BEACH EROSION ADJACENT TO STABILIZED MICROTIDAL INLETS

Francis A. Galgano
Department of Geography and the Environment
Villanova University
800 E. Lancaster Avenue
Villanova, Pennsylvania 19085

ABSTRACT*: Stabilized tidal inlets have caused severe downdrift erosion that threatens structures and barrier island stability. This problem has long been established, but the full impact has often been misinterpreted, as most researches have not recognized the "s" signature of this mode of shoreline behavior. Furthermore, damaging erosion along beaches in front of coastal communities has sometimes been attributed to tidal inlets because simple sediment budget models have been used (incorrectly) to quantify the problem. A comparison of six inlets along the U.S. Northeast coast demonstrates a consistent pattern of change: the arc of erosion is a mobile planform feature, its spatial behavior is time dependent, it expands downdrift at a non-linear rate, and the area of change consistently manifests an "s" pattern. Long-term (100+ year) shoreline change data were used to identify these relationships and quantify the impact of tidal inlets on downdrift beaches. This paper will focus on Moriches Inlet along the southern shore of Long Island, New York.*

Keywords: *Beach Erosion, Tidal Inlets, Jetties, Shoreline Change Data, Historical Shoreline Changes*

INTRODUCTION

Tidal inlets are the most important element of the barrier island system in terms of littoral processes, and inlets have been shown to have a considerable influence on shoreline behavior along adjacent shorelines and within large-scale coastal compartments (Hayes, 1979; Rice and Leatherman, 1983; Bruun, 1996; Galgano, 1998). In the case of stabilized inlets, jetties extend into the ocean, block natural sediment transport, and have the most demonstrable effect on adjacent beaches of any shoreline engineering structure. They can potentially alter natural barrier island configuration. Hayes (1975 and 1979) demonstrated the dominant role of inlets in controlling the cyclic nature of barrier island morphodynamics by modeling inlet behavior in meso- and micro-tidal conditions. Dean and Walton (1975) indicated that tidal inlets represent the largest sediment sink along the coast, and are believed to be responsible for much of the beach erosion in Florida. Leatherman (1989) showed how inlet activity controls the geomorphic configuration and long-term stability of microtidal barrier islands and is the principle mechanism for landward migration.

Inlet dynamics can give rise to dramatic modifications of adjacent beaches over time. Anders et al. (1990), Dean and Work (1993), Dean (1991), Nummendal et al. (1977), FitzGerald et al. (1978), Bruun (1996), Mehta (1996) and FitzGerald (1996) suggest that tidal inlets are responsible for most of the beach erosion along U.S. East Coast barrier islands. The impact of Ocean City Inlet along northern Assateague Island, Maryland is well-documented (Leatherman, 1979 and 1984). Galgano (1998) demonstrated that 70% of the barrier beaches along the mid-Atlantic coast are influenced by inlet activity.

Jetties disrupt the transport of sand along the beach. The ensuing erosion is caused by an adjustment of the barrier island system to new hydraulic, sedimentary, and wave energy conditions (FitzGerald et al., 1979). Jetties stabilize numerous inlets along the mid-Atlantic barrier island coast and these structures have acutely altered preexisting sediment transport patterns. Sediment transport near tidal inlets is the greatest concern to coastal scientists and engineers because it is at these locations that the potential exists for substantial beach erosion (Dean and Walton, 1975). After the construction of jetty systems, adjacent beaches experience elevated erosional and depositional changes until the shorelines adjust to the new conditions (Komar, 1996).

A review of relevant literature (e.g., Leatherman, et al., 1987; Dean and Work, 1993; Douglas and Walther, 1994; Fenster and Dolan, 1996; Mehta, 1996; Pilkey and Dixon, 1996; Bruun, 1996; Kraus and Galgano, 2001) indicates that while the spatial extent of inlet-induced modification of adjacent beaches is intuitively understood, the modeling results are variable and have not been quantitatively assessed on a systematic basis. Nummendal et al. (1977) observed that the erosional and accretional nature of South Carolina's barrier islands is intimately connected with the behavior of tidal inlets. Oertel and Kraft (1994), and Rice and Leatherman (1983) illustrated the dominant role of inlets in controlling the coastal configuration of the Virginia barrier islands. Everts (1983), Anders et al. (1990) and Galgano (1998) suggested that the greatest variability of shoreline change rates occurred near inlets in their analyses of shoreline movements of the U.S. Atlantic coast. Galgano (2008) illustrated how beaches adjacent to tidal inlets are "erosion hotspots" with consistently and anomalously high rates of erosion. Hubbard et al. (1977) pointed out that the mainland beaches of South Carolina are stable everywhere except near tidal inlets; only where there are 15-20 km between inlets is there no influence on the shoreline.

There is a long history of inlet stabilization (Smith, 1988), but unfortunately this activity was usually accomplished with little or no knowledge of the consequences for downdrift beaches (Inman and Nordstrom, 1978 and Bruun, 1986). While the morphology of tidal inlets is well defined, the spatial extent and temporal behavior of inlet-induced beach erosion was not delineated on a systematic basis (Bruun, 1996 and Mehta, 1996). The fundamental problem is that our understanding of the precise nature of the spatial and temporal impact of jetties on adjacent beaches was very limited, and there was a paucity of spatially dense, long-term shoreline change data (Mehta, 1996). By way of example, published estimates of the erosion downdrift from St. Lucie Inlet, Florida on Jupiter Island vary between 4.5 and 48 kilometers—a considerable range in the data (Finkl, 1996; Walton, 1978, Douglas and Walther, 1978; and Dean and Work, 1993).

Barrier island management requires an understanding of the processes that bring about short- and long-term beach erosion trends. Hence, continued investigation of inlet-induced shoreline changes is of fundamental importance to geomorphologists, coastal planners, and engineers. The adverse impacts of tidal inlets on downdrift beaches have been difficult to quantify because of data constraints, but it appears to be 10-20 kilometers in extent (Mann, 1993). A number of examples of the interaction of inlets with adjacent beaches are presented in the literature. However, they tend to treat the arc of erosion as a static feature and consider only the short distance effects (i.e., 5-10 km) of inlets (e.g., Dean and Work, 1993 and Fenster and Dolan, 1996). The temporal behavior and longer downdrift effects have been ignored or missed because of data constraints (Bruun, 1996). Contemporary research has relied on shoreline change measurements taken along a few spatially diffuse survey lines over short temporal spans. Therefore, despite seemingly extensive documentation of the impacts of tidal inlets, our ability to predict their influence on adjacent beaches is considerably less than what is necessary for estimating long-term changes (Mehta, 1996).

Hence, there appears to be a two-fold requirement for understanding the spatial and temporal characteristics of erosion downdrift from stabilized inlets. First, research must ascertain the length of shoreline adversely affected by stabilized inlets using high quality, long-term shoreline change data with spatially dense sampling intervals. Second, the temporal and spatial characteristics of this modification must be identified. The literature has clearly established that tidal inlets and jetties generate significant downdrift beach erosion; however, the important research question that has not been adequately answered involves how this erosional stress is propagated downdrift as a function of time (Bruun, 1996). To that end, this investigation employs an historical trend analysis of long-term shoreline change data to determine the temporal and spatial behavior of beaches adjacent to tidal inlets.

