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Considerations for Shoreline Position Prediction

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ABSTRACT

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CROWELL *et al.* (1997), using series of sparsely sampled sea-level values as surrogate data for shoreline change, evaluated several well-known shoreline position prediction algorithms. They concluded that in the absence of physical changes such as opening of inlets or shore engineering, linear regression over the longest possible period was the most reliable predictor of shoreline trends for extended intervals (30+ years). They also noted that shorelines, like sea-level, have unpredictable interannual and longer quasi-periodic fluctuations that can mask an underlying trend for many years. Thus an effective prediction algorithm for predicting shoreline position at all temporal scales must reflect persistence of these variations while at the same time correctly accounting for the underlying long-term trend. Successful interpretation of shoreline behavior and prediction of future position requires knowledge of the nature and impact of past erosional events, particularly due to major storms. A simple mathematical model that mimics many of the characteristics of shoreline position variation and real shoreline position data from Delaware between 1845–1993 are employed to illustrate the difficulties of the prediction problem. The northeaster of March 1962, the largest in this century, provides a revealing case study of the response of a shoreline to a severe storm event. The effect of this storm, which lasted through five high tides, was to "overshoot" the long-term trend of erosion by a very large amount, with subsequent accretion taking place for a decade or longer back toward the position predicted by the underlying long-term (~150 year) trend. Thus for a long time, the beach appeared to be accreting rather than eroding. Long-term planning, such as for 30 or 60 year building setbacks, requires the most careful attention to the long-term erosion trend and the historical record of storms, including their impacts on the shoreline position and beach recovery.

ADDITIONAL INDEX WORDS: *Coastal erosion, erosion rates, erosion, forecasting, development setbacks.*

INTRODUCTION

Shoreline-change data exist for most coastal states. These data have been compiled by the states, usually in conjunction with university and private sector specialists (NATIONAL RESEARCH COUNCIL, 1990). Many of these databases are in digital format and compatible with Geographic Information System (GIS) software.

The primary use of shoreline-change data is for delineating areas that are determined to be erosion-prone. These mapped "erosion hazard areas" are incorporated into land-use planning, ranging in purpose from providing information and ed ucation to property owners, to establishing regulatory coastal construction setbacks. Approximately one-third of coastal states employ shoreline-change data to establish erosion setbacks (NATIONAL RESEARCH COUNCIL, 1990). Developmental restrictions vary depending on state regulations within or seaward of the setbacks. Usually the setback is based on what is taken as the average annual erosion rate (AAER) at a site, multiplied by a specified number of years, commonly 30 and 60 years. The computed setback is then measured landward from an erosion reference feature. This feature, which is intended to be the most realistic indicator of erosion at the site, varies from state to state, but is typically the top edge of a bluff, dune escarpment, vegetation line, beach scarp, or high water line.

Erosion-based setbacks are designed to forecast where a shoreline will be located at the end of the time span used to define the setback. If the rate of erosion used to calculate the setback was correct, houses located landward of, for example, the 30-year erosion setback, are expected to be standing in thirty years, unless destroyed by a coastal storm or some other disaster. To illustrate, Figure 1a is a hypothetical example showing the 30-year setback delineated on a segment of previously undeveloped coast. The AAER at this site, taken to be 0.6 m per year for this example, requires that the 30-year setback is measured 18 m landward of the current (1997) position of an erosion reference feature (perhaps an eroding dune). All new construction is prohibited within the 30-year setback.

This method for establishing the building setback explicitly assumes that over the next 30 years the beach will continue to erode at an average rate of 0.6 m per year, and by the year 2027, the shoreline will be located 18 m landward of its 1997 position. However, it is known that severe storms can occur which can cause substantial departures of the shoreline position from the orderly retreat described in this example. In fact, 30 years into the future we might see a situation like

