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SHORELINE BEHAVIOR ALONG THE ATLANTIC COAST OF DELAWARE

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ABSTRACT: *Delaware's Atlantic coast is relatively short and straight (about 40 km), yet there are major variations in shoreline behavior which are largely determined by antecedent geology and inlet morphology. Rates of coastal erosion are not only quite variable in a spatial sense, but also temporally because of the influence of episodic events. This examination uses long-term (>100 year) shoreline position data to delineate the temporal and spatial variability of shoreline change and demonstrate the influence of tidal inlets and antecedent geology on shoreline configuration. The results indicate that tidal inlets play an important role in shoreline behavior over large segments of the coastal zone, and that antecedent geology appears to play an important role in shoreline stability as well as the long-term evolution of beach position and configuration.*

Keywords: *Beach erosion, Shoreline mapping, Antecedent geology, Storm climatology*

INTRODUCTION

Coastal development in the U.S. has proceeded rapidly over the past several decades, notwithstanding increasing occurrences of property loss from beach erosion and coastal storms (Leatherman, 2000). Financial losses brought about by beach erosion and storm damage are approaching economically and politically insupportable levels. Avoiding larger losses in the future requires more effective land use management policies based on accurate, long-term shoreline change data and an understanding of modes of shoreline behavior.

Beach erosion is difficult for the public to appreciate because of the temporal scales involved. It is hard to differentiate the changes in beach width driven by winter-summer profile changes (10s of meters), or those induced by the episodic occurrence of a large storm (10s to 100s of meters), from long-term beach erosion (centimeters to meters per year). In a spatial sense, the public does not recognize the ubiquitous nature of beach erosion, believing that the problem exists at only a few, well-publicized erosional hot spots. To further confound the problem, there is a paucity of quality long-term shoreline change data as well as the publication of some less than adequate analyses: i.e., assigning a rate-of-change to an entire state (Galgano and Douglas, 2000). Consequently, important policy decisions are typically based on shoreline change rates developed from short-term, spatially diffuse data in the absence of a geomorphic framework (Zhang, 2002).

Shoreline change along Delaware's Atlantic coast is spatially inconstant, with rates of change varying from +10 m/yr to -2.7 m/yr. (Galgano, 1998), thus assigning a single erosion rate to the entire length of this shoreline is misleading. When short periods-of-record (i.e., < 60 years) are used to determine erosional trends, incorrect findings often result (Galgano and Douglas, 2000). This is clearly the case in Delaware where more detailed analyses employing long-term (>100 year) data with dense sampling intervals show that Delaware's Atlantic coast is eroding everywhere except the tip of Cape Henlopen and at the south jetty of Indian River Inlet (Kraft et al., 1975; Galgano, 1998).

This analysis combines shoreline position data from National Ocean Survey (NOS) "T" Sheets, aerial photographs and GPS surveys to generate long-term shoreline change maps of Delaware's Atlantic coastline from Cape Henlopen to Fenwick Island (Figure 1). Source data were corrected and digitally compiled to produce long-term (i.e., 152-year) shoreline change maps that delineate shoreline movements from 1845 to 1997. Transects were measured at 250-meter intervals along the shoreline, and a linear regression model was used to estimate the long-term rate-of-change for each transect. Finally, data were complied by geomorphic unit to illustrate spatial variability.

COASTAL GEOMORPHIC SETTING

Delaware's Atlantic coast is a dynamic landform, and is the product of an eroding headland and transgressive barrier island system that has evolved during a period of rising sea level. The transgression commenced at the termination of the Wisconsin Ice Age, 11,000-14,000 years B.P. Since that time, the barrier system migrated landward in response to Holocene sea-level rise. Consequently, most of the Delaware shore is eroding except for accretion along the Cape Henlopen spit complex, and sand backup on the southern flank of the Indian River Inlet jetty (Galgano, 1998). Shoreline reshaping is largely the product of longshore sediment transport along with the effects of tidal currents at inlets and spit tips. However, antecedent geology has been shown to strongly influence modes of shoreline behavior and long-term shoreline evolution in Delaware (Kraft et al., 1975).

