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# Rates and Processes of Marsh Shoreline Erosion in Rehoboth Bay, Delaware, U.S.A.

**Reed A. Schwimmer**

Department of Geological and Marine Sciences
Rider University
Lawrenceville, NJ 08648, U.S.A.

## ABSTRACT

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The marsh shoreline in western Rehoboth Bay, Delaware, is rapidly eroding due to wave attack. A 30–90 cm vertical scarp characterizes the shoreline and exposes the present-day rootmat and the underlying mud unit. Using an Electronic Total Station surveying instrument, marsh erosion rates were determined for six 10-meter shoreline sections. Over a three-year period, averaged erosion rates ranged from 14 cm/yr to 43 cm/yr.

Three styles of shoreline erosion were observed. (1) Cleft and neck formation—V-shaped notches are cut into an initially "straight" shoreline. Between adjacent clefts, marsh necks, up to three meters in length, occur creating an undulatory shoreline geometry. (2) Neck cut-off—marsh necks can be cut off from the marsh creating a small marsh "stack." (3) Undercutting with rootmat toppling—wave action erodes the lower mud unit faster than the overlying rootmat creating an overhang that eventually topples into the bay. At a decimeter scale, shoreline geometry is due to successive changes in erosional style. In contrast, the geometry of a fringing marsh shoreline over several hundred meters is likely controlled by antecedent topography and not by lateral variations in erosion rates.

Rates of erosion are correlated with wave power. The wave power potentially impinging on nine selected marsh shoreline sites was calculated using wind, bathymetric, and fetch data. Erosion rates for each site were plotted against estimated wave powers producing a regression equation that allows erosion rates to be predicted. As wave power increases, the rate of erosion increases.

**ADDITIONAL INDEX WORDS:** *Coastal retreat, recession, wave power.*

## INTRODUCTION

The areal distribution of salt marshes along the Delaware coast has not been static. As marshes evolve, they may either expand or diminish through time, a process which may directly affect the ecology and economy of a region. With estimates of global sea-level rise from about 0.2 m to over 1.0 m by the year 2100 (WIGLEY and RAPER, 1992; IPCC, 1995; TITUS and NARAYANAN, 1995; HOUGHTON, 1997), the salt marshes of Delaware and elsewhere will most certainly be affected. The loss of these ecologically important areas will have a lasting effect on not only the abundance and diversity of wildlife in the coastal environment but also on the condition and preservation of the Delaware bays and of the coastal communities.

Understanding the mechanisms of marsh shoreline erosion is therefore an important step in understanding how the coastal environments will change over time and how this will affect coastal communities. Previous studies of shoreline erosion in Delaware Bay (MAURMEYER, 1978; HARDISKY and KLEMAS, 1983; PHILLIPS, 1985, 1986a, 1986b; KRAFT *et al.,* 1992; FRENCH, 1990), along the Atlantic coastline of Delaware (GALGANO, 1989; KRAFT *et al.,* 1992), in Rehoboth Bay (SWISHER, 1982) and in Chesapeake Bay (ROSEN, 1977, 1980; SPOERI *et al.,* 1985; DALRYMPLE *et al.,* 1986; KEARNEY and STEVENSON, 1991; DOWNS *et al.,* 1994; WRAY *et al.,* 1995; WILCOCK *et al.,* 1998) have clearly demonstrated that shoreline erosion is a significant coastal process in the mid-Atlantic region. The majority of the shorelines that were examined, however, were sandy beaches or coastal bluffs and not marsh shorelines. Furthermore, erosion rates from these studies were estimated over relatively large distances using primarily aerial photographs and NOS Coastal Survey Maps (T-sheets) to map shoreline changes. Consequently, they do not provide details of how the shoreline is changing over relatively short distances such as a few meters.

In contrast, this study presents a detailed investigation of the rates and processes of wave erosion along a marsh shoreline. In addition, I propose that the rate of marsh shoreline erosion may be expressed as a function of wave power (energy flux). Consequently, wind, bathymetric, and fetch data are used to develop a predictive tool that can be used to estimate marsh shoreline erosion rates for different geographical settings. Wave attack is considered to be the dominant erosional process in the study area. Human activities that may affect the shoreline, such as channel dredging and bay maintenance projects did not occur in the study area during the time of the investigation. Clam digging was rarely observed in the area and never on or adjacent to the shoreline scarp. Boat wakes and ice formation, as discussed below, are not considered to be a significant factor in shoreline erosion in the area. In addition, longshore currents are unlikely to erode the shoreline because the highly irregular geometry of the shore-

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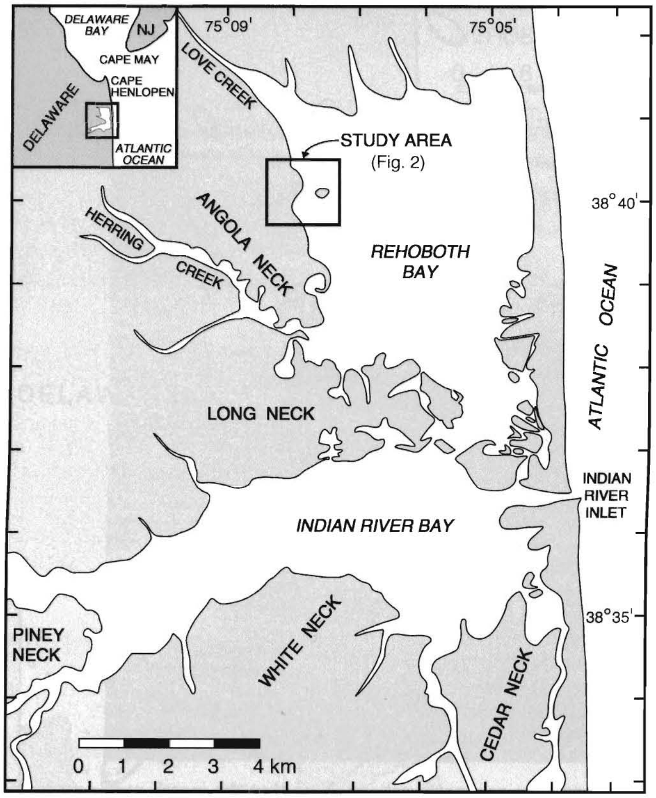

Figure 1. Map of the Delaware Inland Bays illustrating location of study area and other physical features.

line, where waves do not break before the shoreline but rather hit squarely against the scarp, inhibits strong, persistent currents from forming. Also, tidal action is not considered to be a significant erosional process as the tidal range is relatively small, approximately 30 cm, in Rehoboth Bay. Consequently, it is the relentless wind-driven waves that jar the sediment loose from the scarp and transports the debris away allowing the shoreline to retreat.

