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Forecasting Beach Erosion along the Oceanic Coastlines of the Northeast and Mid-Atlantic States

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FORECASTING BEACH EROSION ALONG THE OCEANIC COASTLINES OF THE NORTHEAST AND MID-ATLANTIC STATES

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APPROVAL SHEET

This thesis is submitted in partial fulfillment of

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DEDICATION

To my loving wife Olga, whose understanding and support made this work possible.

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ABSTRACT

A beach erosion equation which can be used to forecast qualitative estimates of beach erosion along the oceanic coastlines of the Northeast and Mid-Atlantic States (Maine to Virginia) has been developed by statistical evaluation of beach erosion reports and selected parameters from previous storms. The forecast equation was derived with a multiple regression screening program. The regression program was used to correlate qualitative estimates of erosion (predictand), with meteorological and oceanographic parameters (predictors) from 36 winter season (November 1 through April 30) extratropical storms, occurring during the period 1962-1973. The qualitative estimates of erosion (none, minor, moderate, major, and severe) were extracted from the Environmental Data Service publication, Storm Data, and then subjectively converted to numerical values. The trial predictors were tide height at National Ocean Survey tide stations, storm duration, mean amplitude of the spring tide, length of time between erosion events, type of beach material, month of the year, wave height and period at offshore light stations, and wave height and period computed by the Sverdrup-Munk-Bretschneider (SMB) hindcast equations for deep and shallow water. A generalized beach erosion equation was derived which computes beach erosion intensity as a function of storm duration, maximum tide height, maximum storm surge height, and month of the year. The multiple correlation coefficient associated with this equation was 0.69. The derived beach erosion equation was tested on independent data. The results of these tests indicate that the beach erosion equation provided meaningful forecast guidance.

The limited sample of erosion data (36 storms) showed that the greatest number of erosion events between November 1 and April 30 occurred during November, December, and February. January had the fewest number of erosion events. During the 12 winter seasons for which data were available, Maine and Massachusetts experienced about two erosion events per season. New Jersey, Delaware, and Virginia experienced about one event every two seasons. As for intensity of erosion (minor, moderate, major, and severe), New York and Virginia had severe erosion about one time every five seasons. Maine, Massachusetts, Rhode Island, New Jersey, and Delaware experienced severe erosion about one-half that often or about one time every 10 seasons.

Wave heights and periods were computed by the SMB deepwater and shallow-water wave equations for the 36 storms at six light stations located along the northeast coast of the United States (Portland, Boston, Buzzards Bay, Ambrose, Five Fathoms, and Chesapeake). Input data to the SMB equations were observed (measured) winds at the time of the maximum observed (visually estimated) wave height at the light stations. The computed wave heights were compared to the maximum observed wave heights at the light stations. For these comparisons, the correlation coefficient associated with the SMB shallow-water equation (0.52) was slightly higher than the correlation coefficient associated with the SMB deepwater equation (0.45). The root mean square error associated with each equation was approximately five feet.

FORECASTING BEACH EROSION ALONG THE OCEANIC COASTLINES OF THE NORTHEAST AND MID-ATLANTIC STATES

INTRODUCTION

The coastal storm of early March 1962 affected the entire Atlantic Coast of the United States causing severe erosion at locations between Long Island and Cape Hatteras. This storm was the most devasting extratropical storm on record, as it caused property damage estimated in excess of $200 million (Pore, et al., 1974). It is fortunate that storms causing this much damage are rare. However, storms with large erosion potential can occur each winter. Accurate forecasts of these storm-related beach erosion events are important. In regards to the importance of beach erosion forecasts, Silvio G. Simplico, Director of the Eastern Region of the National Weather Service, stated the following in a memo dated March 12, 1973:

> In recent years there has been a series of rather serious beach erosion problems along the east coast. I am fearful that there could, someday, be a major beach erosion disaster along our eastern seaboard, due to wind related wave action, with consequent loss of life and property. With this in mind I have asked the Scientific Services Division of the Eastern Region Headquarters of the National Weather Service to assist the field offices in developing a systematic approach to the problem of beach erosion forecasting.

Accurate forecasts of beach erosion would give coastal residents time to prepare for erosion. Property such as automobiles and furniture could be moved to safer areas. Homes, threatened by erosion, could be protected from concomitant fire and water damage by disconnecting electrical and water lines. While it is impractical for residents to move their homes from an area where severe erosion is forecast, residents who receive advance (36 to 48-hour) warning, could construct temporary protective bulkheads around their homes. The critical time to forecast beach erosion by the National Weather Service Forecast Offices occurs simultaneously with many other forecast responsibilities with ensuing coastal storms. It is therefore desirable to develop an automated objective technique which will provide the forecaster with accurate beach erosion forecast guidance.

TYPES OF BEACH EROSION

Beach erosion is the removal of portions of the beach by wave action, tidal currents, littoral currents, or winds (U.S. Army Coastal Engineering Research Center, 1973, p. A-3). Portions of the beach may also be removed by other storm-induced activity such as washovers from both the ocean and the bay after a storm.

The rates of erosion may be measured over several time scales. Long term erosion is measured in years, seasonal erosion in months, while erosion related to storms is measured in days or hours. It is storm-related erosion that the National Weather Service has the responsibility for forecasting. Although long term erosion rates are very important in planning coastal communities and locating coastal industries, they are not addressed in this study.

BEACHES ALONG THE OCEANIC COASTLINES
OF THE NORTHEAST AND MID-ATLANTIC STATES

The term "beach" is defined as a zone of unconsolidated material extending landward from the mean low water line to the locality where there is a change in material or physiographic form, such as a zone of permanent vegetation, a zone of dunes, or a sea cliff (Shepard, 1973, p. 125). Figure 1 depicts the principal general subdivisions of beaches and the adjacent shallow-water area. The beach nomenclature used in this figure and other portions of the text are defined in Appendix A.

Beaches vary according to sand size, the amount of tide, and exposure to wave attack (Shepard, 1973). Fine-sand beaches (0.25 to 0.125 millimeters) have very gentle foreshore slopes. The foreshore slope shows a strong correlation with grain size which, in turn, is related to beach permeability (Shepard, 1973).

In seas with small tide ranges, beaches are often bordered by a series of longshore bars and troughs. In seas with large tidal ranges, beaches are likely to have broad terraces. Each terrace will have at least one large bar exposed at the low tide level (Shepard, 1973). These offshore conditions will vary greatly with the state of the beach at any particular time.

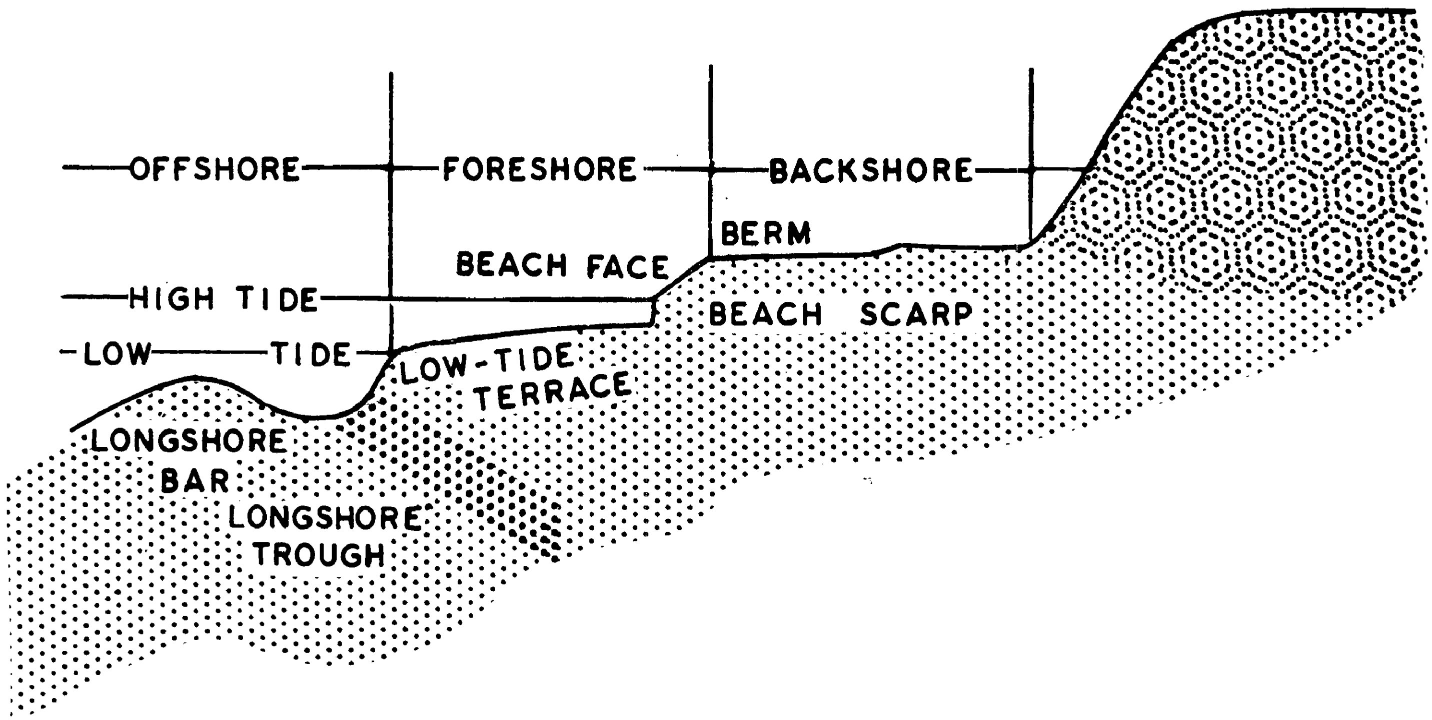


Figure 1. Principal general subdivisions of beaches and the adjacent shallow-water area (Shepard, 1973).

Beaches which are exposed to large waves have a lower inclination of the foreshore inside the zone of large waves than beaches which are exposed to small waves (Shepard, 1973).

The New England coast of the United States is generally characterized by rocky headlands separating short beaches of sand, gravel or cobbles. Exceptions to this dominant condition are the sandy beaches in northeastern Massachusetts, and along Cape Cod, Martha's Vineyard, and Nantucket. From the eastern tip of Long Island, New York to the North Carolina Coast, the beach materials are characteristically sand with median diameters in the range of 0.2 to 0.6 millimeters (2.3 to 0.7 phi). This material is mainly quartz sand (U.S. Army Coastal Engineering Research Center, 1973, p. 4-22).

CAUSES OF STORM-RELATED EROSION

Factors that are important in determining storm-related erosion (Hayes and Boothroyd, 1969; U.S. Army Corps of Engineers, 1971; King, 1972; and U.S. Army Coastal Engineering Research Center, 1973) are:

(1) winds (speed and direction)

(2) waves, swell, and effect of offshore bathymetry

(3) breakers

(4) astronomical tide

(5) storm surge

(6) initial condition of the beach

Winds

Winds impart energy to the water, producing currents and waves. If the wind-induced surface currents are traveling toward the shore, then there is significant return flow along the bottom which may transport sediment seaward. If there are strong offshore winds, then the result is an offshore surface current and an onshore bottom current which may transport sediment landward (Wiegel, 1964, p. 323-327). Winds modify existing waves. Onshore winds will increase the heights of incoming shoaling waves, while offshore winds will reduce the heights of these waves.