The Delaware coast is located on a low-lying coastal plain, which is part of a larger geologic structure, the Western Atlantic Coastal Plain-Continental Shelf Geosyncline. The coastal plain is broad and flat, sloping gently to the southeast at approximately 30 cm/km (Kraft, 1974). Delaware's Atlantic shoreline extends from Cape Henlopen to Fenwick Island and can be classified as a barrier island-headland shoreline. The coastal plain is composed of unconsolidated and semi-consolidated materials that include Pleistocene and Holocene sands and gravels (Kraft, et al., 1975).

Delaware's Atlantic coast exhibits five distinct physiographic units and several discrete coastal configurations (Figure 1). The ocean shoreline is generally linear in nature; however, it exhibits irregularities imposed by geologic factors and human-induced influences (Galgano, 1998). The mainland lagoon shoreline is highly irregular and follows the incised paleodrainage system (Demarest and Leatherman, 1985). The net direction of longshore sediment transport is to the north and has been documented to be as high as 122,000 m^3/yr (Perlin et al., 1983), however, the littoral volume is normally much smaller, perhaps 76,000 to 92,000 m^3/yr. (Kraft et al., 1975). The northern end of the littoral drift system is the Cape Henlopen spit complex, which is accreting rapidly into Delaware Bay at +10 m/yr (Galgano, 1998). Three discrete coastal physiographic units exist along the 40 kilometer-long coastline (Figure 1): 1) spit-marsh complex; 2) baymouth barrier shoreline; and 3) Pleistocene headlands.

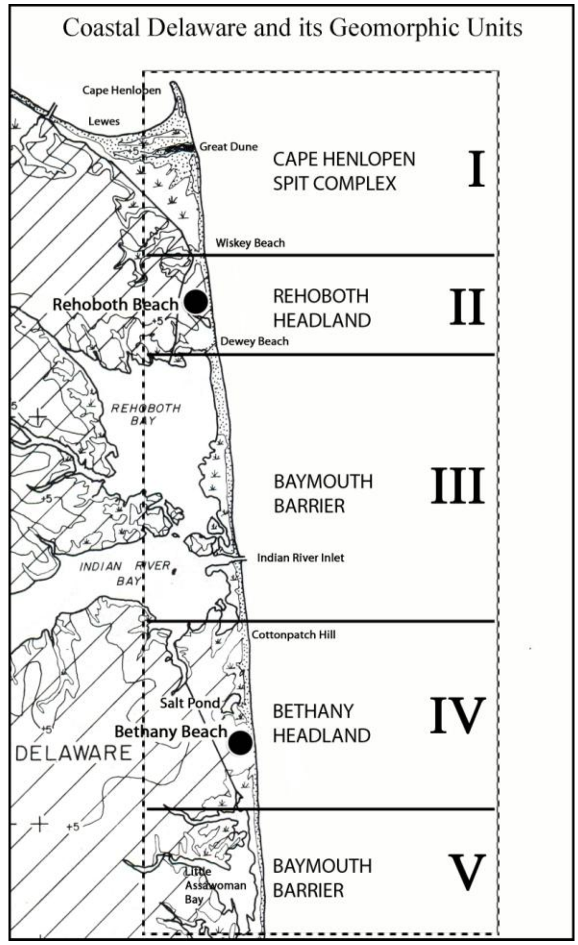


Figure 1. Map of coastal Delaware illustrating geomorphic units.

Spit-Marsh Complex

The Cape Henlopen spit system is a triangular-shaped area extending from Lewes, around the apex of the cape, then southward to Wiskey Beach on the Atlantic shoreline (Figure 1). The cape has evolved for at least the last 2,000 years from a series of recurved spits. Construction of a breakwater in 1830 significantly disturbed the sediment transport to the extent that the cuspate foreland accreted north into Delaware Bay forming present-day Cape Henlopen (Kraft and John, 1976).

