme.
Figure 4.12 EDUNE sensitivity to (a) $D_{50}$, the median grain diameter, (b) $S$, the storm surge elevation, (c) $H_{b,\text{rms}}$, the rms breaking wave height, (d) $H_\infty$, the significant offshore wave height, and (e) $T_p$, the peak wave period. Sensitivity is evaluated through a mean calculation of predicted gross volume change ($\text{m}^3/\text{m}$) for the 30 Assateague North profiles. Each error bar represents the 95% confidence interval on the mean value.
Figure 4.13  EDUNE calibration curves for values of $D_{50}$, the median grain diameter on the Assateague North study site. Each error bar represents the 95% confidence interval on the mean value.

Storm Surge Elevation

Storm surge elevation effects erosion of the subaerial profile by altering the cross-shore location of the surf zone. As water levels increase, the location of breaking moves landward onto the beach and the dune. As the surf zone moves landward across the beach, the swash zone also moves landward, and swash-induced transport impinges on the dune face. For this reason, erosion on the subaerial profile should increase with increasing storm surge elevation.

In order to investigate the sensitivity of the model to storm surge, the original record from NOAA tide gauge 8570283 is offset vertically by fixed values ranging from -1 m to 1 m. Figure 4.14 presents plots of a single profile from Assateague North and corresponding model results for each representative storm surge time series. The trend in profile change is clear, in that erosion increases on the dune as storm surge elevations increase. Only mild beach erosion occurs with the smallest surge values, while the dune is completely flattened when surge values increase. It is important to note that when the dune erodes completely, overwash deposits do not form due to the model’s continuity requirement that sediment is conserved between the dune crest and the seaward-most contour.
Figure 4.12(b) presents sensitivity results for storm surge, concluding that mean GVC increases rapidly with increasing storm surge elevation. The change GVC across the test range is 455%, which is statistically significant at the 95% confidence level. Therefore, it is important to obtain the most accurate storm surge time series possible when running the EDUNE model, as slight deviations from the true time series can significantly alter model results. Figure 4.15 presents both error statistics as a function of storm surge, and encouragingly shows that both error statistics are minimized with the observed storm surge time series.
Figure 4.14 Profile 4362 from Assateague North is used as an example of model response to changing representations of storm surge elevation. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Breaking Wave Height

Breaking wave height has a single function in the EDUNE model, which is to determine the depth at breaking as defined by the criterion $\gamma_b=0.32$. Large waves break further offshore than their smaller counterparts, increasing the width of the surf zone. When the surf zone width increases, wave-induced transport acts over a greater length of the profile. This effect is extremely important at the height of the storm when the surf zone impinges on the beach and dune. Therefore, increases in $H_b$ should increase GVC values.

In order to test model sensitivity to $H_b$, the entire time series is multiplied by constant coefficients ranging from 0.5 to 1.5. Figure 4.12(c) showing that mean GVC increases by 54% over the range of $H_b$ time series, confirming the hypothesis that larger wave heights should generate greater erosion. Sensitivity to breaking wave height is not as large as expected, because the GVC measurement only captures change on the subaerial profile as opposed to the entire profile.

Figure 4.16 presents calibration curves for the breaking wave height time series. The means and variances of the error statistics for all representations of $H_b$ are not significantly different from the error statistics produced by the ‘true’ time series at the 95% confidence level.
Because error does not change over this range of variation in the input time series, it is possible to conclude that the accuracy of the breaking wave height time series is not as critical as the accuracy of the storm surge time series. This is an important observation, as breaking wave heights must be predicted by an external wave model.

![Figure 4.16 EDUNE calibration curves for varying representations of the rms breaking wave height time series on the Assateague North study site. Each error bar represents the 95% confidence interval on the mean value.](image)

**Significant Offshore Wave Height**

Although EDUNE’s original numerical scheme does not include significant offshore wave height, the runup calculations introduced in Equations 4.1 through 4.3 are all dependent on $H_\infty$. As values of $H_\infty$ increase, runup elevations increase, which expands the width of the swash zone and increases erosion across the subaerial profile. Therefore, a direct relationship between $H_\infty$ and eroded volume is hypothesized, with mean GVC increasing as $H_\infty$ increases.

In order to explore the sensitivity of model results to this variable, the $H_\infty$ time series is multiplied by constant coefficients ranging from 0.5 to 1.5. Figure 4.12(d) displays sensitivity results for the various $H_\infty$ time series, and shows that mean calculated GVC increases slightly (35%) over the range of modified time series. This observation confirms the hypothesis that increased offshore wave heights enhance subaerial erosion by increasing the width of the swash
zone. However, the relatively small sensitivity suggests that small inaccuracies in the $H_\infty$ time series will not significantly alter model results.

**Wave Period**

Similarly, wave period ($T_p$) enters the model’s numerical scheme through calculations of runup elevations in Equations 4.1 through 4.3. Increasing values of wave period decrease wave steepness, therefore increasing the value of the Iribarren number in Equation 4.2. This increase in Iribarren number subsequently increases runup elevations, widening the swash zone and increasing the total erosion on the subaerial profile. Therefore, a direct relationship between period and erosion is expected, with GVC increasing as $T_p$ increases.