Winds also act directly on beaches by blowing sand off beaches (deflation) and by depositing sand on dunes (Savage and Woodhouse, 1968). Sand transport by wind occurs by saltation, creep, and suspension (in order of importance). Because of the large differences in density between sand grains and air, transport by suspension is relatively unimportant in coastal dunes (Goldsmith, 1975). Deflation usually removes the finer material, leaving behind coarser sediments and shell fragments. Sand blown seaward from the beach usually falls into the surf zone. Even though this sand will be introduced into the littoral transport system, this sand may be lost from a particular section of the beach through the action of longshore currents.

Sand blown landward from the beach may form dunes, add to existing dunes, or be deposited in lagoons behind barrier islands. Dune building material is supplied to the foreshore zone by streams, erosion of the shore by waves and currents and in some cases by onshore movement of sand from deeper water (U.S. Army Coastal Research Center, 1973). For dunes to form, there must be a significant quantity of sand available for transport by wind as well as features for trapping the moving sand. The principal features that trap sand are topographic irregularities, the dunes themselves, and vegetation (U.S. Army Coastal Engineering Research Center, 1973). If a section of a beach does not have these trapping features, dunes will not form. The moving sand will be transported to another section of the beach, or to areas behind the beach. Where there are no dunes or inadequate dunes, storm water will wash over lowlying land.

On sections of the beach where there are features for trapping moving sand, dunes will form. Dunes are built as wind-blown sand accumulates around beach grasses. For example, along the North Carolina coast _Spartina patens_ (salt meadow hay) and _Uniola panoculata_ (sea oats) serve as grass traps. Both grasses grow upward as the dunes increase in height. Further back on the Carolina beach, the vegetation is much more dense, and includes such plants as _Fimbristylis_, _Muhlenbergia_, _Eragrostis_ and _Scirpus_ (bulrush). Along sections of this coast where overwash is infrequent, thickets of _Baccharis halimifolia_ (sea myrtle), _Myrica cerifera_ (wax myrtle), and _Iva frutescens_ (marsh elder) develop. On older dunes which are protected from salt spray, the shrub thickets contain _Ilex vomitoria_ (yaupon), _Juniperus virginiana_ (red cedar), and _Quercus virginiana_ (live oak) (Dolan, et al., 1973).

Waves, Swell, and Effect of Offshore Bathymetry

Waves which are generated by, and still under the influence of wind are called wind waves. These waves are usually defined by their height, length (Figure 2), and period. The height, length, and period of wind waves are determined by fetch (distance over water that the wind has essentially constant direction and speed), wind speed, and duration (length of time the wind blows).

Shallow water depths will affect the height, length, and velocity (forward speed) of the individual wave form. At a depth of about one-half the deepwater wave length, incoming waves start to "feel"

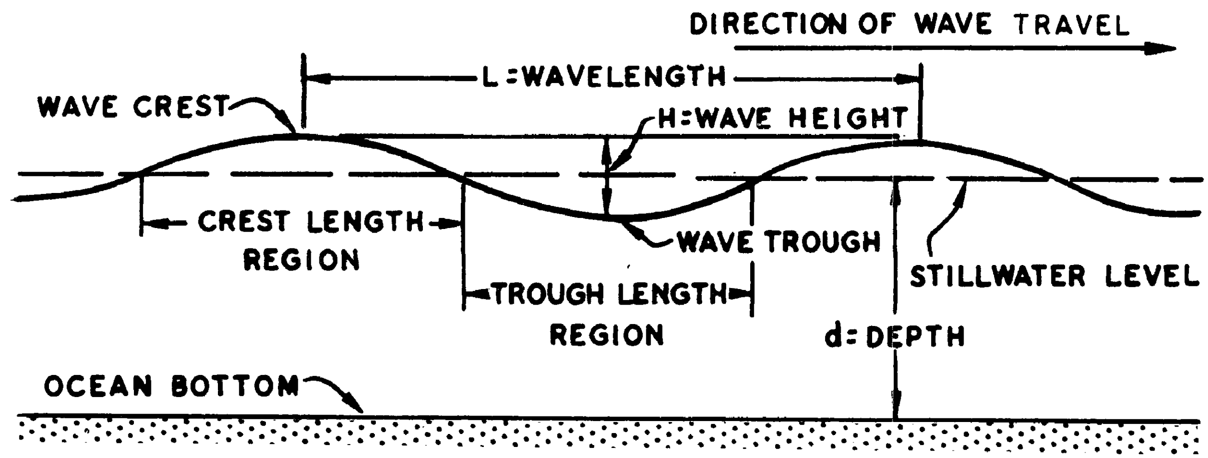


Figure 2. Wave characteristics (U.S. Army Coastal Engineering Research Center, 1973).

bottom, and their height, length, and velocity begin to change. The height of the shoaling wave first decreases slightly and then increases until reaching the breaking point (Johnson, 1952). As waves enter shallow water, they also undergo height changes due to refraction (bending of wave due to bathymetry). Although the incoming waves tend to become parallel to the shore due to refraction, they usually break at a slight angle to the shore. This breaking angle will be discussed in the next section (Breakers). At the beach, waves break and release most of their energy. This process of breaking often builds an offshore bar in front of the beach. This bar will "trip" following waves and absorb some of their energy before they reach the beach. If a wave breaks far enough offshore, it will reform to break again and may do this several times more before finally rushing up the foreshore of the beach.

During beach accretion, a ridge of sand is formed at the top of the wave uprush (swash). This ridge of sand protects the beach against the uprush of following waves. Beyond this ridge, or berm crest, lies the back beach which is reached only during spring tide and by high storm waves. During periods of low wave heights, differential velocities are sufficient to move sand onshore except in zones of rip currents (Shepard, 1973). Studies of orbital velocities in the surf zone (Inman, 1956) and data from wave tank experiments (U.S. Corps of Engineers, 1941) have confirmed that velocities of onshore motion under advancing wave crests are greater than velocities of offshore motion under troughs.

Onshore sand migration is particularly large with long period waves because the long period allows more opportunity for sand to be deposited. High waves with short periods can keep sand in suspension, and the beach will retreat if sand washed off the foreshore by backwash is carried into a rip current moving seaward to relatively deep water. Bascom (1964) makes a very interesting observation: each time a sand grain is lifted, it lands in a slightly different location. Uncounted millions of sand grains are picked up and relocated by every wave. The sand need not move very far each time, for there are some eight thousand waves a day. Sand grains that move one-tenth of an inch per wave could migrate nearly seventy feet in a day, and as a result, beaches constantly shift position.

If waves are generated by a distant storm, they may travel hundreds, or even thousands of miles of storm-free areas before reaching shore. Under these conditions, short steep waves are eliminated, and only relatively long waves of low steepness reach the shore. Such waves have lengths from 30 to more than 500 times their wave heights and are called swells. Because of their great lengths, swells feel bottom in much deeper water than wind waves, thus bringing in sand from deeper water. Swells tend to build beaches, but they can be destructive. During three storms between 1962 and 1967, storm waves traveled as much as 1,000 miles from their area of generation before breaking on the northern coast of Puerto Rico. Yet, these waves caused destruction of ocean front structures, leaving hundreds of people homeless (Fields and Jordan, 1972).

Breakers

As a wave moves on shore, it finally reaches a depth of water which is so shallow that the wave collapses or breaks. This depth is equal to about 1.3 times the wave height (McCowan, 1891). Breaking waves (breakers) have been classified according to Shepard (1973) as:

(1) plunging breakers, which have hollow (concave upward) fronts and generally come from long swells approaching a gently sloping beach;

(2) spilling breakers, which have steep but not hollow fronts, accompany most short-period wind waves; and

(3) surging breakers, which do not actually break but surge up steep beaches.

The most damaging breakers are those with hollow fronts (plunging breakers) because the water drops vertically with great force. The breaking wave results in the sudden dissipation of wave energy, which causes a great amount of turbulence in the water, and stirs up the bottom material. The primary agent causing onshore, offshore, and longshore movement of sand is the breaking wave. It has been estimated that as much as 80% of the material moved longshore by wave action is moved in the area from the point of breaking to the limit of uprush of the wave on the beach (Mason, 1942).

After breaking, the water travels forward as a foaming, turbulent mass, expending its remaining energy in a rush up the beach slope. The water which falls back under the influence of the force of gravity runs down the beach slope to the sea.

There is generally a small angle (B) between the breaking wave crest and the shoreline. Because of this angle, there is a small longshore component of motion (Figure 3). If wave refraction were such that B equaled zero, any sand grain in motion would oscillate back and forth along a line normal to the shoreline, and there would be no longshore transport. Since longshore transport is often expressed as a function of sin(2B) (May and Tanner, 1972), the larger the angle B, up to 45°, the greater the longshore motion of sand. Shorelines tend to be at nearly right angles to the direction of dominant wave approach (King, 1959). This shoreline orientation is the most stable because longshore drift is at a minimum.

Astronomical Tide

The astronomical tide is caused by changes in gravitational forces exerted on the hydrosphere and the earth by the moon and the sun (Williams, 1962). There is a noticeable tide cycle during the synodic month which is the 29.5 day interval between conjunction of the sun and moon relative to the earth. The tide during the synodic month ranges from a maximum during spring tides to a minimum during neap tides. Spring tides occur when the moon is in conjunction or opposition to the sun relative to the earth (new moon and full moon). Neap tides, tides of decreased range, occur at quadrature (first and last quarter moon phases).

