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U.S. MID-ATLANTIC BARRIER ISLAND GEOMORPHOLOGY[1]

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ABSTRACT

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Quantitative analysis of 15 geomorphic attributes of the mid-Atlantic barrier coast has revealed that there are systematic variations in the geomorphic arrangement of coastal features. Our analysis of attributes (measured at 1 km intervals along the 800 km study reach from Cape Henlopen, Delaware, to the North Carolina border) has resulted in an atlas of coastal geomorphic types that can be classified at scales ranging from tens of kilometers (regional scale) to several kilometers (local scale). Similar data collection of coastal geomorphic attributes could be made for other coastal areas and could be quantitatively compared to the mid-Atlantic coast through the use of principal components analysis.

Additional Index Words: *Barrier island, geomorphology, mid-Atlantic, principal components analysis, classification.*

INTRODUCTION

DOLAN *et al.* (1980) discussed barrier island dynamics and shoreline processes and suggested that there exists a regional organization to the arrangement of geomorphic features on barrier islands. This paper describes the spatial variations in physical attributes of the mid-Atlantic barrier islands on a regional scale and introduces a geomorphic model based on our analysis. In addition, we summarize a classification of barrier types (KOCHEL *et al.*, 1983). The study area includes an 800-km reach of the mid-Atlantic Coast stretching from Cape Henlopen, Delaware, south to the North Carolina-South Carolina border (Figure 1).

Barrier islands within the mid-Atlantic area vary from 4 to 40 km in length, range from less than 1 km to 5 km in width, and are separated from the mainland by lagoons and bays up to 48 km wide. By a first approximation, the coast can be divided into major geomorphic types based on large-scale morphology: (1) mainland coasts and attached barriers; (2) long, continuous barriers (greater than 25 km in length) with few inlets; and (3) short, discontinuous barriers with frequent inlets. Figure 2 illustrates the systematic recurrence of this morphologic sequence progressing from north to south along the study area. These barrier island "ensembles" were first noticed by FISHER (1967) and later elaborated on by HAYDEN and DOLAN (1979). Along the open coast south of the Delaware and Chesapeake bays, the barrier beaches are welded to the mainland (Figure 2). South of these two areas long, continuous barriers dominate the coastline, then grade into short, segmented barriers along the Virginia and southern North Carolina coast (Figure 2). This transgressive barrier coastline has a limited terrigenous clastic sediment supply. Tidal range varies from 0.9 m to 1.6 m and is minimal near the Chesapeake Bay.

No detailed classification models have been proposed for the mid-Atlantic barrier coast. In fact, few classification models focus on barrier coastlines. The regionalized classification models of PRICE

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(1959) and TANNER (1960), the hierarchical model of DOLAN *et al.* (1972), and the sandy coastal plain model of KEARNS (1974), relate better to the mid-Atlantic coastline than the general world models, but still do not provide an effective system for classifying the geomorphic variations occurring along that coast.

GEOMORPHIC ATTRIBUTES

Fifteen attributes of barrier coastlines were measured at 800 sites spaced at 1-km intervals along the coast from the North Carolina-South Carolina border to the Delaware Bay (Table 1). Figure 1 illustrates the spatial variation of ten selected attributes.

Four attributes are measures of energy incident upon the coastline: 10-year storm surge, 1.5 m wave frequency, 3.4 m wave frequency, and mean tide range. A storm surge, or meteorological tide, is the piling up of water along the coastline associated with passage of a storm, particularly pronounced in the case of tropical storm landfall. The maximum storm surge expected to recur once every 10 years was calculated from National Oceanic and Atmospheric Administration studies of storm surge based on tide gauge records and the National Weather Service's numerical-dynamic storm surge prediction model (HO and TRACEY, 1975a, 1975b; HO *et al.*, 1976). The percentages of onshore and alongshore directed waves above two arbitrary heights — 1.5 m and 3.4 m — were determined from Summary of Synoptic Meteorological Observations data (U.S. NAVAL WEATHER SERVICE COMMAND, 1975).