For sensitivity tests, the peak period record was modified by shifting the entire time series by several seconds, ranging from -4 to 6 s. The modifications are asymmetric in order to avoid negative wave periods, but also to test the sensitivity of the model to a 10 second range. Sensitivity results are presented in Figure 4.12(e), which shows that as hypothesized, mean calculated GVC values increase by 24% over the range of modified $T_p$ time series, which is statistically significant at the 95% confidence level. As with $H_\infty$, small inaccuracies (<4s) in the peak period time series should not significantly alter model results.

**Model Results: Assateague Island**

**Calibration Site: Assateague North**

The Assateague North study area is comprised of 30 profiles with tall dunes averaging 6.5 meters in elevation at the dune crest. Figure 4.17 displays ten profiles from the study area with accompanying EDUNE model results. These results were calculated using calibration values of empirical parameters from the previous section, including a K-value of $2.0\times10^{-5}$ m$^{4}$/N. These profiles suggest that the model correctly delineates between cases of beach erosion and dune scarping. With respect to profiles that erode only on the beach, the EDUNE model
Figure 4.17 Ten profiles selected from Assateague North and the predicted EDUNE results. The first profile (4122) is the southernmost profile in the study area, and the last profile (4392) is the third northernmost profile. The profiles are spaced approximately 300 meters apart in the longshore direction. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
correctly predicts this response but does not replicate the true concave nature of the observed profiles. In instances of dune scarping, the dune base occurs consistently between elevations of 2.8 and 2.9 m, which correspond favorably with the elevations of maximum storm surge plus runup. This observation indicates that the shape of the post-storm profile predicted by EDUNE is highly dependent on the processes that act at the height of the storm. This dependence on conditions at the height of the storm is conceptually correct, seeing that the measured post-storm profiles similarly maintain a dune base in the same elevation range.

The process that allows EDUNE to delineate between beach erosion and dune scarping appears to be the conditioning of the beach prior to the arrival of maximum storm surge. If the beach erodes significantly prior to the height of the storm, runup will impinge on the dune and the dune face will erode through swash-induced transport and avalanching. If a large volume of sand remains on the beach at the peak of the storm, the beach protects the dune from the brunt of swash-induced erosion, and the dune face will not erode. Therefore, it is appropriate to conclude that the pre-storm volume of the beach is an important variable in the dune erosion process.

Figure 4.18 plots error statistics for the 30 Assateague North profiles as a function of latitude. Errors are particularly low to the south, corresponding to profiles that experienced only beach erosion. In the north, errors are larger due to the tendency of the model to either overpredict erosion on the dune face or underpredict erosion on the beach. Mean RMS error is 0.51 m, which is significantly higher than SBEACH model results at the 95% confidence level. Similarly, the mean GVE of 0.38 m$^3$/m is also significantly higher than for SBEACH model results.
Berm Profiles: Assateague South

The Assateague South study area consists of 30 profiles with an average maximum elevation of 2.8 m at the berm crest. Because these profiles lack a dune, sediment transported by waves accumulates landward of the original berm crest forming overwash deposits. Figure 4.19 plots ten profiles from Assateague South and corresponding EDUNE model results. These plots show that for a majority of cases, EDUNE does not predict sufficient erosion on the beach, nor does it reproduce the small overwash deposits. As noted previously, overwash deposits do not form due to the model’s continuity requirement that sediment is conserved between the dune crest and the seaward-most contour.

Additionally, Figure 4.20 presents error statistics for the 30 Assateague South profiles as a function of latitude. A portion of the error is due to the inability of the model to predict the overwash deposits, while most of the remaining error is due to the lack of erosion on the beach. The mean RMS error statistic of 0.51 meters is significantly greater than SBEACH model results at the 95% confidence level. Additionally, the mean GVE statistic of 0.44 m³/m is also significantly greater than SBEACH results.
Figure 4.19 Ten profiles selected from Assateague South and the predicted EDUNE results. The first profile (3692) is the southernmost profile in the study area, and the last profile (3962) is the third northernmost profile. The profiles are spaced approximately 300 meters apart in the longshore direction. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Previous analysis has shown that the EDUNE model is sensitive to both $K$, the transport rate coefficient, and $\eta_{tanb}$, the equilibrium beach slope. Figure 4.21 presents calibration curves for both empirical parameters, in order to compare calibration values between study sites. Mean error statistics appear to decrease with increasing $K$-values, leveling off for values greater than the calibration value of $K = 2.0 \times 10^{-5} \text{ m}^4/\text{N}$. Because the mean error statistics do not reach a statistically significant minimum in this range of $K$-values, it is impossible to confirm the validity of the Assateague North calibration value on this study site. Calibration curves for the equilibrium beach slope, $\eta_{tanb}$, are similar to those produced with Assateague North data. Both error statistics are minimized in the range of $2^\circ$ to $3.5^\circ$, encompassing the calibration value of $2.5^\circ$. 