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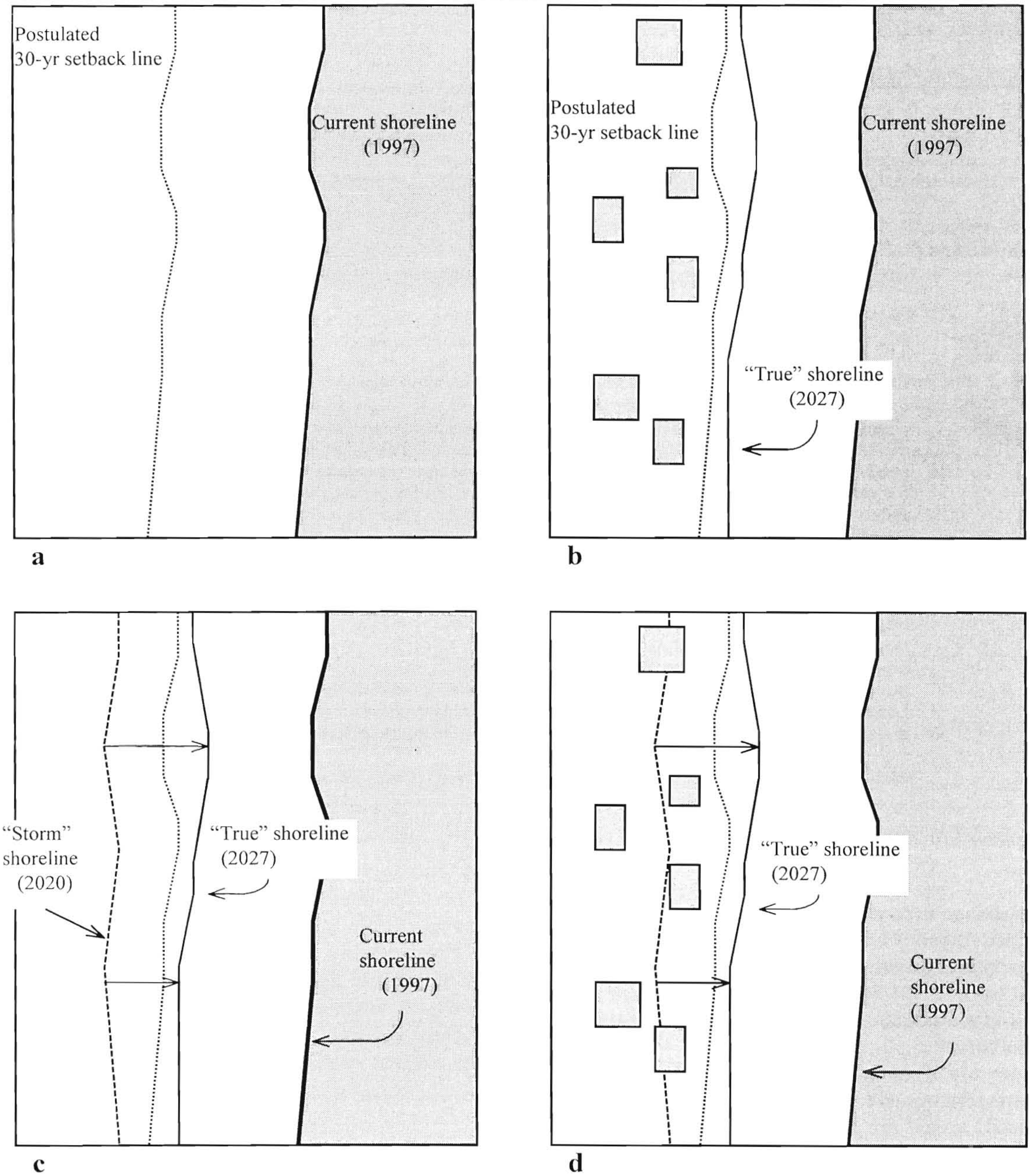

Figure 1. (a) Hypothetical current (1997) shoreline and postulated 30-year setback line. (b) Thirty years into the future (2027), with plot of 30-year setback line (as forecasted in 1997), and position of "true," shoreline located slightly seaward of its *predicted* 2027 position. (c) Shoreline location after hypothetical severe storm in 2020, with subsequent accretion to 2027 shoreline position. The variability of shoreline position is such that a great storm can move the shoreline shoreward of the predicted position. However, coastal researchers in 2027 who study the accuracy of the shoreline position forecast in 1997 would conclude that the forecast was a good one. (d) Same figure as c., except buildings are plotted. When the placement of immobile structures is considered, the quasi-periodic nature of the shoreline position, as well as the long-term rate of erosion, must be considered in evaluating the hazard. Future coastal managers, or owners of the front row of houses, would conclude that the forecast was inadequate.

that represented in Figure 1b. Suppose in this case the AAER predicted 30 years ago in 1997 was too conservative. The "true" shoreline is then located slightly seaward of its predicted 2027 position, and all structures that were built landward of the 30-year setback as delineated in 1997 would still be on dry land. But in actuality, beaches do not erode at a constant rate through time. Unpredictable, large-scale changes result from severe tropical and extratropical storms. During these storms, beach width changes within a short time interval (hours to days) can be much larger that than the accumulated erosion over many previous decades. Large quantities of sand can be eroded from the beach and dunes, with erosion scarps forming tens of meters landward of the prestorm shoreline. Much of the eroded sand is deposited offshore, forming large storm bars. Subsequent post-storm swells usually move most of the sand back onshore, particularly the long-period swells characteristic of the summer season.

Following a severe storm of long duration, beach recovery can go on for many years (MORTON, *et al.*, 1994). Figure 1c illustrates the effects of this last phenomenon. A hypothetical large-scale storm occurs in 2020, causing severe erosion. But during the next few years, much of the beach that was lost is regained during a period of relative storm quiescence. By the year 2027, the shoreline has recovered to a location near to the 30-year setback as delineated in 1997. Future coastal researchers who study the accuracy of the shoreline position forecast made in 1997 would conclude that the forecast was a good one. The 2027 location of the shoreline was very near to its predicted location. However, when the placement of immobile structures such as houses are considered (Figure 1d), the quasiperiodic nature of the shoreline must be considered in evaluating the forecast. As such, to a coastal manager (or one of the unfortunate owners of the houses built just landward of the 30-year setback line), the forecast would have been inadequate. In the aftermath of the 2020 storm, the front row of structures would have been destroyed or damaged even if they were built on pilings high and deep enough to withstand the vertical erosion. This situation occurred because in delineating the 30-year setback, an implicit assumption was made that the shore was going to erode at a constant rate of 0.6 m per year, with no consideration given to the natural quasi-periodic beach width fluctuations.

