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Beach Erosion Potential for Severe Nor'easters

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ABSTRACT

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Beach erosion is one of the most significant impacts of coastal storms because beach width is a measure of coastal vulnerability for beachfront houses. Storm tide, wave energy, and duration are three major factors determining storm erosion potential. Several authors have proposed erosion indexes for large storms in terms of storm intensity measured by wind speed or wave energy and duration, but the role of the storm tide has not been fully incorporated into previous analyses. It has been found that the erosion potential of severe nor'easters is more dependent on storm tide than wave energy and duration. Thus, we propose a quantitative index of storm erosion potential that includes storm tide based on hourly water level measurements. Our storm erosion potential index (SEPI) is the sum of the products of hourly storm surge and corresponding storm tide water levels, and it correlates well with observed erosion.

ADDITIONAL INDEX WORDS: *Coastal storm, erosion potential index, storm surge, nor'easter.*

INTRODUCTION

Short-period, energetic waves associated with winter storms (nor'easters) can drastically reduce beach width along U.S. East Coast barrier islands. However, long-period swell waves characteristic of spring and summer usually move most of the sediment back onshore from the storm bars created in the winter so that beach width is restored. The occurrence of an unusually large storm can cause beach erosion requiring many years for beach recovery (MORTON, 1991; MORTON *et al.*, 1994; GALGANO *et al.*, 1998).

Beach erosion caused by a large storm does not necessarily correspond to the usual measures of storm intensity, such as wind speed, wave energy, or duration. It has long been speculated that the semi-monthly tidal cycle plays a role (WOOD, 1982), but proof based on quantitative measurements has been lacking. In addition, beach erosion caused by storms is a complicated process. Erosion induced by a storm at a particular site can also be affected by the pre-storm beach profile and geological conditions. Large storm waves are the major agents of erosion, but the storm tide determines the position (and elevation) where storm waves attack beaches and dunes. The storm tide is the sum of the astronomical tide and storm surge, which is the anomalous increase of water level due to the storm. Some researchers use storm tide and surge interchangeably, but storm surge and storm tide have different meanings in this paper.

Which factor, storm tide or wave, is the most important influence on beach erosion? EDELMAN (1968; 1972), HUGHES and CHIU (1981), VELLINGA (1982), SAVAGE and BIRKEMEIER (1987), DEAN (1991), and STEETZEL (1993) have proposed that the storm tide is the most important factor relating beach erosion to storms. But this hypothesis has not been examined using an extensive data set, that is, shoreline position response to large storms.

STORM EROSION POTENTIAL INDEXES

The tremendous damage caused by coastal storms provides the motivation for construction of an index of storm erosion potential in order to compare and predict their impact. Several indexes that might relate to erosion potential have been proposed. BRYANT (1988) and FENSTER *et al.* (1993) utilized annual storm counts (frequency). However, a storm count does not necessarily reflect total annual storm energy. ALLEN (1981) proposed a storm index (SI) based on prevailing onshore winds which reflects storm energy and can be defined as follows:

$$SI = (n/N)\nu^2 \qquad (1)$$

where n is the number of storm days during which onshore winds prevail at least 6 hours, N is total number of days in the study interval, and ν is the mean onshore wind velocity during storms.

There are two major types of storms that affect the U.S. East Coast: hurricanes and nor'easters. Hurricanes are tight and strong low pressure systems with high wind speed. They usually influence a relatively small area, about 150 kilometers. Saffir and Simpson ranked hurricanes into five categories in terms of central pressure, wind speed, storm surge height, and damage (SIMPSON, 1974). This classification has been used extensively in both scientific and public arenas. By

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contrast, nor'easters are diffuse and weaker low pressure systems with wind peak speed seldom greater than those of the weakest hurricane (about 70 knots). However, nor'easters occur more frequently and are much larger in size. They can continue for several days and affect almost the entire U.S. East Coast. DOLAN and DAVIS (1992) suggested a nor'easter power index (P) which is also indicative of storm energy based on hindcasting wave height from daily weather charts:

$$P = (H_{1/3})^2 t_D \tag{2}$$

where $H_{1/3}$ is the significant wave height and t_D is storm duration.

MORGAN and STONE (1985) proposed a storm wave susceptibility (SWS) index for the Florida barrier island coast:

$$SWS = \frac{E_1}{(H^2 + X_{BW}) + (X_{SF} + X_{EW})^{0.5}} \tag{3}$$

E_I is defined as an energy factor that has been assigned a value of 1×10^4 for high energy coasts, 2×10^4 for moderate energy coasts and 3×10^4 for low energy coasts. H is maximum primary dune crest elevation, X_{BW} is beach width., X_{SF} is shoreface width, and X_{EW} is effective island width. Note that this formulation is not strictly a beach erosion index as one term involves island width.

All of the above indexes define storm erosion potential mainly based on storm energy or frequency. None of them include storm tides which play the most important role in beach erosion (HUGHES and CHIU, 1981; DEAN, 1991; STEETZEL, 1991). ORFORD *et al.* (1992) and ORFORD and CARTER (1995) employed an annual summation of the amplitude of storm surges occurring at the highest water level during a day to derive an index. This approach served to partially incorporate the role of storm tides by counting the storm surge incident with the highest daily water level. However, their index does not take into account the timing of occurrence relative to the semi-monthly tidal cycle and hence does not differentiate between storms occurring at spring and neap high tides.

KRIEBEL and DALRYMPLE (1995) proposed a nor'easter risk index (I) for beach erosion at the Delaware coast by combining the effects of storm surge, wave, and duration. Their index is given by

$$I = SH(t_D)^{0.3} \tag{4}$$

where S is maximum storm surge height, H is offshore significant wave height, and t_D is duration. The storm duration was converted into the number of tidal cycles by dividing by 12 hours for a semi-diurnal tide. The duration was raised to the 0.3 power, reflecting a weak functional dependence on storm duration.

By assembling and analyzing available field data on storm-induced beach erosion along the U.S. East and Gulf Coasts, BALSILLIE (1986; 1999) found a high correlation between beach erosion above mean sea level (Q_{avg}), peak storm tide elevation (S) and storm tide rise time (t_r). The following formula was proposed to compute the storm induced beach erosion

$$Q_{avg} = 1/1622(g^{1/2} t_r S^2)^{4/5} \tag{5}$$

He also developed a beach erosion damage potential scale based on the Saffir/Simpson (SIMPSON, 1974) hurricane scale.

The severity of coastal erosion and damage induced by storms is determined by a combination of storm tide, wave energy, storm duration, and the character of the beach and shoreface. Storm waves determine the destructive potential of a storm, but storm tide dictates the onshore spatial range influenced by storm waves. At low tide, even large waves will have relatively minor impact on beach and dunes. When a storm coincides with high tides, especially spring high tides, storm waves can cause significant erosion and property damage because the waves experience less attenuation and can reach and attack higher up on the beach profile.

DEAN (1991) suggested that beach erosion induced by storms is much more strongly related to storm tide than storm wave height based on the equilibrium beach profile theory. He estimated that beach retreat attributable to the storm tide is about 16 times that caused by storm wave height. EDELMAN (1968; 1972) also identified the storm tide as the most important variable causing dune erosion based on pre- and post-storm field observations in the Netherlands. He proposed an empirical model for beach response to storms using maximum storm tides as a single parameter. VELLINGA (1982; 1986) enhanced EDELMAN'S erosion model by simulating in a large-scale wave tank the severe 1953 storm that heavily impacted the Netherlands. He verified that storm tides play the most important role in dune erosion.

STEETZEL (1991; 1993) summarized the wave tank experiments of storm effects on beach profile changes at the Delft Hydraulics Laboratory and developed a numerical model to simulate cross-shore sediment transport. He found that the storm tide is the most important factor in causing beach erosion with the storm wave height being a secondary effect. An increase of 20% in storm tide caused a 60% increase in erosion, while the same increase in wave height resulted in only 10–15% additional erosion. Furthermore, some of the extra erosion due to an increase in wave height is related to additional wave set-up.