The position of the moon in its orbit around the earth also has an effect on the range of the tide. At perigee, when the moon is

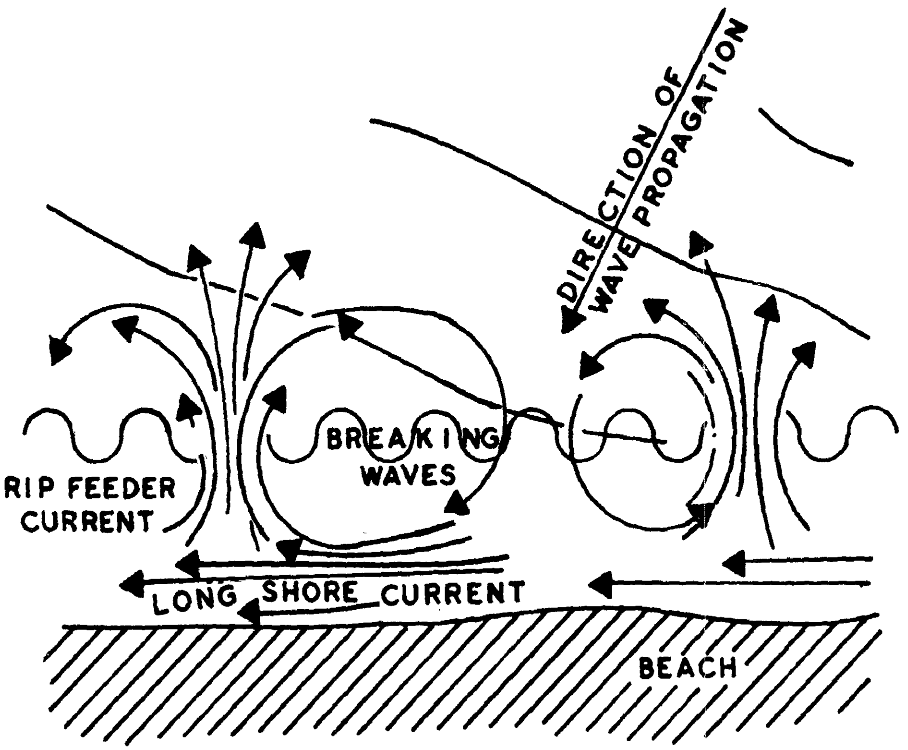


Figure 3. Littoral system which consists of longshore currents and rip currents. The currents are caused by waves which break at oblique angles to the beach (Walton, 1973).

closest to the earth, the tidal range is increased. The opposite condition exists during apogee.

According to Defant (1958, p. 56), a tidal curve can have one of the four following forms:

(1) Semidiurnal form. Two high and low waters of approximately the same height.

(2) Mixed, predominantly semidiurnal form. Two high and low waters daily, but with strong inequalities in height and phase; these inequalities reach a maximum with a maximum declination of the moon.

(3) Mixed, predominantly diurnal form. After maximum declination of the moon, only one high water per day. Otherwise, two high waters with strong inequalities in height and phase.

(4) Diurnal form. One high water per day. Possibly two high waters at neap tide (during the passage of the moon through the plane of the equator).

The oceanic coastlines of the northeast and mid-Atlantic states experience semidiurnal tides which have a period of approximately 12.4 hours. This period corresponds to one-half the interval between two successive passages of the moon over a particular meridian.

Storm Surge

Storm surge is a meteorological effect on sea level and is defined as the algebraic difference between the observed tide and the astronomical tide (Pore, et al., 1974). Factors that are important in determining the height of the storm surge (Pore et al., 1974) are:

(1) astronomical tide

(2) wind stress

(3) atmospheric pressure

(4) transport of water by waves and swell

(5) coastline configuration and bathymetry

The phase of the astronomical tide at the time of a meteorologically produced water level is important. If the storm surge occurs at the time of high astronomical tide, the water above the nearshore slope will be higher and the nearshore slope will have less effect (refraction and shoaling) on the incoming waves. These wind waves (large heights and small periods) will break high on the beach face because of the super elevated water level of the combined high astronomical tide and storm surge. These steep wind waves will place a large quantity of water on the beach in a short time and the water will not have enough time to percolate through the beach face. Thus, the runback of each wave on the beach face carries away more sand than is brought to the beach by the runup of the next wave. The beach face migrates landward, cutting a scarp into the berm (Figure 4).

Initial Condition of the Beach

Most storms move large amounts of sand from the beach to areas offshore, but after the storm, the lower waves that follow tend to restore this sand to the beach face. Depending on the availability

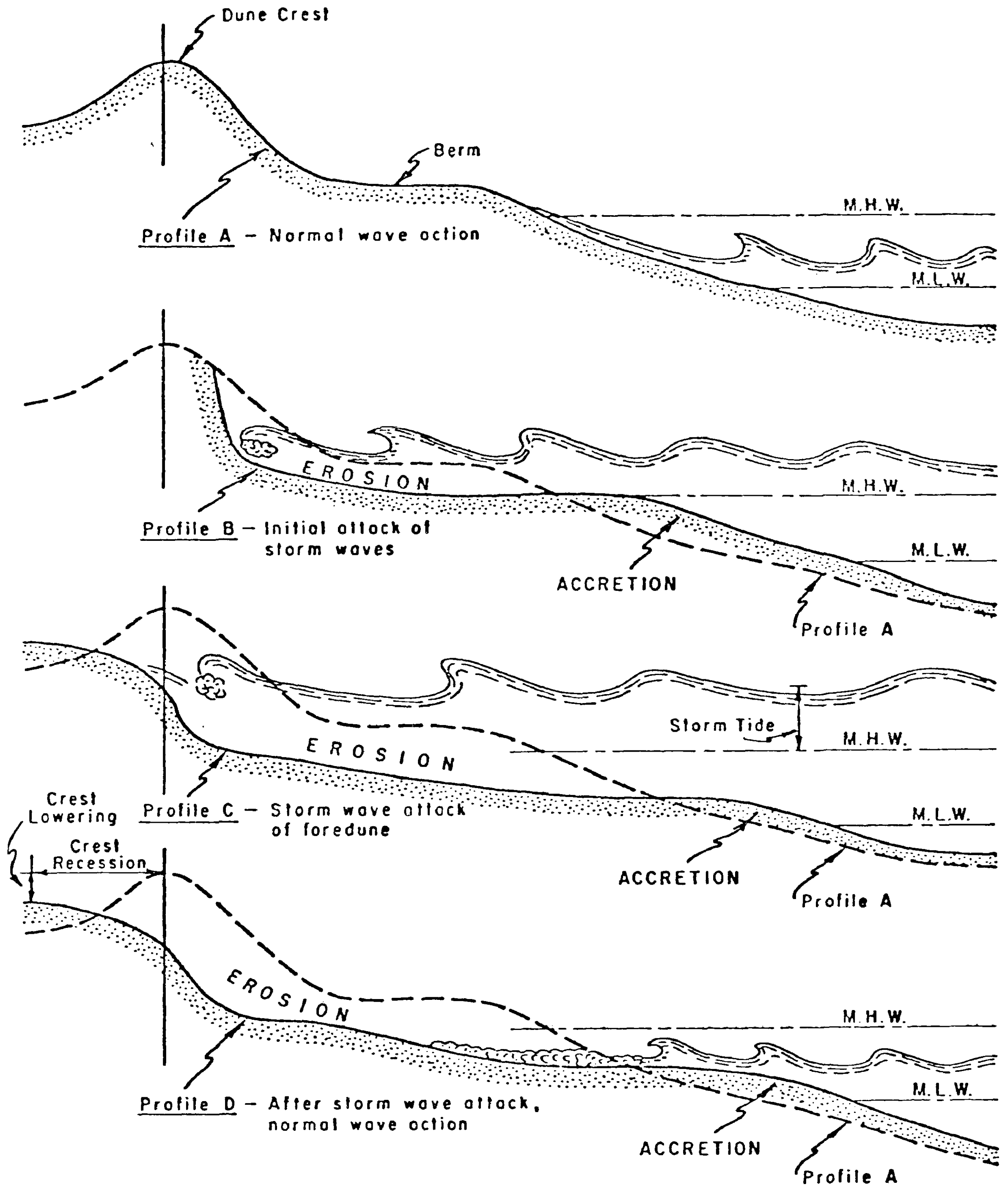


Figure 4. Schematic diagram of storm wave attack on a beach (U.S. Army Coastal Engineering Research Center, 1973).

of updrift sand for restoration, a storm may result in little permanent change. Storm path and wave direction are important factors in determining the amount of material moved alongshore. If a storm causes a direction of longshore transport opposite to the net direction of transport, then the sand will be returned in the months after the storm and permanent beach changes will be small. If the direction of transport before, during, and after a storm is the same as the net direction of transport, then large amounts of material removed by the storm have little possibility of being restored (U.S. Army Coastal Engineering Research Center, 1973). Successive storms on the same beach may cause significant transport in opposite directions (Everts, 1973). Therefore, wave approach before, during, and after storms is critical in determining whether erosion is permanent.

In severe storms, or after a series of moderate storms, the backshore may be completely eroded, after which, normal wave activity will begin to erode the coastal dunes, cliffs, or mainland behind the beach (U.S. Army Coastal Engineering Research Center, 1973).

APPROACHES TO RELATE EROSION TO METEOROLOGICAL AND OCEANOGRAPHICAL PARAMETERS

Forecasting beach erosion is not new. George Washington studied the erosion of the Long Island coast and ordered that the Montauk Point Lighthouse at the eastern tip of Long Island, N. Y. be built at least 200 feet from the edge of the cliff so it would last 200 years. At the present rate of erosion, the lighthouse will last just about that long. A recent measurement showed that the base of the lighthouse now stands about 40 feet from the edge of the cliff (Bascom, 1964). Beach erosion has been studied by many people in many private and government agencies. These studies are of two types:

(1) Wave tank and laboratory studies which are conducted in a controlled environment (Johnson, 1952). These studies, as well as other laboratory studies, are described by Wiegel (1964, p. 373-376).

(2) Field studies which are conducted in the uncontrolled environment. Field studies can be subdivided into dynamical studies and empirical (statistical) studies. Dynamical studies relate erosion to physical laws and principles (Bagnold, 1966). Empirical studies relate erosion to a set of independent variables based on observations (Harrison et al., 1971; Davis and Fox, 1972; and Wasserman and Gilhousen, 1973).

The dynamical approach has been used by Wang et al.(1975) to develop a computer model which predicts the littoral drift along irregular shorelines as a function of offshore wave climate. Through the use of conservation of mass arguments for bottom sediments, the model predicts erosion and deposition in the offshore and surf zone areas. Within the surf zone, littoral drift is apportioned across a beach in a fashion to derive an equilibrium beach profile under steady wave conditions. Inputs to the model are deepwater wave conditions, tidal conditions, and nearshore bathymetry.

Empirical (statistical) equations which have attempted to relate various parameters to beach erosion for littoral transport rates of sand have been derived by Krumbein (1944), Shay (1951), Watts (1953), and Saville (1957).

The concept of a "beach erosion index" for New Jersey and Long Island, N. Y. was introduced by Wasserman and Gilhousen (1973). This index is defined as $\frac{(A \times B)}{C}$, where: A is setup time in hours, B is maximum fetch in nautical miles that existed during the setup time, and C is the minimum distance (nautical miles) that existed between four millibar (mb) spaced isobars. To determine setup time, maximum fetch and strongest pressure gradient, the following procedure is followed: the angle of the predominant observed wind direction with respect to the coastline is measured; this angle is determined from three-hourly maps prior to and during the time of erosion. The coast is assumed to be straight for a broad expanse where erosion is reported, and wind direction is averaged across this broad expanse. It is assumed that wind direction is related to the angle of approaching deepwater waves. The angle of the predominant observed wind direction with the coastline may vary greatly with fast moving storms. However, the storms investigated by Wasserman and Gilhousen (1973, p. 4) did not vary greatly because they were associated with slow eastward moving high pressure systems over southeastern Canada, and slow northeastward moving "lows", which were deepening off the east coast of the United States.