Cape Henlopen is the only naturally accreting area on the Delaware coast and is comprised of sufficient sand to form an extensive dune field, wide beaches, a broad tidal flat and nearshore sand bars. Though the spit is prograding northward, the eastern shore of the spit is eroding at a substantial rate as the formally bulbous shaped cuspate foreland is retreating landward. The spit complex is attached to the northern extension of the barrier system at Wiskey

Beach. This low-lying barrier fronts Lewes Creek Marsh (Figure 1). Whiskey Beach is a typical washover-dominated barrier (Kraft et al., 1975).

Baymouth Barrier System

South of Rehoboth Beach, the coastline is composed of a baymouth barrier-inland bay system. It is characterized by a narrow, sandy barrier, which separates the ocean from the bay. Components of the barrier include tidal deltas, marshes, barrier flats, dunes, and beaches. Barrier elevations are low with the barrier dune rising some 3-5 meters above sea level (Kraft, 1974). The barrier varies between 350 and 1,700 meters in width. Marsh sediments and pre-Holocene clays crop out on the shoreface along the barrier to a depth of 10 meters. These facies are frequently exposed on the lower beach face during storm events. North of Indian River Inlet, the barrier rests on a submerged Pleistocene highland, which extends seaward through the shoreface (Perlin et al., 1983).

Baymouth barriers front Rehoboth, Indian River, and Little Assawoman Bays. Presently only Indian River Inlet, which was stabilized in 1940, links bay waters with the Atlantic Ocean. Numerous, ephemeral inlets have opened along this barrier system during periods of storms (Figure 2). Where major inlets are known to have occurred, the barrier is relatively broad, but manifests higher rates of erosion (Moody, 1964; Kraft et al., 1975; Galgano, 1998).

Pleistocene Headlands

Eroding Pleistocene headlands at Rehoboth and Bethany interrupt the barrier system. Headlands are composed of unconsolidated and semi-consolidated sands and gravels, and have surface elevations of 3 to 15 meters above sea level. Because Pleistocene sediments outcrop in the nearshore, they supply the longshore transport system with sandy materials through shoreface erosion (Kraft et al., 1975; Kraft and John, 1976; Perlin et al., 1983). The shoreface is composed mostly of Pleistocene clays capped with only a thin veneer of sand (Dalrymple and Mann, 1985).

Two ancient barrier systems form the headlands at Bethany and crop out on the shoreface (Figure 2). The Cedar Neck and Bethany Barriers have been dated at 600,000 and 60,000 years B.P., respectively (Demarest and Leatherman, 1985). These represent ancient barrier islands, which lie at an angle to the modern shoreline. The shoreface configuration at Bethany Beach is essentially the same as at Rehoboth. The nearshore is steep, composed largely of Pleistocene clay and mud and covered by a 30-cm veneer of sand (Dalrymple and Mann, 1985).

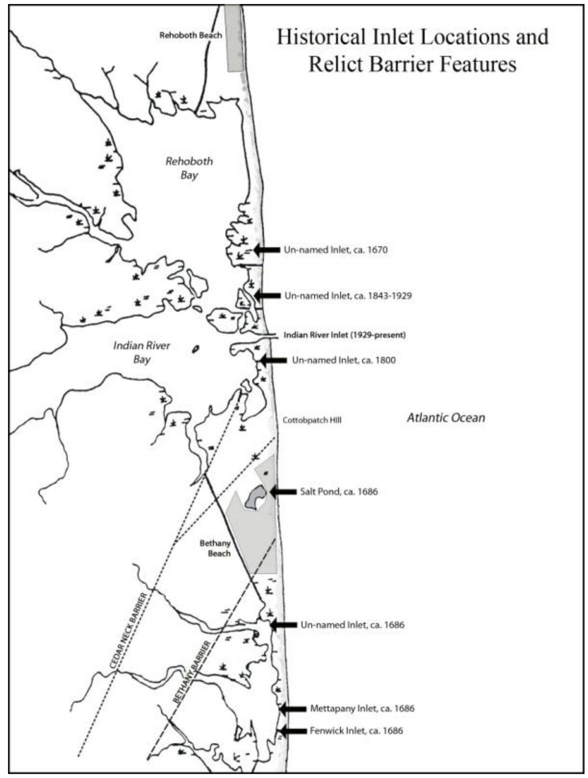


Figure 2. Map illustrating locations of relict historical inlet locations and relict barrier islands along Delaware's Atlantic coastline.