## STUDY AREA

Horse Island marsh and Marsh Island are located on the northwestern margin of Rehoboth Bay, Delaware (Figure 1). Five sites were chosen on Horse Island marsh and one on Marsh Island to survey the geometry of the shoreline (Figure 2). Horse Island marsh is bounded by two upland interfluves and is approximately 100 ha in size. Horse Island is a prominent upland hill or "island," surrounded by marsh, and presently is part of the shoreline forming a short stretch of sandy beach. Vegetation on the marsh consists of patches of *Spartina alterniflora*, *Spartina patens*, and *Distichlis spicata*. Marsh Island is located about 400 meters east of Horse Island marsh and is comprised solely of *Spartina alterniflora*. The island is approximately 0.9 ha in size and is presently the largest marsh island in Rehoboth Bay.

The shorelines of Horse Island marsh and of Marsh Island are characterized by a vertical scarp, with an approximate range of 30–90 cm in height (n = 100, mean = 70 cm, standard deviation = 13 cm), which exposes the rootmat and the underlying muds (Figure 3). The relatively unconsolidated muds erode faster than the overlying rootmat. As a result, the rootmat commonly forms an overhang (Figure 3). The length of the overhang ranges from 0 cm (vertical scarp) to about 50 cm (n = 50, mean = 24 cm, standard deviation = 13 cm). Sandy beaches occur where the eroding shoreline has intersected upland areas. This occurs at Horse Island and at the interfluve marking the southern extent of Horse Island marsh (Figure 2).

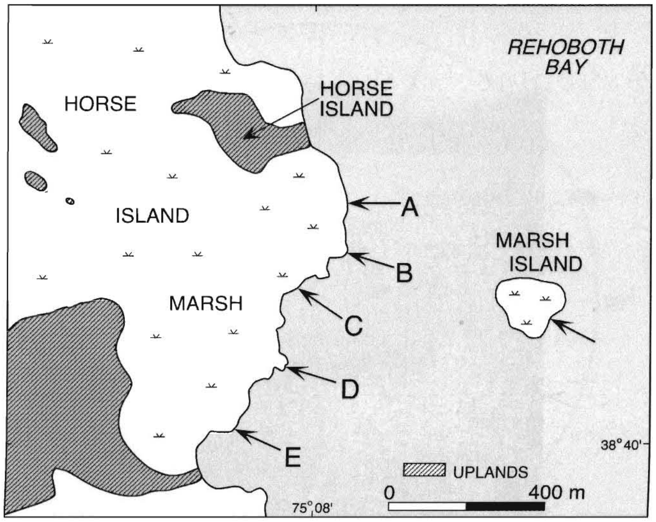

Figure 2. Location of the six survey sites along the Horse Island marsh and Marsh Island shorelines.

## METHODS

### Erosion Rates

A Topcon Electronic Total Station was used to survey the marsh shoreline at six sites within the study area. The prism rod was moved along the shoreline at intervals of approximately 10 to 30 cm depending on the geometry of the shoreline. Wooden posts were driven into the marsh, approximately 10 m from each other, at each survey site to serve as benchmarks. The benchmarks served as stable reference points that allowed subsequent surveys to be graphically overlain in order to discern a change in shoreline position. The results were then plotted and an average erosion rate was calculated by dividing the area between two consecutive shorelines by the average shoreline length. The rates were then normalized to a one-year time period. The geographic information system ARC/INFO was used to digitize the graphs and to estimate the eroded area and shoreline length.

### Error Estimate for Erosion Rates

Because shoreline positions were surveyed in the field, many of the potential errors that are associated with using historical maps and aerial photographs (see CROWELL *et al.*,

Figure 3. View of the Horse Island marsh shoreline illustrating the erosional scarp and the rootmat overhang. Note that the marsh neck next to the meter stick in the foreground is beginning to topple due to excessive undercutting.

1991), to document shoreline changes, do not apply. The precision of the total station coupled with a morphology that helps define the shoreline edge (a vertical marsh scarp versus a gently sloping beach face), provides a high degree of precision for locating shoreline positions. In spite of the high precision, surveying can realistically only cover relatively small stretches of shoreline and long-term historical changes cannot be documented. The sources of error for this method can be broken down into three areas.

### Electronic Total Station

Each survey was initiated and closed on the benchmarks (using a nail head in each wooden post to accurately relocate the prism rod). The coordinates of each benchmark typically varied less than 0.6 cm. Marsh surface instability for the tripod, changing temperatures throughout the day, and wind gusts moving the prism rod, most likely account for most of this error.

### Determining the Edge of the Shoreline

The lateral extent of the rootmat was used as the edge of the shoreline. Often the sediment between the roots at the edge of the eroded scarp was eroded leaving only a flimsy network of roots. This would make placing the prism rod difficult as there was no firm soil to set the rod. This area of exposed roots, if present, would likely give an error range of ± 2 cm.

### Digitizing Error

Assuming a 0.25 mm operator error and 0.25 mm digitizer error (CROWELL *et al.,* 1991), the total error range would be approximately ± 1.5 cm.

Overall, the calculated erosion rates have an estimated combined error range of ± 4 cm.