INLET DYNAMICS

Along the Atlantic coast there is a classic inlet-shoreline configuration associated with stabilized microtidal inlets (Figure 1). There is characteristic accretion of sand along the updrift side of the inlet (i.e., zone of accretion) and severe erosion downdrift (i.e., arc of erosion), with a minor back up of sand along the downdrift jetty caused by wave refraction. These changes are induced by the obstruction of the littoral system and prevention of natural sand bypassing by the jetties and tidal jet (Oertel, 1985). The literature suggests that the impoundment of sand along the updrift jetty and the area of downdrift erosion are roughly equal in magnitude based on conservation of sand. This premise is the baseline assumption in most sediment budget models (Bruun, 1996 and Mehta, 1996).

Sediment transport around inlets result from the combined effects of wave energy, tidal prism, sediment supply, and ebb-shoal interactions (Dean and Walton, 1975). The example given in Figure 1 is consistent with stabilized inlet configurations along the U.S. mid-Atlantic coast. The most conspicuous and troublesome aspect of inlet stabilization is the propagation of the downdrift arc of erosion caused by sediment starvation (Figure 1). Regions with relatively high longshore transport volumes will experience greater downdrift erosion (Dean and Walton, 1975). When an inlet channel is established and later stabilized the flow of water to the bay on the flood tide and to the ocean on the ebb tide is increased. This leads to an increase in the ability of the channel to flush sediment to the inner bay system or outer shoal system, aggravating sediment starvation downdrift (Walton, 1978). Thus, the updrift jetty and inlet channel act as barriers to littoral sediments. The sediments flushed inland into the flood delta cannot work its way back into the system, hence these shoals are net sinks (Walton, 1978).

Figure 1. Shoreline changes adjacent to Ocean City Inlet, Maryland. The arc of erosion is evident in the shoreline change map and has expanded downdrift to a length of 16.1 kilometers by 1995 (Galgano, 1998).

Ebb shoals have been shown to include substantial volumes of littoral materials (e.g., 6 million m^3 at Ocean City Inlet) that can be re-introduced into the sediment transport system if favorable conditions can be established (Walton, 1978 and Leatherman et al., 1987). However, this is difficult in regions like the U.S. mid-Atlantic coast where moderate wave conditions persist, the littoral drift is substantial, and the ebb shoal is deeper than 5 meters below MSL. Under these conditions, it is not likely that wave processes will be effective in establishing sufficient natural sediment bypassing after jetty construction (Dean and Walton 1975 and Bruun, 1986).

Galgano (1998) demonstrated that 70% of the shorelines in four major coastal compartments (Long Island, New York; New Jersey; Delmarva; and South Carolina) are undergoing significant shoreline changes induced by tidal inlets. For example, two thirds of Delaware's Atlantic beaches are influenced by Indian River Inlet (Galgano, 2009). In Florida, 85% of the beach erosion has been attributed to inlet-induced processes (Dean, 1996). However, our quantitative knowledge of the temporal and spatial behavior of the arc of erosion remains poorly understood (Mehta, 1996). Early researchers viewed inlets fundamentally as a problem of open-channel flow (Leatherman 1991). O'Brien (1931 and 1969) changed this conception by relating tidal prism and sediment transport considerations into tidal inlet models. Consequently, the sediment budget method became a universal approach for quantifying sources and sinks for a given control volume to predict changes in shoreline behavior adjacent to tidal inlets. This technique is appealing because the problem is reduced to an understanding of the interruption and loss of sediment making the prediction of the downdrift impact relatively straightforward (Bruun, 1986). However, this methodology can be limited because gross sediment budgets are not easy to determine and there is a universal lack of sedimentary data at most tidal inlets (Mehta, 1996). Further, the fundamental assumption that updrift accretion equals downdrift erosion appears to be flawed (Bruun, 1996 and Galgano, 1998).

In view of the limitations of available sedimentary data, several methods have been developed to demonstrate inlet-induced shoreline modifications. Douglas and Dean (1989) used the sign change from erosion to accretion in shoreline rate-of-change values to indicate the spatial extent of the arc of erosion. Work and Dean (1990), Dean and Work (1993), and Douglas and Walther (1994) applied an odd/even numerical model to assess the impact of stabilized inlets in Florida. Fenster and Dolan (1996) employed a model that measured the cessation of abrupt changes in shoreline change rates to determine the extent of tidal inlet influence in microtidal and mesotidal conditions. These studies generally ignored the effect of time on the propagation of shoreline changes. Leatherman et al. (1987) employed a sediment budget analysis using long-term shoreline change data in a case study of Ocean City Inlet, Maryland. The authors showed that the arc of erosion extended 10 kilometers downdrift, but was growing through time. It was recognized that the arc of erosion is a mobile feature that is not terminated downdrift in a temporal sense, and suggested that beach planform is similar to a logarithmic-spiral shape.

The logarithmic-spiral or crenulated arc of erosion has been the basis of many downdrift erosion models. Crenulated landforms are common in regions downdrift of natural headlands (Bascom, 1964). Yasso (1965) was the first to fit the planform of embayments to logarithmic spirals. Silvester (1976) presented an empirical method to predict the equilibrium or final planform of crenulated-shaped bays between two headlands. Everts (1983) adapted an extension of this method to allow for the time-dependent evolution of an arc of erosion adjacent to a littoral barrier using Cape May, New Jersey and Ocean City Inlet, Maryland as examples. The basic premise behind this method is that the crenulated arc of erosion will terminate at some point downdrift when it achieves equilibrium with wave and sediment conditions (Everts, 1983). Antithetically, Plenard-Considere (1956) suggested that the effects of the arc of erosion continue to expand downdrift infinitely. Bodge (1993) and Bruun (1996) presented examples supporting the theory that the arc of erosion expands downdrift as a function of time with no observable termination as suggested by Leatherman et al. (1987). Bruun (1996) used examples from 17 tidal inlets to illustrate that there is a short component to the arc of erosion that corresponds to the crenulated planform, but there is also a long distance segment that is driven by sediment starvation and wave action. The entire feature is mobile as suggested by Plenard-Considere (1956) and has a characteristic "s" shape (Figure 2).

METHODOLOGY

Long-term shoreline change data were examined to ascertain the temporal and spatial behavior of beaches adjacent to stabilized microtidal inlets. Analysis focused on: (1) determining the maximum spatial extent and temporal behavior of inlet-induced changes; and (2) delineating the arc of erosion and its rate of growth over time. Shoreline change maps used in this analysis were compiled from NOS T Sheets, aerial photographs, and GPS surveys using procedures defined in Leatherman (1984) and Galgano (1998).

Historical trend analyses are based on examination and comparison of shoreline behavior before and after inlet opening and stabilization. Such analyses are based on the assumption that shorelines modified by inlets will vary from pre-existing background trends, but will return to the long-term trend at a point beyond the influence of the inlet (Figure 3). The historical trend is established by a linear regression rate-of-change calculation derived from shoreline positions prior to inlet opening and/or stabilization using a 50-meter spatial sampling interval. Shoreline change rates are measured between discrete time intervals after inlet opening and stabilization to determine the magnitude of modifications. The differences between the historical background rates (i.e., the shoreline trend prior to inlet opening and stabilization) and post-inlet shoreline change rates are used to define the "convergence point" or point at which inlet influence terminates.