The other eleven attributes used in the study represent responses to the energy regime of the coastline. The mean rate of shoreline change (erosion or accretion), mean overwash penetration distance, and the number of longshore bars, were measured by comparison of multiple sets of vertical aerial photographs. Overwash penetration distance is defined as the width of the "active" sand zone; that is, the distance between the ocean shoreline and the zone of dense vegetation that typically extends to the seaward face of barrier foredunes. The rate of shoreline change and overwash penetration distance were measured using the Orthogonal Grid Mapping System, a technique developed at the University of Virginia (DOLAN *et al.*, 1978a, b).

The remaining attributes — shoreline strike, dune frequency, inlet frequency, island width, lagoon width,and offshore slope to a depth of 9.1 m — were measured from U.S. Geological Survey bathymetric charts at 1 km intervals along the 800 km study reach. Shoreline strike is a measure of the local orientation of the coastline relative to north. Island width, lagoon width, and inlet frequency are all measures of barrier island morphology in a horizontal plane. Dune frequency and offshore slope are descriptions of the topography of the barrier islands and nearshore region.

ANALYSIS

Regression Analysis

The 800-case, 15 variable data matrix was analyzed using regression and principal components analysis (PCA) to examine spatial relationships and variations between the coastal attributes. During the initial analysis it became apparent that there are varying degrees of spatial organization present at different scales, so separate analyses were run for the entire 800-km region and six subregions (Figure 1) ranging from 56 to 195 km long. The delineation of these subregions was based on major geomorphic features along the mid-Atlantic coast such as the Chesapeake Bay and the Carolina capes. Our previous studies have shown that coastal attributes such as shoreline erosion rates often have anomalous values within 4 km of capes and 2 km of inlets due to the influence of these features on sediment transport processes (VINCENT *et al.*, 1976; DOLAN *et al.*, 1977). Therefore, we ran additional analyses of the 800-km reach and each of the subregional data sets excluding data at all sites within the realm of influence of capes and inlets. Only correlations that were significant at a level of .001 [using the T table in KLEINBAUM and KUPPER (1978)] were accepted. For purposes of rating the strength of the correlations that passed this significance test, r values in the 0.35-0.59 range were considered moderate correlations, and r values greater than 0.60 were considered strong correlations.

Regression analyses were run for five different data sets covering the entire 800-km region: (1) 1K/ALL — data measured at 1-km intervals; (2) 1K/EXC — data measured at 1-km intervals excluding inlet and cape zones; (3) 5K/INT — data measured at 5-km intervals; (4) 5K/ALL — data measured at 1-km intervals and averaged over 5-km intervals; and (5) 5K/EXC — data measured at 1-km intervals and averaged over 5-km intervals excluding inlet and cape zones. Table 2 lists the number of moderate and strong significant correlations found in analyses of these data sets. The 5-km averaged data set excluding inlets and capes (5K/EXC), the

1-km interval data excluding inlets and capes (1K/EXC), and the 5-km interval data (5K/INT) all showed approximately the same number of significant correlations, and nine pairs of variables showed