HUGHES and CHIU (1981) performed movable-bed modeling of storm erosion in a wave tank. They noticed that a meter increase in storm tide level resulted in 10 m of dune erosion in the prototype, but wave height increase had much less effect on dune erosion. WOOD (1982) suggested that perigean spring tides, coinciding with strong onshore winds from storms, resulted in hundreds of severe coastal floods from 1635 to 1976 based on historical records from newspapers, magazines, and books. BALSILLIE (1986; 1999) stated that peak combined storm tide elevation is the most important variable related to storm-induced erosion along the U.S. East and Gulf Coast, contributing about 75% of the erosion volume. As a further argument for including the storm tide in an erosion potential index, consider the great Ash Wednesday Storm of March 1962. This storm caused the most severe beach erosion along the U.S. mid-Atlantic coast not only because it spanned five high tides, but it also coincided with perigean spring tides (FITZGERALD *et al.*, 1994). It is clearly desirable to incorporate storm tide effects into a storm erosion potential index (SEPI).

Storm duration is also an important variable. BALSILLIE

(1986; 1999) estimated that the storm tide rise time accounts for about 25% of the storm-induced beach erosion. Storm duration determines whether there is sufficient time for storm waves to erode the beach. A large nor'easter can impact the shore for several tidal cycles, while a hurricane may only influence the shore for a few hours. The large winter storm of December 1992 with duration of 91 hours resulted in severe erosion along the south shore of Long Island, New York coast. Thus, ideally, an erosion index should include storm tide, storm wave energy, and storm duration. Unfortunately, continuous long-term wave records that coincide with hourly water level data are not available along the U.S. East Coast. Wave buoy records there only extend back about twenty years.

There is a demonstrable relationship between wave height and surge height. TANCRETO (1958) demonstrated a high correlation ($r = 0.88$) between storm surge heights and hindcast significant wave heights. We have further investigated this relationship using data recorded at the Field Research Facility (FRF), Duck, North Carolina by U.S. Army Corps of Engineers. Surge levels for each hour were computed by subtracting the astronomical tide from hourly water level records. The distribution of all residuals after tide components were removed closely approximates a normal distribution. Thus, a criterion of greater than two standard deviations (SD) was chosen to identify a major storm event (ZHANG *et al.*, 1997). The Field Research Facility researchers use 2 m as the criterion to identify storm wave heights (www.frf.usace.army.mil). Therefore, we use storm surges greater than 2 SD of the annual surge level, and wave heights larger than 2 m to investigate surge and wave height relationship of large storms. Figure 1 shows that there is a linear relation between storm surge and wave height. Thus, it is reasonable to use storm surges as surrogates for storm waves to represent the strength of large storms.

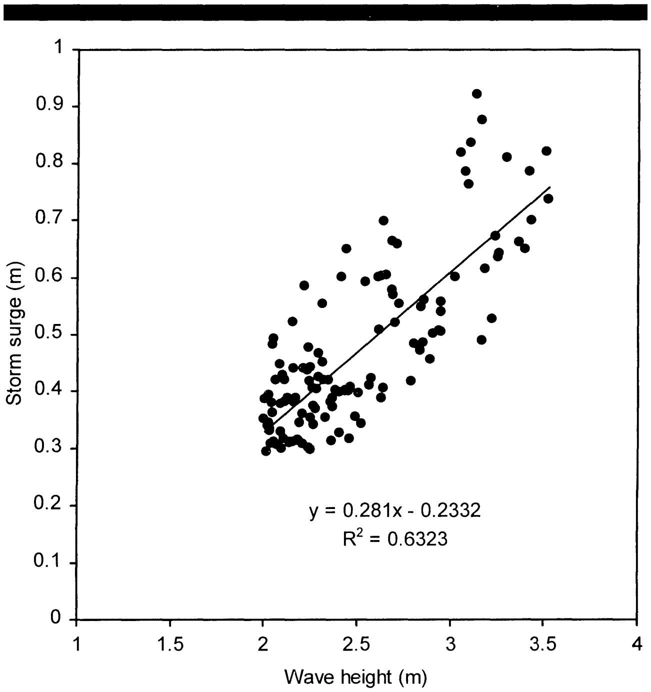


Figure 1. The relationship between wave height (an energy-based statistic equal to four times the standard deviation of the sea surface elevation in each 34 minute record) greater than 2 m, and storm surges over 2 SD at Duck, North Carolina during 1988. Note that there is a strong linear relationship between wave and surge heights.

It is feasible to use storm surge data to represent the strength of a storm, but it is also necessary to incorporate a form of the storm tide into a storm erosion potential index. Laboratory experiments (HUGHES, 1983) and field observations show that dune erosion and beach profile changes are small until the water level rises to the toe of the dune and the dune begins to be exposed to storm wave action. Thus there is a critical elevation above which storm waves have their greatest effect.

Water level fluctuates as the tide rises and falls along the coast. Generally, the mean high high water (MHHW) calculated from tide gauge records approximates the beach berm elevation. In addition, storm surges are mainly composed of the abnormal water level caused by onshore wind stress, low atmospheric pressure, and wave set-up induced by breaking waves. Storm surges caused by atmospheric factors have a relatively large spatial scale on the open coast, consistent within an alongshore distance of 10–100 kilometers for relatively straight barrier islands. However, the storm surge at a particular location may change considerably over a short distance due to the effect of wave set-up since the size of breaking waves is controlled by interactions with local topography. The storm surge recorded at tide gauges does not include the effect of wave set-up because the tide gauges are usually located outside the surf zone. Therefore, the MHHW calculated from long-term tide gauge records does not include the local wave set-up effect. The significant wave heights caused by severe nor'easters along the U.S. East Coast are about 4–8 m (DOLAN and DAVIS, 1992; FULFORD *et al.*, 1994; KRIEBEL and DALRYMPLE, 1995). KRIEBEL and DALRYMPLE (1995) estimated that wave set-up is about 0.125 of significant wave height in deep water based on large-scale laboratory experiments. Thus wave heights of 4–8 m can produce wave set-up of 0.5–1.0 m. This wave set-up plus the swash run-up (NIELSEN and HANSLOW, 1991) is considerably higher than MHHW at high tides so that storm waves will ride up the beach to an elevation high enough to attack the dunes directly. In addition, the higher the storm tides are above MHHW, the more forceful is the attack of storm waves on dunes or bluffs. Thus the value of water level higher than MHHW can be introduced into a storm index as a weight. For these reasons, a storm erosion potential index (SEPI) is proposed here as the sum of the product of hourly values of storm surge height above two standard deviations, $S_{2SD}(t)$, and water level greater than MHHW, S_{MHHW}, as:

$$\mathrm{SEPI} = \sum_{t=0}^{t_D} S_{2SD}(t) H_{MHHW}(t) \Delta t \tag{4}$$

where Δt is the time interval (in this work $\Delta t = 1$ hr), and the quantity t_D is the integer number of hours of storm duration. Figure 2 presents an example of this index for the

