Journal of Coastal Research | 7 | 2 | 451–463 | Fort Lauderdale, Florida | Spring 1991

Predicted Dune Recession on the Outer Banks of North Carolina, USA

Nancy M. DeKimpe[†], Robert Dolan[‡] and Bruce P. Hayden[‡]

[†]Aubrey Consulting, Inc.
350 Gifford Street
Falmouth, MA 02540, USA

[‡]Department of Environmental Sciences
University of Virginia
Charlottesville, VA 22903, USA

ABSTRACT

DEKIMPE, N.M.; DOLAN, R. and HAYDEN, B.P., 1990. Predicted dune recession on the Outer Banks of North Carolina. *Journal of Coastal Research*, 7(2), 451–463. Fort Lauderdale (Florida). ISSN 0749-0208.

A stochastic beach-barrier dune model is presented that predicts the timing of barrier dune demise for the Outer Banks of North Carolina. The model was run for the reach of coast which was entirely stabilized with barrier dunes in the 1930s and 1940s. Model output statistics indicate that the Outer Banks will come to a new equilibrium over the next 100 years. By the year 2090, about 70% of the reach will be in a natural dune configuration and 30% will remain with its barrier dune.

ADDITIONAL INDEX WORDS: *Barrier dunes, barrier islands, dune stabilization, shoreline erosion, prediction model of erosion, storm surge.*

INTRODUCTION

In the 1930s, a barrier dune was built along the Outer Banks of North Carolina from the Virginia-North Carolina state line south to Ocracoke Island. The dunes restricted wave uprush, storm surge, and overwash and altered salt spray. Before the dunes were constructed, the distance between the shoreline and natural dune crest was between 100 and 125 m; by the mid-1940s this distance had narrowed to 70 to 100 m (DOLAN, 1972). Today beaches as narrow as 10 m are found and in areas where the barrier dunes are eroding, the average beach width is 39 m.

The Outer Banks are in transition; the beach in many places is so narrow that even minor winter storms erode the artificial barrier dunes (Figure 1). As a matter of policy, the National Park Service is not replacing or repairing the man-made dunes as they erode. The loss of the barrier dunes is now creating management problems; storm surge damage to buildings and highways is increasing and greater property losses in the future are a certainty. Adequate planning for this readjustment to a more natural barrier island requires estimates of the rates of erosion of the barrier dunes. With the assistance of the Cape Hatteras National Seashore, we developed a stochastic model incorporating barrier island dynamics to forecast the transition from a stabilized to a natural system. We used historical shoreline, dune, and overwash rates of changes derived from aerial photographs (DOLAN *et al.*, 1978) to predict future shoreline and dune locations and areas of potential overwash.

BACKGROUND

In the mid-1930s, the federal government established a national seashore and a national wildlife reserve on the Outer Banks of North Carolina (WPA, 1936). For this new park and for future development on the North Carolina barrier islands, a high, protective barrier dune was recommended to prevent storm surge from reaching the existing island communities. It was argued that the barrier dune would preserve the islands and protect the mainland from direct wave attack. The plan also included extensive grass plantings to stabilize the dunes. Sand fences were erected on the beaches by the Civilian Conservation Corps to trap wind blown sand and encourage barrier dune growth.

The environmental effects of the dune con-

88071 received 23 November 1988; accepted in revision 12 May 1990.

Figure 1. Installation of sand fencing along the Outer Banks of North Carolina in the 1930s.

struction were investigated in the 1960s and 1970s. Comparisons of old maps and charts, as well as 1937 and 1960 beach profile surveys, documented that severe erosion had occurred along the Outer Banks before and after the project had started (BIRKEMEIER *et al.*, 1984). FISHER *et al.* (1984) analyzed the shorezone changes that occurred during the post-dune construction period using 1937 and 1976 beach profile data; the data showed a narrowing and steepening of the beach following stabilization. DOLAN (1972) stated that the altered islands could not reach a dynamic equilibrium with rising sea level. The man-made, grass stabilized dunes were fixed and did not migrate landward.

The National Park Service decided in the early 1970s to end their program of dune stabilization because of the maintenance costs and the negative geological and ecological implications (NPS, 1978). The barrier dunes would be left to erode; it was believed the natural, scattered dunes that existed before stabilization would eventually return (BIRKEMEIER *et al.*, 1984).

THE BEACH-BARRIER DUNE SYSTEM

The shoreline of a barrier island typically experiences episodes of erosion and accretion such that the shoreline appears to "oscillate" landward and seaward through time. The shoreline moves landward during stormy periods and the beach builds seaward during periods of calm (KOMAR, 1976). During the past century, however, erosion on the Outer Banks between Oregon Inlet and Cape Hatteras has exceeded accretion with a net shoreline erosion of 1.5 m/yr (DOLAN, *et al.*, 1979). This erosion is largely due to the relative sea-level rise, changes in the frequency, magnitude and tracks of storms, and sediment deficits (DOLAN & HAYDEN, 1983 and KRIEBEL & DEAN, 1984, 1985).