## Using Wave Power to Predict Erosion Rates

SUNAMURA (1992) summarized previous shoreline erosion studies that have used different parameters to associate with erosion rates, such as wave height, compressive strength of the shoreline material, beach elevation, and cliff height. ROSEN (1977, 1980) studied how variations in tidal range influence erosion rates as well as variations in shoreline type. WILCOCK *et al.* (1998) related erosion rates to variations in the ratio of wave pressure and cohesive strength of the shoreline material. As wave attack is the likely cause of shoreline erosion, wave power was the variable chosen to predict erosion rates in this study. Indeed, SPOERI *et al.* (1985) stated that wave power is likely the most important factor in predicting rates of shoreline erosion. HÉQUETTE and RUZ (1991) found that landward migration rates of barrier islands are well correlated with wave power. GELINAS and QUIGLEY (1973) and KAMPHUIS (1987) previously used wave power to correlate with erosion rates along the north shore of Lake Erie. These three previous studies, however, focused on beach shorelines and glacial till bluffs and not marsh shorelines.

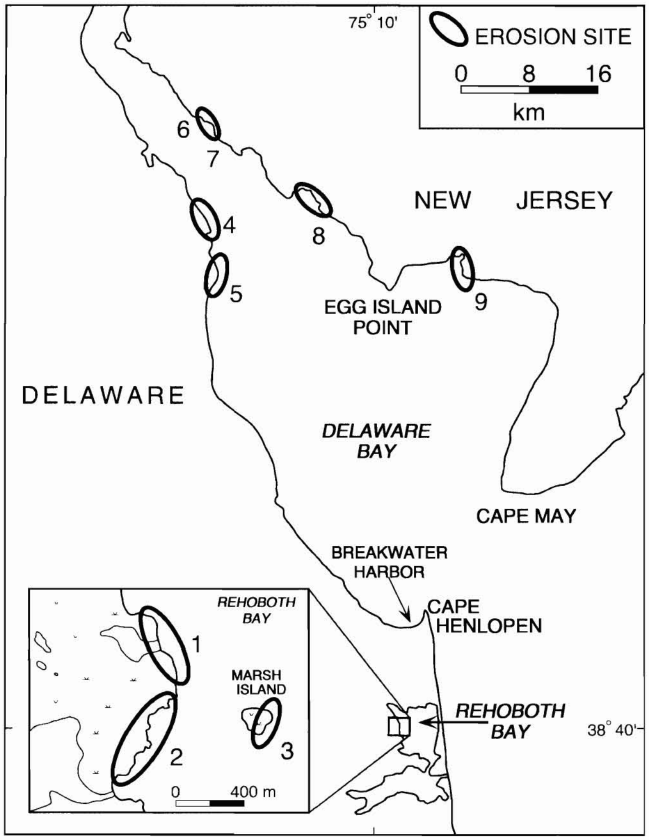

Figure 4. Location map of the nine stretches of shoreline used to relate wave power to erosion rate.

Nine stretches of shoreline were chosen from previous studies to test the relationship between wave power and erosion rates: three from the Horse Island marsh area (SWISHER, 1982), and six from Delaware Bay (MAURMEYER, 1978; PHILLIPS, 1985; FRENCH, 1990) (Figure 4). These stretches were selected because long-term erosion rate data were previously reported for each site. The Delaware Bay sites were chosen in order to include areas that have erosion rates that are significantly greater than the Rehoboth Bay sites. These six sites are believed to represent the only marsh shorelines in Delaware Bay that do not have a sandy beach along their bay margin and where long-term erosion rates have been estimated.

Estimated wave powers for each site were calculated from wind, bathymetric, and fetch data. The wind data are from Dover Air Force Base, Delaware, and consist of 87,636 hourly observations from the years 1969–1970 and 1973–1981 (Figure 5). The data are broken down by wind speed and wind direction and provide the frequency of occurrence for each combination. The reported wind speeds were corrected for instrument elevation and air-sea temperature difference, and were then converted to a wind-stress factor (U.S. ARMY, 1984). Nautical Charts of the Delaware Bay and Rehoboth Bay regions were used to calculate fetch and average water depth along each wind direction for each erosion site.

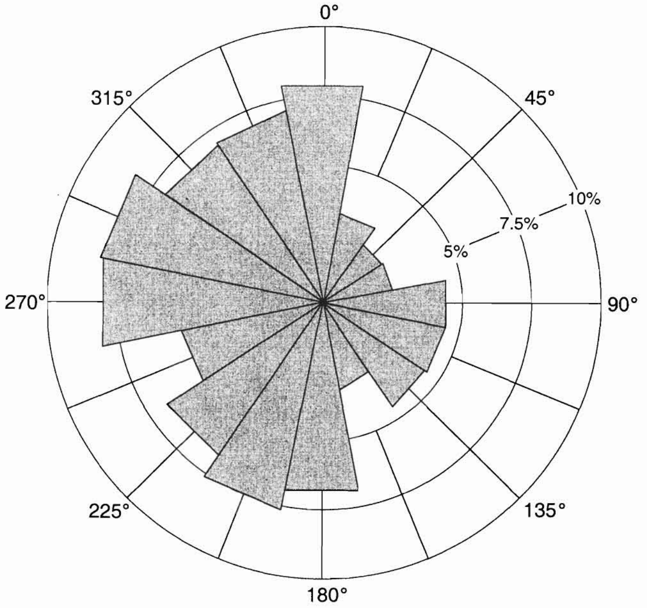

Figure 5. Rose diagram of the Dover Air Force Base wind data illustrating the frequency of winds from sixteen directions. Each wind direction includes data from all recorded wind speeds.

For each of the nine sites, wave powers were estimated for all wind speed and direction combinations that produce wind waves that potentially strike the shoreline. Each wave power was then normalized by the frequency of occurrence for each wind speed/direction combination. The cumulative wave power for each wind direction was then normalized by the angle between the wind direction and the shore parallel direction. The total estimated wave power for all wind directions was then plotted against the associated erosion rate for each site.

## RESULTS

### Erosion Rates

Five sites on Horse Island marsh and one site on Marsh Island were surveyed over a three-year period to determine yearly shoreline erosion rates. On a yearly basis, erosion rates ranged from 9 ± 4 cm/yr at site E to 52 ± 4 cm/yr at site D (Figure 6). The greatest average rate of erosion, over the entire three-year period, was 43 ± 4 cm/yr on Marsh Island while site C reveals the lowest average rate at 14 ± 4 cm/yr. Along the Horse Island marsh shoreline, a pattern is revealed for the erosion rates. Sites A, B, D, and E all have relatively high rates of erosion the first survey year, lower rates the second year, and then higher rates the third year (Figure 6). The overall average rate of erosion along the Horse Island marsh shoreline was 24 ± 4 cm/yr. The surveyed positions of the shorelines at each site are illustrated in Figure 7.