Although Delaware's Atlantic coast is generally straight, there are significant local anomalies. These variations are the product of geologic factors and human intervention. In either event, these "anomalies" are important to this study because they furnish valuable insight for the analysis and understanding the modes of shoreline behavior. Figure 3 illustrates the location and nature of each of these irregularities in an otherwise straight shoreline.

SHORELINE CHANGE DATA

Shoreline change data in Figure 3 depict a transgressive coastline. Although the shoreline appears to be generally straight, there are significant local variations in beach planform apparent in the shoreline change data. The 152-year record of shoreline change indicates that Delaware's Atlantic shore is entirely erosional with two exceptions. The tip of Cape Henlopen, the only naturally accreting segment of the shoreline, prograded northward at a

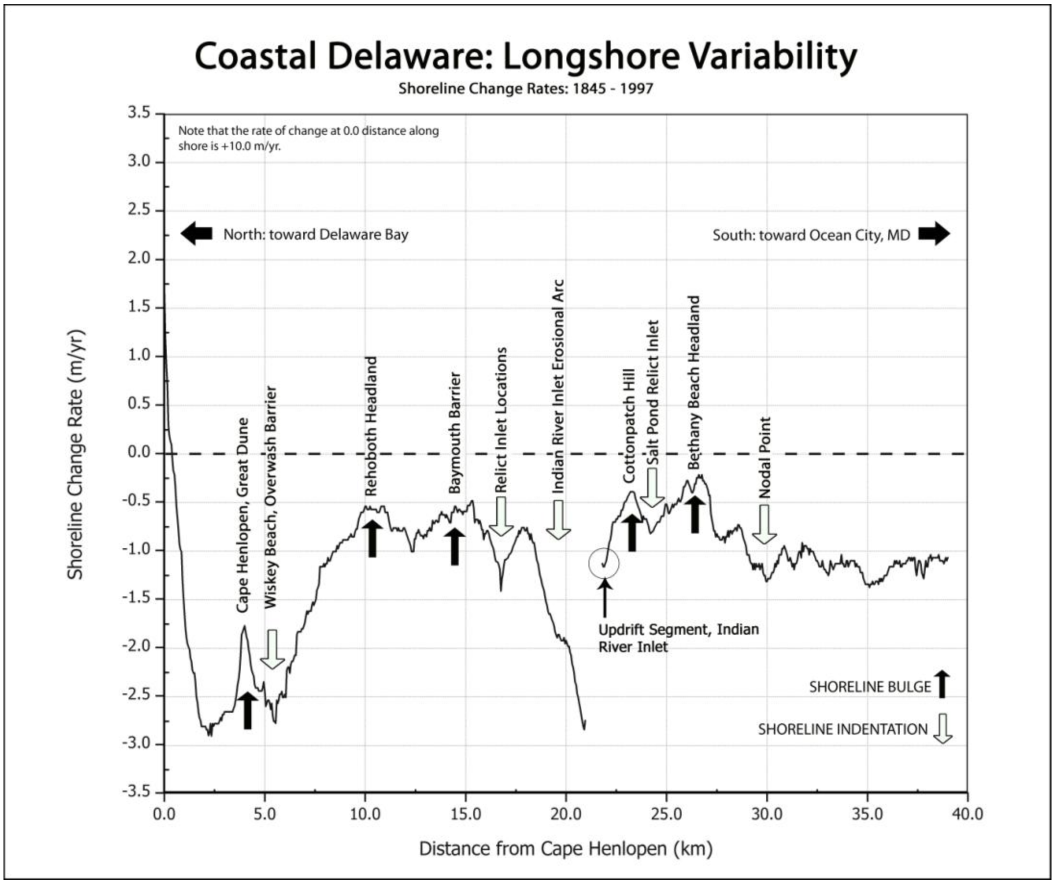


Figure 3. Shoreline change rates sampled at 250 meter intervals along Delaware's Atlantic shoreline. The data illustrate a number of shoreline anomalies, which are manifested as bulges and indentations in the shoreline. Shoreline change rates are estimated from a linear regression of shoreline positions derived from maps, aerial photographs, and GPS.

rate of +10.0 m/yr during this period, however its Atlantic beaches have been eroding at extremely high rates (-2.70 m/yr). Sand backup at the southern flank of the Indian River Inlet jetties represents the only other accretional segment of the coastline—although the long-term background rate is erosional (Figure 3). This 4-kilometer segment of beach has accreted at 1.8 m/yr since jetties were emplaced in 1939.

Although the 152-year record of shoreline change is erosional, there are significant spatial and temporal variations in these trends. Longshore variations are evident in each physiographic unit. A plot of all transects (Figure 3) offers a more complete picture of the spatial variability of shoreline change rates and illustrates the degree of variability within a discrete geomorphic unit. As shown by Figure 3, it is difficult to generalize shoreline change rates (i.e., a state-wide average erosion rate), and analysis must be undertaken on a very detailed level in order to truly capture shoreline behavior and the underlying processes driving change. A careful analysis of shoreline change data reveals prominent bulges and indentations in the shoreline. These "anomalies" are manifest in the variable shoreline change rates (Figure 3). Each anomaly can be explained by geologic and anthropogenic conditions.