Figure 2a illustrates a typical cross-section of the stabilized barrier dune system along the Outer Banks. The artificial dunes are up to 5 m high and 80 m wide. Erosion during storms cuts a near vertical seaward dune face. The barrier dune protects the inland areas as long as the storm surges and runup do not exceed the dune height and the dune remains unbreached.

As waves attack the dune, the dune mass and width are reduced due to erosion on the seaward side; eventually the dune completely erodes away (KRIEBEL, 1986). Once this occurs and new and scattered incipient foredunes form, the barrier island has returned to a more natural state (Figure 2b). In a natural state, the fore-

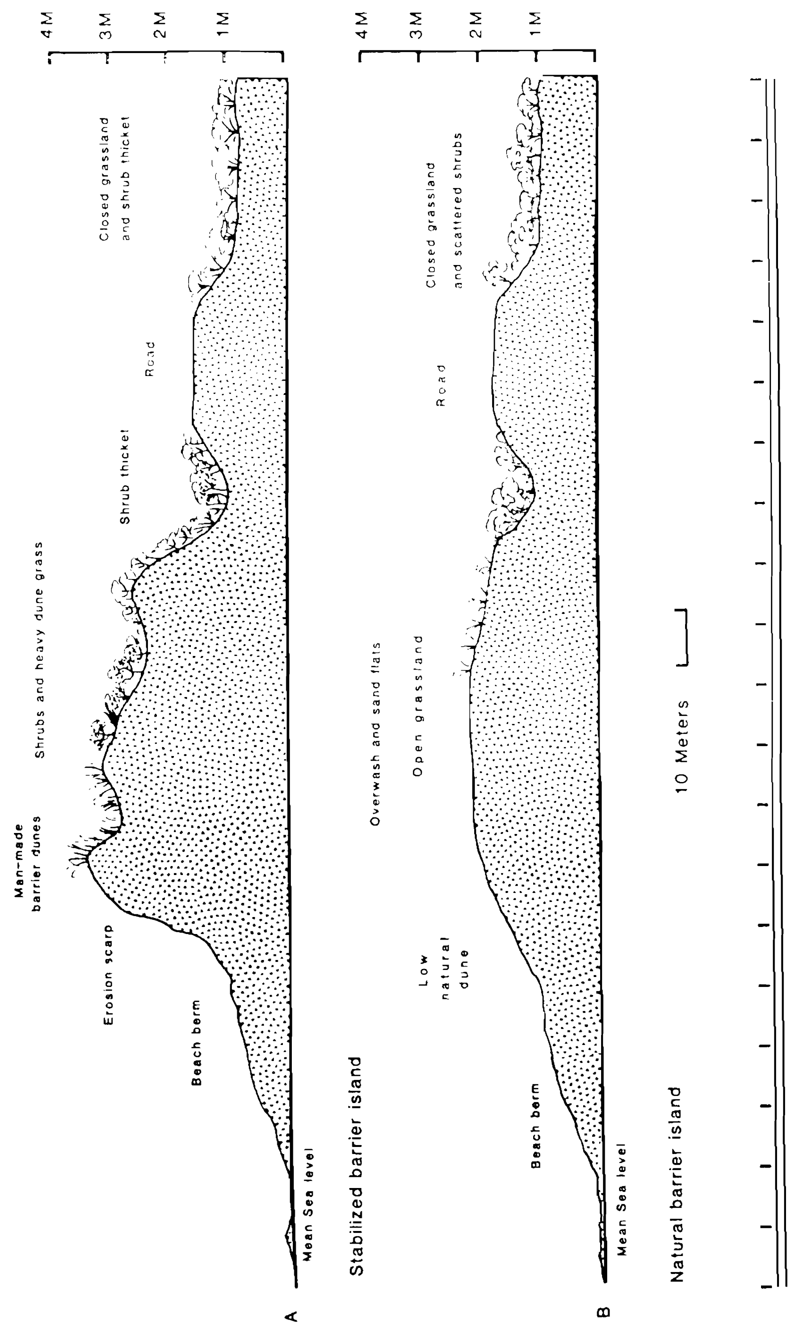

Figure 2. Cross sections of stabilized (a) and natural (b) barrier islands.

shore, backshore, and berm are wider and present only a minor obstruction to the inland penetration of storm surge. The topographic high point of the beach (we term the beach "threshold") migrates landward with shoreline recession.

The beach threshold of a natural beach is often exceeded by storm surge during severe storms. The bore of water generated by the wave uprush penetrates inland with the distance and is a function of storm surge and tide height, and wave height (DOLAN & HAYDEN, 1985). As the bore travels inland, its energy is dissipated across the beach and berm, and through the natural dunes and overwash terraces. The bore of water finally flows into the marsh areas (DOLAN & GODFREY, 1973). As the bore velocity falls below sand transport velocities, overwash sediments are deposited. This results in an increase in island height.