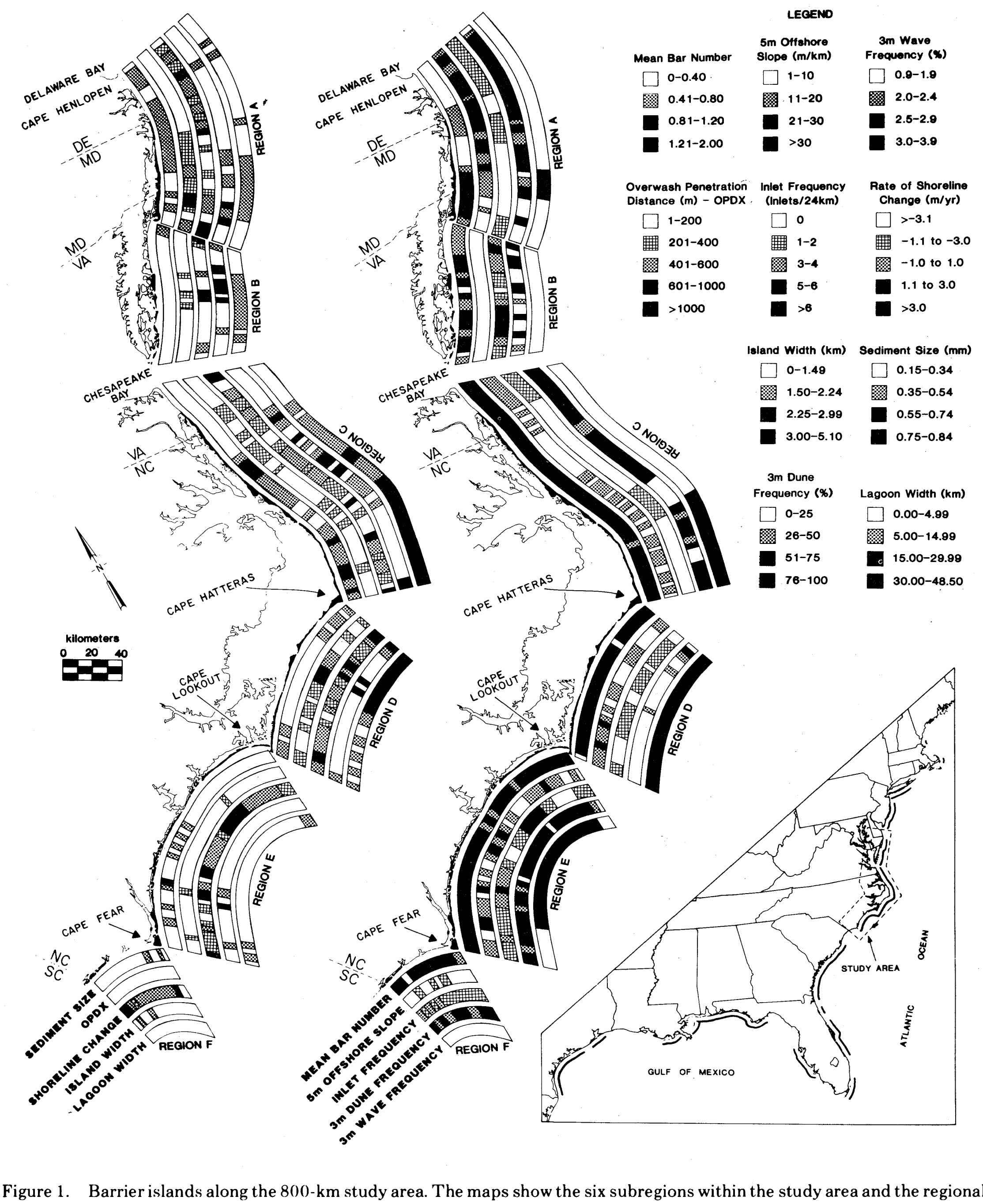

Figure 1. Barrier islands along the 800-km study area. The maps show the six subregions within the study area and the regional variation of 10 selected geomorphic attributes based on measurements made at 1-km intervals.