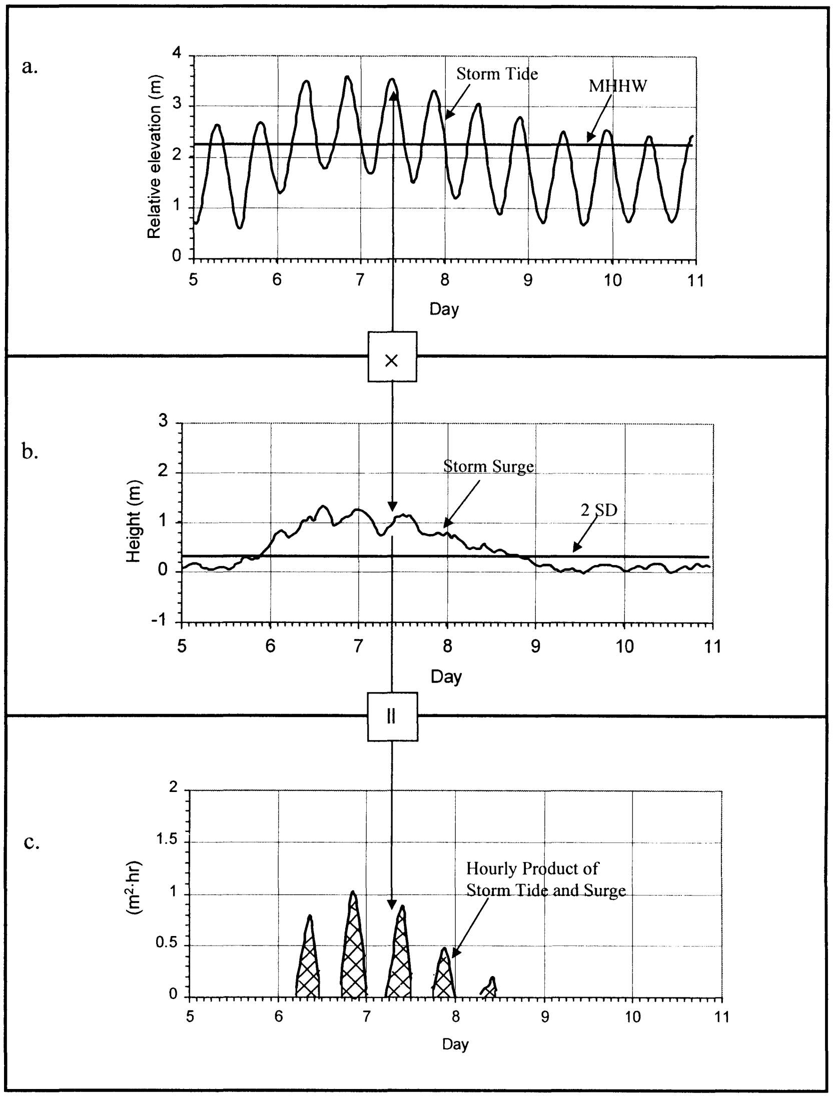


Figure 2. Storm tides (sum of the astronomical tide and storm surge) relative to local datum (a) and storm surges (b) at Sandy Hook during March 5–9, 1962. Further information about local datums can be found at www.opsd.nos.noaa.gov. The coincidence of perigean spring tides with storm surges results in five large high tides greater than MHHW. The cross-hatched area is the storm erosion potential index (SEPI) value (c), a measure of storm erosion potential. The SEPI is the sum of the hourly products of surges above 2 SD and storm tides above MHHW.

nor'easter of March 5–9, 1962 for data taken at the Sandy Hook, New Jersey tide gauge. The standard deviation of storm surges was estimated using the entire storm surge record for the gauge.

Hourly water level records from more than ten tide gauges with length of 60–90 years along the U.S. East Coast were analyzed in this study. Hourly water levels and MHHW for all US East Coast tide gauge locations were obtained through the online database of the National Ocean Service (NOS) of NOAA (www.opsd.nos.noaa.gov).

TESTS AND COMPARISIONS OF THE SEPI WITH FIELD DATA

To examine the relationship between SEPI and beach erosion, quantitative data on shoreline retreat magnitude or beach volume loss caused by severe storms with different intensities are required. Unfortunately, only limited such data are available for the U.S. East Coast. Ideally, a shoreline or beach profile survey immediately before and after a storm would be required to derive the exact erosion magnitude caused by that storm. It is difficult and expensive to obtain such data using traditional surveying techniques so little data are available, but there are reports obtainable from local and state governments concerning property damage caused by large historical storms. Although property damage is related both to storm severity and the development status of a specific beach, property damage data still provide a qualitative indication of severity of storm impact in space and time. It is reasonable to compare property damage data with storm erosional potential index to examine their relationship qual-

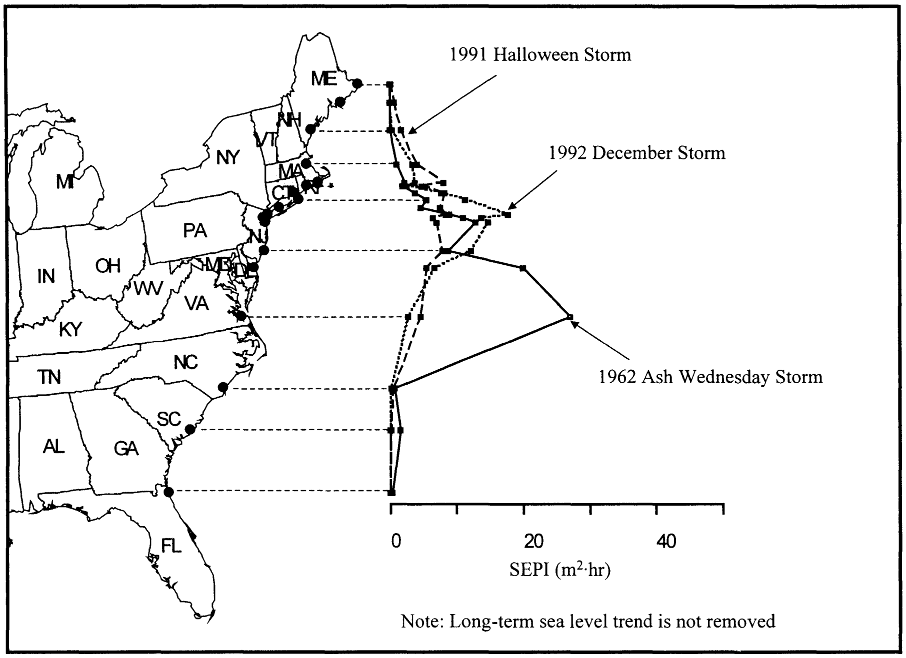


Figure 3. Spatial Variation of the SEPI for the 1962, 1991, and 1992 storms.

itatively. Three storms (1962 Ash Wednesday, 1991 Halloween, and 1992 December nor'easters) were selected for such an investigation because they were major events impacting the U.S. East Coast since the 1950s, and there are rich records about these storms and resulting property damage.

The 1962 storm began to develop as a weak circulation pattern off the Atlantic coast of Florida on March 4 (O'Brien and Johnson, 1963). The storm intensified on March 5, and a large low pressure with several separate centers developed in the Atlantic Ocean between Florida and the south coast of North Carolina (Cooperman and Rosendal, 1962). At the same time, the low-pressure centers moved north-northeastward. The movement almost stagnated on March 6 because of the blocking of a high-pressure system over Canada. The low-pressure system then moved slowly east-northeastward along the U.S. East Coast on March 7 and 8. At the same time, the low-pressure system was elongated as a result of the southward movement of the high-pressure system over Canada. This resulted in a very deep pressure gradient on the north side of the low-pressure center. The strong northeasterly winds from this deep pressure gradient and elongated fetch produced a high storm surge and large waves which severely battered beaches from New England to Cape Hatteras, North Carolina.

The 1991 Halloween Storm started on October 28 when a low-pressure cell reached the North Atlantic as a cold front moved across New England (National Weather Service, 1991). The storm moved west-southwestward from October 29 to 31, then took a "U" turn toward northward on November 1, proceeded northward on November 2, and reached Canada on November 3 (Fitzgerald *et al.*, 1994). In addition, a subtropical low developed near Bermuda on October 26. This low moved northward and intensified to become Hurricane Grace on October 28. Grace moved northward and finally merged with the nor'easter on October 29. The combination of the nor'easter and Hurricane Grace resulted in erosion and considerable property damage along the U.S. East Coast (National Weather Service, 1991).

The 1992 December storm originated from a migratory low-pressure system. The storm moved northward to the Delmarva peninsula from southern Georgia on December 10. It lingered over the Delmarva coast on December 11 because a strong high-pressure system over Canada retarded the northward movement of the storm. The storm moved offshore early on December 12 (Deitemyer, 1993; Campbell and Vietri, 1994). The large storm waves and high storm surges coincided with spring high tides, resulting in extensive erosion from New York to Delaware (Fulford *et al.*, 1994).

Figure 3 shows the spatial distribution of the SEPI (the integral of the product of storm surge and storm tide) for the 1962, 1991, and 1992 storms along the U.S. East Coast. The 1962 storm had by far the greatest erosion potential, 1992 storm was second, and the 1991 storm had the least. Field surveys showed that the 1962 storm caused extensive overwash from Long Island, New York to Hatteras Island, North Carolina. Numerous dunes were eroded away completely and flattened (Stewart, 1962; Cooperman and Rosendal, 1962; Bretschneider, 1964; Friedlander *et al.*, 1977; Savadove and Buchholz, 1993). By comparison, the 1991 storm only produced modest beach erosion along the U.S. East Coast, and most dunes were left intact. Even in Massachusetts, one of the most severely impacted areas, beach erosion was limited to the berm area (Fitzgerald *et al.*, 1994). Much of the damage was caused by flooding as the long