Figure 4.20 RMS error and GVE as a function of latitude for EDUNE model results on the Assateague South study site.
Extreme Longshore Variability: Chincoteague

The Chincoteague study area consists of 30 profiles with an average dune crest elevation of 5.8 m. The response of the dunes varied significantly across the length of the site, from mild beach erosion to overwash accompanying the complete erosion of the dune. As noted in previous chapters, because the dunes themselves were similar in pre-storm shape and size, the variability in response may be due to gradients in longshore forcing. Ten profiles from the Chincoteague study area are plotted in Figure 4.22, along with corresponding EDUNE model results. Similar to SBEACH model results, EDUNE is unable to capture the variability in dune response observed along this section of coastline. However, unlike SBEACH, model results are more likely to
Figure 4.22 Ten profiles selected from Chincoteague and the predicted EDUNE results. The first profile (550) is the southernmost profile in the study area, and the last profile (820) is the third northernmost profile. The profiles are spaced approximately 300 meters apart in the longshore direction. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
predict extreme impacts, correctly predicting the complete erosion of the dune on 5 of 6 overwashed profiles.

Figure 4.23 plots error statistics for the 30 Chincoteague profiles as a function of latitude. Error varies considerably along the study area, with a mean RMS error of 0.66 m, and a mean GVE of 0.50 m³/m. Although both of these means are smaller than reported for SBEACH model runs, the large variances associated with the means render SBEACH and EDUNE errors statistically equivalent at the 95% confidence level. Figure 4.24 plots calibration curves for K and etanb on the Chincoteague study site. The large variance associated with both error statistics makes it impossible distinguish the mean errors from one another at the 95% confidence level, and therefore no conclusions can be drawn about the suitability of the Assateague North calibration values to this study site.

Figure 4.23  RMS error and GVE as a function of latitude for EDUNE model results on the Chincoteague study site.
Figure 4.24 EDUNE calibration curves for increasing values of K, the transport rate coefficient, and etanb, the equilibrium beach slope on the Chincoteague study site. Each error bar represents the 95% confidence interval on the mean value.

Model Results: Hatteras Island

Verification Site: Hatteras North

The Hatteras North study area consists of 30 profiles with an average dune crest elevation of 6.7 m. As a consequence of the conditions generated by Hurricane Isabel, the dunes along this stretch of coastline eroded vertically by several meters. Ten profiles from Hatteras North are plotted in Figure 4.25, along with corresponding EDUNE model results. The calculated profiles reproduce both the slope of the beach and the narrow and peaked shape of the dune well, although the placement of the beach and dune is often incorrect. The general shape of the profiles
produced by EDUNE is much different than those predicted by SBEACH, which exhibited wide, rounded dunes that had been eroded several meters below the dune crest.

Another feature present on several of the EDUNE profiles is the accretion of the beach above the initial pre-storm elevation. In some instances the accretion is significant, causing considerable deviations between the predicted and observed profiles. The general mechanism that produces these accretionary features is onshore sediment transport that is initiated when storm surge elevations slightly exceed the elevation of the beach. This situation produces an extremely shallow surf zone, and consequently energy dissipation in this region is extremely low. Therefore, onshore transport is simulated across this portion of the profile via Equation 4.6. Subsequently, the beach grows in elevation as long as accretion can keep pace with water levels. The onshore transport mechanism shuts down only when surge rises significantly at the peak of the storm.

This type of profile response has not been observed previously, because it requires precise pairing of beach morphology and water levels. As Figure 4.25 shows, these accretional features appear on only a few profiles along this section of coastline, indicating that they occur infrequently even when model conditions are favorable. These observations show that this affect can be significant, producing wide, elevated beaches that protect the dune from erosion. Figure 4.26 plots error statistics for the 30 profiles as a function of latitude. RMS error and GVE are both relatively low along most of the coast, with spikes occurring as a result of the accreted beach profiles. The mean RMS error for this section of coastline is 0.50 m, which is not significantly different than the mean RMS error for SBEACH model results at the 95% confidence level. Likewise, the mean GVE value of 0.36 m$^3$/m is not statistically different than for SBEACH. Calibration curves for K and etanb are presented in Figure 4.27, all showing little structure and indistinguishable minimums. Therefore, no conclusions can be drawn about the suitability of the Assateague North calibration values to this study site.
Figure 4.25  Ten profiles selected from Hatteras North and the predicted EDUNE results. The first profile (17790) is on the southwestern edge of the study area, and the last profile (17819) is the third profile from the northeastern edge. The profiles are spaced approximately 30 meters apart in the longshore direction. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Figure 4.26 RMS error and GVE as a function of latitude for EDUNE model results on the Hatteras North study site.