The accuracy of erosion rate forecasts has been discussed in a number of papers. Topics include the accuracy of source maps and photography (MORTON, 1974; DOLAN, *et al.*, 1978; LEATHERMAN, 1982; CROWELL, *et al.*, 1991; ANDERS and BYRNES, 1991), and the use of long-term versus short-term data in the forecast (MORTON, 1979; DOLAN *et al.*, 1991; CROWELL *et al.*, 1993; FENSTER *et al.*, 1993). In addition, CROWELL, *et al.* (1997) evaluated algorithms seeking to improve on linear-based forecasts. In this paper we analyze sequences of shoreline positions as time series in an attempt to discover what is required for a useful forecast of future positions that reflects the character of both the trend and variability of shoreline position.

Shore erosion is a ubiquitous and serious problem for most of the US coastline (NATIONAL RESEARCH COUNCIL, 1990). In addition to an underlying trend that may be driven by sea-level rise, shoreline position fluctuates by large amounts seasonally, and even interannually due to severe storms (ELIOT and CLARKE, 1989). This means that a very extended period of properly selected data are required to reveal the underlying trend of shoreline-change.

DOLAN *et al.* (1991) studied the apparent erosion and accretion of the shoreline in North Carolina (Oregon Inlet to Cape Hatteras) and noted the existence of interannual reversals of shoreline position change that could be larger than the change predicted by the long-term (100+ year) trend. The importance of reversals of shoreline trend to the prediction problem was noted by FENSTER *et al.* (1993). CROWELL *et al.* (1997), following the arguments of LEATHERMAN *et al.* (1997) that sea-level data are suitable as a surrogate for shoreline data, demonstrated that because of interannual variability in the data, the most reliable *long-term* forecasts of shoreline position should be made using linear regression over the longest possible time series.

The fact that linear regression gave the best results for prediction in the tests made by CROWELL, *et al.* (1997) does not mean that linear regression is the true optimum scheme for prediction. The linear regression model assumes that the observations are the sum of a trend and Gaussian random measurement noise; this is clearly *not* the case for the shoreline problem. In fact, measurement error plays a minor role in predicting shoreline position for most US beaches. This is so because the 1-σ position error in NOS T-sheets or post-W.W.II aerial photographic data is of the order of 7.5–8.9 M (CROWELL, *et al.*, 1991). Seasonal variations of beach width are several times this much, and interannual beach width fluctuations even larger (MORTON, *et al.*, 1994; also this paper). The former are due to the usual winter/summer-erosion/recovery cycle, and the latter come from great storms and are unpredictable in occurrence. Thus an historical record of shoreline positions resembles a time series consisting of an underlying trend with superimposed relatively small random error, significantly larger seasonal fluctuations, and unpredictable, very large anomalies due to great storms. The last of these are characterized by an essentially instantaneous loss of beach, and subsequent extended recovery that can reverse the trend from erosion to accretion for an appreciable number of years. Reversals from erosion to accretion may also occasionally take place due to the occurrence of long period swell waves generated by offshore storms.

The normal seasonal erosion-accretion cycle is the reason that trends of shoreline position are properly derived from summertime shoreline data; by summer, the sand moved offshore by annual winter storms will have been mostly returned to the beach by the long-period waves typical of the summer season. If the trend of shoreline position is determined from a series of data including winter-time beach positions, or storm events that required more than a year for recovery, clearly a computed trend will be biased.

TIME SERIES ASPECTS OF SHORELINE POSITION CHANGE

The obvious problem in treating a sequence of real shoreline positions as a time series is one of undersampling. Typically the number of shoreline positions at a site that are available for analysis is less than 10, and these will be poorly distributed in time. CROWELL *et al.*, (1997) employed temporally complete sea level time series in their tests of prediction algorithms to evaluate the consequences of the undersampling. In this paper we take another approach, which is to construct for our analysis a model time series that has many of the characteristics of shoreline position variation.

The concept for our model time series is very simple. If the shore is subject to random erosion and accretion events that