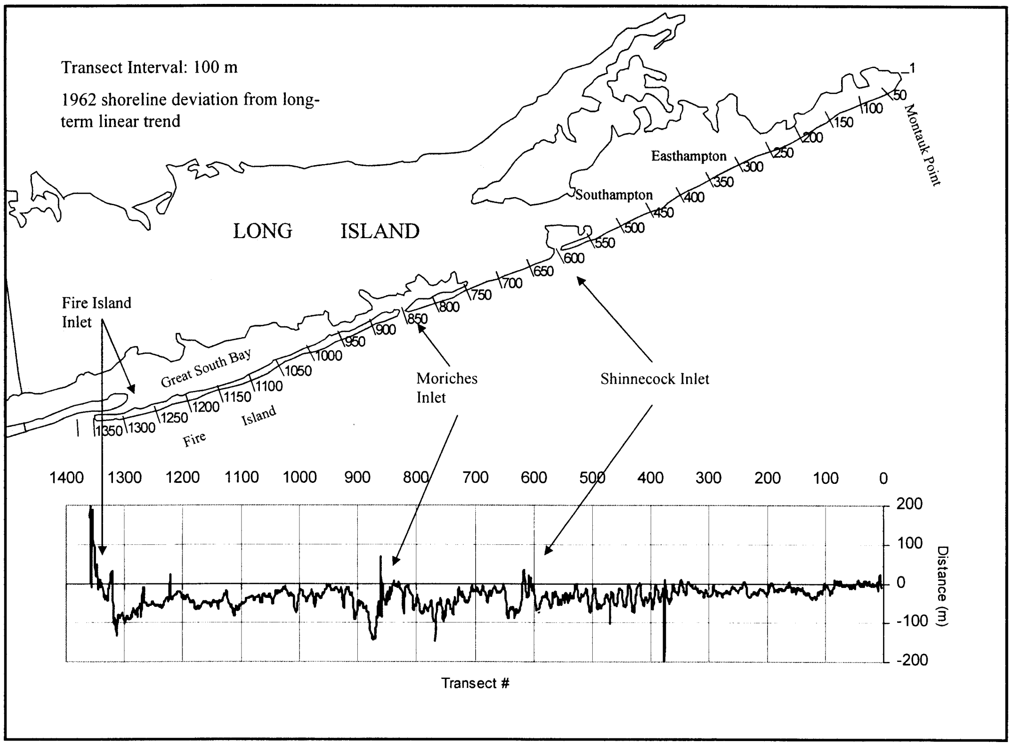


Figure 4. Shoreline position change caused by the 1962 Ash Wednesday Storm for the south shore of Long Island, New York.

period waves overtopped beaches and low-lying dunes. The 1992 storm caused extensive beach and dune erosion and overwashed many locations along the south shore of Long Island, New York. Sea walls and bulkheads failed at Coney Island, New York and elsewhere. Two breaches were created by the storm at the erosion "hot spot" downdrift of the Westhampton Beach groin field (TERCHUNIAN and COVELLO, 1994). Limited erosion occurred at New Jersey because of protection afforded by coastal engineering works and beach nourishment projects, although the road surface was washed away at some places (FULFORD *et al.*, 1994). Clearly, the 1962 storm caused the most severe erosion along the U.S. East Coast, and 1991 storm resulted in the least beach erosion. The 1992 storm produced an intermediate level of erosion. Thus the beach erosion induced by 1962, 1991, and 1992 storms agrees with the magnitude of the storm erosion index in a qualitative fashion.

The geographical change of the SEPIs indicates the spatial extent of storm influence. Figure 3 shows that the 1962 storm had the largest erosion potential for the Delaware and Maryland coasts. The erosion potential decreased both north and south. The storm erosion index becomes very small north of Cape Cod and south of Cape Hatteras. Field surveys demonstrated that most property damage occurred between Cape Cod and Cape Haterras (COOPERMAN and ROSENDAL, 1962). Delaware experienced the most severe beach erosion. Erosion at the New Jersey and south shore of Long Island, New York coasts was somewhat less severe, but New Jersey suffered more property damage since there were more beachfront buildings at risk at that time (COOPERMAN and ROSENDAL, 1962).

No systematic field survey of the U.S. East Coast shoreline position or beach volume was carried out after the 1962 storm. However, available field surveys of high water marks after the storm do show a general increased trend from mid-Long Island to the south end of New Jersey (HARRIS, 1963). The 1962 storm shoreline positions were recorded along the length of Long Island, New York. The magnitude of shoreline retreat increased westward from Montauk to Fire Island Inlet, although there were considerable small-scale spatial fluctuations (Figure 4). This agrees with the increased trend of the storm erosion index from the east to west along Long Island (Figure 3). Although the lesser erosion at Montauk may be also related to more erosion-resistant headlands composed of glacial deposits, the spatial change of SEPI played an important role in causing this westward increase of erosion along the south shore of Long Island. The SEPI for 1992 showed relatively large values at the tide gauge sites at the Long Island, New York, New Jersey, and Delaware coasts. Field surveys after this storm show that these areas suffered the most severe erosion (FULFORD *et al.*, 1994; TERCHUNIAN and COVELLO, 1994). Thus, variations of the SEPI index do reflect the extent of beach erosion on a spatial basis.

The value of the storm surge integrated intensity is defined as the area under the storm surge water level curve above two standard deviations (ZHANG *et al.*, 1997). For the 1962 and 1992 storms, the maximum values are almost equal, although peaks occur in different locations (Figure 5). Numer-

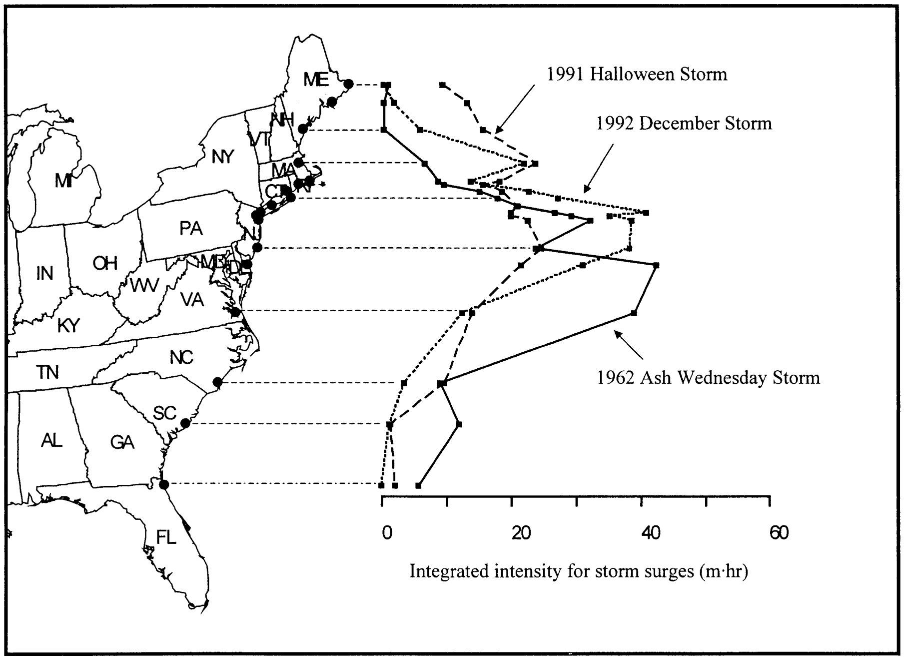
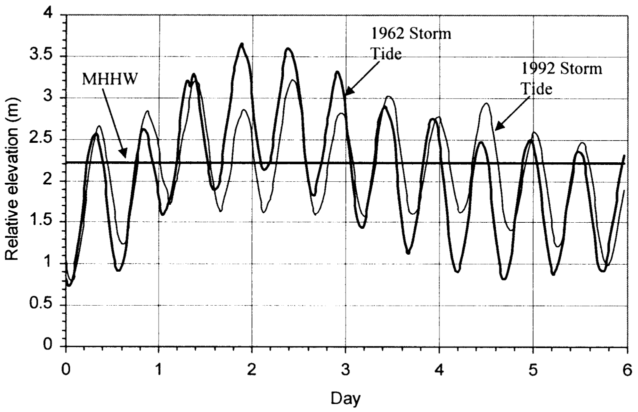


Figure 5. Spatial distribution of integrated intensity for selected storm surges. Note that the integrated intensities for the 1962 and 1992 storms are about the same, but the locations of the peak values are different.

ical simulations of storm waves also showed that wave heights from both storms were similar (FULFORD *et al.*, 1994). However, the maximum erosion potential of the 1962 storm is much larger than that in 1992, indicating that the 1962 event resulted in more severe erosion of beaches and dunes. This is true because erosion potential is not only related to storm strength but also to the magnitude of the astronomical tides upon which the storm rides. The 1962 storm coincided with a perigean spring tide. The consecutive high storm tides had almost equal amplitudes (Figure 6). But the amplitudes of consecutive high water levels of the 1992 storm are very different. There is only one large storm tide within two cycles; it is the consecutive high tides that make the 1962 storm so much more destructive.