Figure 4.27 EDUNE calibration curves for increasing values of $K$, the transport rate coefficient, and $etanb$, the equilibrium beach slope on the Hatteras North study site. Each error bar represents the 95% confidence interval on the mean value.
**Extreme Impacts: Hatteras Breach**

The Hatteras Breach study area consists of 30 profiles averaging 4.5 meters in elevation at the dune crest. Conditions during Hurricane Isabel caused the island to breach in this location, scouring a channel several meters below sea level. Figure 4.28 plots ten profiles from the Hatteras Breach site, as well as corresponding EDUNE results. Most notably, EDUNE does not correctly predict the breach or even the flattening of the dune. On several profiles, the beach accretes significantly on both the beach and dune face. This process is described in detail in the previous section, and is due to a flawed description of onshore transport in the model’s governing equations. Once accretion is initiated, the profile continues to build as water levels rise slowly, and ceases only when water levels rise significantly above the beach. These observations show that onshore transport allowed by EDUNE can severely mask the true impact caused by an extreme storm.
Figure 4.28 Ten profiles selected from Hatteras Breach and the predicted EDUNE results. The first profile (17736) is on the southwestern edge of the study area, and the last profile (17763) is the third profile from the northeastern edge. The profiles are spaced approximately 45 meters apart in the longshore direction. In each figure, the blue profile represents the pre-storm profile, red represents the post-storm profile, and black indicates the calculated model result.
Chapter Five
Discussion

Introduction

The objective of this chapter is to provide a comprehensive comparison of the two models, as well as recommendations for future dune erosion studies involving a macroscale modeling approach. The first section of this chapter compares the two models in terms of overall accuracy in hindcasting erosional events, sensitivity to empirical parameters, and observed inconsistencies in model performance. The second section comments on both models’ lack of predictive skill on the Chincoteague and Hatteras Breach study sites, and discusses the implications of gradients in longshore forcing which most likely contribute to the lack of model skill on Chincoteague. This section also provides a possible explanation for the inability of the models to predict the Hatteras Island breach, and includes a discussion of hypothesized transport mechanisms that may lead to breaching events. Finally, the third section presents recommendations for future studies of macroscale dune modeling, including priorities for modifications to the models’ sediment transport processes.

Model Comparison

One desired outcome of this study is to determine which of the two models is most accurate in its prediction of dune erosion, a determination that will provide direction for future macroscale modeling approaches. The quantitative accuracy of the two models can be measured with mean RMS error and mean GVE statistics from the four non-breaching study sites. In
Figure 5.1, mean error statistics are plotted as a function of study site with each error bar representing the 95% confidence interval about the mean value. A fifth entry to these graphs is labeled as ‘total,’ and specifies mean error for all 120 profiles included in the four study sites. As these graphs show, mean error produced by SBEACH is significantly lower than EDUNE at the 95% confidence level on both the Assateague North and Assateague South study sites. In comparison, the mean error statistics on Chincoteague and Hatteras North are statistically equivalent between the two models. Total error for the four study sites is statistically equivalent at the 95% confidence level. Tables 5.1 and 5.2 list the mean and standard deviations of RMS error and GVE for both models.

The statistical equivalence of total error suggests that both models are equally suited to the task of predicting dune response to extreme storms. However, results presented in the previous two chapters suggest that a quantitative comparison of the two models is not sufficient evidence to make this conclusion. In order to determine which model is best suited for predictive purposes, it is necessary to consider additional factors, including the consistency of calibrated empirical parameters between study sites and recognized inconsistencies in model performance. The following paragraphs will address both of these aspects in more detail, and will make the case that while the quantitative accuracy of the two models is statistically equivalent, SBEACH is the preferred model for predictive applications.
Figure 5.1 Mean RMS error and mean GVE are plotted as a function of study site for both the SBEACH and EDUNE models. The final entry labeled ‘total,’ depicts model error combined for all four study sites. Each error bar represents the 95% confidence interval on the mean value.

<table>
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<th>SBEACH</th>
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<th>$s_{RMS}$</th>
<th>$\bar{GVE}$</th>
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<tr>
<td>Total</td>
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<td>0.27 m</td>
<td>0.39 m$^3$/m</td>
<td>0.21 m$^3$/m</td>
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Table 5.1 Compiled error statistics for SBEACH model runs for the four non-breaching study areas. Total error is based on the 120 profiles included in these four study sites.

<table>
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<th>EDUNE</th>
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<th>$s_{RMS}$</th>
<th>$\bar{GVE}$</th>
<th>$s_{GVE}$</th>
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</tr>
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<td>Hatteras North</td>
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<td>0.20 m</td>
<td>0.36 m$^3$/m</td>
<td>0.16 m$^3$/m</td>
</tr>
<tr>
<td>Total</td>
<td>0.55 m</td>
<td>0.26 m</td>
<td>0.42 m$^3$/m</td>
<td>0.21 m$^3$/m</td>
</tr>
</tbody>
</table>

Table 5.2 Compiled error statistics for EDUNE model runs for the four non-breaching study areas. Total error is based on the 120 profiles included in these four study sites.
A primary consideration for determining which model is best suited for predicting dune erosion is overall confidence in the calibration values of empirical parameters. Because empirical parameters enter the models to account for unknown processes, it is important that they are constrained to account for the same processes at each study site. It is necessary for empirical parameters to be robust between coastal locations in order that site-specific calibrations are not required to minimize model error. The following paragraphs will review and discuss the ability of the calibrated empirical parameters to minimize error across the four non-breaching study sites. This discussion suggests that empirical parameters are well constrained by the SBEACH model, while it is difficult to have confidence in the calibration values of empirical parameters inherent to the EDUNE model.