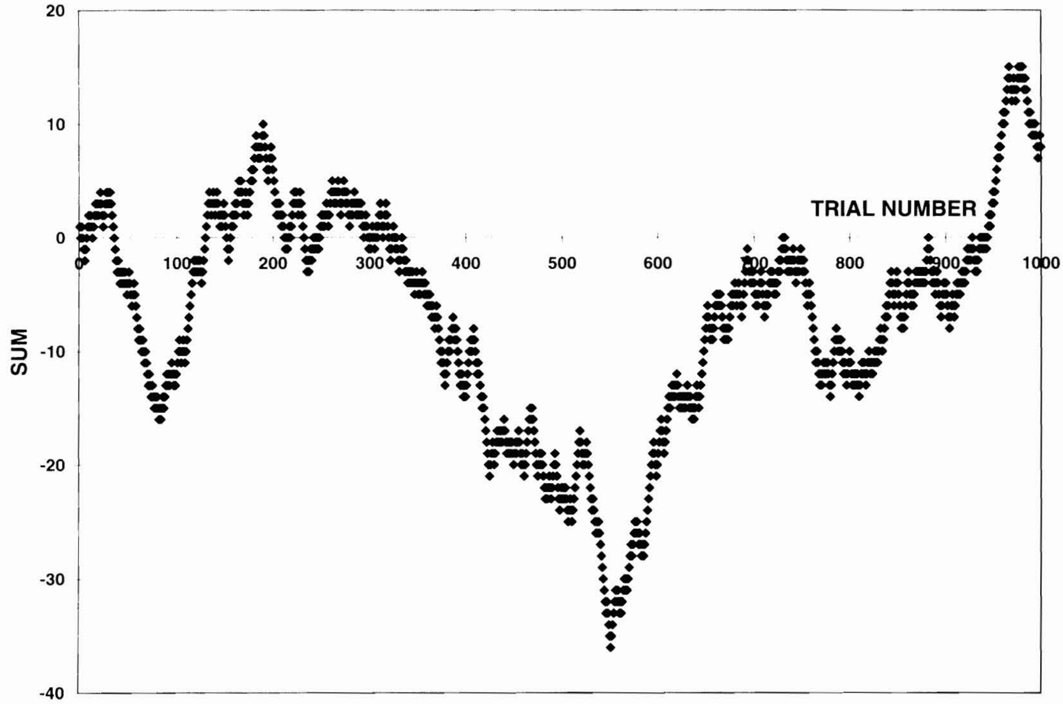

Figure 2. A fair game of Peter and Paul. Note that there is persistence in the sum (score), but that it is not useful for long-term prediction because of the inherent unpredictability of the sum for this game. The sum has an expected value of zero for an arbitrarily large number of trials, but the variance increases without bound along with the number of trials.

individually result in a *net* loss or gain, what form should the resulting time series of positions have? The so-called "game of Peter and Paul" provides a solution. It is a coin-flipping game in which if the result is heads, Peter pays Paul one dollar, and if tails, Paul pays Peter one dollar. To simulate this game, we used the random number generator in the Microsoft Excel© spreadsheet program, which returns a random value between zero and +1. Subtracting 0.5 from the supplied random numbers gave random numbers between −0.5 and +0.5. The resulting negative values were set equal to −1, and the positive values set equal to +1. The spreadsheet program was then used to tally one player's winnings as a function of the number of coin tosses (trials).

Figure 2 shows the results of a particular 1000-trial game. The intuitive result, which is usually thought to be a series that stays very close to an even (zero) score, is not at all what occurs in this game. Note also that longer series of trials result in larger excursions from the mean, so that with an increasing number of trials, the probability of the score being near zero becomes increasingly small. In fact, the spectrum of this sum is "red," that is, the greater the number of trials (coin flips) made, the greater the amplitude of the excursions. It must be emphasized that Figure 2 was generated by simply tallying the score of the coin-flipping game described after each trial. But that score has unexpected properties. There is a *memory* in this sum generated purely by summing random inputs that has the appearance of some definite process, but there is no predictability. This is not a trivial result. It suggests that a *lack* of variability would be more surprising than its presence.

One can see from this example that there is a certain similarity of the game of Peter and Paul to the beach erosion problem. The shore is subject to random gains and losses of sediment at intervals of a few hours (*e.g.*, waves) to seasonal and longer, and its position at any time is the sum of all of the erosion and accretion events that have previously occurred (*e.g.*, ELIOT and CLARKE, 1989; MORTON, 1979; DOLAN, *et al.*, 1991; FENSTER, *et al.*, 1993) In reality, of course the analogy of the game to the shore-erosion problem is imperfect. First, there is an inherent bias in the shoreline problem toward losing (*i.e.*, erosion) for most of the US coastline due to sea-level rise (NATIONAL RESEARCH COUNCIL, 1990). In addition, there are more large negative events, such as the erosion resulting from a very severe storm, than large positive ones. The latter can arise, as noted earlier, from offshore storms that generate long period swells, but they are much less common than episodes of loss from great storms.

A game with an outcome more like that of shoreline variation can be constructed by using a biased coin to reflect the one-sided effect of sea-level rise and great storms on beach erosion. Figure 3 presents one outcome of such a game, biased 53/47 in favor of loss. The values in Figure 3 do not resemble those of Figure 2 because Figure 3 is a new "game," that is, the random number generator supplied a new set of random numbers. The curves in Figures 2 and 3 bear a striking resemblance to many geophysical time series, as pointed out by