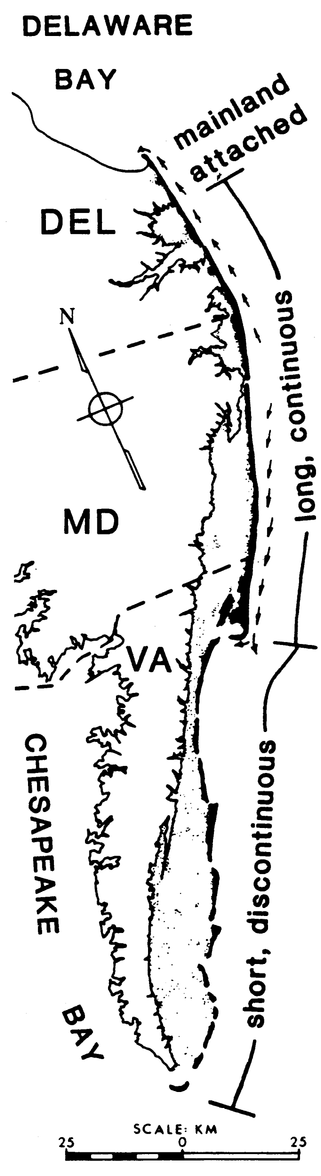

Figure 2. A barrier ensemble occurs along the Delmarva coast showing progressive change in coastal geomorphology along the shoreline. South of Cape Henlopen the mainland coast grades into long, continuous barriers. South of Chincoteague Inlet, short, discontinuous barriers characterize the Virginia coastline to the Chesapeake Bay. Arrows indicate dominate longshore drift patterns.

significant correlations in all three of these data sets. These results do not provide any firm conclusion regarding the best sampling resolution for capturing the interdependencies of coastal geomorphic attributes through linear regression analysis.

The data sets with capes and inlets excluded (1K/EXC and 5K/EXC) clearly showed more pronounced spatial relationships among variables than the corresponding data including capes and inlets (1K/ALL and 5K/ALL). A significant amount of noise was removed from the system by deleting cases adjacent to inlets and capes, which allowed the associations between geomorphic variables to be more readily observed. This finding lends support to the hypothesis mentioned above that geomorphic processes within several km of tidal inlets or capelike features are strongly influenced by their presence. Hence, the impact of inlets and major shifts in shoreline orientation should be taken into consideration when developing a regional coastal classification.

When all five 800-km regional data sets are taken together, the variables that had the highest number of significant correlations were 3.4 m wave frequency, 10-year storm surge, shoreline strike, inlet frequency, and offshore slope to the 5.5 m depth contour. The only strong correlations (r greater than 0.60) were between tide range and 10-year storm surge (in all five data sets), and between shoreline strike and frequency of waves greater than 1.5 m.

Correlation analyses were also run on the six subregions (Figure 1) with data measured at 1 km intervals excluding capes and inlets. Table 3 lists the number of moderate and strong significant correlations in each subregion. In general, there were a greater number of significant correlations in the individual subregions, and many more of the significant correlations were strong (r greater than 0.60), than in the 800-km regional data sets discussed above. In addition, various subregions showed major differences in the type and degree of correlation; in fact, there was not a single significant correlation present in all six subregions. These findings indicate that many of the relationships between geomorphic attributes are organized on a scale that is specific to each geographic subregion, but these relationships change their overall pattern along the 800-km study reach.

Subregion A (Cape Henlopen, Delaware, to Chincoteague Inlet, Virginia) and Subregion E (Cape Lookout, North Carolina, to Cape Fear, North Carolina) had the greatest number of significant

Table 1. *Coastal Geomorphic Attributes*

Variable	Definition	Significance of Change
Tidal range	Mean tidal range (m)	+ greater tidal range − lower tidal range
Storm surge	Maximum 10 yr-storm surge (m)	+ higher storm surge elevation − lower storm surge elevation
Wave frequency	Percentage of onshore and alongshore waves greater than 1.5 m and 3.4 m high (%)	+ greater frequency of storm waves − lower frequency of storm waves
Overwash penetration distance	Mean distance from shoreline to dense vegetation boundary (m)	+ greater overwash penetration − lower overwash penetration
Rate of shoreline change	Mean rate of shoreline movement over period of photo coverage (m/yr)	+ greater accretion − greater erosion
Bar number	Mean number of longshore bars observed on air photos	+ greater number of bars − lower number of bars
Shoreline strike	Azimuth orientation of shoreline strike (degrees); 0 = north	(see island orientations relative to north on Figure 1)
Dune frequency	Percentage of dunes greater than 3 m elevation (%)	+ higher island topography − lower island topography
Inlet frequency	Number of inlets within 24 km of coastline centered on the site	+ greater inlet density − lower inlet density
Offshore slope	Mean shoreline slope measured from shoreline to 5.5 m and 9.1 m depth contours (m/km)	+ steeper offshore slope − gradual offshore slope
Island width	Island width measured normal to shoreline strike (km)	+ wider island − narrower island
Lagoon width	Lagoon width measured normal to shoreline strike (km)	+ wider lagoon − narrower lagoon