### Styles of Erosion

Figure 8 illustrates the three different shoreline responses observed during marsh erosion: (1) cleft and neck formation,

(2) neck cut-off, and (3) undercutting with rootmat toppling. Clefts are formed when erosion cuts a V-shaped notch into a relatively linear stretch of shoreline. When two clefts form adjacent to one another, the portion of the shoreline in between the clefts is referred to as a marsh neck. These necks were observed to reach three meters in length. Many stretches of shoreline in the study area exhibit an undulatory geometry of alternating clefts and necks (Figure 9). At sites A and the northern portion of site B, and to a lesser extent site C (Figure 7), clefts eroded at a faster rate than the adjacent necks. This changed the shoreline geometry from a relatively linear stretch to a series of alternating clefts and necks. At sites D, E, and the southern portion of site B, this cleft–neck–cleft geometry was already established at the start of the survey and was presumably sustained by a uniform erosion rate along the shoreline length. At sites A, B, D, and E, individual marsh necks eroded as much as two meters per year while sites A, B, and E show similar rates of erosion in the formation of clefts (Figure 7).

Marsh necks can also be eroded at their base faster than at the tip of the neck creating an hour-glass or pinched appearance (Figures 8a and 10). Eventually, erosion will separate the neck from the shoreline leaving only a small marsh stack (Figures 8a and 11). This isolated portion of marsh is then rapidly eroded away.

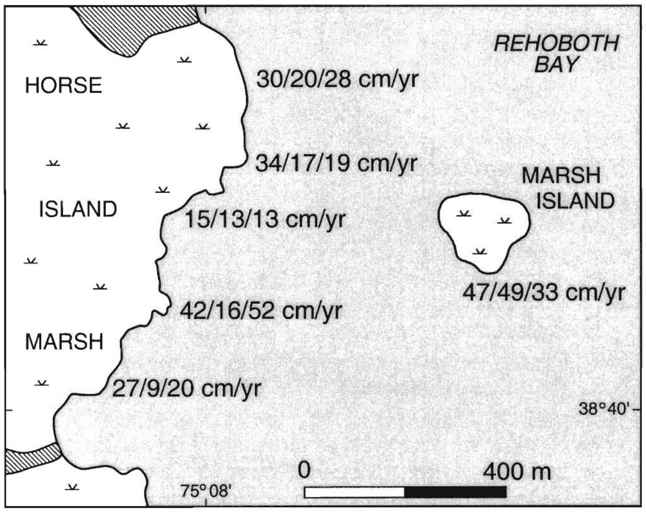

Figure 6. Averaged yearly erosion rates for the six surveyed sites over a three-year period. Estimated error for each erosion rate is ± 4 cm/yr.

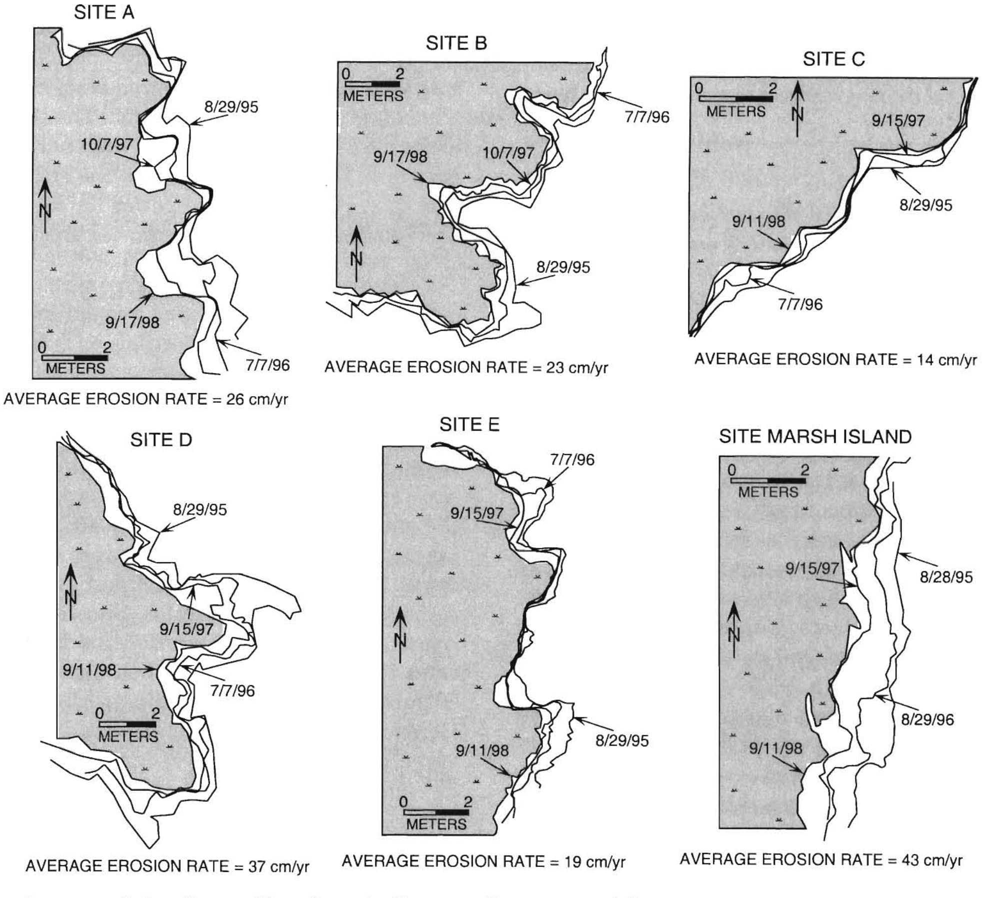

Figure 7. The change in surveyed shoreline positions for each site over a three-year period.