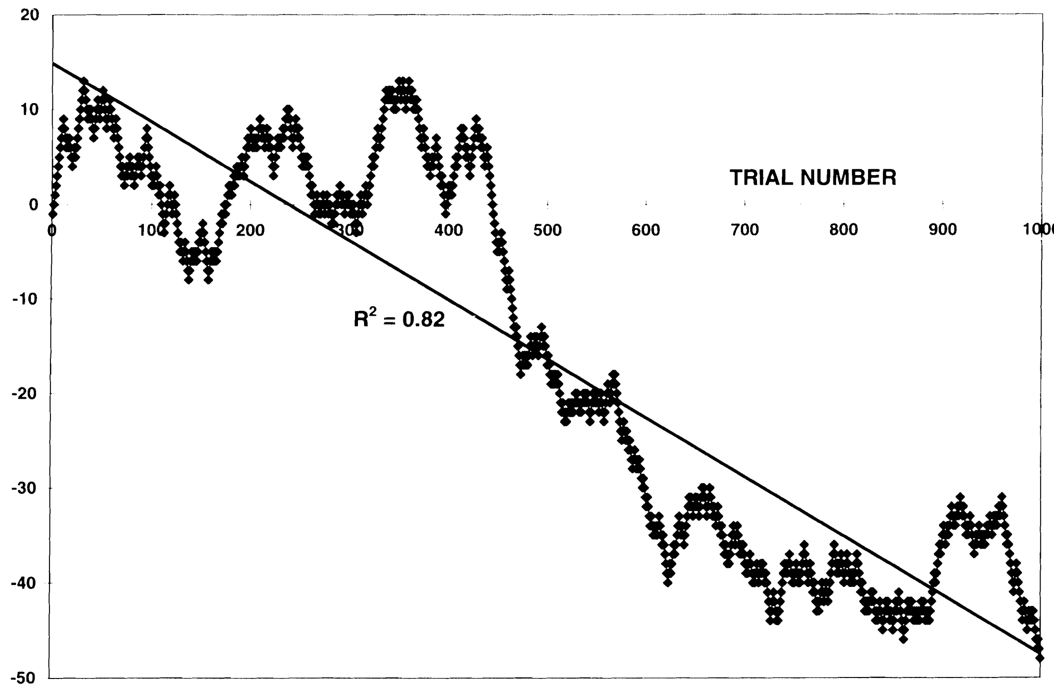

Figure 3. A biased game of Peter and Paul. The bias was set at 53/47 for loss. There is a downward (negative) overall trend, but large positive variations occur that yield unpredictable, persistent positive slopes in the sum for extended intervals.

WUNSCH (1992) in an exceptionally clear and interesting paper which also contains the mathematical details of the game of Peter and Paul, really a special case of a first-order autoregressive process. The occurrence of variability, and its increase with series length in functions generated this way is a result of their formulation, and always occurs.

In the sample of 1000 trials in Figure 3 (taken from the biased game), there is an additional overall downward trend (R^2 = 0.82). Figure 3 shows many of the characteristics of shoreline recession, and since we know that the coin was biased in a negative way (or that rising sea-level causes erosion), we can anticipate that the over a long time, the overall trend will be negative, but with persistent and unpredictable periods of positive slope. Figure 4 underscores this point. What is shown is the results for two new 1000-trial biased games. (The lower series is offset by 20 units for the sake of clarity). Both figures show the result of the 53/47 negative bias in that they both have an overall downward trend. However, the quasiperiodic fluctuations are very different in onset and amplitude, with no predictability. Thus, by analogy, making predictions of future shoreline position based on a small number of temporal samples, with older shoreline datapoints discarded or de-emphasized (as would be done using the Minimum Description Length algorithm (FENSTER, *et al.*, 1993)), cannot be expected in general to yield accurate results. This is so because the slope of the time series can change sign at any time, even though the long term trend over the entire record remains negative.

As noted, the actual shoreline is biased toward loss (erosion) because of sea-level rise and possibly by great storms that result in a permanent loss of sand. Thus, the question for the coastal planner is this: is there a maximum period over which we can be certain that the maximum recovery to be attained after a severe storm has taken place? Of course there are natural geomorphological situations (such as cutting of inlets or complete overwashing of barrier island dunes), and anthropogenic ones (for example, jetty and groin construction) which can fundamentally alter the sediment supply. But barring these special cases, we can look to the largest storms for insight into the details of the erosion-recovery cycle. This is a critical issue for evaluating shoreline position over time. It is entirely possible that moderate storms and even some severe ones do not contribute to net erosion over time, but rather only to variability of position. As an example, MORTON, *et al.* (1994) report that in the decade subsequent to Hurricane Alicia in 1982, the integrated recovery of sand volume for the southeastern Texas coast they studied was 92%. Their results also showed that recovery was greatest for transects with the smallest long-term erosion rate.