SBEACH exhibits sensitivity to the empirical coefficient K, the transport rate coefficient. Model results are highly sensitive to K, displaying a 369% increase in mean GVC over one order of magnitude of K-values. As shown in Figure 5.2, the calibration curves for each of the four non-breaching study sites is similar in shape to the original curve produced on Assateague North, and error is consistently minimized in a narrow range encompassing the calibration value of K=5.0x10^-7 m^4/N. This observation suggests that K accounts for the same unknown processes at each study site, which is a desired characteristic of all empirical parameters. Therefore, despite the high level of sensitivity to the K-value, the calibration is well constrained across the four non-breaching study sites. Therefore, site-specific calibration is not a requirement for the SBEACH model.
Figure 5.2 Mean RMS error and mean GVE are plotted for SBEACH results as a function of K-value for four study sites. Each error bar represents the 95% confidence interval on the mean value.

The EDUNE model also exhibits sensitivity to the empirical coefficient K. When values of K are varied over one order of magnitude on the Assateague North study site, mean GVC increases by 207%. While EDUNE is less sensitive to K than SBEACH, the calibration is not well constrained between study sites, as seen in Figure 5.3. Each calibration curve takes on a different shape, with the range of error minimizing K-values increasing considerably on the Assateague South, Chincoteague, and Hatteras North study areas. This figure suggests that the empirical K-value absorbs different processes at each study site, and that the role of K is not well constrained within the model’s governing equations. This observation indicates that the best-fit value of K is dependent on study site, which implies that the model should be calibrated separately at each distinct location along the coast. The necessity of site-specific calibration with
respect to K prevents the use of EDUNE for predictive applications. The sensitivity of the EDUNE model to an empirical parameter that is not well constrained argues against its use as a tool for widespread application for the prediction of dune erosion.

![Figure 5.3](image)

**Figure 5.3** Mean RMS error and mean GVE are plotted for EDUNE results as a function of K-value for four study sites. Each error bar represents the 95% confidence interval on the mean value.

An additional fundamental concern about the ability of EDUNE to predict erosional events is the inconsistency in model performance that results from the incorrect description of onshore transport in response to shallow water depths. The result of the rapid onshore transport mechanism is the formation of accretionary features on the beach, which are observed on both the Hatteras North and Hatteras Breach study sites. The negative consequence of this cause-and-effect relationship is most clearly seen in Figure 4.28, where instead of predicting the flattening of the dune and breaching, the model predicts that the dune grows over the course of the storm.
The occurrence of these anomalous accretionary features weakens confidence in the model to correctly predict dune erosion. Therefore, despite the good performance of the model on the other study sites, EDUNE is rendered ineffective due this inconsistency in model performance.

Based on total error statistics compiled for the four study sites, the two models are statistically equivalent in their ability to predict dune erosion. However, several concerns about inconsistencies in EDUNE model results create a preference for the use of SBEACH for the prediction of dune erosion. Inconsistencies in calibration curves for the empirical parameter $K$ necessitate site-specific calibration, which is not conducive to predicting erosion at new study sites. Additionally, the onshore transport mechanism that leads to anomalous accretionary features on the beach is of serious concern, as it may mask extreme impacts similar to model results on the Hatteras Breach study site. Conversely, the SBEACH model exhibits consistency in calibration value for the empirical parameter $K$, and no inconsistencies were noted in model results during the testing phase of this study. Therefore, the conclusion of this study is that SBEACH is most suitable for macroscale modeling of dune erosion during extreme storm events.

*Longshore Variability and Barrier Island Breaching*

One conclusion that can be drawn from this study is that model error increases significantly in the presence of extreme longshore variability in dune response and barrier island breaching. As shown in Figure 5.1, mean error statistics for both models are highest on the Chincoteague study site, which exhibits the greatest variation in dune response among the five study areas. Dune response on this section of coastline varies from mild beach erosion to complete destruction of the dune, with no observed longshore trend (Figure 1.8). This variability in dune response does not appear to be a function of pre-storm dune morphology, which is relatively uniform in the longshore direction. The dune crest elevation along this stretch of coastline varies only slightly, with a mean of 5.6 m and a standard deviation of 0.35 m.
In the absence of extreme variability in pre-storm profile shape, the observed differences in dune response are most likely a function of processes that act in the longshore direction, and that may exhibit significant gradients on spatial scales smaller than 3 kilometers. Potential processes that may cause extreme longshore variations in dune response include the dissipation of wave energy over longshore-variable sandbars, wave refraction over arbitrary bathymetry, rip currents and associated circulation cells, and longshore currents that flow along the beach in response to gradients in dune elevation. Because the SBEACH model excludes longshore sediment transport processes by assuming that cross-shore gradients in transport dominate under storm conditions, the presence of any of these four processes may cause significant deviations between observed and predicted dune response. While the processes described in the following paragraphs are not exhaustive, the magnitude of any one of these processes may be large enough to account for extreme variability in dune erosion on spatial scales on the order of several kilometers.