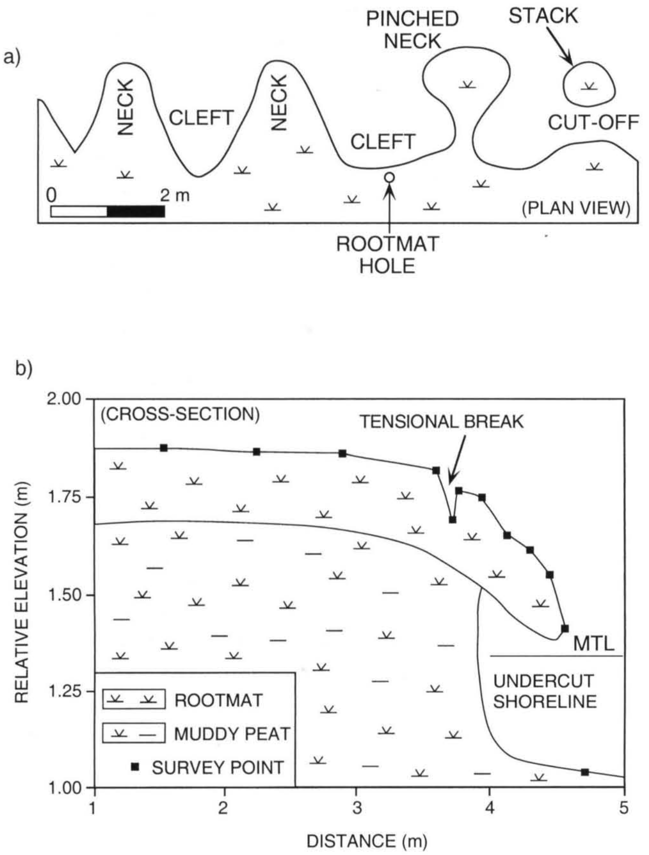

Figure 8. a) Cartoon sketch of the main features developed along a marsh shoreline due to wave erosion. b) Cross-section of a marsh overhang from surveyed data illustrating the relationship between the marsh rootmat and the underlying muds. MTL = estimated mean tide level.

Figure 9. An example of cleft and neck shoreline development. Note the meter stick for scale.

Due to the exposure of the shoreline scarp and the erodibility of the underlying muds, wave action undercuts the rootmat forming a marsh overhang (Figures 3 and 8b). The rootmat, with its intertwining network of roots accompanied by a mass of ribbed muscles on the surface, is remarkably rigid, forming overhangs up to 50 cm in length. Undercutting enlarges the overhang until it breaks off and topples into the bay. Tensional cracks can develop on the marsh surface as toppling begins (Figure 8b). This style of erosion is referred to as beam failure and has also been observed on river banks (PIZZUTO, 1984). Toppled portions of the rootmat are commonly observed in the water at the base of the scarp. This undercutting–toppling process was observed on both linear stretches of shoreline as well as on marsh necks. As the waves hit the shoreline underneath an overhang, the water is forced upward against the rootmat. This upward movement of water can produce a hole through the marsh surface that erodes the sediment leaving only a network of grass roots (Figure 8a). This process was observed along linear stretches of shoreline and at the apex of clefts and hastens erosion as the marsh is now being eroded from two directions.

## Erosion Rate Predictions

The calculated wave power for each of the nine long-term erosion sites (Figure 4) is listed in Table 1. The average erosion rate for each site was then plotted against the estimated wave power (Figure 12). A positive correlation between these two variables is apparent with the calculated regression equation:

$$R = 0.35P^{1.1} \tag{1}$$

where R is erosion rate (m/yr) and P is wave power (kW/m) (adjusted $r^2 = 0.80$, standard error = 0.27 log units, significance $F = 0.0007$). The three Rehoboth Bay sites (1, 2, 3) plot with the lowest wave powers and erosion rates. The two Delaware River sites (6 and 7) plot slightly higher for both variables. The four Delaware Bay sites (4, 5, 8, 9) plot with the greatest rates of erosion and wave powers. Overall, as the amount of wave power that reaches a marsh shoreline increases, the shoreline erosion rate also increases.

Figure 10. A marsh neck exhibiting a pinched appearance due to wave erosion.

## DISCUSSION

### Erosion Rates

Surveying shorelines over short distances and time periods presents some interesting problems when trying to interpret erosion rates. The shoreline is commonly undercut by wave action causing the marsh rootmat to form an overhang. This marsh overhang continues to develop until it breaks off and topples into the bay. Consequently, there are two processes of erosion associated with a marsh shoreline. The first is relatively more continuous as the underlying mud is eroded by waves breaking against the shoreline. The second is episodic as the overhang breaks away from the marsh. As long-term shoreline erosion rates are usually determined from aerial photographs and presented in plan view, it is the erosion rate that is related to the retreat of the marsh surface (*i.e.*, rootmat) that is of primary significance when estimating erosion rates.

Surveying the shoreline over short time intervals (six months or less), can result in significantly different erosion rates depending on the relative timing of the survey and of the toppling events. Once the marsh overhang reaches a threshold, toppling most likely occurs over a span of only a few days or perhaps in only one day as the result of a storm event (WRAY *et al.,* 1995). As a result, surveying a stretch of shoreline over a period that includes a toppling event will produce relatively large yearly erosion rates. On the other hand, surveys conducted just after a toppling event and before the next may result in relatively low yearly erosion rates. It is therefore important to compare short-term average erosion rates to longer-term average erosion rates to access the significance of the short-term surveys.

SWISHER (1982) documented erosion rates in Rehoboth Bay over a 43–year time period (1938–1981) using aerial photographs. The average erosion rate for the southern portion of Horse Island marsh (equivalent to the stretch between sites B and E in this study) was calculated to be about 23 cm/yr and for Marsh Island about 50 cm/yr (SWISHER, 1982). Over a three-year period, average erosion rates from this study are 23 ± 4 cm/yr and 43 ± 4 cm/yr for these two areas, respectively. The similarity of these rates either means that average erosion rates from a three-year survey can be used as a proxy for long-term erosion rates or that it is a mere coincidence that these rates are so similar. Until additional surveys are conducted to understand the short-term natural variations of shoreline erosion rates, I will assume that the similarity is an interesting coincidence.