After the predominant observed wind direction is determined, then the following can be derived:

(1) The setup time: This is defined as the duration of coastal winds within $\pm 20^{\circ}$ from the wind direction as determined above. A long setup time should be conducive for wave development.

(2) Maximum fetch: The longest fetch from the coastline during the setup time. Fetch is defined here as the distance out to sea in which the wind direction for a given three-hourly time did not vary by more than $\pm 20^{\circ}$ from the wind direction at the shoreline. Wind direction over the ocean is inferred from ship reports and pressure analysis. A long fetch should be conducive to wave development favorable for beach erosion.

(3) The strongest pressure gradient: This is measured along the fetch during setup time. It is determined from four mb isobar spacings on the National Meteorological

(3) cont'd

Center map analysis. A strong pressure gradient should be conducive for wave development favorable for beach erosion.

The "beach erosion index" gives a very high erosion potential to the March 1962 and February 19, 1972 storms. Wasserman and Gilhousen pointed out that while the index may provide useful information concerning a storm wave's potential for beach erosion, the effect of tide and angle of approaching deepwater waves must also be considered. Wasserman and Gilhousen also stated that the vulnerability of the beach to erosion processes includes such important factors as bottom topography and initial conditions of the beach.

Rush (1973) recommended that qualitative forecasts (minor, major, etc.) of beach erosion could be computed as a function of deepwater wave steepness (H_o/L_o, where H_o is deepwater wave height and L_o is deepwater wave length). Input to this scheme would be deepwater waves as forecast by the Techniques Development Laboratory wave model of the National Weather Service (Pore and Richardson, 1969).

Harrison et al. (1971) monitored beach profile changes at 16 transects along the Virginia Coast for 18 months. Changes in beach sand volume computed from profile data were correlated with various meteorological parameters by a linear multiple regression technique. The purpose of this study was to develop an operational scheme to predict storm-induced beach changes. However, the correlation study did not yield completely reliable beach-change predictor equations.

Harrison, et al., (1971) concluded their study with a number of recommendations for further beach-change studies. Two of their recommendations follow:

(1) Primary effort should be devoted to better prediction of storm surge and beach erosion.

(2) It would seem advisable to use such terms as "slight", "moderate", or "severe" when forecasting the extent of beach erosion for the entire coast of Virginia. When a significant storm surge is not anticipated, it would probably be best not to forecast any type of beach change, inasmuch as beach accretion would probably be indicated.

Since the study of Harrison, et al., (1971), the National Weather Service has developed a statistical forecast method to predict storm surge at 11 locations along the U.S. east coast (Pore, et al., 1974). These forecasts should provide meaningful information to a beach erosion forecast technique.

DEVELOPMENT OF A STORM-RELATED BEACH EROSION INTENSITY SCALE

A beach erosion forecast which predicts the transport of sand along or away from a beach in dimensions of volume per unit time (cubic yards per hour) would not mean very much to the general public. A much more useful prediction would be a qualitative forecast of erosion (minor, moderate, major, and severe) as recommended by Harrison, et al., (1971) and Rush (1973). As a first step in developing a qualitative beach erosion forecast technique, a storm-related erosion intensity scale is developed. The intensity of erosion is defined by the qualitative terms (minor, moderate, major, and severe). Sources of data that were considered for development of this scale were:

(1) Beach profile data from Coastal Engineering Research Center (CERC). Since the March 1962 storm, the Beach Evaluation Program of CERC has collected and processed some 35,000 profile surveys obtained from the Atlantic Coast (Everts, 1973). In most cases, the profiles at any one point are monitored at one-month intervals. However, CERC does make a special effort to profile the beach before and after a storm.

(2) Detailed beach profile studies (frequent profiling intervals in time and space). A very detailed study of beach processes in the Outer Banks, N. C. was conducted by the Coastal Studies Institute of L.S.U. (Dolan, et al.,

(2) cont'd

1969). More recently, Cape Hatteras, N. C. beaches have been profiled daily (Fisher, et al., 1975b). Another area extensively studied was Cape Cod, Mass. (Zeigler, et al., 1961). Small areas along the shores of the Great Lakes and Gulf of Mexico have been studied in great detail (Davis and Fox, 1972). The basic approach of Davis and Fox was to investigate a small area in great detail by monitoring all changes that took place here. By conducting such investigations at a number of locations, they believe that it is possible to cover a broad spectrum of conditions and thereby provide sufficient empirical data for meaningful simulation models. They measured wave period, breaker height, breaker distance from shore, breaker angle, breaker type, and longshore current velocity three times a day. In addition to these data, wind speed and direction, barometric pressure, air and water temperature, humidity, precipitation, and sky conditions were also recorded.

(3) Storm summaries. Since 1959, an expanded record of all severe storms has been published monthly in a special report entitled Storm Data (U.S. Environmental Data Service). This data source summarizes in tabular form for each month, storm data and unusual weather phenomena

(3) cont'd

of the U. S. by locality (state), date, and time of occurrence. These summaries include reports of beach erosion.

(4) Aerial photography. The Chesapeake Bay Ecological Program Office of the National Aeronautics and Space Administration at Wallops Island, Va. maintains a file on post storm aerial photographic flights along the east coast of the U.S. between North Carolina and Delaware. Stafford (1971) has developed a procedure to use aerial photographs to survey beach erosion.

Although CERC has collected many beach profiles, these data (source 1) are not easily used in constructing a storm-related erosion intensity scale for the oceanic shoreline of an entire state. These profiles are for specific locations along the coast. The sampling interval of these profiles is generally one month, instead of before and after a storm. Since there is not sufficient warning time of an approaching storm, it is difficult for a field party to profile a beach before a storm.

The detailed studies of source 2 are excellent for a localized study, but are not easily expanded to cover the shores of an entire state. The aerial data coverage of source 4 is too infrequent to adequately cover storm-related erosion.

Storm Data summaries of source 3 are the most usable source of erosion data for this study. Although there is a certain amount of subjectivity involved in writing these summaries, this is the best data source for constructing a storm-related erosion intensity scale for the oceanic shoreline of an entire state.

In an earlier study, Mather, et al., (1964) investigated 170 damaging storms affecting the east coast of the United States from 1921-1962. They classified these storms into eight types based on origin, structure, and path of movement. Damage was defined by Mather, et al., (1964) as "at least some water damage", and included "wave damage, coastal flooding, and tidal inundation". Storms which caused damage by wind alone were excluded. The prime source of all storm data used by Mather, et al., (1964) was U.S. Weather Bureau Climatological publications.

Storm Data was compiled by the National Weather Service State Climatologists until 1972. Since 1972, these storm summaries have been prepared by National Weather Service Forecast Offices. In the case of shoreline damage, the sources of reported damage are newspaper articles, conversations and correspondence with CERC and, in some cases, personal interviews with residents of a storm-damaged area. Because of the source of these shoreline damage reports, the areas with reported damage abound in the more populated areas. For example, erosion reports along the Virginia coast probably pertain to the Virginia Beach area, and not remote areas of the Eastern Shore.

A storm-related erosion intensity matrix has been constructed for the following east coast states: Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, Maryland, Virginia, North Carolina, South Carolina, Georgia, and Florida. This matrix was constructed in the following manner: A numerical value was associated with a qualitative term which described the intensity of the storm-related beach erosion for a coastal state. The numerical values and their associated qualitative terms are: 0 (no erosion), 1 (minor erosion), 2 (moderate erosion), 3 (major erosion), and 4 (severe erosion). Beginning with March 1962 and continuing through April 1973, all winter Storm Data volumes (November 1 through April 30) were scanned for all Atlantic Coast states. Any time there was mention of erosion or wave damage along an Atlantic Coast state, an intensity of 1, 2, 3, or 4 was assigned to the affected state. The assignment was made in accordance with the descriptive terms shown in Figure 5. Through this procedure, the storm-related erosion intensity matrix shown in Table 1 was constructed. The March 1962 storm was chosen as a starting point because erosion-reporting procedures were somewhat standardized after that disastrous storm.

Although summer storms can cause beach erosion, only winter storm data were scanned because storm surge forecasts (Pore, et al., 1974), one of the proposed inputs to the beach erosion forecast model, are available only for winter months. November was chosen as the beginning of winter because erosion events which occur in October are often associated with tropical storms (these storms were not considered in this study). For example, during the month of October (1962-1973), there were seven reports of erosion along the northeast coast of the United States. Five of these erosion events were

Numeric Value	Qualitative Term	Reported-Descriptive Terms
4	Severe Erosion	Severe Tremendous Serious
3	Major Erosion	Considerable Widespread Heavy Markedly Badly Much
2	Moderate Erosion	Erosion Some Erosion Erosion of Dunes Beach Erosion Coastal Erosion Dunes Moved Moderate Erosion
1	Minor Erosion	Beach Change Damage to Jetties and Piers Some Loose Sand Moved Light Erosion Sea Wall Pounded Heavy Surf Limited Damage Erosion Noted
0	No Erosion	No Mention of Erosion No Erosion

Figure 5. Storm-related erosion intensity scale and associated qualitative and reported-descriptive terms.

Table 1. Storm-related erosion intensity matrix for the 14 states which border the Atlantic Ocean

Storm Dates	Me.	N.H.	Mass.	Conn.	R.I.	N.Y.	N.J.	Del.	Md.	Va.	N.C.	S.C.	Ga.	Fla.
Mar. 6-9, 1962	1	1	1	2	3	4	4	4	4	4	4	1	0	3
Nov. 3, 1962	0	0	1	0	0	0	0	2	1	0	0	0	0	0
Nov. 14-15, 1962	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Nov. 26-30, 1962	0	0	0	0	0	0	2	2	2	3	3	2	0	3
Dec. 5-6, 1962	1	0	1	0	0	1	0	0	0	0	0	0	0	0
Feb. 3-5, 1963	1	0	0	0	0	0	0	0	0	0	0	0	3	3
Nov. 6-8, 1963	1	0	1	0	0	3	0	0	0	0	0	0	0	0
Nov. 29-30, 1963	3	0	2	2	2	3	0	0	0	0	0	0	0	0
Feb. 12, 1964	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Feb. 19-20, 1964	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Feb. 25, 1965	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Jan. 23-24, 1966	0	0	0	0	0	1	2	0	0	0	0	0	0	0
Dec. 29, 1966	1	2	1	0	0	0	0	0	0	0	0	0	0	0
Apr. 28-29, 1967	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Dec. 3-4, 1967	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Nov. 11-13, 1968	1	2	3	1	3	4	4	0	0	1	0	0	0	0
Dec. 22-23, 1968	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb. 19-20, 1969	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Mar. 2-3, 1969	0	0	3	0	0	2	0	0	0	0	0	0	0	0
Nov. 1-5, 1969	1	1	1	0	0	0	0	0	0	0	2	3	0	0
Dec. 11, 1969	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Dec. 26-28, 1969	0	1	0	0	0	0	0	0	0	0	0	0	0	0