THE DELAWARE SHORELINE 1845–1993

We turn now to an actual case study that illustrates the challenges in predicting shoreline position. Figure 5 shows the end-point erosion rates for 1845–1993 determined from about 500 shoreline transects spaced 76 m (250 feet) apart on the open Atlantic Coast of Delaware. The shoreline position for 1845 was taken from US Coast and Geodetic Survey T sheets, and the 1993 data from a GPS survey. The variation

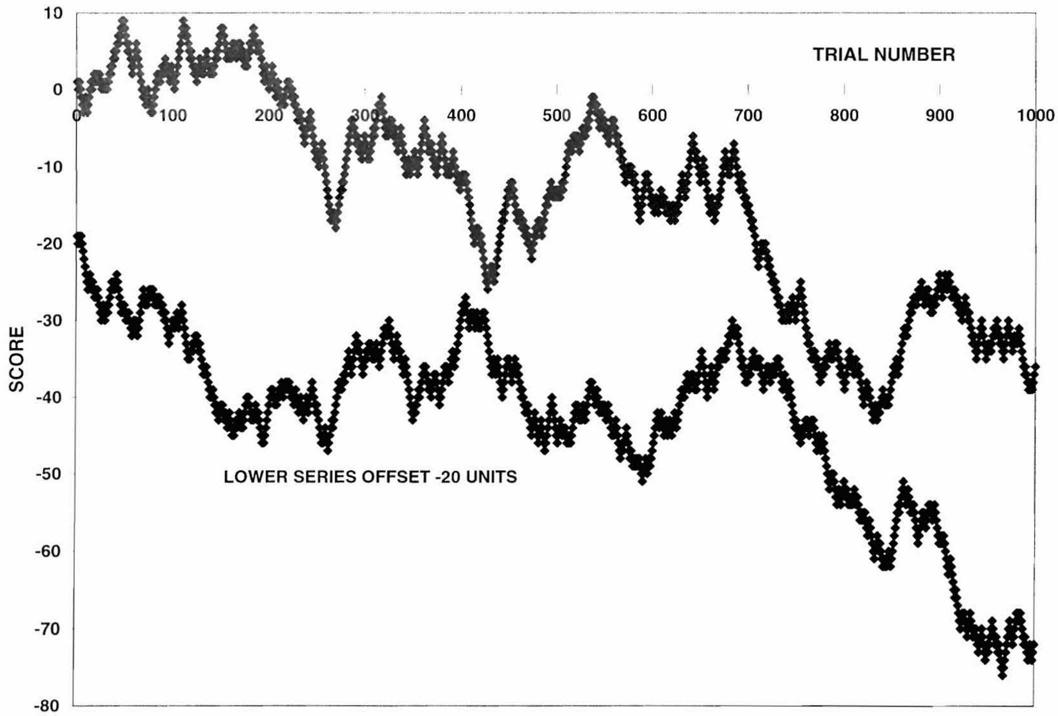

Figure 4. Two new realizations of the 1000-trial game of Peter and Paul biased 53/47 for loss. As in the case of Figure 3, there is an overall downward trend due to the bias, but the fluctuations are clearly unpredictable.

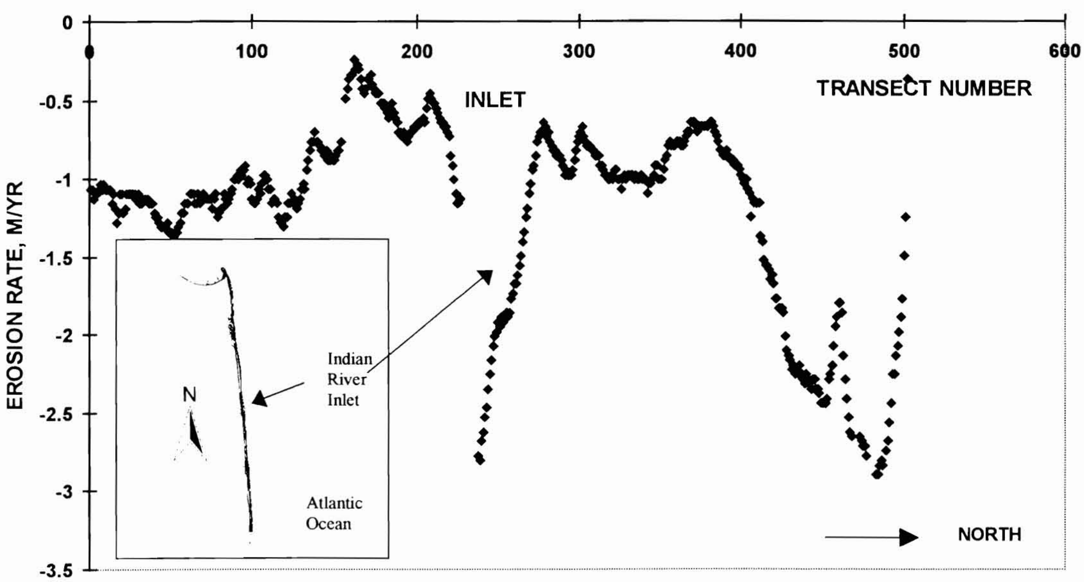

Figure 5. End-point erosion rates for the Delaware Atlantic shoreline. The transects are spaced by 76 m (250 feet). Note the influence of the Indian River Inlet jetties on erosion rates in the vicinity of transects 200–300. The high erosion rates after transect 400 are a consequence of the evolution of Cape Henlopen.