Four of the five survey sites along the Horse Island marsh shoreline (sites A, B, D, E) exhibit a similar variation in erosion rates over the three-year span (Figure 6). From the first year to the second year, a decrease in erosion rates occurs and then the rates increase from the second year to the third year. This would suggest that the total amount of wave power striking the shoreline at each site also varied in a similar manner. This line of reasoning can be extended to one of the controlling variables of wave power, such as wind speed. If

Figure 11. A marsh stack formed by the separation of a marsh neck from the shoreline.

there were extended periods of strong winds, during storms for example, throughout a particular year, this would produce a greater frequency of relatively high wave heights. This in turn would generate greater wave powers, which theoretically would produce higher erosion rates.

RAMSEY *et al.* (1998) tabulated the number of storm events that produced tides greater than seven feet above MLLW (mean lower low water) at Breakwater Harbor (see Figure 4 for location). In 1996, three such storm events occurred, in 1997 only one storm, and in 1998 there were again three storm events. This storm activity correlates well with the variations in erosion rates and suggests that storm events are strongly associated with shoreline erosion. KAMPHUIS (1987) also showed that storms are a primary factor in the erosion of glacial till bluffs. Therefore, over time periods of a year or so, marsh shoreline erosion rates are highly variable as they are, in part, related to the frequency and magnitude of storm events.

Table 1. *Long-term erosion rate and wave power data for individual sites. See Figure 4 for site locations.*

| Site | Average Erosion Rate* (m/yr) | Wave Power (kW/m) |
|---|---|---|
| 1 | 0.17 | 0.66 |
| 2 | 0.23 | 0.75 |
| 3 | 0.50 | 0.78 |
| 4 | 4.50 | 6.48 |
| 5 | 7.30 | 7.43 |
| 6 | 0.77 | 3.01 |
| 7 | 1.10 | 5.12 |
| 8 | 6.12 | 8.77 |
| 9 | 1.96 | 9.21 |

* Associated time periods and sources of erosion data:
Sites 1, 2, 3 = 1938–1981 (SWISHER, 1982)
Sites 4, 5 = 1842–1977 (FRENCH, 1990) and 1843–1956 (Maurmeyer, 1978)
Sites 6, 7, 8, 9 = 1940–1978 (PHILLIPS, 1985)

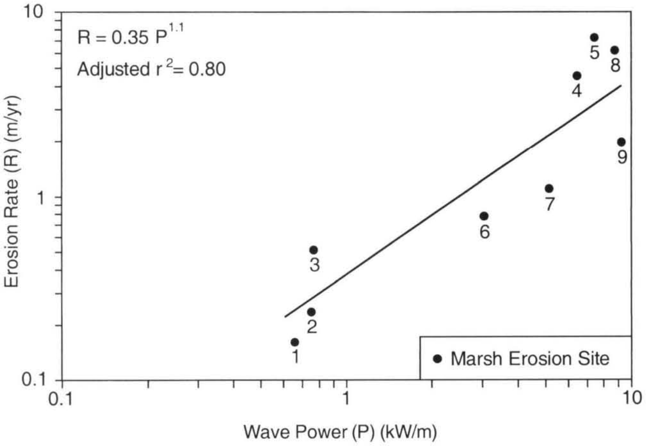

Figure 12. Erosion rate vs. wave power for nine selected marsh shorelines.

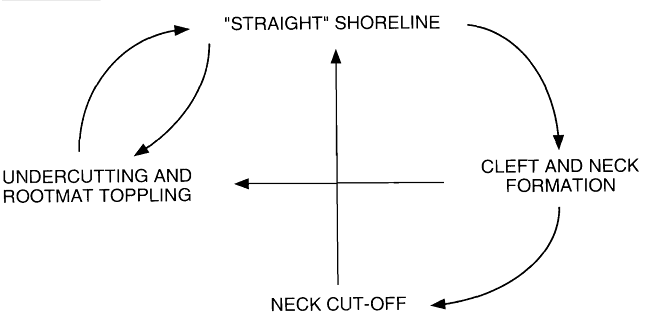

Figure 13. A possible cyclic process of marsh shoreline erosion.

## Styles of Marsh Shoreline Erosion

Three styles of shoreline erosion were observed in the study area: (1) cleft and neck formation, (2) neck cut-off, and (3) undercutting and rootmat toppling. Although data obtained from this study do not provide a quantitative relationship among these styles a qualitative relationship can be proposed. The shoreline geometry over relatively short distances (*e.g.,* ten meters), is controlled by lateral variations in erosion rates. Because the lithology of the scarp sediment is consistent along the marsh shoreline, it is likely that erosion rates are influenced by the interaction of waves with the nearshore bathymetry and the shoreline. As the geometry of the shoreline changes, the nature of this interaction also changes thereby altering the constructive and destructive wave interference patterns. Consequently, the foci of wave erosion along the shoreline also changes. This interactive relationship can be illustrated through the changing styles of erosion. Figure 13 presents a possible cyclical process of marsh shoreline erosion in Rehoboth Bay.

Starting with a relatively straight or linear shoreline, the process of erosion can change this initial geometry to one that is undulatory, consisting of clefts and necks. The marsh necks can then be eroded quickly, through undercutting and toppling, or be cut off at the base. In either case, the shoreline geometry is changed back to a more linear shape (Figure 13). A linear shoreline can also retain this geometry through undercutting and toppling along its length. If these zones of higher erosion rates (*e.g.,* apex of clefts, tip and base of necks) are designated by the interaction of waves with the nearshore bathymetry and the shoreline, then these areas will change location as the shoreline geometry changes.

Clefts, for example, are formed by relatively rapid erosion rates. However, clefts are usually limited to three meters in depth within the study area. Why are deeper clefts not found and why did the erosive process slow down? Perhaps as the cleft developed, a threshold was reached where the erosive force is attenuated due to the depth and narrow geometry of the cleft. As the adjacent marsh necks continue to erode, the depth of the cleft becomes smaller which may allow erosion rates in the cleft to increase to a level similar to that of the necks. The alternating cleft–neck geometry may then be maintained as the shoreline retreats. Alternatively, the marsh neck could be undercut or cut off which would reestablish a more linear shoreline, potentially allowing the process to begin again. Overall, there is a potential feedback mechanism that occurs as the shoreline geometry changes due to erosion which alters the variables that direct the erosive forces that in turn change the shoreline geometry.