- continued -

Table 1, continued

Storm Dates	Me.	N.H.	Mass.	Conn.	R.I.	N.Y.	N.J.	Del.	Md.	Va.	N.C.	S.C.	Ga.	Fla.
Feb. 2-4, 1970	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Apr. 2-3, 1970	0	0	1	0	1	0	0	0	0	0	0	0	0	0
Dec. 16-17, 1970	0	0	2	0	2	0	0	0	0	0	0	0	0	0
Dec. 31, 1970	0	0	0	0	0	0	0	0	0	0	2	4	0	0
Mar. 3-5, 1971	3	0	3	0	1	0	0	0	0	0	0	0	0	0
Mar. 25-28, 1971	0	0	1	0	0	0	0	0	0	1	2	0	0	0
Apr. 6-7, 1971	0	0	0	0	0	0	0	3	0	2	0	0	0	0
Dec. 3, 1971	0	0	0	0	0	0	0	0	0	0	0	2	2	0
Feb. 4, 1972	1	1	1	2	0	1	0	0	0	0	0	0	0	0
Feb. 12-13, 1972	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Feb. 19-20, 1972	4	1	4	1	4	1	0	0	0	0	0	0	0	0
Nov. 8-9, 1972	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Nov. 26, 1972	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Dec. 15-17, 1972	1	0	1	0	0	0	0	0	0	0	0	0	0	0
Dec. 22, 1972	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Jan. 28-29, 1973	0	0	3	0	0	0	0	0	0	0	0	0	0	0
Feb. 9-11, 1973	0	0	0	0	0	0	0	0	3	4	3	0	0	0
Mar. 21-22, 1973	0	0	0	0	0	0	3	0	0	0	3	0	0	0
Apr. 1-3, 1973	1	1	0	0	0	0	0	0	0	0	0	0	0	0

associated with tropical storms (Daisy 1962, Ginny 1963, Isbell 1964, Gladys 1968, and Gilda 1973). The remaining two erosion events were associated with extratropical storms which caused only moderate erosion along the coast of Maine and Massachusetts.

COMPARISON OF BEACH EROSION INTENSITY MATRIX WITH PHOTOGRAPHS TAKEN BEFORE AND AFTER STORMS

The beach erosion intensity values shown in Table 1 were compared to photographs (Figure 6 through Figure 11) taken before and after the March 1962 and February 1973 storms. These photographs are of the oceanic coastlines of Delaware, Virginia, and North Carolina. The photographs shown in Figures 6 and 7, taken by N. A. Pore of the National Weather Service, show the property damage at Rehoboth Beach, Del. and Virginia Beach, Va. following the March 1962 storm. The erosion intensity values, from Table 1 for each of these states for this storm, were 4 (severe erosion). The photographs show a great deal of erosion damage at Rehoboth Beach and Virginia Beach.

The next set of photographs (Figure 8 through Figure 11) is of the Outer Banks, N. C. These photographs were taken before and after the February 1973 storm. The photographs shown in Figures 8 and 9 were taken by CERC. These photographs of the Nags Head area show a great deal of erosion damage which has caused the collapse of beach cottages. The next set of photographs shown in Figures 10 and 11 was taken by the National Aeronautics and Space Administration as part of their Chesapeake Bay Ecological Program. The photograph shown in Figure 10 depicts that part of the Outer Banks just north of Avon Pier. This photograph was taken about two hours before low tide on January 18, 1973, about one month before the February storm. This aerial photograph, from about 5,000 feet, shows a rather broad beach

Figure 6. Photograph of property damage at Rehoboth Beach, Del. following the March 1962 storm.

Figure 7. Photograph of property damage at Virginia Beach, Va. following the March 1962 storm.

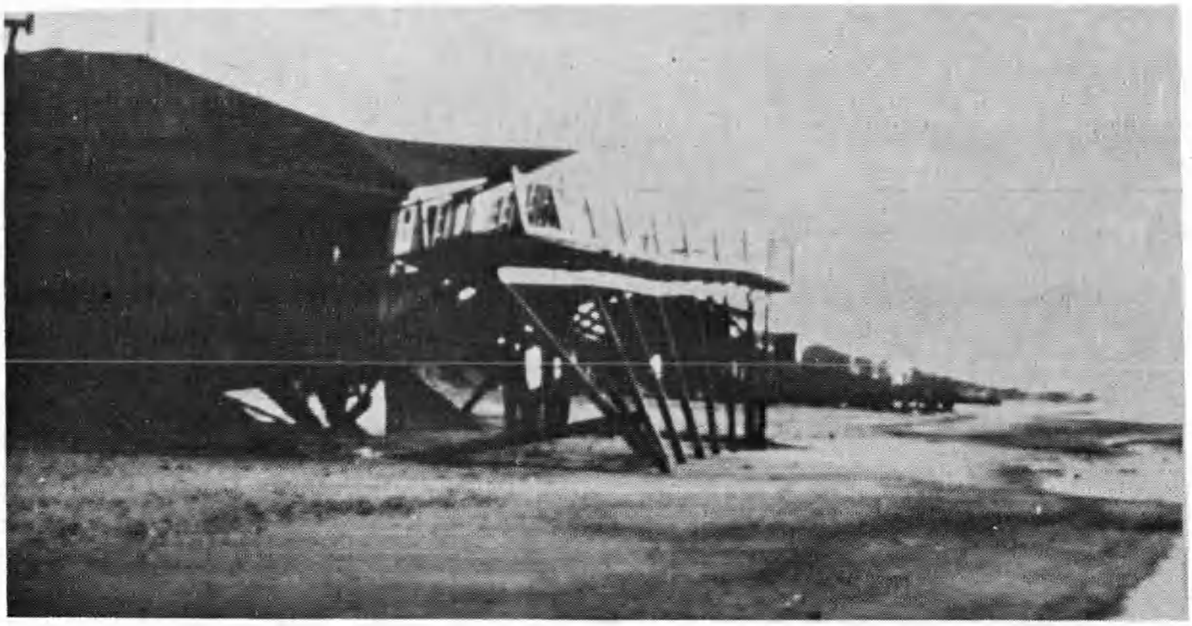


Figure 8. Photograph of property damage along the Outer Banks, N. C. following the February 1973 storm.

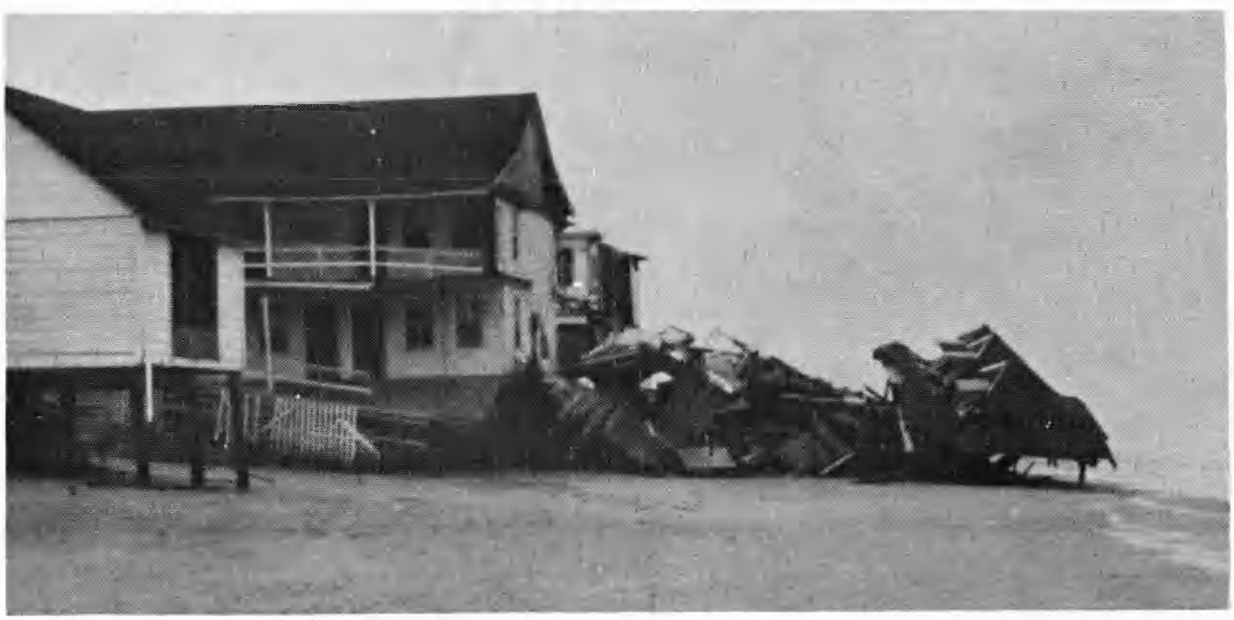


Figure 9. Photograph of property damage along the Outer Banks, N. C. following the February 1973 storm.

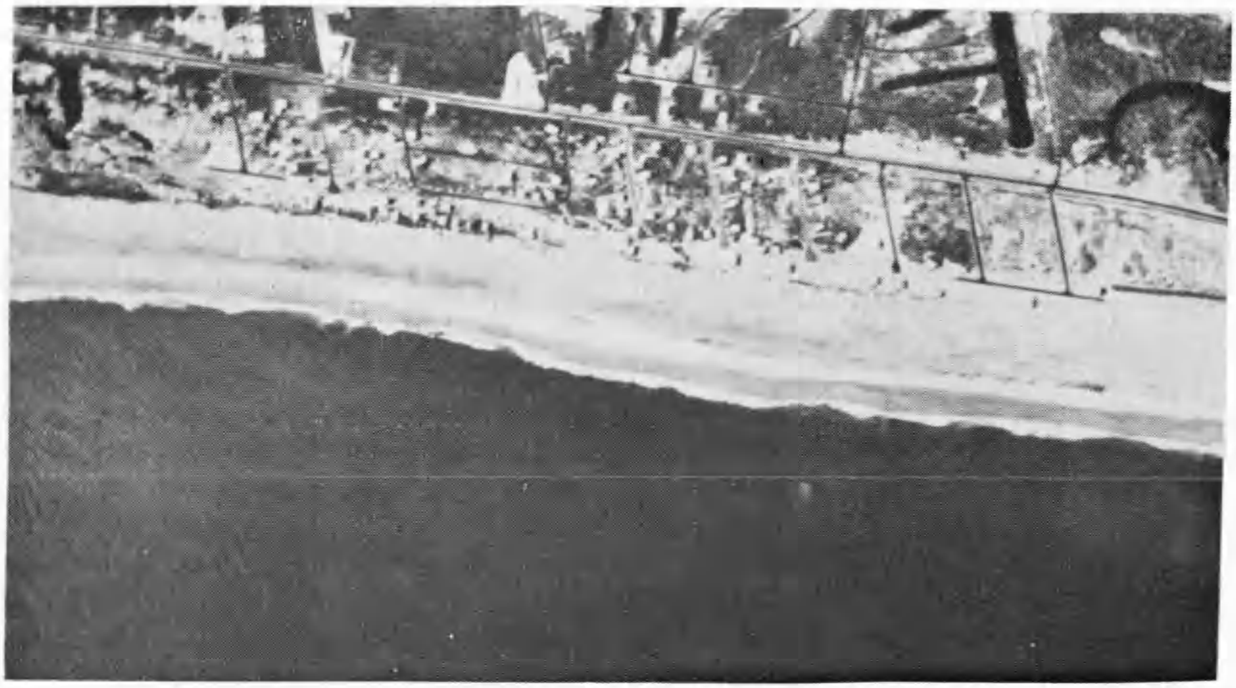


Figure 10. Aerial photograph of the beach north of Avon Pier, N. C. on January 18, 1973.