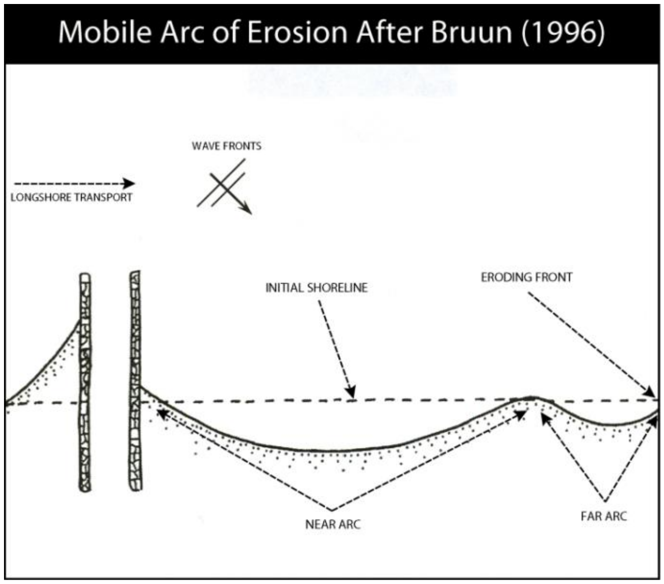

Figure 2. Idealized diagram of the arc of erosion configuration described by Bruun (1996). The arc of erosion is mobile and the eroding front expands downdrift over time. There are two parts to this configuration: a short distance arc caused by the shadow of the jetty; and a long distance arc caused by sediment starvation. The general configuration of this arc of erosion is a double "s" shape (Bruun, 1996).

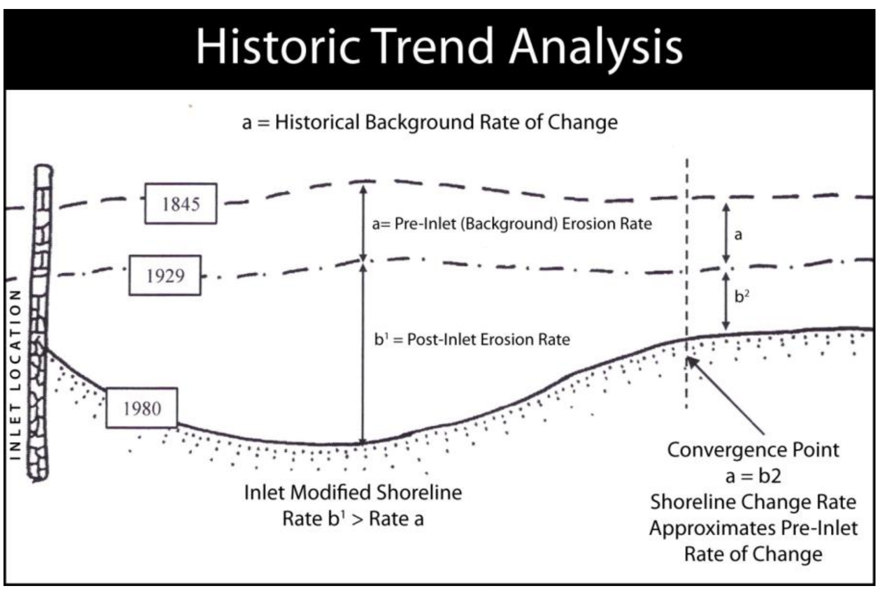

Figure 3. Historic trend analysis of inlet-induced shoreline behavior. A pre-inlet historic trend is represented by rate "a." The post-inlet shoreline trend is represented by rate "b." The point at which rate "b" equals rate "a" indicates the distance downdrift where inlet influence ceases. This point is determined by subtracting rate "a" from rate "b."

This methodology incorporates the following steps: (1) estimating the historical background trend (pre-inlet shoreline change rate) and post-inlet shoreline change rates at 50-meter intervals downdrift from the inlet. Shoreline change rates were estimated along each transect using a linear regression model; and (2) differences between pre- and post-inlet data for discrete time intervals are plotted to determine the distance from the inlet at which the post-inlet trend reverts to pre-inlet shoreline behavior (Figure 3). This point is designated where the differences between the rates are zero and post-inlet shoreline change rates approximate the historic trend. This is similar to the odd/even methodology employed by Work and Dean (1990), Dean and Work (1993), and Douglas and Walther

(1994). However, this methodology differs in that the data are more robust in a spatial and temporal sense, the differences in rates-of-change are decomposed between discrete time intervals, and it does not assume that the trends are symmetrical around the inlet. This methodology was applied to six stabilized microtidal inlets along the U.S. East Coast (i.e., Shinnecock and Moriches Inlets, NY; Manasquan and Cape May Inlets, NJ; Indian River Inlet, DE, and Ocean City Inlet, MD); however, this paper will focus on Moriches Inlets in New York.

RESULTS

Shoreline change maps show that the stabilization of tidal inlets initiates considerable changes in shoreline behavior for many kilometers downdrift. An arc of erosion is a clearly definable mode of behavior that is consistent between inlets (e.g., Figure 1). Moriches Inlet, New York is presented here as representative example. The arc of erosion varies in length based on longshore sediment transport volume and time; and this mobile feature elongates downdrift at a non-linear rate and exhibits a characteristic "s" shape as proposed by Bruun (1996).

Moriches Inlet (Figure 4) is located between Fire Island and Westhampton Beach on the South Shore of Long Island. Moriches Inlet opened by bayside breaching during a 1933 northeaster (Leatherman and Allen, 1986).

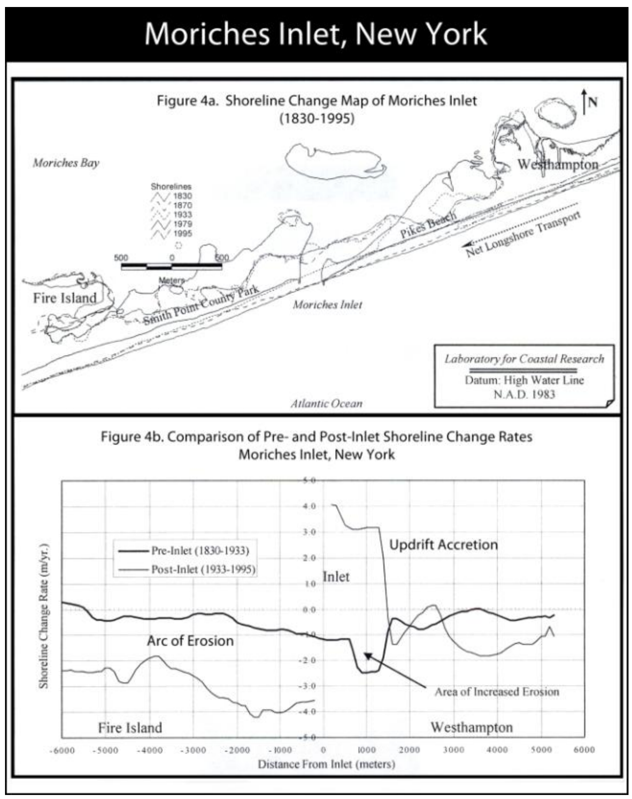

Figure 4. Long-term shoreline behavior at Moriches Inlet, New York. Long-term shoreline movements between 1830 and 1995 are illustrated in the shoreline change map (Figure 4a). The map shows the modification of the up- and downdrift shorelines, which is evident in the pre- and post-inlet shoreline change data (Figure 4b). The comparison of the shoreline change rates reveals the accretion and erosion generated by the inlet jetties. The data in Figure 4b suggest that there is an area of elevated erosion in the pre-inlet shoreline change data at the site of the breach.