Changes in the beach width and thus wave runup relative to the dune position are the controlling factors in initiating dune erosion (KRIEBEL & DEAN, 1984). As the shoreline recedes, the beach width (dune to shoreline distance) decreases and the probability of dune erosion during storms increases. The beach may build seaward after storms as eroded sands are moved shoreward but the man-made barrier dunes do not rebuild once they erode. Barrier dune erosion is thus largely a function of the shoreline erosion, beach width and the variations in the frequency and magnitude of storms. Dune erosion occurs during storms when the beach width is narrow relative to the magnitude of the storm. With post-storm progradation of the beach and increasing beach width, dune recession abates. Shoreline change rate and existing beach width and dune mass (width and height) determine the amount of time required for the beach-dune system to return to a natural, non-barrier dune state. Storm surge and overwash penetration (bore heights) become important factors once the barrier islands return to their natural state.

In our model the relationships between dune recession rate, shoreline recession rate and the standard deviation of shoreline recession rate are determined from regression techniques using data taken from historical aerial photographs. The model is driven with time steps in years. The shoreline erosion rate for each step includes the mean plus a standard deviation, which may be chosen either at random from a normal probability density function or selected from the same function in order to specify a particular probability level for the outcome. In the model output statistics presented here, specified probability levels were used.

SITE DESCRIPTION

The area studied to document the processes responsible for dune erosion is a 70 km stretch along the Cape Hatteras National Seashore beginning 7 km north of Oregon Inlet and extending south to Cape Hatteras (Figure 3). This section of the Outer Banks has a wide range of shoreline erosion rates and associated dune response. Shoreline rates of change range from more than 22 m/yr of erosion to over 10 m/yr accretion. In some areas the shoreline and dunes are eroding rapidly while in other areas the beaches are wide enough to limit and preclude dune erosion. In a few locations, the dunes are receding although the shoreline shows net accretion and a few areas are relatively stable in that neither the dunes nor the shoreline are eroding.

RESULTS

Aerial photographs were used to measure shoreline change, dune recession, dune widths, beach widths and storm surge or overwash distances (Table 1). Measurements were made at 100 m intervals along the coast using the Orthogonal Grid Address System (OGAS) developed by DOLAN *et al.* (1978). The reliability of dune width measurements taken from aerial photographs was verified with field survey data. Along some areas of the Outer Banks, the dunes are not eroding, so dune recession rates could not be measured from aerial photographs. Future rates of dune recession were predicted from regression relationships established between shoreline and dune changes for eroding dune areas.

The relationship between shoreline change rates (SLX), the standard deviation of shoreline change rates (SLSD) and dune recession rates (DX) was determined by linear regression analyses. By convention, erosion is negative and accretion is positive. The multiple correlation coefficient (r) is .75, $p < .0001$; $DX = 2.78 + 1.24(SLX) - 0.24(SLSD)$. The dune recession rate is positively correlated with the shoreline change rate [$r = .70$; $p < .0001$; $DX = 1.43 + 1.46(SLX)$] and negatively correlated with the standard deviation of the shoreline change rate [$r = -.50$; $p < .0001$; $DX = .22 + .40(SLSD)$]. Areas having high rates of shoreline erosion and high variability in shoreline erosion rate

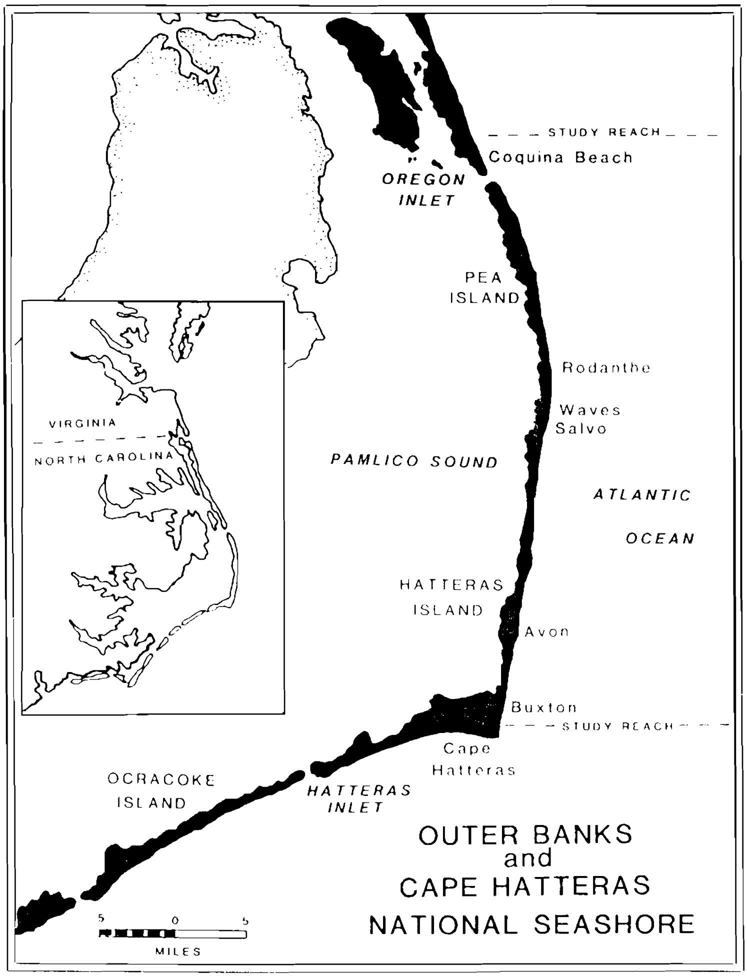

Figure 3. The study site.