correlations and Subregion B (Chincoteague Inlet to Chesapeake Bay) had by far the fewest significant correlations. The apparent lack of geomorphic organization within Subregion B is most likely related to the high frequency of inlets and great local variance in shoreline orientation. Subregions with consistent coastal strike (*i.e.*, relatively straight coastlines) tend to exhibit higher degrees of correlation between geomorphic attributes than subregions with pronounced or frequent shifts in shoreline orientation. Coastal strike appears to be a key variable that influences the development of many other geomorphic attributes.

Principal Components Analysis

Principal components analysis (PCA) was run on the 800-km regional data set measured at 1-km intervals excluding capes and inlets (1K/EXC), and on each of the six geographic subregional data sets with capes and inlets excluded. PCA has been pre-

Table 2. *Entire 800-km study area: number of significant correlations (.001 level) between 15 geomorphic attributes*

Correlation	Data Set				
	1K/ALL	1K/EXC	5K/AVG	5K/ALL	5K/EXC
Moderate correlation ($0.35 > r < 0.60$)	8	13	14	6	16
Strong correlation ($r > 0.60$)	1	2	1	1	2

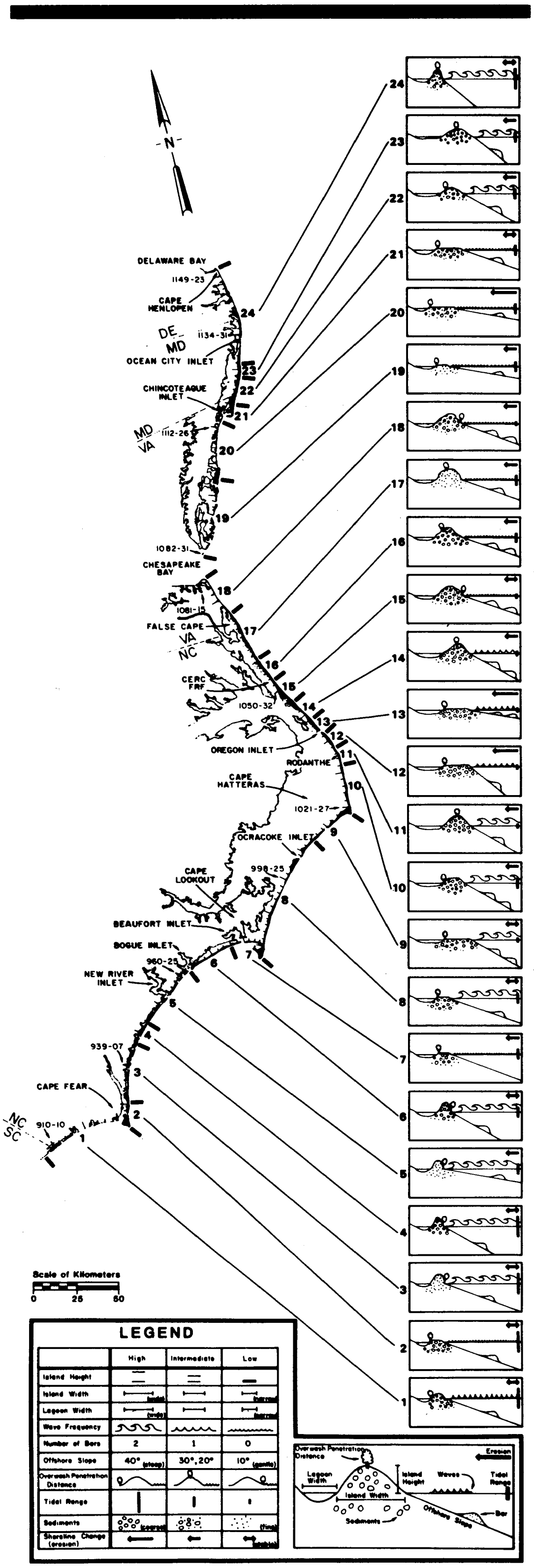

Figure 3. Schematic geomorphic classification of the mid-Atlantic barrier coast based on principal components analysis of the 15 attributes in Table 1. Each illustration is the mean state for that segment relative to the remainder of the coast. Sketches do not conform to actual scale but they illustrate relative scale between the segments.