Numerous attempts were made to stabilize the inlet between 1938 and 1950, and by 1951 the inlet closed. The inlet was reopened and permanently stabilized by the U.S. Army Corps of Engineers in 1953. The inlet was stabilized with two 432-meter long jetties to maintain a 241-meter wide channel (Smith, 1988). The net littoral transport is to the west, and the sediment volume has been estimated to be 161,300 m^3/yr (Leatherman and Allen, 1986). The impact of these jetties on adjacent shoreline has been particularly problematic. Shoreline changes between 1830 and 1995 at Moriches Inlet were examined and are depicted on the shoreline change map (Figure 4a). The shoreline change map illustrates the pre- and post-stabilization shoreline changes up- and downdrift from the inlet. There is a distinct offset in the shoreline configuration caused by accretion beside the updrift jetty and the downdrift arc of erosion. The historic background trend and post-inlet shoreline changes rates are given in Figure 4b. The data indicate that downdrift from the inlet, erosion rates exceed -4.0 m/yr within the arc of erosion, and in general, erosion rates have increased by a factor of two. Figure 4b also shows that there is an area of increased erosion at the site of the inlet breach distinguishable in the pre-inlet shoreline change rates. The historic background trend near the inlet is slightly erosional (-0.02 m/yr); however, shoreline change rates elevate to -2.5 m/yr at the site of the breach suggesting a precursor to inlet breaching may be detectable in certain situations.

The spatial and temporal behavior of the arc of erosion is illustrated in Figure 5. Three arcs of erosion are depicted and they portray a mobile feature that reached a maximum length of 18.6 kilometers by 1995. The data also show that as the arc of erosion extends downdrift, rates of erosion within the arc decrease over time (Figure 5a). The rate of growth of the arc of erosion is shown in Figure 5b. These data suggest that the rate of growth is accelerating over time based on a limited number of data points and exhibits non-linear behavior.

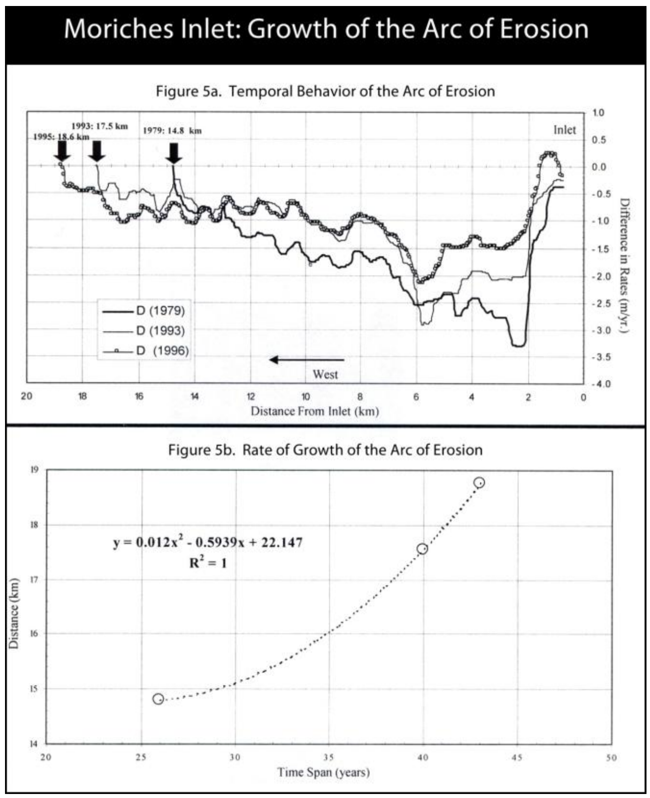

Figure 5. Temporal behavior of the arc of erosion downdrift from Moriches Inlet. The data indicate that the arc of erosion is mobile and expanded to a length of 18.6 kilometers by 1995 (Figure 5a). The data suggest that the arc of erosion expanded at a non-linear rate (Figure 5b).

DISCUSSION

These results suggest that the beach downdrift from a stabilized inlet exhibits a unique mode of behavior. First, the arc of erosion is non-stationary and does not replicate a crenulated or logarithmic-spiral planform as many models assume, and its spatial behavior is time dependent—it expands downdrift at a non-linear rate. The spatial magnitude of the arc of erosion is site specific, with maximum lengths ranging from 18.6 kilometers at Moriches Inlet, New York to 5.8 kilometers at Cape May Inlet, New Jersey (Figure 6). Although the results show that inlet behavior is site specific in terms of downdrift extent, the arcs of erosion demonstrate the same mode of behavior.

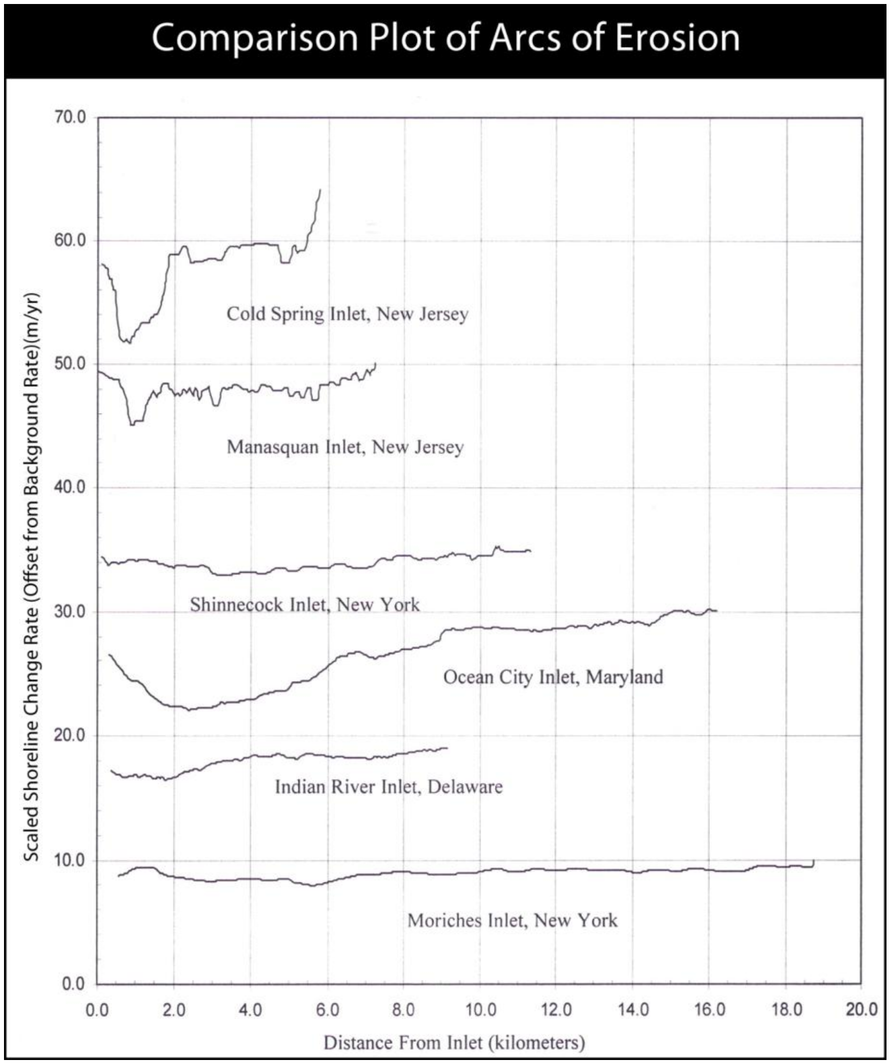

Figure 6. Shoreline change data for each fully developed arc of erosion. The arcs of erosion are plotted to scale, and it is difficult to observe and compare their configuration in this format.