Figure 11. Aerial photograph of the beach north of Avon Pier, N. C. on February 13, 1973.

with very little offshore wave activity. However, the aerial photograph (Figure 11), taken on February 13, 1976, depicts an entirely different scene for the same beach. The photograph, from about 6,500 feet, was also taken about two hours before low tide. Avon Pier can be seen in the lower left portion of the photograph. This photograph shows that water has traveled far up on the backshore of the beach and is threatening some structures. Even though this photograph was taken two days after the storm, the photograph shows large swell advancing from the east-northeast. The white patches on the ocean surface are caused by strong west winds which are blowing the tops off of breaking waves. The erosion intensity associated with this storm for the North Carolina coast was 3 (major erosion). These photographs depict moderate to severe erosion along these sections of the Outer Banks.

A few photographs certainly do not give a complete picture of the erosion along an entire coastline of a state, but they do give some credibility to the beach erosion intensity matrix (Table 1).

STATISTICAL SCREENING PROCEDURE

The beach erosion intensity matrix (predictand) was correlated with meteorological and oceanographic parameters (predictors) using a statistical screening procedure. In this procedure, the predictand is expressed as a linear function of a number of predictors using the method of least squares. The screening procedure has been described by Klein (1965) as follows:

> The object of the screening procedure is to select from a large set of possible predictors only those few which contribute significantly and independently to the forecast of a predictand. This is accomplished by a forward method of multiple regression in which significant predictors are picked in a stepwise fashion, one by one. As a result, a small number of predictors can be selected which contain practically all the linear predictive information of the entire set with respect to a specific predictand. The importance of using a small set of predictors to prevent redundancy and instability of the multiple regression equation and to insure good results when applying it to new data has been emphasized by Lorenz (1956, 1959), Grant (1956), Panofsky and Brier (1958), and others.

Excerpts from a detailed description of the selection of predictors by screening according to Miller (1958) are contained in Appendix B. The beach erosion intensity predictors are screened in the following manner:

(1) $BE = A_1 + B_1X_1$

(2) $BE = A_2 + B_2X_1 + C_1X_2$

(3) $BE = A_3 + B_3X_1 + C_2X_2 + D_1X_3$

.

.

(n) $BE = A_n + B_nX_1 + C_{n-1}X_2 + \ldots + NX_n$

where: BE is Beach Erosion Intensity, A_1, A_2, A_3, etc., are constants, X_1, X_2, X_3, etc., are predictors, and B_1, C_1, D_1, etc., are regression coefficients.

In this procedure, one first selects the predictor (X_1) which has the highest correlation with the predictand for regression Equation 1. The second regression equation contains the first predictor (X_1) and the predictor (X_2) that contribute most to reducing the residual after the first predictor is considered. This screening procedure is continued until the desired number of predictors is included or until the additional variance explained by adding predictors reaches some cutoff value. For this study, the cutoff value was chosen at 0.01.

An interesting comparison between empirical and theoretical (numerical integration of basic equations of motion and continuity) methods has been made by Harris (1962) concerning methods of forecasting storm surge. These comparisons are also appropriate for this erosion study. Harris (1962) pointed out that the two methods are not entirely independent, as the theoretical models often contain terms that must be determined empirically. Proper use of the empirical method calls for physical reasoning in selecting possible predictors for statistical models. Harris (1962) described the advantages of each method. Briefly, the theoretical approach can be generalized toward a better description of nature and can reveal useful information about the physical processes. The empirical approach does not reveal the physical processes we well as the theoretical approach, nor can it be generalized as well to describe natural processes. However, a forecast method derived empirically leads from the predictor data to the forecast by a much shorter route than one developed theoretically. Also, an empirical approach usually makes the most efficient use of the available data.

An important point discussed by Harris (1962) is that in developing a forecast method by either approach, the quality and quantity of input data available under operational conditions should be considered. A perfect computation scheme, without the required input data, would be of little use for operational forecasting. For this reason, the operational beach erosion equation which was derived contained only predictors which could be operationally forecast at least 48 hours in advance.

PREDICTAND

Limited availability of storm surge data necessitated limitation of the derivation of the beach erosion equation to the following states: Maine, Massachusetts, Rhode Island, New York, New Jersey, Delaware, Maryland, and Virginia. Since there is no tide gage located along Maryland's outer coast, and because reported estimates of erosion for Maryland were similar to reported estimates of erosion for Delaware, the states of Delaware and Maryland were combined (Delmar) and one gage (Breakwater Harbor) was used to represent the tides along the Delaware and Maryland coasts.

There were 36 storms which caused erosion along some portion of the outer coast of these seven states during the winter seasons (November 1 through April 30) of 1962 through 1973. The monthly distribution of these erosion events is shown in Figure 12. The greatest number of erosion events occurred during November, December, and February. January had the fewest number of events. The few erosion events in January could be partly attributed to the limited sample of data (12 winter seasons). However, Miller (1946) found that the frequency of cyclones which originated over the ocean and moved in a northeasterly direction reached a minimum in January. Wave data compiled by Gutman (1977) for the Virginia coast also showed a lull period in January.

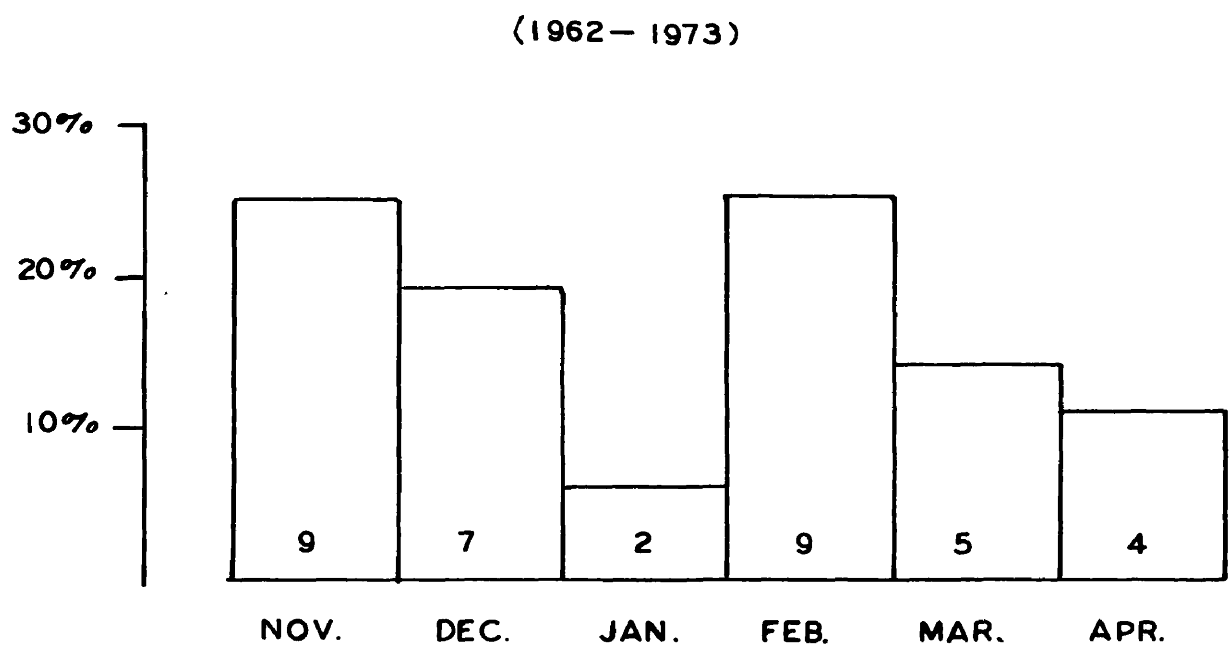


Figure 12. Monthly distribution of erosion events. The number of erosion events that occurred in a month is indicated above the month.

The number and intensity of erosion events per winter season for each of the seven states are shown in Figure 13. For example, during 12 winter seasons, Maine and Massachusetts experienced about two erosion events per season. For this same time period, New Jersey, Delaware, and Virginia experienced about one event every two seasons. As for the intensity of erosion (minor, moderate, major, and severe), New York and Virginia have severe erosion about once every five seasons. The other five states experience severe erosion about one-half that often, or about one time every ten seasons.

There was no clear relationship between the length of the coastline of a state and the number of times the state experienced erosion. The states of Maine and Massachusetts have the longest coastlines of the seven states, and also experience the greatest number of erosion events. However, it does not follow that the number of erosion events is a function of the length of the coastline, because a large part of Maine's coastline is rocky and not easily eroded. The greater frequency of erosion events along the coasts of Maine and Massachusetts may be due to coastal storms that deepen (central pressure of the storm becomes lower) and intensify off the New England coast. The deepening of these storms can be seen on Northern Hemisphere Surface Charts of the National Weather Service. These deep intense storms cause large waves and high storm surges which result in beach erosion.

Figure 13. Number and intensity of erosion events per winter season for each state.

PREDICTORS

Those meteorological and oceanographic parameters which were discussed earlier were considered as possible beach erosion predictors. These predictors (discussion follows) were:

(1) maximum observed tide height above mean sea level (MSL)

(2) mean amplitude of the spring tide

(3) storm duration

(4) frequency of erosional storms

(5) observed winds and waves at east coast light stations

(6) wave height and period computed using Sverdrup-Munk-Bretschneider (SMB) hindcast equations for "deep" and "shallow" water

(7) breakers

(8) wave steepness

(9) maximum storm surge height

(10) type of beach material

(11) monthly beach cycles

Maximum Observed Tide Height

Tide is an important factor in beach erosion (U.S. Army Coastal Engineering Research Center, 1973, p. 1-5). However, areas with little tide do experience erosion. For example, erosion is a problem at the western end of Lake Erie, even though the tidal range on Lake Erie is only 8 cm.