(high standard deviation) are most prone to dune erosion (Table 2).

The regression equations above are based on analysis of data for the entire study reach. Examination of the plot of the shoreline recession rates versus dune recession rates, however, indicated there are some outliers corresponding to the northern end of Pea Island, where much dredging of Oregon Inlet has occurred. The regression analysis was run again excluding these values. The equations derived are $DX = -.96 + .64\ (SLX)\ [r = .50;\ p < .0001]$; $DX = -1.43 - .17(SLSD)\ [r = -.42;\ p < .0001]$; and, $DX = -.05 + .55(SLX) - .14(SLSD)\ [r = .60;\ p < .0001]$ (Table 3). Although the correlation coefficient from the regression analysis for the entire data set was higher, it was felt that the equation was not as accurate for areas having less recession because the high rates of shoreline and dune recession at Pea Island dominated the regression. Therefore, two regression segments constituted the model; the magnitude of the shoreline change rate determined which segment applied.

Model Description

The regression relationships provide a means of estimating future dune recession rates using easily measured dependent variables. From the

Table 1: *Measured variables in beach-barrier dune model*

Measured Variable	Method	Time Period
Shoreline change rate	OGAS	1945-1986
Standard deviation	OGAS	1945-1986
Shoreline location	OGAS	1986
Dune recession rate	OGAS	1958,1965, 1978,1986
Dune location	OGAS	1986
Dune width	field profiles OGAS	1986
Beach width	OGAS	1986
Overwash penetration distance	OGAS	1930s
Storm surge and bore height	field observations historic record	1945-1986

shoreline erosion and dune recession rates the future status of the dunes can be forecast (Figure 4). Since the variances of shoreline rates of change are known, a probabilistic range of outcomes can be generated. Given the selected probability level, the shoreline change rate is adjusted by adding the appropriate increment to the mean shoreline erosion rate for the location. The adjustment is taken from the normal probability density function from a specified probability level other than 50%. For the probability levels 68%, 95%, or 99% the shoreline change rates will be higher than that for the mean or 50% probability level. The amount of shoreline change between 1986, the base year of the model, and the selected year is determined from the adjusted shoreline change rate. From this, the position of the shoreline location in relation to a baseline and the beach width is computed.

Table 2: *Regression analyses for data including northern Pea Island.*

Data Including Northern Pea Island

Dune recession vs. shoreline recession
(Y) (X)
$Y = 1.43 + 1.46\,(X)$
correlation $r = .70$
sig. = .0000

Dune recession vs. standard deviation
(Y (Z)
$Y = .22 + .40(Z)$
correlation $r = -.50$
sig. = .000

Dune recession vs. shoreline recession, standard deviation
(Y) (X) (Z)
$Y = 2.78 + 1.24(X) - .235(Z)$
multiple $r = .75$
sig. = .0000

Table 3: *Regression analyses for all data excluding the northern end of Pea Island.*

Data Excluding Northern Pea Island

Dune recession vs. shoreline recession
(Y) (X)
$Y = -.96 + .64(X)$
correlation $r = .50$
sig. = .0000

Dune recession vs. standard deviation
(Y) (Z)
$Y = -1.43 - .17(Z)$
correlation $r = .42$
sig. = .000

Dune recession vs. shoreline recession, standard deviation
(Y) (X) (Z)
$Y = .05 + .55(X) = .14(Z)$
multiple $r = .60$
sig. = .0000

If a 50% probability level is selected, dune recession rates are either measured values from aerial photographs, or predicted values from regression equations for the 50% probability level. For other probability levels, dune recession rates were predicted from established regression equations. The shoreline change values used in these calculations had been adjusted for the selected probability level. Based on dune recession rates and 1986 dune widths, the model calculates the dune locations and dune widths for future years. If the dunes were not eroding in the model base year (1986), the year of initial dune scarping is predicted based on the average beach width observed for areas with eroding dunes in 1986 (39 m) and the erosion rate for the site. Dune recession rates may be lower (*i.e.*, higher negative values) than the shoreline change rates and thus the shoreline would eventually reach the dune if erosion continued. Because this is an impossibility, the model compares the calculated shoreline and dune locations. If the beach width is less than 10 m, the dune location is moved 10 m landward of the shoreline location. Beach widths less than this width are in the tail of the distribution of beach widths. Ninety-five percent of the beach widths measured for eroding dune areas are greater than 10 m. The model also predicts