Although the literature often treats the arc of erosion as a static feature (e.g., Work and Dean, 1990; Douglas and Walther, 1994; and Fenster and Dolan, 1996), the data given in Figure 5 indicate that the arc of erosion is a mobile feature and its maximum length is location and time dependent. Furthermore, the arc of erosion expands at a non-linear rate, although there are variations between inlets. The point of maximum erosion, or the deepest portion of the arc, is mobile and generally progresses downdrift at a non-linear rate. As the point of maximum erosion moves downdrift, the magnitude of change at this point decreases over time.

The arc of erosion represents a mode of shoreline behavior with a characteristic time-dependent evolution (e.g., using Ocean City Inlet, Maryland as a representative example; Figure 7). The initial arc is short and causes a very deep cut into the downdrift shoreline characterized by elevated erosion rates along a small spatial area. The shape of this modified beach is roughly parabolic in planform (Time 1, Figure 7). Over time, the arc lengthens (Time 2), and the shape of the area imitates a crenulated planform. The planform illustrated for Time 2 shows the lengthened arc of erosion with decelerating erosion rates. The final form observed (Time 3, Figure 7) is an “s” shape. This planform conforms to the shape postulated by Bruun (1996) and does not replicate a logarithmic spiral. The data for Time 3 (Figure 7) illustrate the attenuation of erosion rates within the arc. In this example, rates at the maximum point of erosion are reduced by a factor of two between Time 1 and Time 3. Furthermore, at the distal end of the Time 3 arc of erosion, rates are only slightly higher than the background rate (Figure 7).

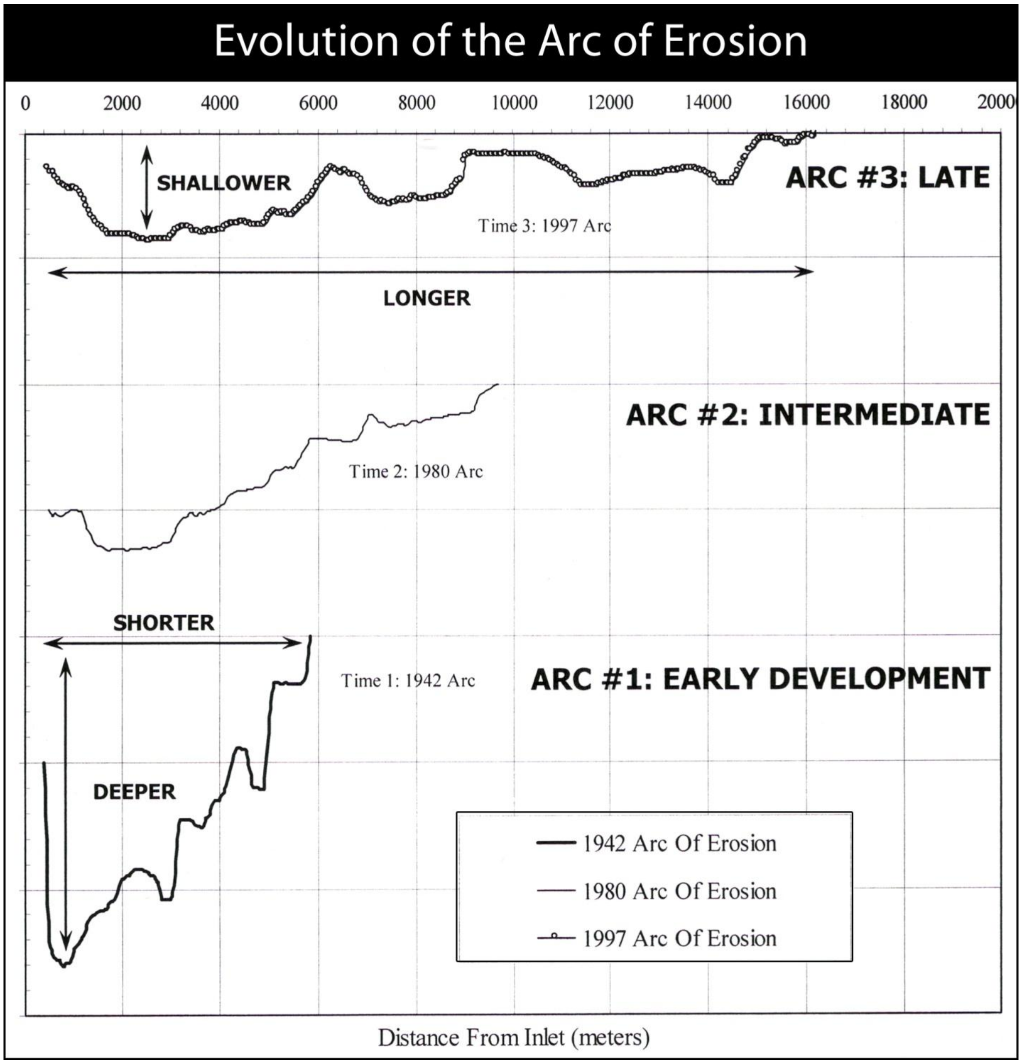

Figure 7. Evolution of an arc of erosion observed using shoreline change data for discrete time intervals. The initial configuration of the arc of erosion is a narrow, deep cut into the downdrift shoreline, and the planform is roughly parabolic (Time 1). As the arc evolves it becomes increasingly longer, but the rates of erosion are increasingly attenuated (Time 2 and 3).

The "s" configuration of the arc of erosion is observed in each of the inlets studied. In order to more clearly view this planform, shoreline change data for Indian River Inlet, Delaware were normalized for length and smoothed by a polynomial function (Figure 8). In this form, the "s" configuration of the fully developed arc of erosion is manifest and composed of a short arc, zero point, and long arc with an eroding front (Bruun, 1996).

The importance of this mode of shoreline behavior is its temporal expansion and relative magnitude of erosion along its length. Clearly, erosion rates within the short length of the arc remain relatively high as depicted in Figure 7. With the passage of time, as the eroding front of the arc expands downdrift, more shoreline is adversely affected by an increase in erosion rates. The zero point may falsely indicate the termination of the arc of erosion because rates-of-change are attenuated and may even become slightly accretional (Bruun, 1996). The presence of the zero point may be responsible for the varied results in the literature because researchers may have wrongly assumed that this point terminated the arc of erosion.