Figures 6. Storm tides at Lewes, Delaware during March 5–10, 1962 and December 10–15, 1992.

The role of storm tides on beach erosion was examined further by comparing storm events that occurred at Boston, MA. Figure 7 shows three storm events identified from the Boston gauge. The storm that occurred from February 24 to 28, 1969 has little erosion potential although it had a significant storm surge. The water level never rose above MHHW since this storm occurred during neap tides.

The most severe storms that influenced the Massachusetts coast are the Blizzard of 1978 (February 6–8) and the Halloween Day Storm of 1991 (October 28–November 1). Field surveys after these two storms indicated that the impact of the Halloween storm was much less than that of the Blizzard (FITZGERALD *et al.*, 1994). The hydrographs of the 1978 and 1991 storms (Figures 7b and 7c) show that the integrated intensity of the two storms was almost the same (24.2 and 25.9 m·hr, respectively), indicating that the severity of the two storms was similar. However, the coincidence with spring tides in 1978 produced two consecutive high storm tides with heights higher than 5 m (relative to local datum, Figure 7b). In contrast to the 1978 storm, only one high storm tide was above 5 m (Figure 7c) during the 1991 storm. The storm erosion potential for the 1978 storm is about 7.8 (m^2·hr), almost twice that of 1991 (4.3 m^2·hr). It was the coincidence with astronomical spring tides that made the 1978 storm more destructive than the 1991 storm.

The dominant role of storm tides in causing erosion is very important for predicting consequences of large nor'easters. It

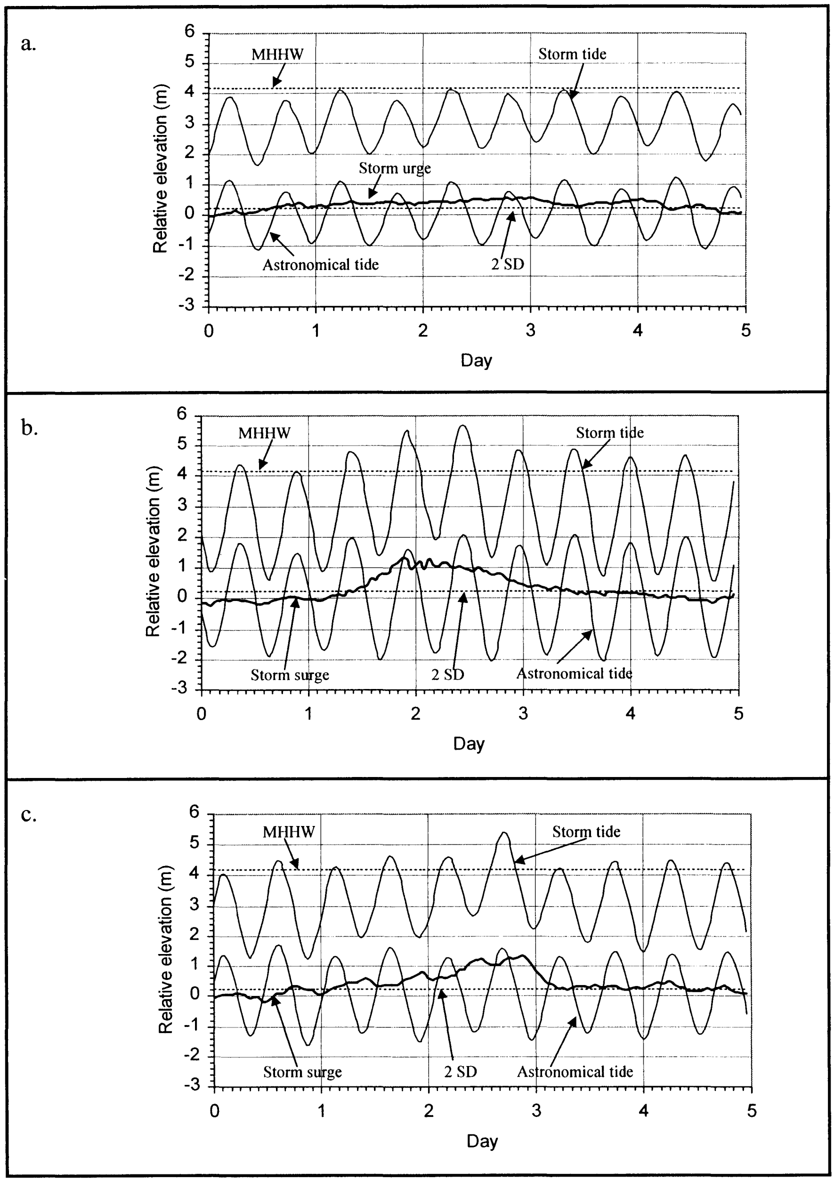


Figure 7. Storm tide, astronomical tide, and storm surge during 2/24/1969–2/28/1969 (a), 2/5/1978–2/9/1978 (b), and 10/28/1991–11/1/1991 (c) at Boston Harbor, MA. The storm tide (i.e., recorded water level) is referenced to local datum.

is difficult to predict the ultimate strength of such storms in real time, but the occurrence of spring and perigean spring tides for even decades into the future is well known from the numerous tide gauge records along the U.S. East Coast. Thus it is practical to compute the future times when tides are above MHHW, their amplitudes and duration. Current numerical weather models can predict movement and intensity of storms for at least several days in advance so that an appropriate warning can be given if a storm is found to be coincident with spring or perigean spring tides.

In addition to examining the spatial correlation between storm erosion index and beach erosion, the SEPI derived from the Lewes, Delaware tide gauge and historical shoreline position data for Delaware were used to investigate the temporal relationship between them. Water level records from 1957 to 1997 are available from the Lewes gauge. The average shoreline positions near Cottonpatch Hill, about 2.5 km south of Indian River Inlet, were selected to delineate historical shoreline change since data are relatively rich there. Figure 8 shows the SEPI at Lewes from 1957 to 1997 and historical shoreline positions at Cottonpatch Hill from 1944 to 1997. There are no water levels available from 1944 to 1957 at Lewes. However, since large storms, especially nor'easters occur at a large spatial scale, it is expected that major storms influencing Delaware also appeared in water level records at the Atlantic City gauge in New Jersey (about 86 km from

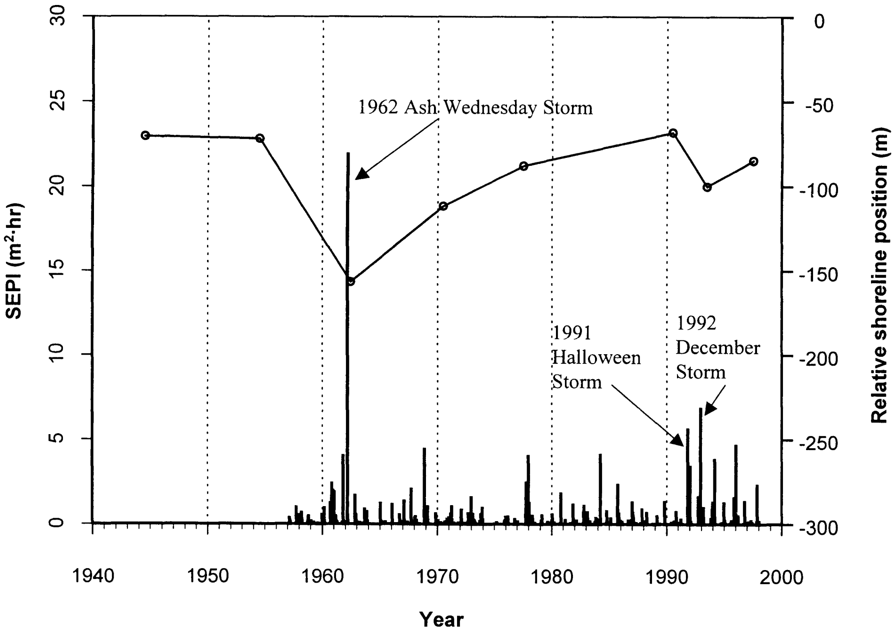


Figure 8. Relationship between storm erosion potential index (SEPI) and shoreline changes. The bar represents the erosion potential of storm events occurring at Lewes, Delaware from 1957 to 1997. The line shows historical shoreline positions at Cottonpatch Hill, Delaware. The shoreline positions are measured relative to the 1845 shoreline. Note the great erosion potential of the Ash Wednesday Storm of 1962 and resulting shoreline retreat.