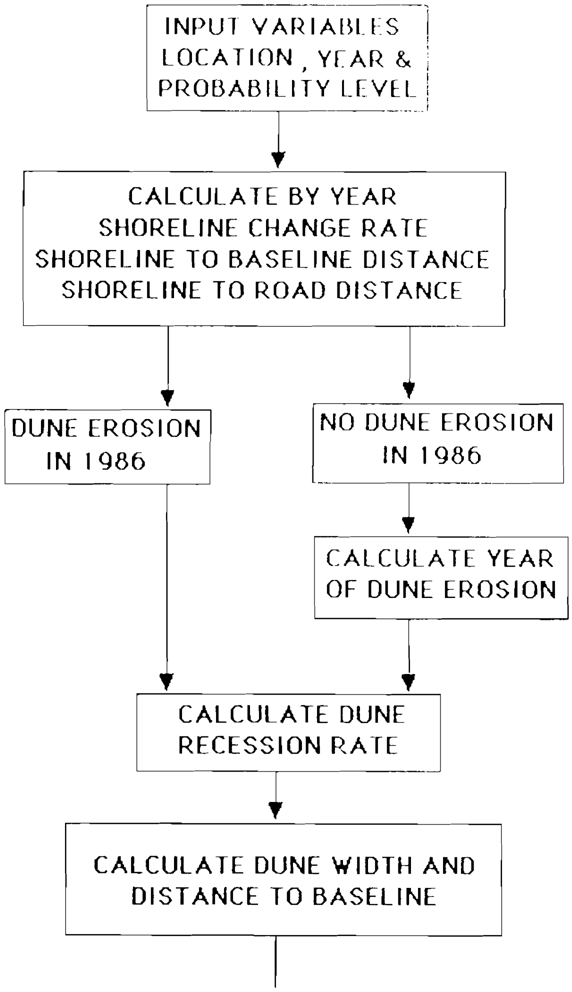

Figure 4. Flow chart for determining future shoreline and dune locations.

the year in which the dunes will be completely eroded (Figure 5). The year the dune is completely eroded is based on the dune width and dune recession rate until the beach width is only 10 meters; then the dune erodes at a rate equal to that of the shoreline. Subsequent incipient dune formation is not modeled.

Once the dunes are eroded, buildings and resources inland are at risk of damage by overwash and flooding. Prior to their demise, the dunes represent the effective beach threshold; therefore, the distance between a structure and the beach threshold is constant as long as the dunes exist. The barrier dunes along the Hatteras coast are high (3 to 10 m) and are not migrating. However, once the dunes have completely eroded, the shoreline erosion will decrease the distance between structures and the beach threshold. The model predicts the distance between the buildings or roads, and the threshold for any year in the near future. In addition, the overwash and bore heights are estimated for various years after the dunes are gone.

The recurrence interval for overwash bore heights at the threshold of the beach is estimated from the return interval curve of DOLAN & HAYDEN (1985) (Figure 6); this

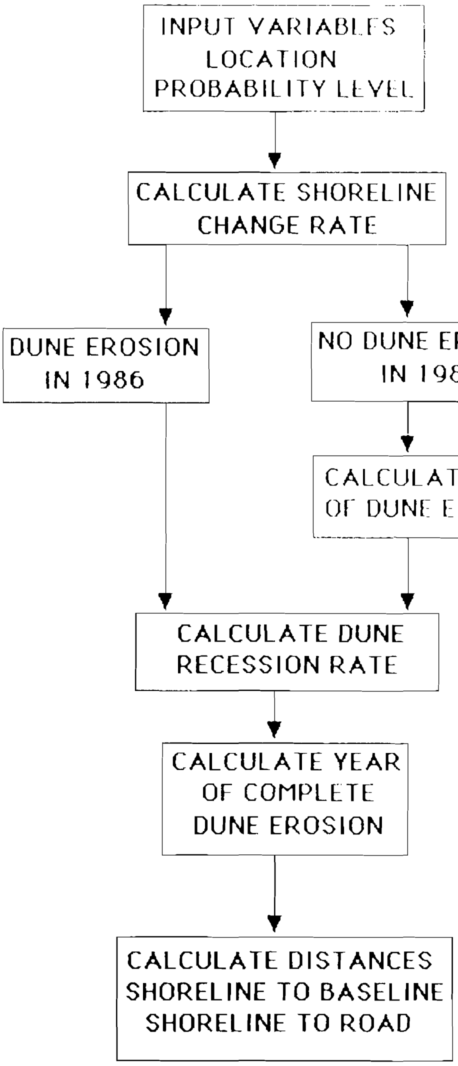

Figure 5. Flow chart for determining year of complete dune erosion.

curve was derived empirically from data on storm frequency and the bore height generated at the Cape Hatteras Lighthouse. For example, a bore height of 1.0 m can be expected at the back of the beach system every 25 years. This estimate for Cape Hatteras is used throughout the study area, *i.e.*, the highest elevation of hydraulically moved sand on the island is assumed constant. 1989 field studies on a Virginia island indicate a range of variations in this height of about 0.3 m. The expected height of water at a structure is calculated based on the change in bore height through time. The slope of the bore is about 1:200; there is a 1 m decrease in bore height for every 200 m the bore travels inland (DOLAN & HAYDEN, 1985). Thus the model predicts bore heights at fixed structures based on the distance between the threshold and structure for various years after the dunes are gone.