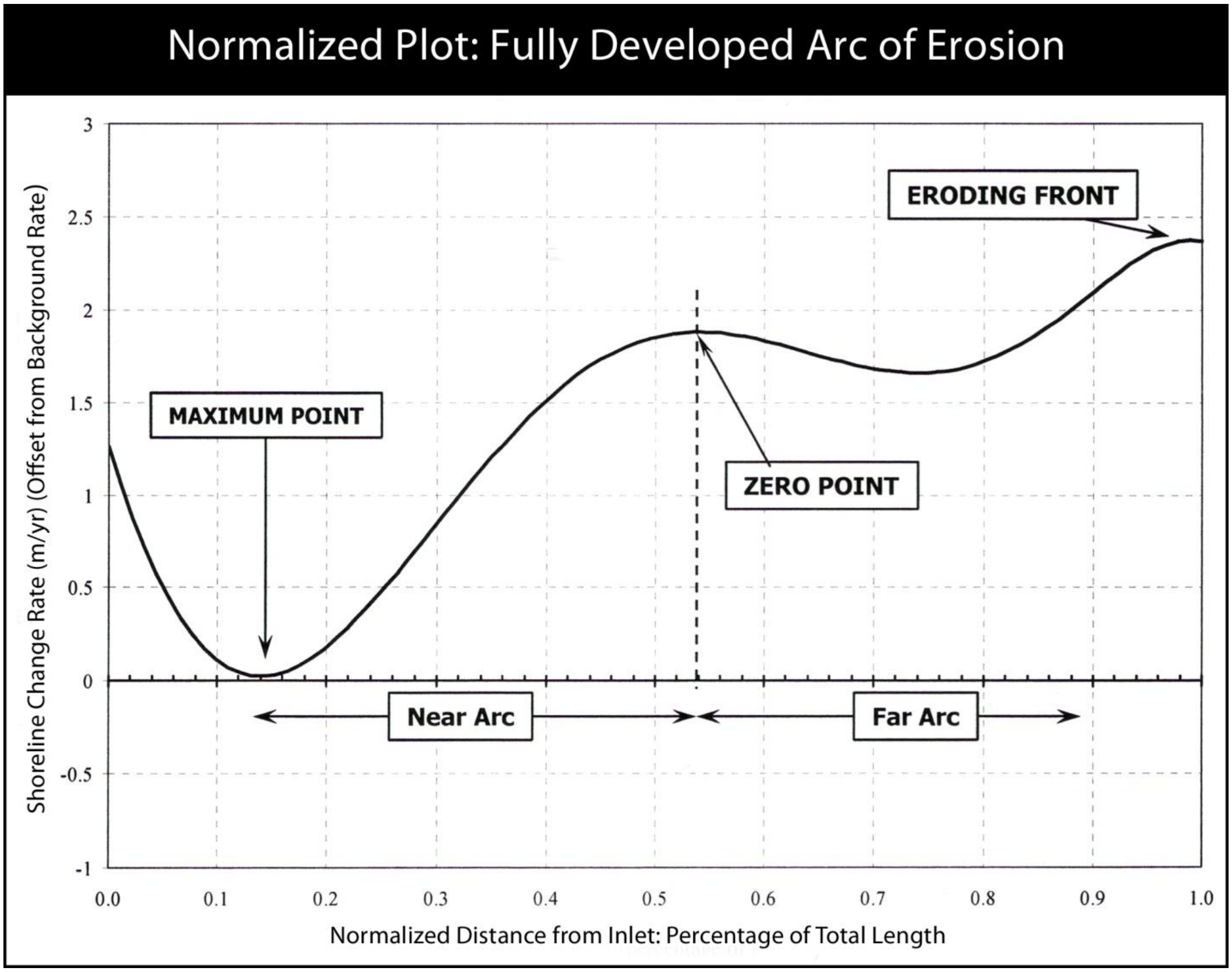

Figure 8. Normalized plot of shoreline change data for the Indian River Inlet arc of erosion. The data illustrate the double "s" configuration of the arc of erosion. This feature is composed of a short arc, long arc, zero point and eroding front (Bruun, 1996).

A model modified from Bruun (1996) explaining the propagation of the "s" arc of erosion is shown in Figure 9. The short distance arc is a geomorphologic feature caused by the "shadow" of the jetty. The jetty completely or nearly completely blocks littoral sediment, inducing the longshore current to "mine" sand from the downdrift beach to achieve its sediment load. This fosters the deep erosional arc characterized by elevated erosion rates. Wave refraction generates a sediment transport reversal accounting for the customary accretion at the jetty itself (Figure 9). The shore profile responds to this situation by flattening and reorienting in response to the change in wave energy and sediment supply (Dean, 1996).

The long distance arc is a response type brought about by a sediment deficit. The zero point creates an angle to the original shoreline (α) that in effect reduces the angle of incident waves by 1-4^{o} (Bruun, 1996). The wave fronts turn because of refraction as they traverse the flattened and reoriented contours within the short distance arc. This brings about a change in wave height (H_{sb}) and breaker angle (θ_b) as waves propagate across the flatter profile and strike the zero point (Bruun, 1996 and Dean, 1996). A change in longshore sediment volume (ΔQ_b) then occurs as compared to the pre-inlet condition (Figure 9). The net effect is that the quantity of material moving downdrift from the zero point is reduced, which must be replaced by erosion downdrift. The net effect is a long distance arc and propagation of the eroding front (Dean and Walton, 1975; Dean, 1996; and Bruun, 1996).