Lewes). Therefore, it is reasonable to use data from the Atlantic City gauge to examine whether there are any large storms from 1944 to 1957, but none were found. Shoreline position data also showed that no significant changes occurred between 1944 and 1954.

The Ash Wednesday Storm of 1962, with the highest SEPI, caused dramatic shoreline retreat along the Delaware Atlantic coast, amounting to 80–90 m. There have been no great storms like the Ash Wednesday Storm affecting the Delaware coast since 1962; the beach recovered gradually over the next decade to a position consistent with its underlying long-term trend (GALGANO, 1998; ZHANG, 1998; DOUGLAS *et al.*, 1998). The 1993 shoreline positions showed retreat in response to the major nor'easter on December 10–15, 1992. Note that the shoreline retreat induced by the 1992 storm was much less than that induced by the Ash Wednesday Storm because the latter had much larger erosion potential. Beach profile data near the Cottonpatch Hill area also demonstrated that only a small part of the dune was eroded away during the 1992 storm, while the 1962 storm flattened the frontal dune (Figure 9).

DISCUSSION AND CONCLUSIONS

The storm erosion potential index (SEPI) proposed herein can be used to characterize the historical and spatial storm impacts on U.S. East Coast beaches because it accurately reflects the severity of storm-induced erosion. Figure 10 displays the temporal changes of the yearly summation of SEPI during this century. The index does not present any discernible long-term trend, but displays remarkable decadal variability. There is an annual difference of 200% to 500% in the SEPI, which gives more weight to large storms with long duration and high surges. For example, the great storm in 1962 (Ash Wednesday Storm) increased the yearly summation of SEPI significantly. Thus a high SEPI does not always mean that a large number of storms occurred. The bias of the SEPI to large storms is reasonable since one great storm often causes much more severe beach erosion than the contribution of many small storms, especially if they do not impact the dune.

The spatial distribution of the average SEPI (Figure 11) indicates that the coast from southern North Carolina to Florida has relatively low storm erosion potential, while the coast from northern North Carolina to Maine experiences relatively higher storm-induced erosion. The average integrated intensity of storms displays a similar pattern. The reason is that the coast north of Cape Hatteras is mainly affected by nor'easters while the coast southward is dominated by hurricanes. Nor'easters are more important than hurricanes in causing beach erosion because of their long duration, large lateral extent, and greater frequency. The Delmarva coast is shown to be the most vulnerable to storm-induced erosion, while the New Jersey and New York coasts also experience considerable storm impact. Actually, the Outer Bank of North Carolina is probably the highest of all, but there are no long-term tide gauge records available for this erosion-prone coast.

There is no significant long-term trend of storm activity during the 20th century along the U.S. East Coast (ZHANG *et al.*, 1997; ZHANG, 1998). Does that mean that the impact of storms has remained unchanged for the past 100 years? Onshore storm impacts are strongly dependent on the storm tide, which is the sum of the astronomical tide and the storm

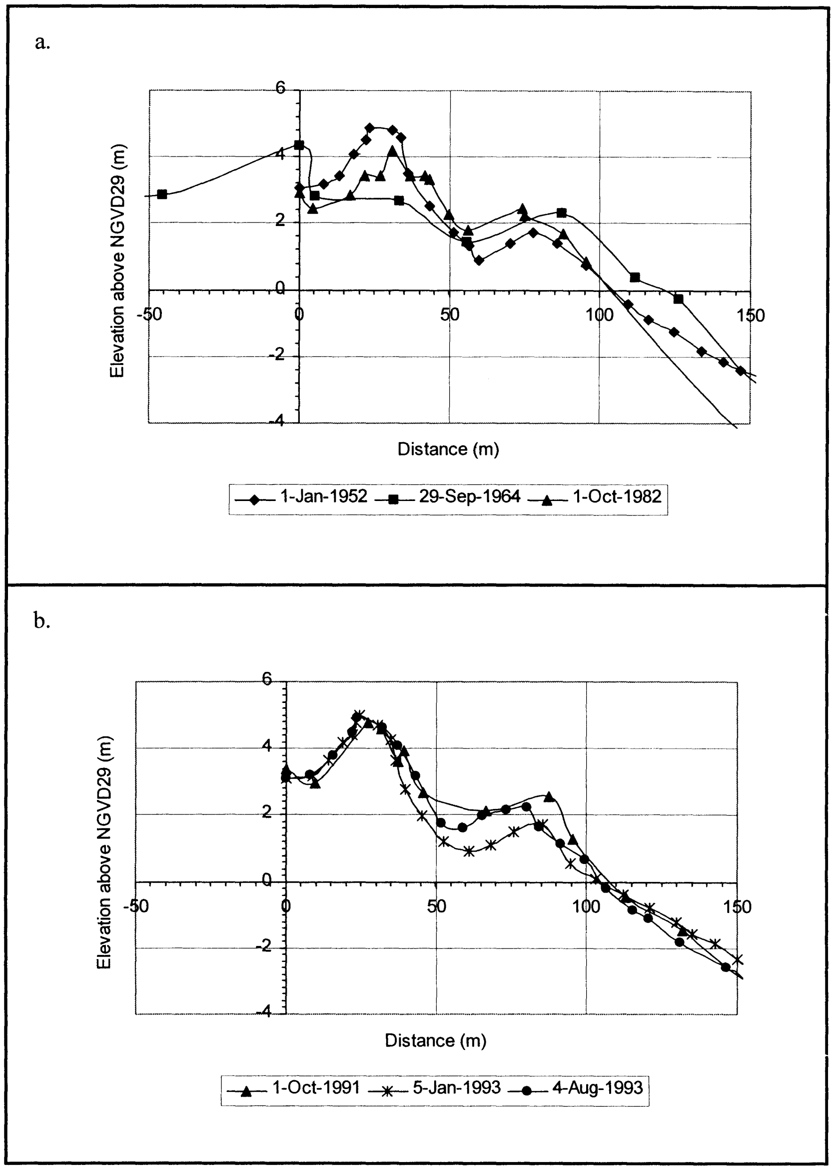


Figure 9. Beach profiles at Cottonpatch Hill, Delaware during 1952, 1964, and 1982. Note that in (a) the frontal dune that existed in 1952 was destroyed by the Ash Wednesday storm of 1962. Dune recovery is evident in the 1982 profile. Chart (b) shows that the later storms did not have a significant impact on the dune.

surge. Wave tank experiments and numerical models demonstrate that a 20% increase in storm tides results in 60% more dune erosion (STEETZEL, 1991). The frequency of occurrence of water level above a certain elevation has increased because of rising sea level during the past century. The tide gauge record of Atlantic City, New Jersey shows that a 36 cm rise in sea level has increased the frequency of water level from 0.2% to 3% at an elevation higher than 2.5 m (Figure 12).

Sea level has risen 20–40 cm along the U.S. East Coast in the past 100 years (DOUGLAS, 1991). This rise has increased the height and duration of storm tides. Thus, even if there is no significant long-term trend in storm activity, sea level rise exacerbates erosion and flood damage from modern-day storms that would have been less important a century ago. Figure 13 shows historical changes of yearly summation of SEPI including and excluding sea level changes at Atlantic City, New Jersey. It is clear that sea level rise has resulted in an increase in storm erosion potential, and coastal structures will suffer more storm impact unless mitigating actions are taken.

We have shown that the Delmarva coast is the most vulnerable to storm-induced erosion, but suspect that the Outer Bank of North Carolina would even exceed this area if long-term data were available. The New Jersey and Long Island, New York coasts also experience considerable storm impact.