The dissipation of energy by sandbars can significantly reduce the magnitude of wave energy available to act on the subaerial profile. Sandbars can be considerable in longshore extent, stretching along the coast for many kilometers. Breaks in sandbars occur where rip currents have scoured the surface of the seafloor, making wave energy dissipation over the sandbar a longshore variable process. Profiles that align with an offshore sandbar will experience significantly less wave energy dissipation, as sandbars initiate the breaking of large waves well offshore. Profiles that align with breaks in the sandbar system will experience greater dissipation of energy closer to shore, leading to greater erosion and leaving the dunes more vulnerable to overtopping by waves.

In addition to single sandbar systems, a recent study by Kannan, Lippmann, and List (2003) has shown that the existence of multiple offshore bars may also effect the response of the shoreline to storm events. These multiple bar systems were shown to correspond to areas of the coast that experienced little to no shoreline change during large storm events. The existence of
multiple bars significantly decreases shoreline erosion in comparison to beaches that are protected by a single longshore bar. If bathymetric data were available for model runs, simulating this process would not require that the model be three-dimensional, because the longshore variability in offshore sandbars would be captured across each profile line.

A second mechanism that may cause longshore variability in dune response is the refraction of waves over arbitrary shallow-water bathymetry. While the east coast does not boast as many complex hard-rock bathymetric features as the west coast, small shoals and stationary transverse bar systems can significantly alter the wave ray path, focusing energy on small sections of the coast, and defocusing energy in other areas. The focusing of energy on a particular location will significantly intensify erosion, increasing the vulnerability of the dune to overtopping and overwash. If specific offshore bathymetry was added to these simple dune erosion models, a three-dimensional approach to wave refraction would be preferred to the simpler two-dimensional SBEACH approach that assumes plane and parallel bottom contours.

Additionally, differences in wave height along the coast create longshore gradients in setup elevation at the shoreline. These gradients in water elevation can lead to the generation of circulation cells and rip currents that extend well past the breaker zone. Komar (1971) observed that longshore currents created by variations in setup elevation produce erosional hotspots where two longshore currents converge at the location of the rip channel. Erosion decreases moving away from the location of the rip channel, to the point of divergence in longshore currents that occurs where two circulation cells meet. The spacing between rip currents can range from tens to hundreds of meters and tends to increase with increasing wave height (McKenzie, 1958). Rip currents and associated longshore currents are therefore another potential mechanism for creating longshore variability in dune response that is not explained by dune morphology and cross-shore transport processes alone.
One process that is essential to the prediction of both longshore variability and barrier island breaching is the funneling of water along the beach in response to gradients in dune elevation. Once wave-induced erosion creates a break in the continuous dune, a pressure gradient is established, causing water to flow along the beach. Water flowing from both directions will converge at the opening in the dune and create an erosional hotspot. This mechanism increases erosion closest to the original break, and decreases erosional pressure in neighboring locations. The initial break may be established where the dune is short and narrow, or where refraction concentrates wave energy on a small section of coastline. The creation of an erosional hotspot may initiate inundation of the island leading to breaching, or simply intensify longshore variability in dune response. Because the SBEACH model does not include a three-dimensional component linking the profiles in the longshore direction, this effect cannot be simulated at the present time.

This discussion of erosional hotspots naturally leads into the question of barrier island breaching. Model results from the Hatteras Breach study area reveal that the SBEACH model is not capable of predicting barrier island breaching (Figure 3.29). While SBEACH readily predicts the overtopping of dunes on the Hatteras North site, there is a clear divide between the model’s ability to predict overtopping and breaching events. The dunes at the Hatteras Breach study site are short and narrow, and are protected by a very narrow beach. The SBEACH model predicts that the dunes erode quickly as water levels rise, allowing water to inundate the island and flow into the bay. What is not simulated in the model is that differences in water elevation between the seaward and landward sides of the island establish a pressure gradient that produces currents moving across the island at significant speeds.

Once water flows freely across the island, the main mechanism for erosion shifts from waves to currents, which are not included in the SBEACH governing equations. In reality, these pressure-induced currents scour sediment from the top of the island and deposit it in large
estuarine deltas. In the case of the Hatteras Island breach, current velocities were great enough and were sustained for a period of time sufficient to scour a channel several meters deep and approximately 600 meters wide. The inability of the models to predict barrier island breaching is not unexpected, based on the lack of current-induced sediment transport mechanisms in the governing equations. In order to create a distinction between the overtopping and breaching, pressure-gradient induced currents and associated transport must be added to the models. These corrections would increase the complexity of the model considerably, as the number of input variables and processes increases.