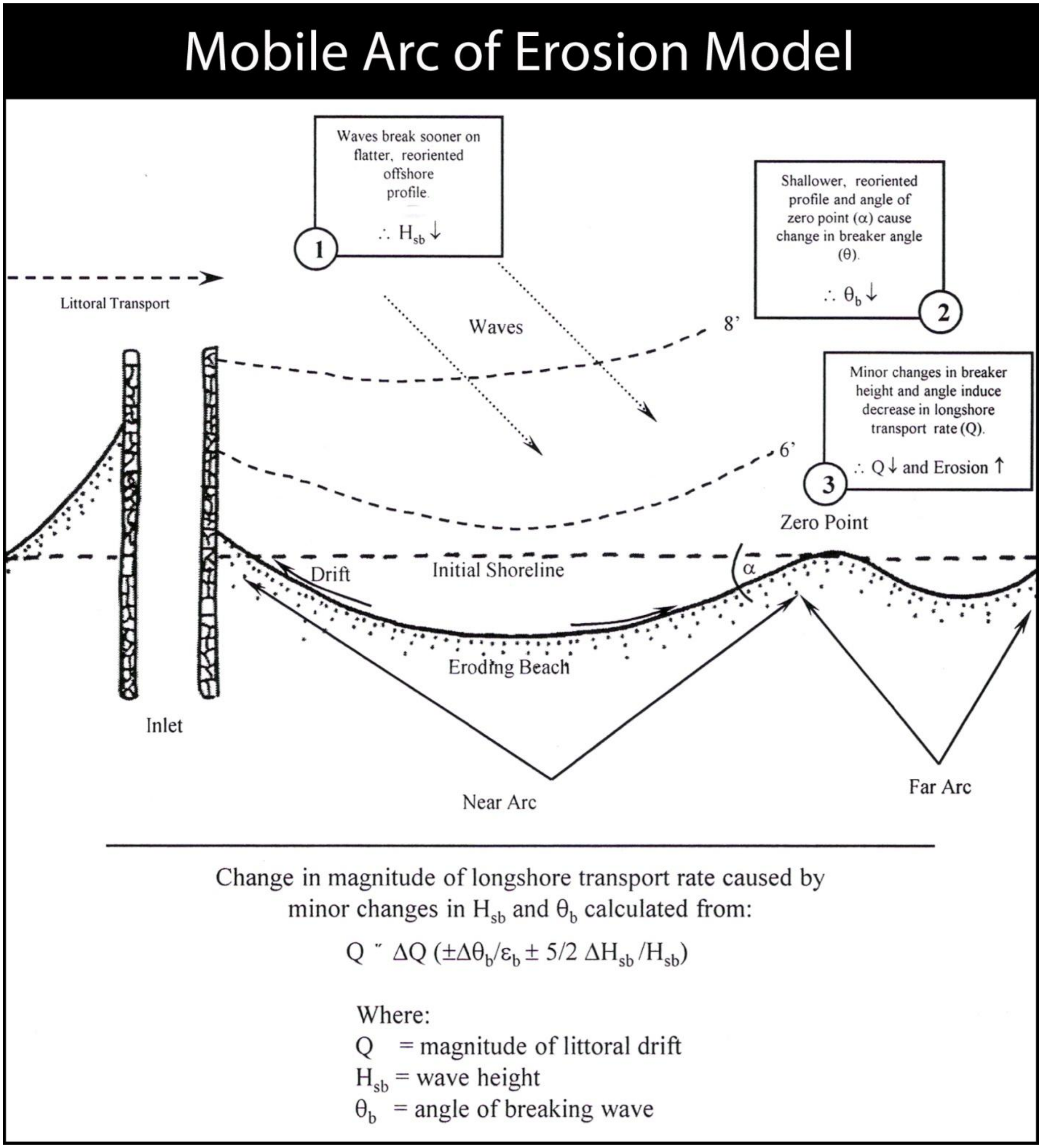

Figure 9. Proposed model for the double "s" arc of erosion configuration modified from Bruun (1996). The short distance arc is a geomorphic feature caused by the shadow effect of the jetty. Wave refraction causes accretion against the jetty. The long distance arc is generated by a sediment deficit. The shore profile along the downdrift beach is flatter and reoriented (Dean, 1996). The changed profile brings about subtle changes in breaker height (H_{sb}) and breaker angle (θ_b) that strike the zero point at a reduced angle. Minor changes in breaker height and angle induce a decrease in the longshore sediment transport volume beyond the zero point. This initiates the eroding front and development of the long distance arc. The zero point can theoretically continue to move and cause the arc of erosion to expand downdrift infinitely (Dean, 1996).

The modification of longshore sediment transport volume induced by changes in breaker height and angle can be explained by the longshore transport uncertainty equation (United States Army Core of Engineers, 1984). Bruun (1996) suggested using the first two terms of a Taylor's series expansion of the uncertainty equation to estimate the change in longshore sediment transport volume (Q) from:

$$\Delta Q \sim Q\,(\pm\, \Delta\theta_b/\varepsilon_b \pm 5/2\ \Delta H_{sb}/H_{sb}) \quad (1)$$

Hence, relatively small changes in wave height (H_{sb}) and angle (θ_b) can have a considerable influence on littoral drift volume and ultimately downdrift erosion. The assumption behind this model is that the inlet is in a region of moderate wave energy with relatively high longshore transport rates (Dean and Walton, 1975, Bruun, 1996). Theoretically, modification of the downdrift shoreline extends infinitely as proposed by Plenard-Considere (1956). Dean and Walton (1975), Walton (1978), Bruun (1986 and 1996), and Dean (1996) demonstrated that in moderate wave energy conditions, the most important factor driving the modification of beaches near tidal inlets is the volume of littoral sediment.

CONCLUSIONS

The arc of erosion adjacent to stabilized inlets exhibits a consistent and definable mode of shoreline behavior. The modification of shorelines by tidal inlets demonstrated by this research contradicts some published models and supports the one presented by Bruun (1996). The results suggest that downdrift shoreline changes are seldom of equal length, which is a baseline assumption upon which most sediment budget models depend.

The arc of erosion caused by a stabilized tidal inlet is mobile and its spatial behavior is time dependent and expands at a non-linear rate. The initial arc of erosion is short with very high rates of erosion. As the arc of erosion expands, the erosion rates within the arc are attenuated, but the area of change remains constant. The final configuration of the arc of erosion is a characteristic "s" shape.

The significance of this mode of shoreline behavior is in its temporal expansion and the relative magnitude of erosion along its length. With the passage of time, as the eroding front of the arc of erosion expands, more and more beach is adversely affected inlet-induced erosion. The zero point may falsely indicate the termination of the arc of erosion because rates-of-change are attenuated and may even become slightly accretional for a period.

The model explaining the development and evolution of the double "s" arc of erosion is straightforward and explained by widely accepted geomorphic principles. The short distance arc is a geomorphologic feature caused by the "shadow" of the jetty. The long distance arc is a response type brought about by a sediment deficit. Relatively small changes in wave height (H_{sb}) and angle (θ_b) have an important effect on littoral drift volume and ultimately downdrift erosion. The net effect is that the quantity of material moving downdrift is reduced, which must be replaced by erosion downdrift; this results in the long distance arc and downdrift propagation of the eroding front. Theoretically, shoreline modification extends downdrift indefinitely.

REFERENCES

Anders, F.J., Reed, D.W., and Meisburger, E.P., 1990. Shoreline Movements, Report 2, Tybee Island, Georgia to Cape Fear, North Carolina, 1851-1983. *Technical Report CERC-83-1*, U.S. Army Corps of Engineers Waterways Experimental Station, Vicksburg, Mississippi, 152 pp.

Bascom, W., 1964. *Waves and Beaches*. New York, N.Y.: Doubleday, Academic Press, 366 pp.

Bodge, K.R., 1993. Gross Transport Effects and Sand Management Strategy at Inlets. *Journal of Coastal Research*, 18: 111-124.

Bruun, P., 1986. Morphological and Navigational Aspects of Tidal Inlets on Littoral Shores. *Journal of Coastal Research*, 2 (2): 123-145.

Bruun, P., 1996. The Development of Downdrift Erosion. *Journal of Coastal Research*, 11 (4): 1242-1257.

Dean, R.G., 1991. Impacts of Global Change: Engineering Solutions. In *Our Changing Planet: Joining Forces for a Better Environment*. Proceedings of Symposium on the Commemoration of the 20th Anniversary of the Graduate College of Marine Studies, University of Delaware, Newark, Delaware, 13-17.

Dean, R.G., 1996. Interaction of Littoral Barriers and Adjacent Beaches: Effects of Profile Shape and Shoreline Change. *Journal of Coastal Research*, 23: 103-112.

Dean, R.G., and Walton, T.L., 1975. Sediment Transport Processes in the Vicinity of Inlets with Special Reference to Sand Trapping. *Estuarine Research, Volume 2,* New York, New York: Academic Press, pp. 125-149.

Dean, R.G., and Work, P.A., 1993. Interaction of Navigation Entrances with Adjacent Shorelines. *Journal of Coastal Research,* 18: 91-110.

Douglas, B.D., and Dean, R.G., 1989. Shoreline Response to Tidal Inlets. *Proc. National Beach Preservation Conference,* Florida Shore and Beach Preservation Association, Tampa, Florida: 185-198.

Douglas, B.D., and Walther, M.P., 1994. Odd/Even Analysis Modified to Account for Sediment Losses to Ebb and Flood Shoals. *Proceedings, National Beach Preservation Conference:* 354-373.

Everts, C.H., 1983. Shoreline Change Downdrift of a Littoral Barrier. *Proceedings, Coastal Structures '83,* American Society of Civil Engineers: 673-689.