viously used to explain the variance and organization in coastal geomorphic systems (VINCENT *et al.*, 1975; WINANT and AUBREY, 1976; RESIO *et al.*, 1977; FISHER *et al.*, 1982). PCA of the 800-km regional data set excluding capes and inlets (1K/EXC), produced four significant eigenvectors (using the criteria established by OVERLAND and PREISENDORFER, 1982), accounting for 63% of the total variance in the system. The first eigenvector explained 23% of the variance. The results of the PCA were interpreted with respect to coastal geomorphology and a schematic model was developed (Figure 3). The basic model was built using the weightings of the statistically significant eigenvectors, then the significant eigenvectors were reconstructed using the formula:

$$R_{ij} = \bar{X}_i\,(\pm c)(\delta_i)\,(\Sigma_{ij})$$

where R is the reconstructed value for the i^{th} variable and the j^{th} vector, $\bar{X}_i$ is the mean for i^{th} variable, and c is a constant, δ_i is the standard deviation of the i^{th} variable, and Σ_{ij} is the weighting on the i^{th} vector for the j^{th} variable (see RESIO *et al.*, 1977, for detailed explanation).

When PCA was run on each of the six subregions, the first four eigenvectors typically accounted for greater than 70% of the variance in the system, with the first eigenvector explaining approximately 40% of the variance. Hence, the degree of organization as defined by PCA in the subregional data is greater than in the 800-km regional data set (1K/EXC). Despite the greater degree of organization evident at the subregional scale, there are few major differences between the models predicted for the subregions by analysis of the entire regional data set and the models predicted by analysis of the subregional data.

MID-ATLANTIC BARRIER ISLAND CLASSIFICATION

Our analysis of barrier island attributes reveal that despite local variations in morphology, a consistent adjustment of coastal morphology to mesoscale processes is evident (VINCENT *et al.*, 1976).

Analyses of shoreface and inner shelf profiles along the Atlantic and Gulf coasts show distinctive modes of variation that can be accounted for by regional differences in wave climate, tidal range, and sediment characteristics (FELDER *et al.*, 1979). Similar studies have also revealed a hierarchy of longshore periodicities in the means and standard deviations of the rates of shoreline change and the rate of change of the storm-surge penetration line (DOLAN *et al.*, 1979). These variations were found to coincide with local beach characteristics and with the location of active and relict inlets. Morphometric analysis of Atlantic coast lagoons, marshes, and barrier islands shows there is also a regional organization of the barrier-lagoon-marsh morphologic system (HAYDEN and DOLAN, 1979). This analysis supports the concept of barrier island ensembles, that is, chains of barrier islands that probably evolved in response to systematic variations in offshore steepness and curvature.

The individual geomorphic process attributes listed in Table 1 display spatial organization at various scales, but little organization appears in interrelationships. First, there is not always a clear coupling of process and response variables. This is common in geomorphic systems because of the problem of equifinality in determining morphometric form. Our data can delineate morphometry on a 1-km scale resolution, but can not describe coastal processes on the same scale. A second interference factor is the difficulty in distinguishing between morphometric features caused by modern processes vs. those associated with relict processes. For example, offshore slope, island width, lagoon width, and sediment size are probably associated with relict phenomena. On the other hand, overwash penetration distance, the rate of shoreline change, and bar number probably are in local equilibrium with modern processes. A third factor causing problems with these relationships between variables is man's manipulation of barrier island processes and island morphology. Massive dune stabilization projects and coastal engineering projects have altered sediment transport and morphology on mid-Atlantic barrier islands. Clearly, a unified classification scheme must utilize fewer attributes in order to develop a smaller number of final classification categories. Relationships between groups of two to four variables exhibit much greater organization. In addition, relationships between variables are well-developed within the various geographic subregions along the coast, while poorer relationships exist when data from the entire study reach is included in the analyses.