Besides wave action, other factors may play a role in shoreline erosion. In Rehoboth Bay, SWISHER (1982) observed ice sheets in the nearshore zone and on the marsh surface up to one meter from the shoreline. After the ice broke up, large sections of the marsh surface were found up to five meters inland from the shoreline. SWISHER (1982) attributed this redistribution to ice rafting and observed that the ice had sheared off the rootmat from the underlying mud. During the time of this investigation, however, ice sheets were not observed in the nearshore zone.

Boat wakes may also cause shoreline erosion. Although power boats can be common in Rehoboth Bay, they are only frequent during the late spring to early fall months. While conducting field work, boats were rarely observed traveling close enough to Marsh Island and at high enough speeds to produce waves that reach the shoreline. The water between Marsh Island and Horse Island marsh is relatively shallow which limits the size and speed of the boats in this area especially during low tides when the shoreline is more susceptible to wave erosion. ZABAWA and OSTROM (1980) examined the role of boat wakes on shoreline erosion in Chesapeake Bay. They concluded that boat wakes ranked third behind storm-driven waves and wind waves in causing shoreline erosion. In addition, ZABAWA and OSTROM (1980) suggested that the type of shoreline plays an important role for the potential of erosion. Shorelines made of sand and gravel, for example, are more easily eroded than marsh shorelines with their tightly-bound rootmats. Overall, their data suggest that boat wakes have an insignificant effect on marsh shoreline erosion (ZABAWA and OTROM, 1980).

Biogenic activity, however, may enhance shoreline erosion (WRAY *et al.,* 1995). Fiddler crab burrows were observed in the erosional scarp during low tide. These burrows occur throughout the scarp from just below the rootmat to the base of the scarp. The burrows may promote erosion by trapping air as waves strike against the scarp. The compressed air increases the shock pressure of the wave which, coupled with the sudden expansion of the air as the wave recedes, may intensify the erosive process. TRENHAILE (1987) considered air compression to be a very effective process of erosion on rocky coasts, although one that is not well understood.

## The Shoreline Geometry of Horse Island Marsh

Over a much larger distance, lateral variations in erosion rates most likely do not account for the general configuration of the Horse Island marsh shoreline as shown in Figure 2. There is a spatial- and temporal-scale problem. It seems unlikely that erosion rates measured over a ten-meter stretch of shoreline determined over three years can explain the general geometry of a one-kilometer stretch of shoreline that developed over the past 200 years (SCHWIMMER and PIZZUTO, 2000). One variable that may have an influence on shoreline

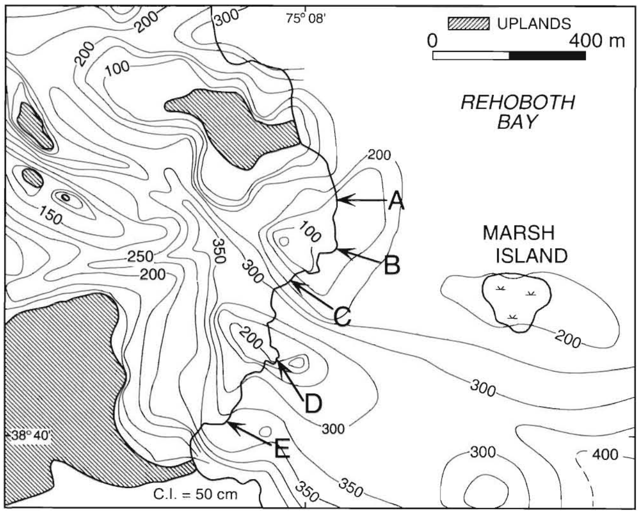

Figure 14. The relationship between depth to the antecedent surface (measured in centimeters from the marsh surface) and the shoreline geometry.

geometry that has not been accounted for is the depth to the antecedent topography.

The antecedent topography is comprised of the Pleistocene Omar Formation (RAMSEY and SCHENCK, 1990), a fine to coarse sand with some gravel, that underlies the marsh deposits and forms the surface over which transgression occurs. The general configuration of the Horse Island marsh shoreline from north to south consists of a headland from just north of Horse Island to just south of site B, an embayment at site C, and another smaller headland at site D (Figure 2). A second embayment is located just south of site E. Here, however, the shoreline is a sandy beach and not a marsh shoreline. Figure 14 illustrates the relationship between depth to the antecedent topography and shoreline geometry. The two headlands are located in areas where the antecedent surface is relatively shallow while the embayment is found in an area where the antecedent surface is relatively deep. Furthermore, the existence of Marsh Island is also significant as it is situated where the antecedent surface is also relatively shallow.

This shoreline geometry suggests a causal relationship between depth to the antecedent surface and shoreline configuration over relatively large distances. As Horse Island marsh developed, rising relative sea level first encroached the paleo-stream valleys (where the antecedent surface is relatively deep) thus restricting the initial growth of salt marsh. As relative sea level rose, transgression moved across the interfluves creating additional areas of salt marsh growth (CHRZASTOWSKI, 1986). The marsh deposits found at the lowest elevations are indeed much older than those found associated with an antecedent topographic high (SCHWIMMER and PIZZUTO, 2000). The early-formed marsh may therefore have experienced a longer duration of shoreline erosion compared to the later-formed marsh. In addition, it is likely that the vegetation of the younger marsh deposits would have initially grown farther out into the bay as they were simply following the mean high water contour line. Therefore, the general shoreline geometry developed as a result of the antecedent topography controlling salt marsh growth and not because of lateral variation in erosion rates.

## Mechanism of Marsh Shoreline Erosion

In Rehoboth Bay, wave attack creates a vertical scarp and commonly undercuts the rootmat forming an overhang which eventually topples into the bay. This process has also been observed in Massachusetts (REDFIELD, 1972), in Chesapeake Bay (COULOMBE, 1986; FINKELSTEIN and HARDAWAY, 1988; DOWNS *et al.,* 1994; WRAY *et al.,* 1995), in Delaware Bay (PHILLIPS, 1986b), and in Great Britain (ALLEN, 1989), suggesting that an erosional scarp is a common feature of retreating shorelines. In order to better understand the erosion process it is necessary to first ask the question, "What is the mechanism that promotes wave erosion?"