Model Verification

Along the 70 km reach studied, there were a few locations at which verification of the model

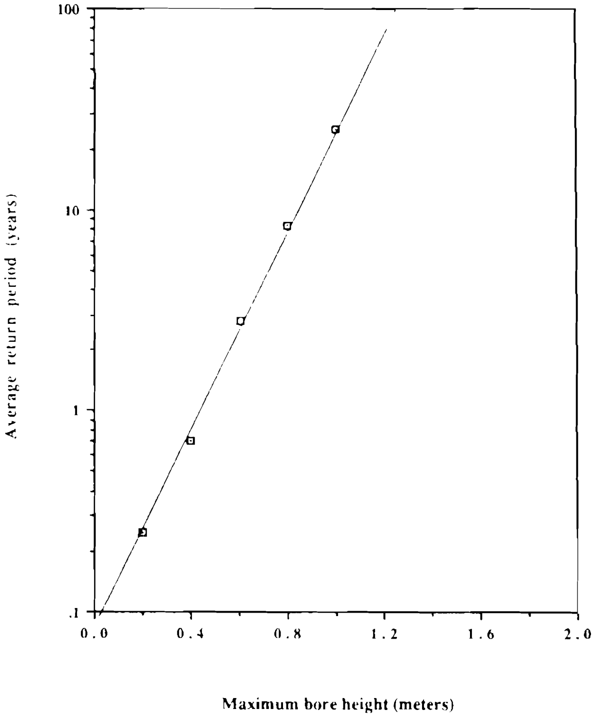

Figure 6. Return period versus bore height (modified from Dolan and Hayden, 1985).

was possible. The dunes at Coquina Beach (Figure 3) are receding at rates of 3 to 5 m/yr. In one section, the barrier dunes are completely gone. The dune width in this area was 60 m in 1965. By using the measured dune recession rate of 4.9 m/yr, the model predicts the dune would have completely eroded by 1977. 1978 photographs indicate the dune was still present, although it was less than 15 m wide; by 1984 it was gone and a smooth beach face existed. The model, using shoreline recession rates and a 50% probability level, estimated dune destruction a year earlier than observed; however, storm frequency and magnitude are highly variable along the Outer Banks (DOLAN *et al.*, 1988) so such differences are expected. Measured and regressed estimates of dune erosion rates gave similar model outputs.

South of Buxton there is another area where the dunes have eroded completely. Dune widths in 1965 photographs ranged from 90 to 109 meters; based on shoreline recession rates, the model predicted, for the 50% probability level, that the dunes should have been gone in the early and mid-1980s. A duneline was evident in the 1978 photographs; the dune widths were measured as zero in the 1986 data. Given that the prediction method is a stochastic one, and the predicted value a stochastic estimate rather than a determinate one, full verification of the model will require a population of estimates and field checks.

Model Output

The model results can be summarized by a series of nomograms constructed from the output statistics (Figures 7–9). Figure 7 indicates the number of years until dunes will begin eroding based on beach width and shoreline recession rate. Thus for a beach width of 70 m and shoreline recession rate of 2 m/yr, the dunes will begin eroding in 15 years. The dune recession rate can be predicted by Figure 8; for a shoreline recession rate of 2.0 m/yr, the dune recession rate is 2.2 m/yr. If the dune width is 30 m, then it will take about 14 years for the

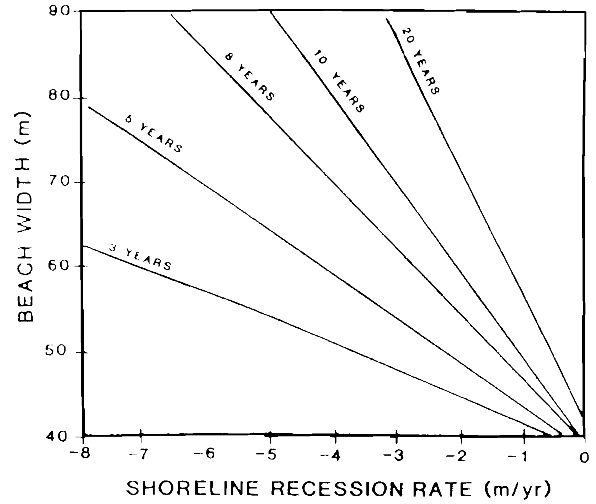

Figure 7. Years until dunes begin eroding.

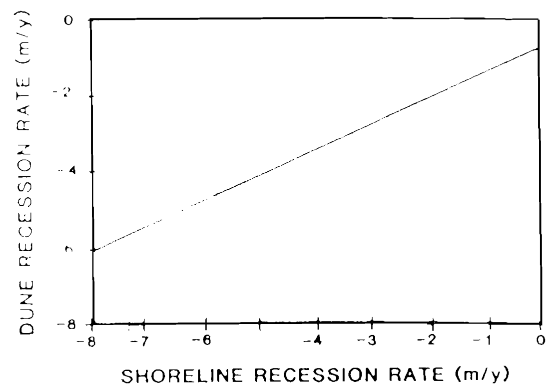

Figure 8. Prediction of dune recession rates.

dune to erode (Figure 9). Thus the dune will be completely eroded in a total of 29 years.