There is a prominent bulge in the shoreline along the eastern base of Cape Henlopen (Figure 3). The large dunes on Cape Henlopen supply a considerable volume of sediment to the littoral drift system at that point. The dunes at the base of Cape Henlopen are shown to be truncated at their seaward terminus on the 1954 USGS topographic map. Hence, a sizable bulge has developed along this section because of this massive infusion of sand-sized sediment (Kraft et al., 1975).

Wiskey Beach is located at the southern terminus of the spit complex, and just north of the Rehoboth headland (Figure 3). Whiskey Beach is a narrow, washover barrier with a sand thickness of only 50-75 cm on the shoreface. This segment of the shoreline is subject to extensive overwash during even mild coastal storms (Kraft, 1974). The shoreline at Wiskey Beach has historically eroded at higher rates, exacerbated since the 1930's by the Rehoboth groin field directly to the south. Hence, a sizable indentation is present in the shoreline (Kraft, et al., 1975, Galgano, 1998). To the south, Rehoboth Beach bulges seaward because of two factors. The groin field, which was constructed in the 1930s, has built the beach seaward and retarded erosion along with several beach nourishment events: i.e., 1962, 1988, 1993, and 1996 (Galgano, 1989, 1998). Additionally, the Pleistocene highland, which crops out on the shoreface, has enabled Rehoboth Beach to recede more slowly than adjacent beaches (Kraft et al., 1975).

On the barrier south of Rehoboth Beach, the coastline again bulges seaward between Dewey Beach and Indian River Inlet (Figure 3). This bulge emanates from three geologic factors which combine to retard erosion rates: (1) presence of large, shoreface-inner shelf sand ridges approximately one kilometer offshore, which refract wave energy away from this location (Moody, 1964); (2) extensive outcropping of backbarrier marsh muds and peat on the shoreface which are somewhat more resistant to erosion than sand; and (3) presence of a semi-consolidated Pleistocene formation which underlies the area and extends seaward through the shoreface (Kraft, et al., 1975; Perlin et al., 1983).