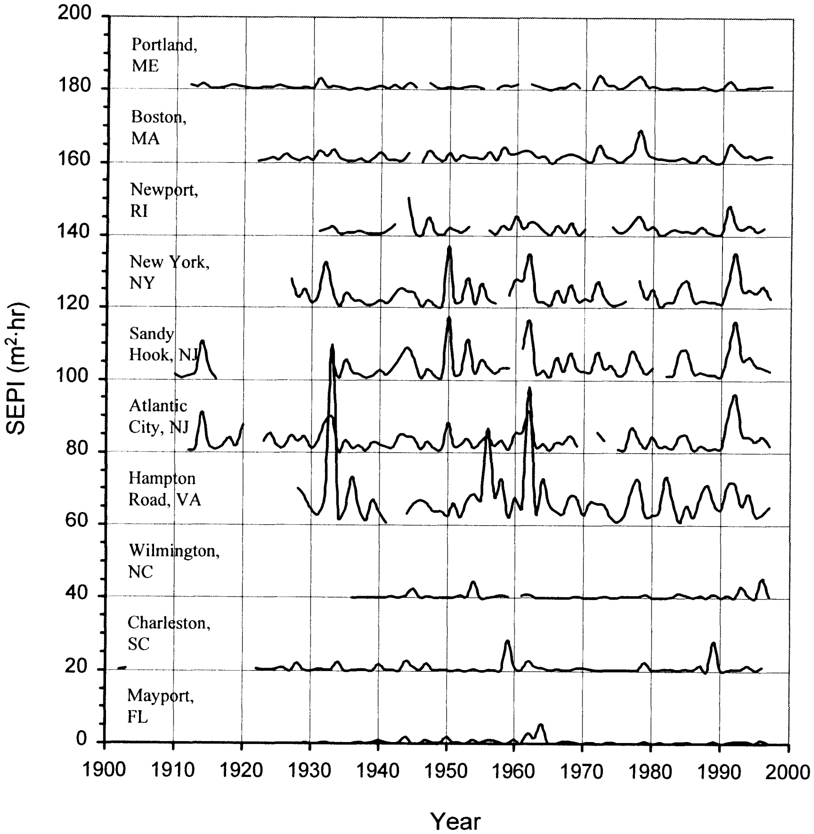


Figure 10. Storm Erosion Potential Index calculated from yearly summation of SEPI for individual storms along the U.S. East Coast.

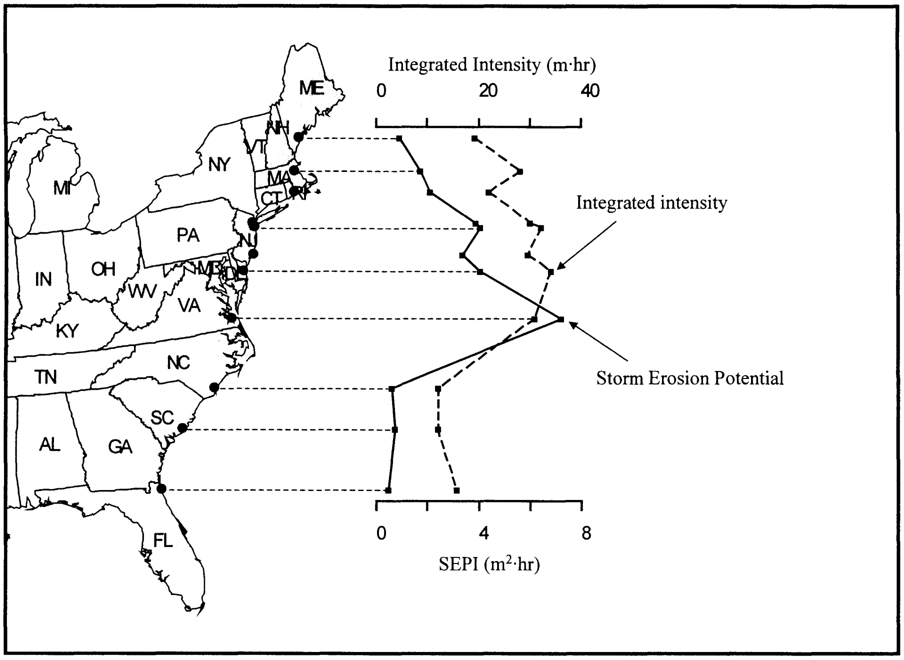


Figure 11. Spatial distribution of the average storm erosion potential index, and integrated intensity along the U.S. East Coast.

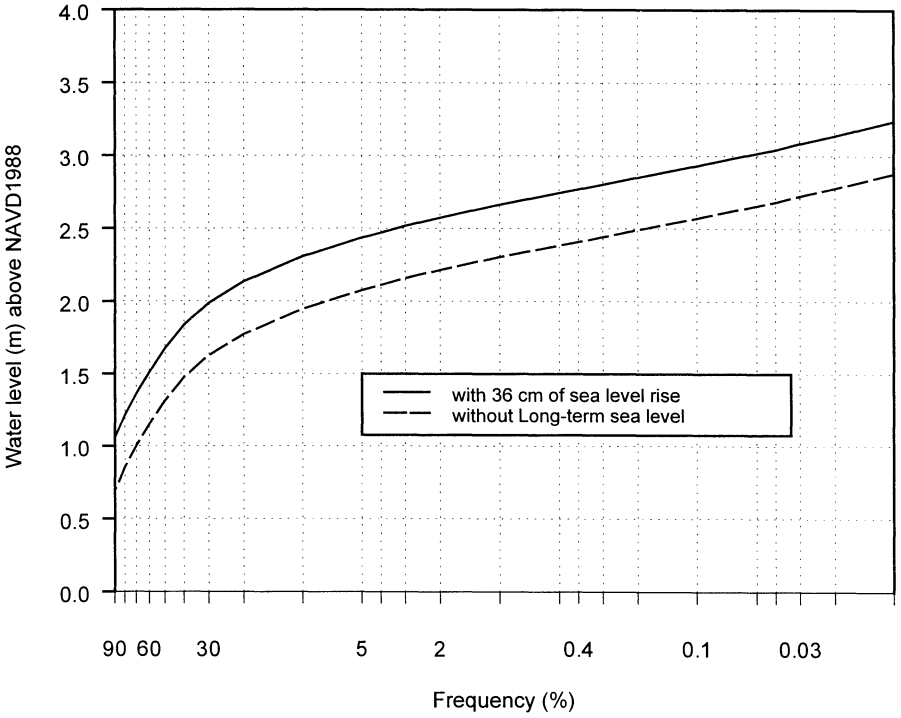


Figure 12. The dashed line represents the frequency of water level heights at Atlantic City, New Jersey from 1911 to 1993 after the long-term sea level trend was removed. The solid line represents the frequency of water level that includes the 0.36 m of sea level rise from 1911 to 1993.

The New England coast suffers less storm-induced erosion by comparision. The coast from southern North Carolina to Florida experiences the least storm-induced erosion because nor'easters are infrequent and less severe there.

In conclusion, the beach erosion potential of large nor'easters is determined by storm tides, waves, and duration. Storm tides have much more effect on beach erosion than storm waves; this finding largely invalidates the index proposed by DOLAN and DAVIS (1992). Thus beach erosion induced by storms is not only related to the strength and

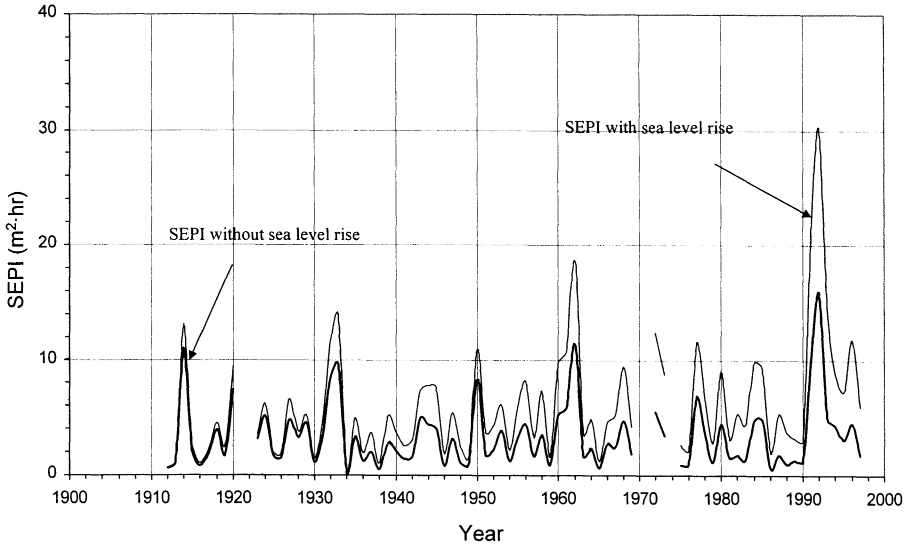


Figure 13. Time series plot of yearly summation of SEPI for individual storms with and without sea level rise at Atlantic City, New Jersey. The apparent secular increase is due to sea level rise during the 20th century, and indicates that rising sea levels exacerbate the effect of storms on coastal areas.

duration of a storm but also depends critically on the astronomical high tide. A large storm coinciding with perigean spring tides will severely impact beaches. The storm erosion potential index (SEPI) proposed in this paper includes the combined effect of storm tides, wave energy and duration, and thus reflects the erosion potential of large storms.