The history of Horse Island marsh, as well as other marshes in southeastern Delaware, contain a period of marsh expansion as the shoreline prograded over lagoonal mud flats (SCHWIMMER and PIZZUTO, 2000). During progradation, the waves presumably did not erode the shoreline and yet relative sea level was still rising and waves were undoubtedly still being generated by winds and storm events. This expansion phase ended about 200 years ago and was followed by the modern-day transgressive phase accompanied by rapid shoreline erosion (SCHWIMMER and PIZZUTO, 2000). So why did the waves not erode the shoreline during marsh expansion and why are waves eroding the shoreline today?

Previous studies have suggested that the present-day erosion of marsh shorelines is due to the recent rapid rate of local relative sea-level rise (PHILLIPS, 1986b; FINKELSTEIN and HARDAWAY, 1988; KRAFT *et al.,* 1992; DOWNS *et al.,* 1994; WRAY *et al.,* 1995). The rate of local relative sea-level rise in Delaware is 0.33 cm/yr (KRAFT *et al.,* 1992). These studies, however, did not present a causal relationship between increased rates of local relative sea-level rise and shoreline erosion. FINKELSTEIN and HARDAWAY (1988) did hypothesize that the recent rapid rise of relative sea level created a deeper estuary with larger fetches. Consequently, larger waves were produced resulting in shoreline erosion. WRAY *et al.* (1995) coupled a lack of sediment input and sediment composition with rapid local relative sea-level rise as the cause of shoreline erosion. However, neither of these studies presented a detailed model illustrating how these variables are interrelated nor a mechanism that could account for alternating periods of erosion and progradation.

A possible model to explain why the shoreline is eroding is presented by SCHWIMMER and PIZZUTO (2000). This shoreline response model is based on the relative rates of local sea-level rise, marsh aggradation, and sedimentation in the nearshore lagoonal area. This model proposes that if the rate of relative sea-level rise is faster than the rate of nearshore lagoonal sedimentation, then the water depth will increase which in turn promotes an increase in wave height and celerity. As wave heights increase, the amount of wave power impinging on the shoreline also increases. The increased wave power causes erosion of the shoreline forming a shoreline scarp.

According to this model, the mechanism that governs marsh shoreline erosion is the relative combination of the rate of local sea-level rise and the rate of sedimentation in the nearshore lagoonal area (the marsh aggradation rate is assumed to keep up with the rate of relative sea-level rise or the marsh will simply drown). The nearshore sedimentation rate is in turn influenced by sediment supply and wave energy. This mechanism allows for a more thorough understanding of the cause of marsh shoreline recession or expansion and also provides clues to paleo-environmental changes that are associated with marsh stratigraphic regressive and transgressive sequences.

### Erosion Rate Predictions

Variations in fetch and in water depth influence the estimated wave powers. The Rehoboth Bay sites (1, 2, 3), which are associated with the smallest fetches and shallowest water depths of the nine sites, plot with the smallest estimated wave powers (Figure 12). Sites 6 and 7 are located in the Delaware River where available fetches and water depths are potentially greater than in Rehoboth Bay but smaller than in Delaware Bay. These sites plot with greater wave powers and therefore potentially greater erosion rates than the Rehoboth Bay sites. The four Delaware Bay sites (4, 5, 8, 9) plot with the greatest potential wave powers and erosion rates. Sites 4, 5, 8, all plot close to one another most likely due to similar fetches, water depths, and orientation of the shoreline relative to the bay. Site 9 also exhibits a large wave power due to larger fetches and potentially deeper water in the lower and wider portion of the bay. Site 9, however, exhibits a lower erosion rate perhaps due to the orientation of the shoreline in relation to the bay. The shoreline is facing northwest toward Egg Island Point and across a shallow embayment (Figure 4) which greatly reduces the available fetch and water depth which in turn reduces the potential wave power for those waves approaching normal to the shoreline. Overall, the positive correlation illustrated in Figure 12 suggests that as wave power increases at one site or from site to site, the associated erosion rate will also increase.

The regression equation obtained from this relationship,

$$R = 0.35P^{1.1}, \tag{2}$$

is similar to that found by KAMPHUIS (1987),

$$R = 1.06P^{1.37}, \tag{3}$$

for the erosion of glacial till bluffs along the north shore of Lake Erie. In addition, KAMPHUIS (1987) presented a reanalysis of GELINAS and QUIGLEY'S (1973) erosion data from the same area of Lake Erie and obtained a regression equation of

$$R = 1.16P^{1.31}. \tag{4}$$

In both cases, the exponent is slightly higher compared to equation (2) suggesting that marsh shorelines are more resistant to wave erosion than glacial bluffs.

This correlation may be used as a predictive tool to estimate erosion rates for marsh shorelines in the Delaware Bay region. Presumably this method could be used elsewhere provided the necessary data are available.

## CONCLUSIONS

1) The primary process that causes marsh shoreline erosion in Rehoboth Bay, Delaware, is attack by wind waves.

2) Over a three-year period, the average rate of shoreline erosion along Horse Island marsh was 24 ± 4 cm/yr. On Marsh Island, the average rate of shoreline erosion was 43 ± 4 cm/yr.

3) Three styles of marsh shoreline erosion were observed in the study area: (1) cleft and neck formation, (2) neck cutoff, and (3) undercutting with rootmat toppling. Over relatively short distances (*e.g.,* ten meters), a possible feedback mechanism between these styles may account for changes in the shoreline geometry over time.

4) Over relative larger distances (*e.g.,* several hundred meters), the configuration of the Horse Island marsh shoreline is controlled by the antecedent topography, which governs salt marsh evolution, and not by the laterally variable rate of shoreline erosion due to wave attack.

5) A positive correlation is revealed when erosion rates are plotted vs. wave powers for selected marsh shorelines. As wave power increases, the rate of erosion increases. This correlation may be used as a predictive tool to estimate shoreline erosion rates for other fringing lagoonal marshes.

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