**Recommendations**

As discussed earlier in this chapter, SBEACH distinguishes itself as the model that is best suited for predicting dune erosion. For future applications of SBEACH to dune erosion studies, the main priority for model development is the inclusion of mean flows generated by pressure gradients, both in the cross-shore and longshore directions. The specification of cross-shore pressure gradients and associated currents will enhance the ability of SBEACH to delineate between overwash and breaching occurrences. Additionally, a three-dimensional form of the model that links profiles in the longshore will allow for the funneling of water to breaks in the continuous dune, improving the ability of the model to predict longshore variable dune response and erosional hotspots. A three-dimensional form of the model will also create the possibility of adding processes such as wave refraction and circulation cells. However, the implementation of pressure-induced currents significant increases in model complexity, through requirements for additional input variables and the tracking of many new processes. One potential approach to these improvements is to link SBEACH to another model such as DELFT-3D that already account for pressure-induced currents and associated sediment transport. It is important to note that increasing the complexity of the model in order to predict breaching and longshore variable dune response reduces the capacity to produce vulnerability maps for large extents of coastline.
Chapter Six

Conclusions

Macroscale approaches to earth systems modeling are appealing for predictions of system behavior on large spatial scales. These models allow the description of landform features with lengths scales of meters, without requiring the specification of small-scale processes that necessitate excessive computation time. SBEACH and EDUNE are two such models that allow the prediction of coastal change over many kilometers of shoreline using only the simple inputs of dune morphology and time series of storm characteristics. The objective of this study was to determine the potential of each model to accurately and consistently predict dune erosion on spatial scales of several kilometers.

SBEACH is the more sophisticated of the two simple models, employing a self-contained wave module that calculates the cross-shore wave height profile. This capability allows the specification of the breaking wave location as a function of offshore wave height and wavelength, water depth, and beach slope. Sediment transport rates are calculated by empirically determined equations in each of four cross-shore regions. The direction of sediment transport is established with an empirical equation that is governed by the offshore wave height and wavelength and the sediment fall speed. Profile change is calculated at each time step by adjusting the vertical elevation at fixed horizontal locations.

This study revealed that the SBEACH model is significantly sensitive to the empirical parameter, \( K \), the transport rate coefficient. A calibration value of \( K = 5.0 \times 10^{-7} \) m\(^4\)/N was established with Assateague North profiles, and remained stationary over the four non-breaching
study sites. The model is well constrained with respect to $K$, and therefore can be operated without site-specific calibration. The model is also sensitive to the value of $D_{50}$, the median grain diameter. An increase in grain diameter decreases erosion on the subaerial profile, which is consistent with the theory that increasing energy is necessary to suspend and transport larger particles. Model error is minimized at the ‘true’ $D_{50}$ value of 0.33 mm on Assateague Island, suggesting that the function of grain size is properly specified within the governing equations. The model is only moderately sensitive to the offshore wave height, which is due to the fact that waves generate profile change in the surf zone, while sensitivity is as a function of subaerial profile change. The model is also sensitive to water elevations, which dictate the location of the broken wave zone. Model error is appropriately minimized with the time series of water elevations obtained from the local NOAA tide gauge.

The accuracy of the model is ascertained from tests on five separate study areas, three from Assateague Island, MD, and two from Hatteras Island, NC. The model performs well with respect to prediction of impact regime, correctly delineating between the swash and collision regimes on Assateague North, and accurately reproducing dune overtopping on Hatteras North. On the Chincoteague study site, the model is less skillful at reproducing the exact post-storm profile, because of the extreme longshore variability in dune response. On the Hatteras Breach study site, the SBEACH model predicts the inundation and flattening of the dune, but no additional erosion indicating the formation of a breach. With respect to quantitative measures of model accuracy, the mean RMS error for the four non-breaching study sites is 0.52 m, and mean GVE is 0.39 m$^3$/m.

Comparatively, EDUNE does not support an internal wave module and relies on calculations of breaking wave height from an external source, which for the purposes of this study is the SWAN model. A simple criterion determines the location of wave breaking based on the ratio of breaking wave height to water depth. Once the location of the surf zone is established,
sediment transport rates are calculated with a theoretical formula that relies on calculations of excess wave energy dissipation per unit volume. As a by-product of this formula, onshore transport is simulated when water depths are extremely shallow and wave energy dissipation is very low. Profile change is calculated at each time step by solving for the horizontal location of a fixed vertical contour. The resulting profile is highly controlled by critical angles that are operational along different horizontal sections of the profile.