The nomograms can be used at probability levels other than the 50% probability solution if the standard deviation of the shoreline change is known. At a 95% probability level, the shoreline change rate corresponding to 1 m/yr erosion with a standard deviation of 2 m/yr is 4.3 m/yr (1 m/yr + 1.64* 2 m/yr = 4.3 m/yr). For a given beach width and dune width, the years until the dunes completely erode can be determined from the nomograms.

There are limitations to the beach-barrier dune model. The time to complete dune erosion may be underestimated by several years because the last phase of dune scarping may be a catastrophic failure. In addition this model treats the dune as an unbreached wall. Barrier dune breaching is more likely and thus the terminal dune demise would be accelerated. The data are insufficient to determine if acceleration of the dune erosion process will marginally increase the rate of dune demise. Additionally, there may be variations in dune change unaccounted for in the model due to wind deflation. ODUM *et al.* (1987) have found through dune

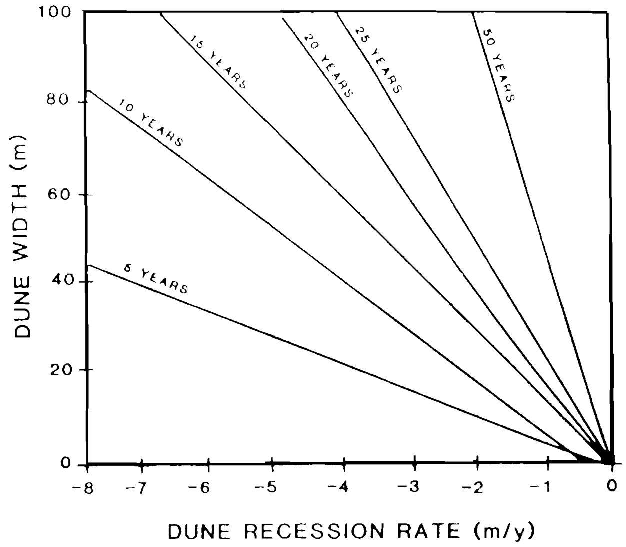

Figure 9. Years until dunes are gone.

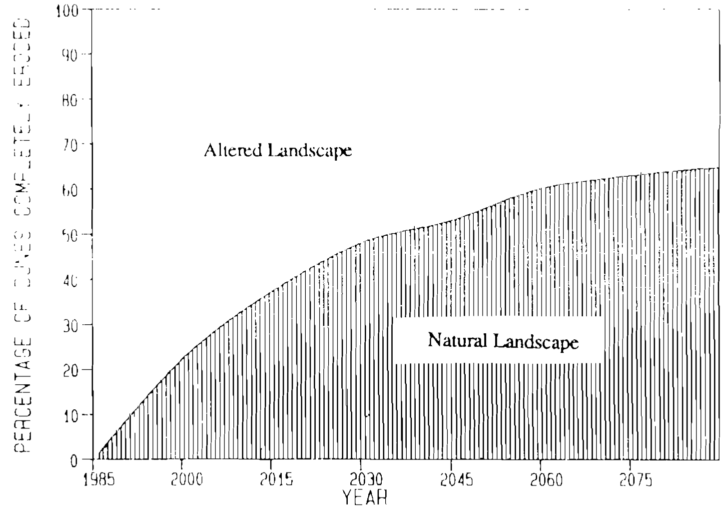

Figure 10. Percentage of stabilized barrier dunes that will be completely eroded for selected years for all reaches of the Hatteras coast where barrier dunes were in place in 1985. For example, the model results show that for the section of the Outer Banks studied, by the year 2030, 50% of the area will revert back to a pre-stabilization state.

profiles on Pea Island that the dunes are losing sand by deflation from the crest and backside as the vegetation dies away. For these reasons, the model predictions presented here may be conservative estimates.

SUMMARY

The beach-barrier dune model predicts dune and shoreline changes for the Outer Banks of North Carolina. At the 50% probability level,