Fenster, M., and Dolan, R., 1996. Assessing the Impact of Tidal Inlets on Adjacent Barrier Island Shorelines. *Journal of Coastal Research,* 12 (1): 294-310.

Finkl, C.W., 1996. Potential Impacts of a Federal Policy Promoting "No New Beach Replenishment Activities" on U.S. Shorelines: Iterations from SE Florida. *Proceedings, 9th National Congress on Beach Preservation Technology,* St. Petersburg, Florida: 1-16.

FitzGerald, D.M., Fico, C., and Hayes, M.O., 1979. Effects of the Charleston Harbor, S.C. Jetty Construction on Local Accretion and Erosion. *Proceedings, Coastal Structures, 1979,* American Society of Civil Engineers, Alexandria, Virginia: 641-644.

FitzGerald, D.M., 1996. Geomorphic Variability and Morphologic and Sedimentary Controls on Tidal Inlets. *Journal of Coastal Research*, 23: 47-71.

FitzGerald, D.M., Hubbard, D.K., and Nummendal, D., 1978. Shoreline Changes Associated with Tidal Inlets Along the South Carolina Coast. *Proceedings, Coastal Zone 1978.* American Society of Civil Engineers: 1973-1994.

Galgano, F.A., 1998. Geomorphic Analysis of Modes of Shoreline Behavior and the Influence of Tidal Inlets on Coastal Configuration, U.S. East Coast. Ph.D. Dissertation, University of Maryland, College Park, MD.

Galgano, F.A., 2008. Types and Causes of Beach Erosion Anomaly Areas in the U.S. East Coast Barrier Island System: Stabilized Tidal Inlets. *Middle States Geographer,* 40: 158-170.

Galgano, F.A., 2009. Shoreline Behavior Along the Atlantic Coast of Delaware. *Middle States Geographer*, 41: 74-81.

Hayes, M.O., 1975. Morphology of Sand Accumulation in Estuaries. *Proceedings, 2nd International Estuarine Research Federation Conference,* Myrtle Beach, SC: 3-22.

Hayes, M.O., 1979. Barrier Island Morphology As a Function of Tidal and Wave Regime. In *Barrier Islands*, ed. Leatherman, S.P., New York, NY: Academic Press, pp. 1-27.

Hubbard, D.K., Barwis, J.H., Lesense, F., Stephead, M.F., and Hayes, M.O., 1977. Beach Erosion Inventory of Henry, Georgetown and Beaufort Counties, South Carolina. *Technical Report No. 8, SC-S5-77-8.* South Carolina Sea Grant, University of South Carolina, Columbia, S.C., 65 pp.

Inman, D.L., and Nordstrom, C.E., 1978. On the Tectonic and Morphologic Classification of Coasts. *Journal of Geology*, 79: 1-21.

Komar, P.D., 1996. Tidal Inlet Processes and Morphology Related to the Transport of Sediments. *Journal of Coastal Research*, 23: 23-44.

Kraus, N.C., and Galgano, F.A., 2001. *Beach Erosion Hot Spots: Types, Causes, and Solutions.* ERDC/CHL CHETN-1144, Vicksburg, Mississippi: U.S. Army Corps of Engineers Waterways Experimental Station, Coastal Hydraulics Laboratory.

Leatherman, S.P., 1979. Migration of Assateague Island, Maryland by Inlet and Overwash Processes. *Geology*, 7: 104-107.

Leatherman, S.P., 1984. Shoreline Evolution of North Assateague Island, Maryland. *Shore and Beach*, 52: 3-10.

Leatherman, S.P., 1989. Role of Inlets in Geomorphic Evolution of the South Shore Barriers of Long Island, New York. *Environmental Management,* 13: 109-115.

Leatherman, S.P., 1991. Coasts and Beaches. In *The Heritage of Engineering Geology, The First Hundred Years, Geological Society of America Special Volume 3*, ed. Kiersch, G. A., Boulder, CO, pp. 183-200.

Leatherman, S.P., and Allen, J.R., 1986. Geomorphic Analysis of the South Shore of Long Island, New York. *National Parks Service Scientific Monograph*, 350 pp.

Leatherman, S.P., Dean, R.G., Everts, C.E., and Fulford, E., 1987. Shoreline and Sediment Budget Analysis of North Assateague Island, Maryland. *Proceedings, Coastal Sediments '87,* American Society of Civil Engineers, New York: 1460-1471.

Mann, D., 1993. A Note on Littoral Drift Budgets and Sand Management at Inlets. *Journal of Coastal Research*, 18: 301-308.

Mehta, A.J., 1996. A Perspective on Process Related Research Needs for Sandy Inlets. *Journal of Coastal Research*, 23: 3-21.

Nummendal, D., Oertel, G.F., Hubbard, D.K., and Hine, A.C., 1977. Tidal Inlet Variability - Cape Hatteras to Cape Canaveral. *Coastal Sediments 1977*, American Society of Civil Engineers, Charleston, SC: 543-562.

O'Brien, M.P., 1931. Estuary Tidal Prisms Related to Entrance Areas. *Civil Engineering*, 1: 738-739.

O'Brien, M.P., 1969. Equilibrium Flow Areas of Inlets on Sandy Coastlines. *Journal of Waterways and Harbors Division,* American Society of Civil Engineers: 43-52.

Oertel, G.F., 1985. The Barrier Island System. *Marine Geology*, 63: 1-18.

Oertel, G.F., and Kraft, J.C., 1994. New Jersey and Delmarva Barrier Islands. In *Geology of Holocene Barrier Island Systems*, ed. Davis. R. A., New York, NY: Springer-Verlag, pp. 207-232.

Pilkey, O.H., and Dixon, K.L., 1996. *The Corps and The Shore*. Covelo, California: Island Press.

Plenard-Considere, R., 1956. Predictions of Beach Planforms with Essai de Theorie de L'Evolution des Forms de Revage an Plage de Sable et de Galets. *4th Journal de l'Hydraulique Les Energies de les Mer*, Question III (1): 239-300.

Rice, T.E., and Leatherman, S.P., 1983. Barrier Island Dynamics: The Eastern Shore of Virginia. *Southeastern Geology*, 24 (3): 125-137.

Smith, E.R., 1988. Case Histories of Corps Breakwater and Jetty Structures, Report Number 5, North Atlantic Division. *CERC Technical Report REMR-CO-3*, U.S. Army Corps of Engineers Waterways Experimental Station, Vicksburg, Mississippi, 113 pp.

Silvester, R., 1976. Headland Defense of Coasts. *Proceedings, 15th Coastal Engineering Conference*, American Society of Civil Engineers: 1347-1364.

Unites States Army Corps of Engineers, 1984. *Shore Protection Manual (3 Volumes)*. Vicksburg, Mississippi: Waterways Experimental Station.

Walton, T.L., 1978. Coastal Erosion - Some Causes and Some Consequences. *Marine Technology Journal*, 12 (4): 28-33.

Work, P.A., and Dean, R.G., 1990. Even/Odd Analysis Of Shoreline Changes To Florida's Tidal Inlets. *Proceedings, 22nd International Coastal Engineering Conference*, American Society of Civil Engineers, 3: 2533-2535.

Yasso, W.E., 1965. Plan Geometry of Headland-Bay Beaches. *Journal of Geology*, 78: 702-714.