Since astronomical tides do occur along the east coast of the United States, it is desirable to incorporate tide measurements if one is planning to develop a beach erosion forecast model for this part of the coast. National Ocean Survey (NOS) tide gages were selected for the states of Maine, Massachusetts, Rhode Island, New York, New Jersey, Delaware, and Virginia. Figure 14 shows the locations of the representative tide gages. The tide along an entire coast of a state is represented by one tide gage. This may be an oversimplification, since the tide is modified by land masses and offshore bathymetry. For example, along the Virginia coast, the mean tidal range (the difference in height between mean high water and mean low water) at Sewells Point, the representative gage for the Virginia coast, which is located within the mouth of the Chesapeake Bay, is 2.5 feet. At False Cape, Virginia (on the ocean coastline 30 miles south of Sewells Point), the mean tide range is 3.6 feet, and the times of high and low tides are one hour and 45 minutes earlier at False Cape than at Sewells Point. The differences in mean tidal ranges along the Massachusetts coast are even greater, especially along the Cape Cod coast. Nevertheless, as a working tool, one tide gage is used to represent the tide along a coastal state. The seven coastal states and their associated tide gages are listed in Table 2. For each of the erosional storms, NOS hourly tide records were scanned for the maximum observed water level recorded for each of the seven representative tide gages.

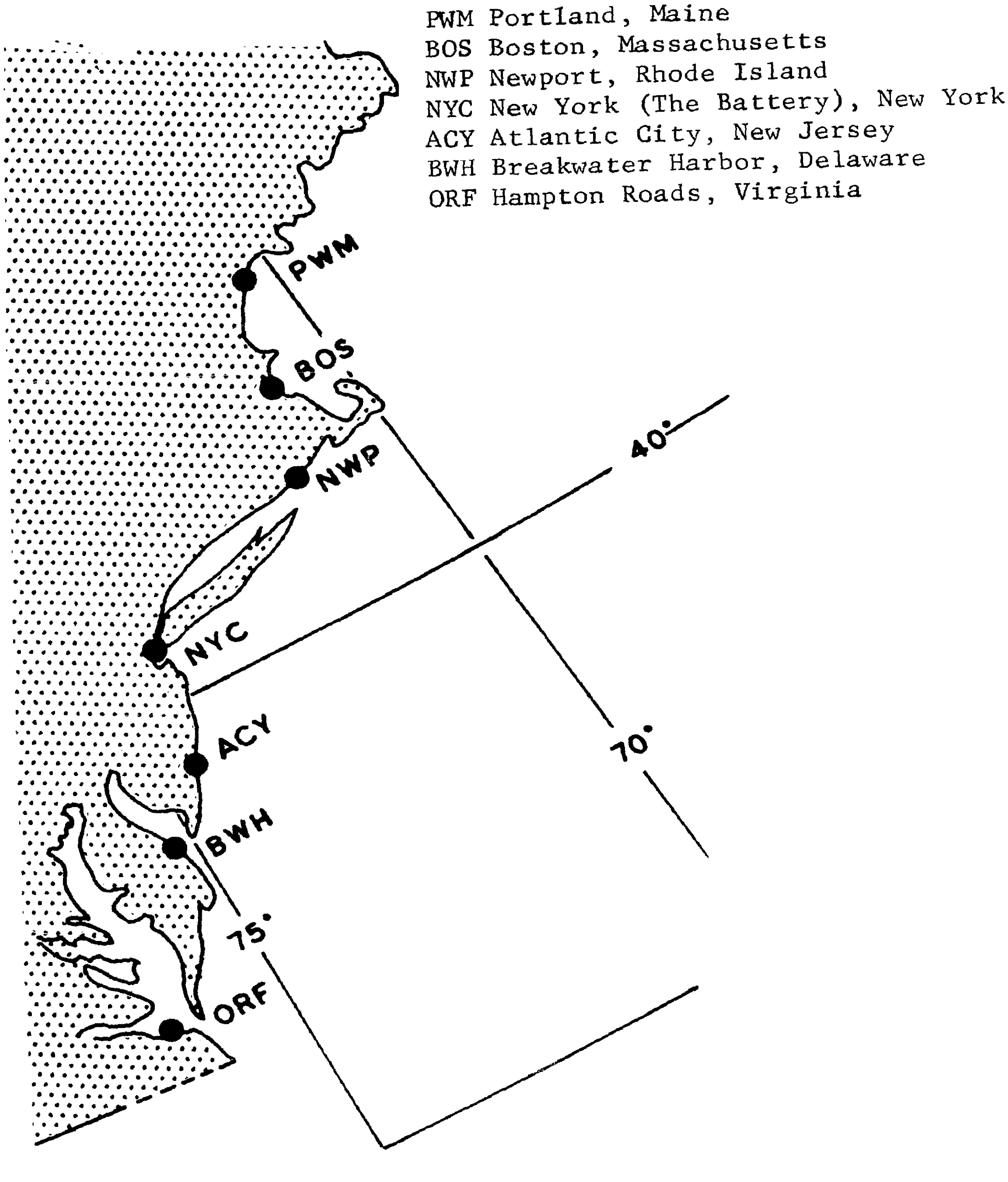


Figure 14. National Ocean Survey (NOS) tide gage locations.

Table 2. Coastal states, associated tide gages, and mean spring range of the tide at these gages.

Coastal States	Associated Tide Gage	Mean Spring Tide Range (feet)
Maine	Portland, Me.	10.4
Massachusetts	Boston, Mass.	11.0
Rhode Island	Newport, R.I.	4.4
New York	New York, N.Y.	5.4
New Jersey	Atlantic City, N.J.	5.0
Delaware	Breakwater Harbor, Del.	4.9
Virginia	Hampton Roads, Va.	3.0

Mean Amplitude of the Spring Tide

The mean range of the spring tide which is based on 19 years of data was extracted from Tide Tables (National Ocean Survey, 1975) for the seven tide gage locations. These tide ranges are shown in Table 2. The mean spring tide range is the average semidiurnal range of the tide at times of new and full moon (U.S. Naval Oceanographic Office, 1966). The mean amplitude of the spring tide is defined as one-half the mean range of spring tide.

Storm Duration

A storm duration term was shown to be very important by Darling (1964). In an effort to develop a warning system which would forecast effects on the coast for an approaching storm, he found that duration (the number of tidal cycles over which a particular peak storm tide is present) and peak storm tide height above mean low water were very important predictors. He related these predictors to beach changes as determined by field surveys. At Atlantic City, New Jersey, Darling developed a "vulnerability curve" which related beach changes to storm duration and peak storm tide. However, he pointed out that this curve is only valid for one beach condition. If the initial condition of the beach changes, another "curve" should be developed.

Storm duration predictors for each coastal state are defined in terms of "critical values". The "critical value" for a state is the mean amplitude of the spring tide at the representative tide gage plus a storm surge height. Storm surge heights of 1.0, 1.5, 2.0, and

2.5 feet were added to the mean amplitude of the spring tide at each of the seven representative tide gages. There were, therefore, four "critical values" for each of the seven states. For each of the 36 erosional storms, NOS tide records for each representative tide gage were scanned. Storm duration is the number of consecutive high tides (approximately 12.4 hours apart) during which a "critical value" is reached or exceeded.

Frequency of Erosional Storms

Past storms play an important role in determining the present state of a beach. Harrison, et al., (1971) suggested that a predictor should be included that reflects the amount of sand available for beach deformation, and the degree to which the beach configuration already matches equilibrium with storm-waves and storm surge conditions. If a beach is already depleted of sand, so as to expose underlying clay or peat, the beach could show no noticeable change, even with high wave energy. In other words, the initial condition of the beach should be considered. In moderate storms, the storm surge and accompanying steep waves will subside before the back beach has been significantly eroded. In severe storms, or after a series of moderate storms, the backshore may be completely eroded, after which the waves will begin to erode the coastal dunes, cliffs, or mainland (U.S. Army Coastal Engineering Research Center, 1973).

A predictor was constructed which is based on the length of time between erosional storms. The predictor is assigned a value for intervals between one and four weeks as shown in Table 3. It is assumed that the beach will fully recover from an erosional storm after four weeks, if there are no other storms. This may not be too bad of an assumption since Hayes and Boothroyd (1969) found that beaches of New Hampshire and northeastern Massachusetts formed "early accretion" features two days to six weeks after an erosional storm. They also found that "late accretion" or "maturity" features occurred six weeks or more after a storm. However, the frequency of erosional storms is a very subjective predictor since there is no exact knowledge of when the beach will return to an equilibrium condition because of the complexity of the processes. Also, since October data were not investigated, nothing can be said about storm frequency during the early part of November.

Observed Winds and Waves at East Coast Light Stations

Wind and wave predictors were obtained from surface weather observation forms from light stations located off the northeast Atlantic Coast. These data were furnished by the Environmental Data Service of the National Oceanographic and Atmospheric Administration (NOAA). The locations of these light stations are shown in Figure 15. A light station was associated with each state. Coastal states, associated light stations and light station water depths are shown in Table 4. There are problems in using these data since the wave height and period are visually estimated, and in many cases, these estimates are made by untrained observers. However, the wind speeds and

Table 3. Storm frequency assignment.

Period of time (T) between erosional storms	Value of storm frequency predictor
One week $\geq$ T	4
Two weeks $\geq$ T $>$ One week	3
Three weeks $\geq$ T $>$ Two weeks	2
Four weeks $\geq$ T $>$ Three weeks	1
T $>$ Four weeks	0