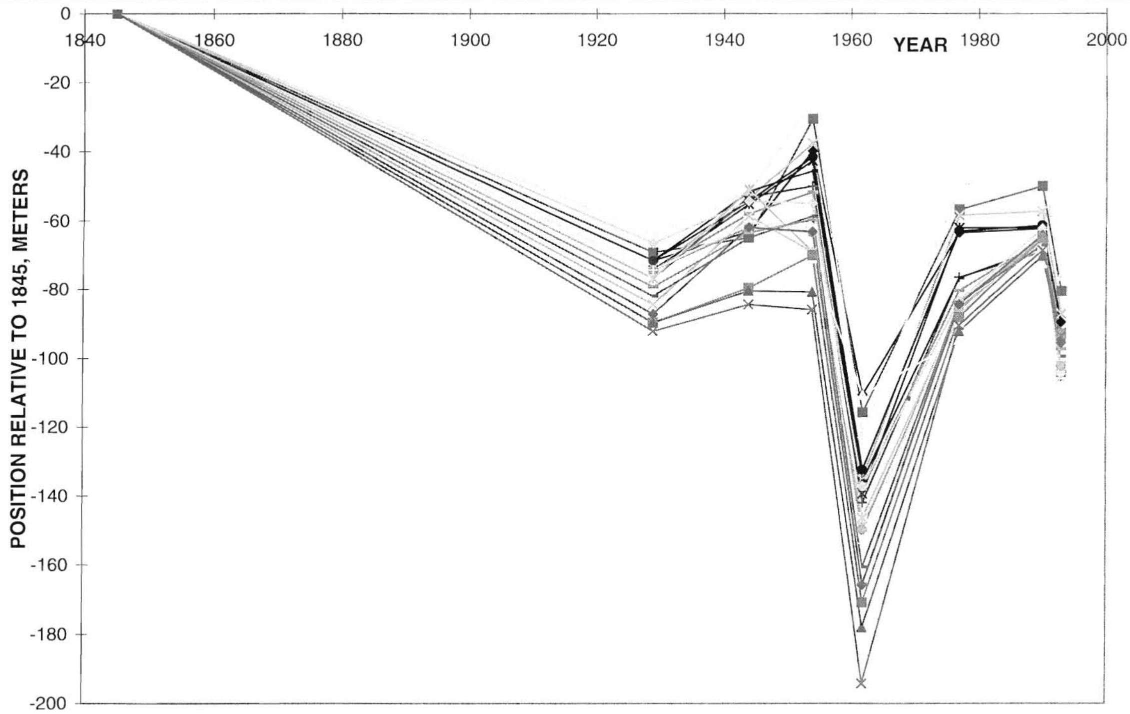

Figure 6. Shoreline position relative to 1845 for transects 183–204. The spectacular erosion and recovery in 1962 is very evident in this group.

of rates ranges from less than 30 cm per year to nearly 3 m per year. Those familiar with this shoreline will recognize the effect of the Indian River Inlet (at transects 227–238 in Figure 5), whose jetties cause sand starvation downdrift (northward). Also apparent are the high erosion rates (*i.e.*, at transect numbers > 415) just south of Cape Henlopen (not shown) which is in contrast accreting at a high rate near its tip. These special situations of capes and inlets clearly distort the "normal" situation for a considerable area (MORTON, 1979; FENSTER and DOLAN, 1996).

Another interesting phenomenon of the Delaware shoreline is the very low rate of erosion near transect #160. There is a local source of sand there from a Pleistocene relict barrier that reduces erosion nearly to zero at this spot (KRAFT, 1971). Apart from these special situations, inspection of Figure 5 suggests that erosion since 1845 has taken place at an *average* rate of about a meter per year. But Figure 5 underscores the idea that such an average is not of much value for an arbitrarily selected site. In this regard, the Delaware shoreline erosion rates resemble the variation reported by MORTON *et al.* (1994) for Galveston and Follets Islands, Texas where the long-term rates vary from about 1 to 10 meters per year over a similar length of shoreline that also includes an inlet (Bolivar Roads).

Of course there have been surveys of shoreline position in Delaware other than in 1845 and 1993. Shoreline positions for 1929, 1944, and 1962 were obtained from National Ocean Survey "T" sheets, and positions for 1954 and 1977 from aerial photographs. Another position for 1990 was obtained from orthophoto data. Unfortunately, the complete shoreline was either not always surveyed or did not produce usable observations everywhere. But a set of transects (nos. 183–204), free of influence of jetties or a local source of sand, that included the erosion from the 1962 Ash Wednesday storm, considered the greatest of this century, is available.

Figure 6 presents the shorelines relative to the 1845 position for these transects. There is scatter in the results, but the effect of the great storm of March, 1962 stands out for its dramatic impact on every transect. The survey was completed in the summer of 1962, so some recovery must have already occurred by the time of the survey. But the beach loss was still about 80 meters for these transects, an order of magnitude greater than the error of the measurement. A spatial average of these transects illustrates more clearly what happened. Figure 7 presents the values of shoreline position at each date averaged over all the transects in the group. The linear regression line shown does *not* include the 1962 position in its calculation. The recovery back to the historic trend line by 1977 is apparent, and additional accretion occurred at least until 1990, bringing the shoreline *seaward* of the position measured for 1929 following a severe storm. It is true that overwash sand from the 1962 storm was bulldozed back onto the beach, but no systematic nourishment program was undertaken here, nor was this section of the beach subsequently armored.