There is a very sharp shoreline indentation adjacent to the north jetty of the Indian River Inlet. This arc of erosion is caused primarily by the impoundment of sediment by the inlet's southern jetty. This in turn causes sand starvation downdrift, and artificially high rates of erosion north of the inlet. However, this area has been shown to be indented on historical maps prior to inlet stabilization in 1940. Moody (1964) and Kraft et al. (1975) suggest that these indentations historically tend to occur where the barrier has been broken by former inlets (Figure 2).

South of Indian River Inlet, there is a shoreline bulge opposite Cottonpatch Hill (Figure 3). Historically this section of shoreline has eroded slowly (-0.4 m/yr). This bulge evolved because of the combined effects of the protection afforded by linear shoreface shoals (Moody, 1964) and a Pleistocene highland at Cottonpatch Hill (Cedar Neck Barrier, Figure 2). This Pleistocene material projects out into the shoreface and is highly resistant to erosion.

Another minor indentation is manifest in the shoreline south of Cottonpatch Hill in the barrier opposite Salt Pond (Figure 3). This indentation corresponds to the position of a known inlet that existed there circa 1686 (Figure 2). Additionally, Kraft et al. (1975) have shown this area to be in a convergence zone due to wave refraction and hence, it is subjected to greater wave-induced erosion. The shoreline bulges seaward again at Bethany Beach (Figure 3). The bulge is caused largely by the Pleistocene barrier (Bethany Barrier, Figure 2), which forms the headland in this area. This formation crops out on the shoreface and supplies a sizable volume of coarse-grained material to the littoral system. Additionally, this beach is protected from wave energy to a certain degree by the linear shoreface sand ridges (Moody, 1964).

The Bethany Beach bulge has been largely attributed to the presence of a groin field built in the late 1930's (Perlin et al., 1983; and Dalrymple and Mann, 1985). However, the effectiveness of this groin field is a matter of contention. The Bethany bulge is present on the shoreline maps of 1850 and 1929, both prior to the construction of the groin field. Further, beach nourishment has played a more important role than the groins in shore stability (Galgano, 1989).

DISCUSSION

Shoreline change trends are difficult to quantify because erosion and accretion are not uniform processes in time and space. The typical record of shoreline change exhibits short term variability that ordinarily masks the underlying trend. This variability is commonly (and incorrectly) described as "noise." This geophysical "noise" can tell an important story about the long-term behavior of the shoreline when combined with sound geomorphic analysis (Leatherman, et al., 1982). Notwithstanding, sometimes this "noise" is misinterpreted and it is often proposed that it is a function of data inaccuracy, or perhaps represents outliers that can be eliminated using statistical techniques (Crowell et al., 1997).

Coastal erosion is a complex physical process encompassing a number of natural and anthropogenically induced factors. Shoreline change occurs in response to these factors in cycles that range from days to millennia. For example, most sections of the beach experience accretion and erosion in response to low-order events (e.g., storm surges, seasonal profile variations) irrespective of their long-term trend. Furthermore, long-term shoreline change trends can be cyclic or linear—shoreline change may persist in one direction (erosion or accretion), or it may experience periodic erosion and accretion (e.g., mesotidal barrier island behavior). To make our ability to discern shoreline change more complex, the rates of change may not be temporally uniform, with intervals of accelerated or decelerated erosion (Galgano and Douglas, 2000). Figure 4 illustrates the significant variations and trend reversals between discrete time intervals during the period of record. Significant storms have generated substantial erosion, followed by periods of long-term recovery expressed as accretion. Thus, a short record can, inadvertently, skew an analysis and ignore the undeniable background trend (i.e., Figure 3).