Geomorphic Compartments

Figure 3 summarizes the results of the principal components analysis of the 15 attributes in Table 1, resulting in 24 distinctive coastal patterns recognized along the 800-km stretch of the mid-Atlantic coast. By deleting three of the variables from direct consideration (tidal range, storm surge, and overwash penetration distance) the coast can be subdivided into eight regions of similar geomorphic attributes. Details of this model are discussed in KOCHEL *et al.* (1983). The northernmost reach of the study area, between Cape Henlopen and southern Assateague Island (Figure 3, segments 22-24), is composed of mainland coast, attached barrier spits and long barrier islands. This area has steep offshore slopes, coarse-grained sediments, zero to one offshore bar, high-profile island topography, high frequency of large waves, a slowly eroding coastline, and moderately wide islands and lagoons. The second geomorphic segment is between southern Assateague Island and the Chesapeake Bay (Figure 3, segments 19-21). This region has short, discontinuous barriers, very gentle offshore slopes, fine-grained sediments, one bar, low-profile islands, and moderately wide lagoons. The third geomorphic segment occupies the reach between the Chesapeake Bay and Nags Head (Figure 3, segments 14-18). This segment begins at the north as a mainland-attached barrier beach and becomes a long, continuous barrier to the south. Geomorphic attributes of this segment include gentle to moderate offshore slopes, coarse- to medium-grained sediments, temporally variable one- or two-bar systems, high-profile islands, low frequency of high waves, slowly eroding coastlines, moderately wide lagoons and wide islands. The fourth geomorphic segment of the study area lies between Nags Head and Rodanthe (Figure 3, segments 11-13). This segment is characterized by long barriers with steep offshore slopes (except near Oregon Inlet), moderately coarse-grained sediments, variable frequency of large waves, rapidly eroding coastlines, and wide islands and lagoons. The fifth geomorphic segment of the mid-Atlantic coast is a reach of long barriers between Rodanthe and Cape Lookout (Figure 3, segments 8-10). This reach is characterized by moderate to steep offshore slopes, medium- to coarse-grained sediments, temporally variable one- or two-bar systems, low-profile islands, high frequency of large

Table 3. Six geomorphic subregions: number of significant correlations (.001 level) between 15 geomorphic attributes

Correlation	Subregion					
	A	B	C	D	E	F
Moderate correlation (0.35 > r < 0.60)	44	0	16	15	32	0
Strong correlation (r > 0.60)	11	6	6	8	8	16

waves, stable or slowly eroding coastlines, moderate to wide islands, and wide lagoons. The sixth geomorphic reach of the mid-Atlantic coast is the small area sheltered from wave activity by Cape Lookout, between the Cape and Beaufort Inlet (Figure 3, segment 7). This reach has moderately gentle offshore slopes, medium-grained sediments, no bars, low-profile islands, low frequency of large waves, slowly eroding coastlines, and moderately wide lagoons and islands. The seventh geomorphic segment of the mid-Atlantic coast is the reach between Beaufort Inlet and Mason Inlet (Figure 3, segments 3-6). The northern part of this reach has long barriers, while the southern part contains short barriers with frequent inlets. This reach has mod erately steep offshore slopes (except for segment 5, Figure 3), variable sediment size, one offshore bar, high-profile islands, high frequency of large waves, stable coastlines, and narrow lagoons and islands. The eighth, and southernmost, geomorphic segment occurs between Mason Inlet and the North Carolina — South Carolina border (Figure 3, segments 1-2). This segment has short barriers, moderate offshore slopes, low-profile islands, low frequency of large waves, one offshore bar, medium-grained sediment, and narrow lagoons and islands.

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