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LITERATURE CITED

Allen, J.R., 1981. Beach erosion as function of variations in the sediment budget, Sandy Hook, New Jersey, U.S.A. *Earth Surface and Landforms,* 6, 139–150.

Balsillie, J.H., 1986. Beach and coast erosion due to extreme event impact. *Shore and Beach,* 54, 22–37.

Balsillie, J.H., 1999. Volumetric beach and coast erosion due to storm and hurricane impact. *Open File Report No.78,* Florida Geological Survey, Tallahassee, Florida, 37p.

Bretschneider, C.L., 1964. The Ash Wednesday east coast storm, March 5–8, 1962: a hindcast of events, causes, and effects: *Proceedings of the 9th Conference on Coastal Engineering,* pp. 617–659.

Bryant, E., 1988. Storminess and high beach changes, Stanwell Park, Australia, 1943–1978. *Marine Geology,* 79, 171–187.

Campbell, T.J. and Vietri, J., 1994. Storm impacts and response on the south shore of Long Island: Fire Island Inlet to Montauk Point: *Alternative Technologies in Beach Preservation, Proceedings of the 7th National Conference on Beach Preservation Technology,* pp. 488–507.

Cooperman, A.I. and Rosendal, H.E., 1962. Great Atlantic Storm, 1962. *Marine Weather Log,* 6(3), 137–145.

Dean, R.G., 1991. Equilibrium beach profiles: characteristics and applications. *Journal of Coastal Research,* 7(1), 53–84.

Deitemyer, D.H., 1993. Effects of December 1992 Nor'easter on water levels. *NOAA Technical Memorandum NOS OES 006,* Silver Spring, Maryland, 51p.

Dolan, R. and Davis, R.E., 1992. An intensity scale for Atlantic coast northeast storms. *Journal of Coastal Research,* 8, 352–364.

Douglas, B.C., 1991. Global sea level rise. *Journal of Geophysical Research,* 96(C4), 6981–6992.

Douglas, B.C.; Crowell, M., and Leatherman, S.P., 1998. Considerations for shoreline position prediction. *Journal of Coastal Research,* 14, 1025–1033.

Edelman, T., 1968, Dune erosion during storm conditions: *Proceedings of the 11th Conference of Coastal Engineering,* pp. 719–722.

Edelman, T., 1972, Dune erosion during storm conditions: *Proceedings of the 13th Conference of Coastal Engineering,* pp. 1305–1312.

Fenster, M.S.; Dolan, R., and Elder, J.F., 1993. A new method for predicting shoreline positions from historical data. *Journal of Coastal Research,* 9(1), 147–171.

Fitzgerald, D.M.; Van Heteren, S., and Montello, T.M., 1994. Shoreline processes and damage resulting from the Halloween Eve Storm of 1991 along the north and south shores of Massachusetts Bay, U.S.A. *Journal of Coastal Research,* 10(1), 113–132.

Friedlander, S.C.; Jackson, S.E.; Lansdale, J.S.; Mather, J.R.; Murray, D.A.; Rees, P.M.; Schellhardt, E.A., and Swave, F.J., 1977. Coastal storm damage 1923–1974. *Technical Report No.4,* Office of Management, Budget and Planning, Dover, Delaware, 442p.

Fulford, E.T., Keon, T. and Gebert, J., 1994, Coastal storm of 11–15 December 1992: Delaware and New Jersey coast: *Alternative Technologies in Beach Preservation, Proceedings of the 7th National Conference on Beach Preservation Technology,* pp. 508–525.

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, 464 p.

Galgano, F.A.; Douglas, B.C. and Leatherman, S.P., 1998. Trends and vaiability of shoreline position. *Journal of Coastal Research,* Special Issue No.26, 282–291.

Harris, D.L., 1963. Coastal flooding by the storm of March 5–7, 1962. *Manuscript,* U.S. Weather Burea, Washington, D.C., 22p.

Hughes, S.A., 1983. Movable-bed modeling law for coastal dune erosion. *Journal of Waterway, Port, Coastal and Ocean Engineering,* 109(2), 164–179.

Hughes, S.A. and Chiu, T.Y., 1981. Beach and dune erosion during severe storms. *TR/043,* Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, Florida, 290p.

Kriebel, D.L. and Dalrymple, R.A., 1995. A northeaster risk index, R & D Coastal Engineering, Newark, Delaware, 33p.

Morgan, J.P. and Stone, G.W., 1985. A technique for quantifying the coastal geomorphology of Florida's barrier islands and sandy beaches. *Shore and Beach,* 53(1), 19–26.

Morton, R.A., 1991, Accurate shoreline mapping: past, present, and future: *Coastal Sediments'91,* pp. 997–1010.

Morton, R.A.; Paine, J.G., and Gilbeaut, J.G., 1994. Stages and durations of post-storm beach recovery, southeastern Texas coast, USA. *Journal of Coastal Research,* 10(4), 884–908.

National Weather Service, 1991. The Halloween Nor'easter of 1991: East Coast of the United States: Maine to Florida and Puerto Rico. *Natural Disaster Survey Report,* NOAA, Silver Spring, Maryland, 61p.

Nielsen, P. and Hanslow, D.J., 1991. Wave runup distributions on natural beaches. *Journal of Coastal Research,* 7(4), 1139–1152.

O'Brien, M.P. and Johnson, J.W., 1963. The March 1962 storm on the Atlantic coast of the United States: *Proceedings of 8th Conference on Coastal Engineering,* pp. 555–562.

Orford, J.D. and Carter, R.W.G., 1995. Examination of mesoscale forcing for a swash-aligned, gravel barrier from Nova Scotia. *Marine Geology,* 126, 201–211.

Orford, J.D.; Hinton, A.C.; Carter, R.W.G., and Jennings, S.C., 1992. A tidal link between sea level rise and coastal response of a gravel-dominated barrier in Nova Scotia. *Geophysical Monograph 69,* 11, 71–79.

Savadove, L. and Buchholz, M.T., 1993. *Great Storms of the Jersey Shore.* Harvey Cedars, NJ: Down The Shore Publishing, 203p.

Savage, R.J. and Birkemeier, A.M., 1987. Storm erosion data from the United States Atlantic coast: *Coastal Sediments '87,* pp. 1445–1459.

Simpson, R.H., 1974. The hurricane disaster potential scale. *Weatherwise,* 27, 169 and 186.

Steetzel, H.J., 1991. A model for profile changes during storm surges: *Coastal Sediments '91,* pp. 618–630.

Steetzel, H.J., 1993. Cross-shore Transport During Storm Surges. Ph.D. dissertation, Deft University of Technology, 242 p.

Stewart, J.Q., 1962. The great Atlantic coast tides of 5–8 March 1962. *Weatherwise,* 117–121.

Tancreto, A.E., 1958. A method for forecasting the maximum surge at Boston due to extratropical storms. *Monthly Weather Review,* 86(6), 197–200.

Terchunian, A.V. and Covello, D.M., 1994. Winter storms of 1992–1993: *Alternative Technologies in Beach Preservation, Proceedings of the 7th National Conference on Beach Preservation Technology,* pp. 594–607.

Vellinga, P., 1982. Beach and dune erosion during storms. *Coastal Engineering,* 6, 361–387.

Vellinga, P., 1986. Beach and Dune Erosion During Storm Surges. Ph.D. dissertation, Delft Hydraulics, 169 p.

Wood, F.J., 1982. *Tidal Dynamics: Coastal Flooding, and Cycles of Gravitational Force.* Dordrecht, Holland: Reidel, 531p.

Zhang, K., 1998. Twentieth Century Storm Activity and Sea Level Rise Along the U.S. East Coast and Their Impact on Shoreline Position. Ph.D. Dissertation, University of Maryland, College Park, MD, 266 p.

Zhang, K.; Douglas, B.C., and Leatherman, S.P., 1997. U.S. East Coast storm surges provide unique climate record. *EOS,* 78(37), 389 and 396–397.