These diverse time scales are complicated by human timeframes of reference in the coastal zone. Engineering projects are considered in 50-year cycles, but ordinarily people tend to think in terms of 5-10 year periods. Seasonal erosion and accretion of the beach, and the sometimes decade-long recovery following a storm of the magnitude of the 1962 Ash Wednesday Storm tend to confuse our perception of the relative stability of a segment of the beach (Kraft, et al., 1975). We should not expect that shoreline change rates will remain constant through time, and should expect considerable longshore variability (Figures 3 and 4). In this regard, spatially diffuse, short-term data are generally less satisfactory than long-term (>100 years) data (Galgano and Douglas, 2000). Further, using mixed samples (i.e., summer and winter aerial photography, and post-storm photography) greatly increases the errors that may originate from a single bad sample (Tanner, 1978; Crowell, et al., 1993).

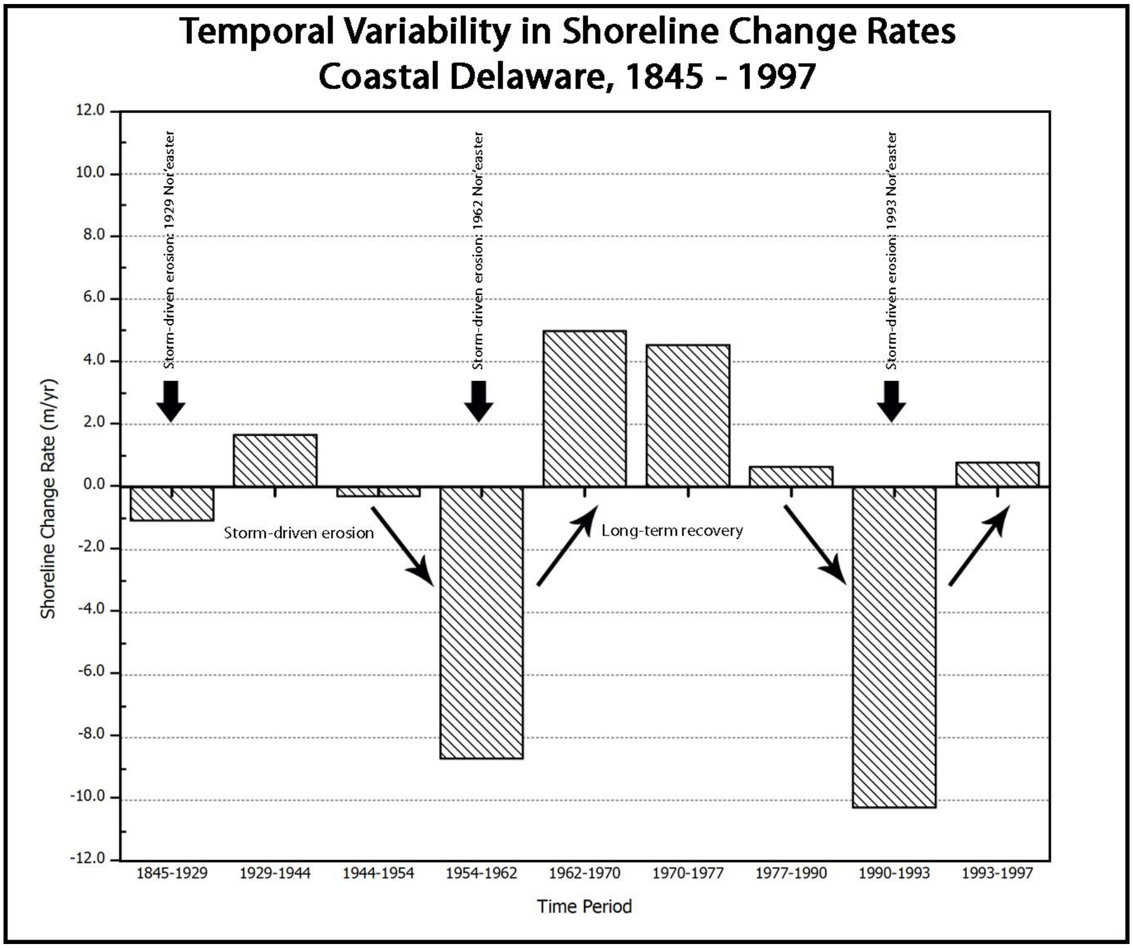
This research indicates that the most reliable method by which to determine the underlying beach trend is to use all available, accurate data in order to extend the record of shoreline change combined with careful geomorphic analyses (Crowell et al., 1993; Leatherman, 1993; Crowell et al., 1997; Galgano and Douglas, 2000; Hammar-Klose, 2002). Until the numerous episodic, low-order events that control the coastline are integrated, a reasonable understanding of long-term morphological response is precluded. Therefore, the longest-term data should be used to calculate the trend even if accelerations and decelerations are evident (Crowell et al., 1997). Considering the diversity of shoreline types and the changing dynamics of processes along the open coast, data obtained from long-term shoreline mapping combined with highly detailed geomorphic analyses are the only reliable means by which to obtain accurate shoreline change rates make reasonably informed land use decisions. To do otherwise will only degrade the accuracy of the results, and largely obfuscate the background trend.