Other important phenomena are apparent in Figure 7. There were also major storms in 1929, 1991, and 1992. Accretion following the 1929 storm apparently continued until at least 1954. The 1993 shoreline position reflects the effect of both the 1991 and 1992 great storms (the former is often

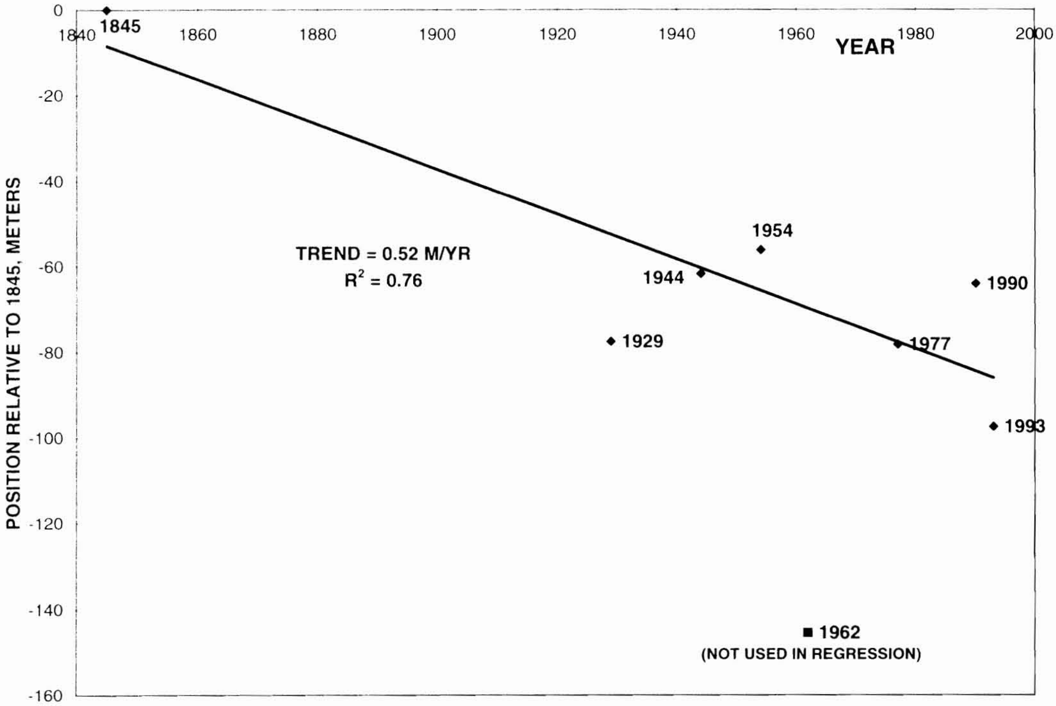

Figure 7. Spatial average shoreline position for transects 183–204. The 1962 shoreline position was not used in calculating the trend shown. The 1993 position clearly shows the effect of a severe storm that occurred in 1992. Accretion can be expected to continue after 1993. Note also the importance of the 1845 shoreline position for determining the erosion trend. Without that position, no trend of erosion could be established from the remaining later data.

called the Halloween storm). This example makes clear the danger of forecasting future shoreline position from a short time series of data such as a few decades. The occurrence of severe erosion from great storms requiring extended periods for recovery is inherently unpredictable so that forecasts of shoreline position will always have a very large uncertainty.

CONCLUSIONS

There is an urgent need to be able to forecast shoreline positions into the future (*e.g.*, 30 or 60 years) at any particular site so that development can take place in a manner that is economically reasonable, and gives full respect to public safety in the event of great storms. At the same time, predictions are needed over short periods on the order of a decade or less in order to assess possible beach recovery from a storm or series of storms and factor it into management decisions. The Delaware shoreline transects shown in this paper reveal the difficulties in achieving these goals. Superimposed on an orderly retreat of the shoreline in response to sea-level rise there are confounding factors including onshore sand supply, opening of inlets, jetty construction, cape migration, and most difficult of all, unpredictable great storms that make illusory the concept of a simple, universal numerical algorithm for forecasting shoreline-change from shoreline position data alone. It is clear from the analysis of this paper that derivation of a long-term shore erosion trend that is meaningful for coastal planning must consider much longer records than even several decades, and also consider the possibility of extended ($\gg$1 year) recovery of the beach. For example, if an estimate is made of the shoreline trend in the Delaware examples used in this paper without the 1845 data but using all of the other points in a linear regression, the result is a rate of -0.18 ± 0.75 meters/year—not statistically significant. Knowledge of the magnitude of the erosion associated with the 1962 Ash Wednesday Storm and other coastal storms and their extended recovery is needed before any understanding of short- and long-term trends of erosion is to be realized. It is also true that persistent accretion after a great storm may indicate that some buildings that survived the storm could see an improvement in their beach situation for many years. We can only conclude that for any site, a history of storms, their intensity and impacts, and the longest and most complete shoreline position records are needed to establish the underlying short- and long-term erosion behavior needed for coastal planning.

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