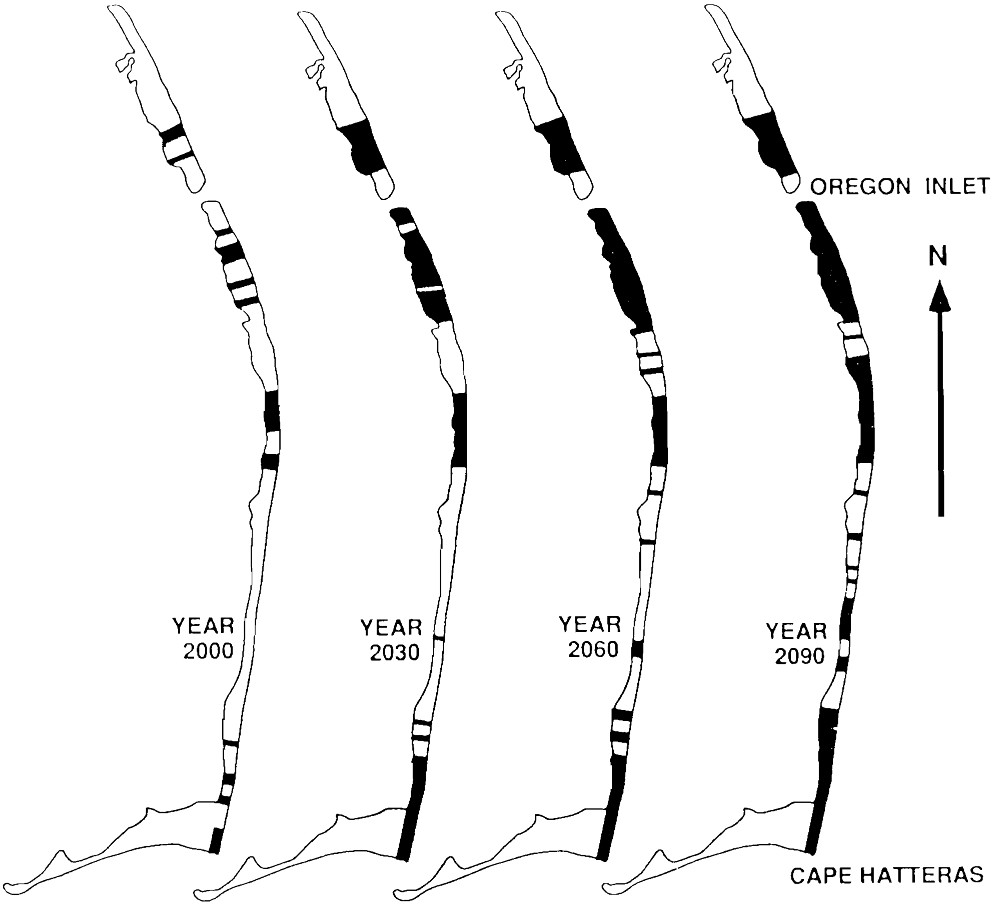

Figure 11. Areas along the Outer Banks of predicted complete dune erosion for the specified year.

the model predicts that by the year 2000, 22% of the barrier dunes will be destroyed by erosion (Figure 10). By the year 2015, the dunes will be eroded away from most of the southern end of Hatteras Island and along most of Pea Island and southern Bodie Island. Figure 11 (a–d) illustrates the sequence of changes from an altered to a natural barrier island system for the 70 km study reach. Areas of complete dune erosion for the corresponding year (2000, 2030, 2060, or 2090) are shaded; unshaded areas are those that remain in an altered state.

For the current rate of sea level rise, the Outer Banks will equilibrate at about 70% natural and 30% artificial (barrier dune) landscape over the next century. Should the rate of sea level rise increase, conversion to natural landscape will accelerate and equilibrium percent of natural landscape will exceed 70%.

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☐ RÉSUMÉ ☐

Le modèle stochastique de dune barrière de plage présenté prédit le temps nécessaire au transfert de la dune barrière pour les Outer Banks de Caroline du Nord. Le modèle a été réalisé pour l'étendue de la côte qui a été entièrement stabilisée avec des dunes barrières dans les années 1930 et 40. Les sorties statistiques du modèle indiquent que les Outer Banks reviendront à un nouvel équilibre dans les 100 prochaines années. Dans les années 2090, environ 70% de l'étendue atteindra la configuration d'une dune naturelle et 30% resteront associés à une dune barrière.—*Catherine Bressolier-Bousquet, Géomorphologie EPHE, Montrouge, France.*

☐ RESUMEN ☐

Se presenta un modelo estocástico de comportamiento de barreras de dunas que ayuda a predecir la evolución temporal de la degradación de la barrera de dunas del Outer Bank en Carolina del Norte. El modelo se aplica a la zona de costa que fue estabilizada por barreras de dunas en 1930 y 1940. Los resultados estadísticos del modelo indican que los Outen banks alcanzarán un nuevo equilibrio en los próximos 100 años. Alrededor del año 2090 el 70% de la franja de costa analizada tendrá una nueva configuración natural de dunas y el otro 30% mantendrá aún la barrera artificial de dunas.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

☐ ZUSAMMENFASSUNG ☐

Ein stochastisches Modell für Strandwalldünen wird vorgestellt, das den Zeipunkt für das Verschwinden der Strandwalldüne der Outer Banks von Nord-Carolina vorhersagt. Das modell wurde auf den Bereich der Küste angewandt, der in den dreißiger und vierziger Jahren dieses Jahrhunderts mit Strandwalldünen vollständig stabilisiert war. Die Ergebnisse der Modellrechnungen weisen darauf hin, daß die Outer Banks in den nächsten 100 Jahren ein neues Gleichgewicht erreichen werden. Im Jahre 2090 werden etwa 60% untersuchten Bereichs eine natürliche Dünengestaltung tragen und 30% werden als Strandwalldüne verbleiben.—*Helmut Brückner, Geographisches Institut, Universität Düsseldorf, F.R.G.*