Delaware's shoreline is undergoing recession; however, it exhibits periods of moderate erosion and accretion, punctuated by severe, storm-dominated beach erosion (Figure 4). The data given in Figure 3 indicate that there is significant longshore variability in rates of change, which is in large measure controlled by antecedent geology. This longshore variability makes it difficult to quantify, in simple terms, a characteristic rate of change. Thus, attempts to assign a rate of change to anything larger than a discrete geomorphic unit is misleading, if not meaningless. Furthermore, long-term net shoreline changes are typically imperceptible to shore dwellers because of seasonally induced beach width fluctuations. Additionally, a major storm can result in significant beach erosion. For example, in the span of several days, the Ash Wednesday Storm of 1962 caused an average of 100 meters of erosion along Delaware's coast, with as much as 210 meters in some areas (Moody, 1964). This is comparable to many decades of "normal' erosion, followed by post-storm beach recovery requiring over 7-10 years.

Shoreline position is affected primarily by geology, relative sea-level rise, sediment supply, wave energy, and episodic storm events (Zhang, 2002). Since storms are probabilistic in occurrence, annual rates of shoreline change can vary considerably over time. Figure 4 illustrates the influence of storms on shoreline position along the barrier island segment (i.e., Section III, Figure 1) and is representative of the entire Atlantic beach. Temporal variations in shoreline change rates are evident on Delaware's Atlantic coast during the 152-year period of study. The shoreline seldom displays uniform retreat through time; instead, recession generally occurs in cycles. The shoreline exhibits periods of relative positional stability in conjunction with periods of erosion and accretion.

CONCLUSIONS

The results indicate that geologic, geomorphic, and anthropogenic factors play an important role in shoreline behavior over large segments of the coastal zone, and that there is considerable short-term temporal variability in shoreline change, linked to major episodic events. These conditions play an important role in shoreline stability as well as the long-term evolution of beach position and configuration. Delaware's Atlantic beaches are almost entirely erosional. Erosional and accretional processes are not steady through time, but rather fluctuate with changes in environmental parameters. Over shorter timeframes, extreme events (e.g., storms) have a greater influence on average shoreline



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change rates. In a spatial sense, Delaware's Atlantic beaches exhibit a wide degree of variability of shoreline change between and within geomorphic units linked principally to antecedent geology and anthropogenic factors. Hence, it is evident that shoreline analysis must be conducted on a very detailed basis to understand the true nature of change. Data smoothing or statistical analyses that average rates for long stretches of coastline can be misleading and hide important trends.

Shoreline change in Delaware is not temporally constant—erosion is more of an event-related phenomenon. Delaware's long-term record exhibits significant variations in beach width over time. Discrete periods from this long-term record reveal contrasting shoreline trends at decadal scales, which can be misleading. For example, if only three data sets (1962, 1970 and 1977) are used in a shoreline analysis, the data indicate a 15-year record of accretion of +4.63 meters per year. This analysis may falsely suggest that a "trend reversal" has occurred in what is an undeniably erosional shore, and further, that only the most recent data are required for projecting future positions.

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