EDUNE employs several simplifying assumptions that were analyzed prior to model testing. First, the model was previously reliant on a constant value of runup estimated by the user. Three representations of runup were considered for inclusion in the governing equations, and the rms runup equation described in Chapter 4 was chosen based on the minimization of model error. Additionally, the breaking criterion of $\gamma_b=0.78$ was found to be inconsistent with the rms breaking wave height statistic, allowing waves to break in the swash zone and eliminating the presence of the surf zone. Sallenger and Holman’s (1985) $\gamma_{rms}$ value of 0.32 was found to minimize model error, by allowing waves to break offshore and defining an appropriate surf zone width.

The EDUNE model is sensitive to two empirical parameters, $K$, the transport rate coefficient, and $etan_b$, the equilibrium beach slope. The calibration value of $K$ was determined to be $2.0\times10^{-5}$ $m^4/N$ with the Assateague North profiles, but was not well constrained across the four non-breaching study sites. Additionally, the calibration value of $etan_b=2.5^\circ$ was not well constrained between sites. EDUNE’s ill-defined empirical parameters establish a preference for the SBEACH model for future predictions of dune erosion.

The EDUNE model also displays sensitivity to $D_{50}$, the median grain diameter. As with the SBEACH model, EDUNE predicts that subaerial dune erosion decreases as grain size increases. However, model error is not minimized at the ‘true’ value of 0.33 mm, but continues to decrease as the value of $D_{50}$ decreases. This suggests that the function of $D_{50}$ is not properly
specified within the governing equations. Additionally, subaerial model results are only moderately dependent on the breaking wave height due to the fact that increases in wave height mainly increase erosion in the surf zone. The model is highly sensitive to the storm surge elevation, which determines the location of the surf zone across the profile. Model error is appropriately minimized for the storm surge time series obtained from the local NOAA tide gauge.

With respect to the prediction of impact regime, EDUNE is capable of correctly delineating between swash and collision on the Assateague North study site, and the occurrence of dune overtopping on the Hatteras North site. Like SBEACH, model results are less reliable on Chincoteague where dune response is extremely variable in the longshore direction. On the Hatteras Breach site, the model does not predict the flattening of the dune, but rather simulates the growth of the dune on many profiles. These anomalous accretionary features are a by-product of the numerical scheme that allows onshore transport when extremely shallow water depths exist. Because these features are the result of an incorrect description of system dynamics and their occurrence cannot be predicted, the EDUNE model is not well suited for predictions of dune erosion. With respect to quantitative measures of EDUNE accuracy, the mean RMS error for the four non-breaching study sites is 0.55 m, and the mean GVE is 0.42 m$^3$/m.

The mean values of RMS error and GVE on the four non-breaching sites are statistically equivalent between the two models at the 95% confidence level. This result suggests that both models are equally suited for predictions of dune erosion. However, previously mentioned inconsistencies in the EDUNE model make it inappropriate for both vulnerability mapping and predictions of post-storm profiles. The inconsistencies include empirical parameters that are not well constrained, and the ill-defined function of D$_{50}$ within the governing equations, and the formation of accretionary features when shallow water depths exist. Each of these
inconsistencies prevents the use of EDUNE as a predictive tool for vulnerability mapping applications.

The failure of the models to accurately reproduce dune erosion on the Chincoteague study site is likely the result of longshore variable processes that are unaccounted for in the model governing equations. Several of these processes were highlighted in the previous chapter, including the dissipation of wave energy over longshore variable sandbars, refraction of waves over arbitrary bathymetry, the generation of rip currents and circulation cells, and longshore currents that respond to gradients in dune elevation. The failure to predict barrier island breaching can be attributed to cross-island pressure gradients and associated currents that are not accounted for by either model.

The future use of the SBEACH model for vulnerability mapping is promising, due to the ability of the model to correctly delineate between the swash, collision, and overwash regimes. With respect to the prediction of post-storm dune shape, it is important to include cross-island pressure gradients and descriptions of current-induced sediment transport in order to correctly predict breaching occurrences. Additionally, it is necessary to specify the longshore pressure gradients and associated sediment transport that results from gradients in the height of the continuous dune. Both of these corrections will necessitate a considerable increase in model complexity, requiring definition of numerous additional hydrodynamic variables, and the specification of multiple additional macroscale processes. The addition of wave refraction and sandbar morphology to the model is desired for fine tuning of model results, but are not as highly prioritized as the inclusion of pressure-induced currents.
References


Kriebel, D.L., 1984(a). Beach erosion model (EBEACH) users manual, Volume I: Description of computer model. Technical and Design Memorandum No. 84-5-1, Beaches and shores Resource Center, Florida State University, Tallahassee, FL.
Kriebel, D.L., 1984(b). Beach erosion model (EBEACH) users manual, Volume II: Theory and background. Technical and Design Memorandum No. 84-5-2, Beaches and shores Resource Center, Florida State University, Tallahassee, FL.


McCowan, J., 1894. On the highest wave of permanent type. Philosophical Magazine, 5 (38), 351-357.


Moore, B.D., 1982. Beach profile evolution in response to changes in water level and wave height. Masters Thesis, University of Delaware, Newark, DE.