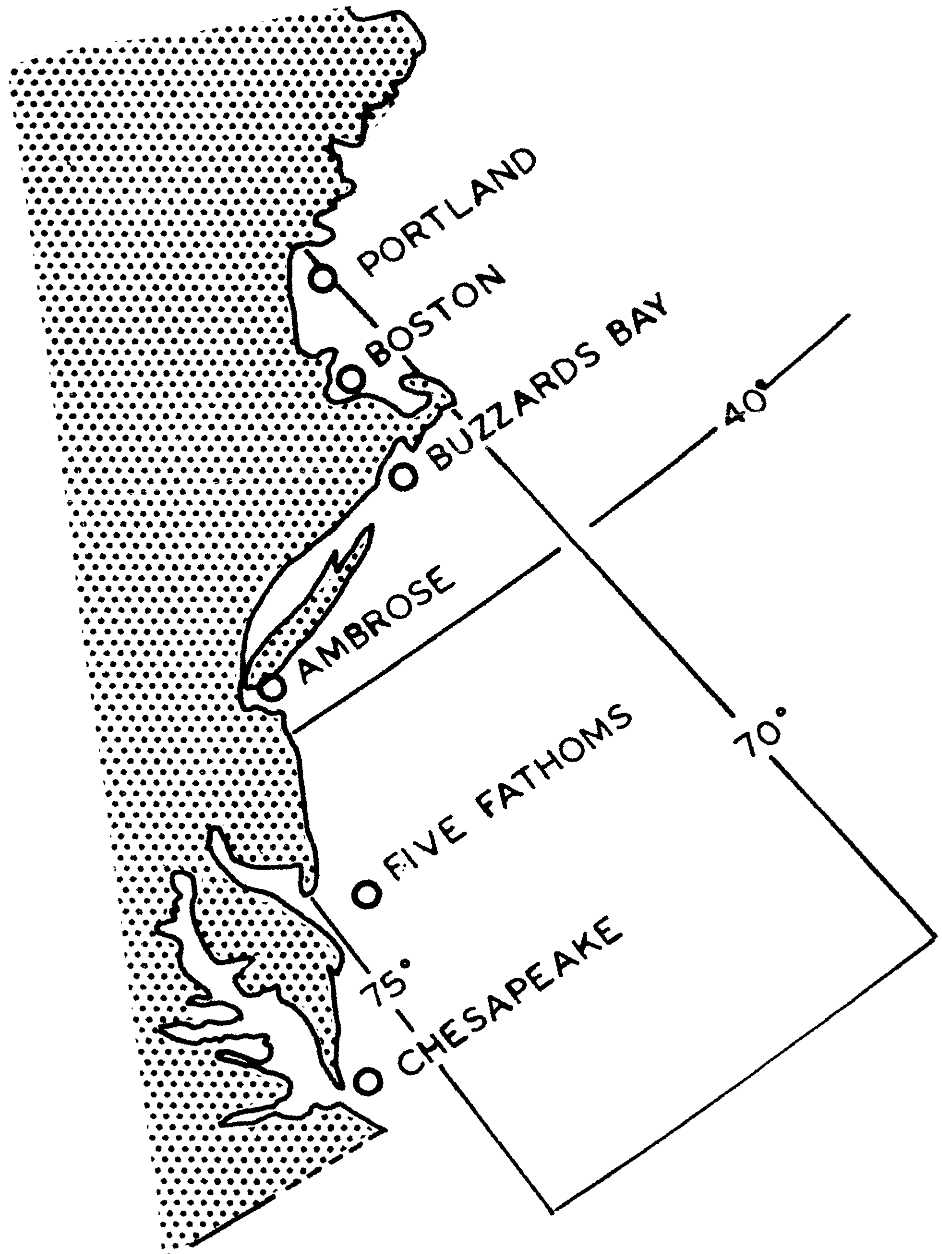


Figure 15. Location of northeast coast light stations.

Table 4. Coastal states, associated light stations, and water depth at light stations.

Coastal states	Light station	Water depth (feet)
Maine	Portland	100
Massachusetts	Boston	70
Rhode Island	Buzzards Bay	70
New York	Ambrose	80
New Jersey	Ambrose	80
Delaware	Five Fathoms	58
Virginia	Chesapeake	60

directions are measured by anemometers. The following data were extracted from light station surface weather observation forms:

(1) maximum wave height and associated wave period during erosional storms

(2) wind direction at the time of maximum wave height, this direction was used as the wave direction

(3) wind speed at the time of maximum wave height and at six-hour intervals before the maximum wave height. The wind duration was limited by either a wind shift of more than 40 degrees, or a duration of 39 hours.

A weighted wind speed was determined for each maximum wave height as outlined by Pore and Richardson (1967).

Wave Height and Period Computed with Sverdrup-Munk-Bretschneider (SMB) Equations

Input to the SMB equations were the weighted wind speed and duration from light station data and a measured fetch length. The fetch length was determined by measuring the over water distance between a light station and the nearest land. This distance was measured along a line defined by the wind direction at the time of the maximum wave height. For those cases where the fetch length was unlimited, duration was used as the limiting factor. The wave was assumed to be fully developed after 39 hours. The following SMB deepwater wave equations (Bretschneider, 1958) were used to compute wave height and period.

$H = U^2/g\ 0.283\ \tanh[0.0125(gF/U^2)^{0.42}]$

$T = 2\pi U/g\ 1.20\ \tanh[0.077(gF/U^2)^{0.25}]$, where:

H is the significant wave height, T is the significant wave period, U is the weighted wind speed, F is the fetch length, and g is the acceleration due to gravity.

These wave equations are based on the following (personal correspondence between C. Bretschneider and N.A. Pore, 1975):

(1) the wind speed is an average wind speed over a minimum fetch

(2) the average wind speed is the 10-meter level, 10-minute average wind speed.

Measured winds at light stations (one-minute average wind measured at approximately a 10-meter level) were used as input to the SMB deepwater wave equations.

The observed significant wave heights are compared with the significant wave heights computed by the SMB deepwater equation at the six light stations (Figure 16) for the 36 beach erosional storms. The correlation coefficient and root mean square error (RMSE) associated with these data are 0.45 and 5.24 feet, respectively. In order to investigate the relationship between observed and computed wave heights at each light station, data at each light station were plotted with different symbols. As can be seen in Figure 16, there is a great deal of scatter at all light stations.

When Tancreto (1958) compared the significant wave height computed by the SMB deepwater wave equation with the magnitude of the

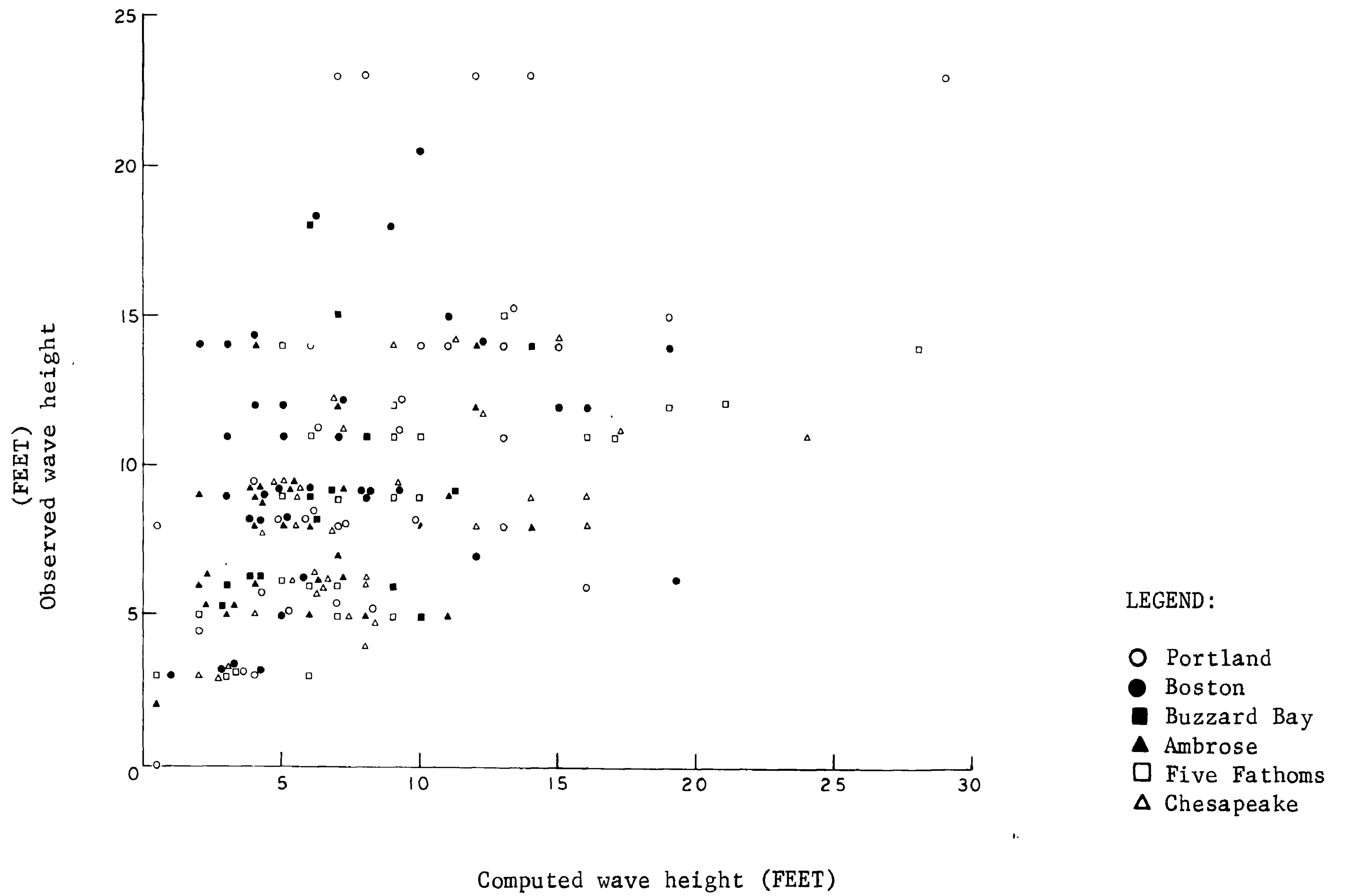


Figure 16. Observed wave heights and wave heights computed by the SMB deepwater wave equation at six light stations for 36 erosional storms. The correlation coefficient and RMSE for these data are 0.45 and 5.24 feet, respectively.

storm surge at Boston for 45 storms, he obtained a correlation coefficient of 0.88. A similar comparison at Boston, by this author, based on 34 erosional storms, resulted in a correlation coefficient of only 0.43. However, Tancreto's study and this study are not really comparable because the studies were based on different storm data. Tancreto's data was restricted to storms with strong winds with an easterly component along and off the southern New England coast. This author's data was not restricted to those storms, but was associated with erosional storms. Tancreto obtained his wind information from six-hourly surface weather maps. The winds used by this author were measured winds at Boston light station.

Light station wind data were also used as input to the SMB shallow-water wave equations. The SMB shallow-water wave equations, which use constant depth (depth of water at a light station) as well as weighted wind speed, duration and fetch (Bretschneider, 1958) are:

$$H = U^2/g\ 0.283\ \tanh\left[0.530(gD/U^2)^{0.75}\right] \tanh\left\{\frac{0.0125(gF/U^2)^{0.42}}{\tanh\ 0.530(gD/U^2)^{0.75}}\right\}$$

$$T = 2\pi U/g\ 1.20\ \tanh\left[0.833(gD/U^2)^{0.375}\right] \tanh\left\{\frac{0.077(gF/U^2)^{0.25}}{\tanh\ 0.833(gD/U^2)^{0.375}}\right\}$$

where: H is the significant wave height, T is the significant wave period, U is the weighted wind speed, F is the fetch length, D is the depth of water at the light station, and g is the acceleration due to gravity.

These shallow-water equations are approximations because the water depths around each light station are not constant. However, the average observed wave period for the light station wave data was about seven seconds. The deepwater wave length (L_o) for a seven-second wave is approximately 250 feet. As shown in Table 4, the water depths (D) at these light stations range from 100 feet at Portland to about 60 feet at Five Fathoms and Chesapeake. The ratio (D/L_o) for a wave with an average deepwater wave length of 250 feet at these light stations would range between about 2/5 to 1/4. According to Eagleson and Dean (1966), waves with this range of D/L_o ratios are transitional waves. Therefore, wave heights computed by the SMB shallow-water wave equation at the light stations may be just as valid as wave heights computed by the SMB deepwater wave equation.

The observed wave heights and the wave heights computed by the shallow-water SMB wave equation at the six light stations for the 36 erosional storms are shown in Figure 17. The correlation coefficient and RMSE for these data are 0.52 and 4.98 feet, respectively. The average computed SMB shallow-water wave height (H_s) for the 36 erosional storms was 6.0 feet, while the average computed SMB deepwater wave height (H_d) was 7.6 feet. Therefore, on the average, for the 36 erosional $H_s = 0.79H_d$. Even though the correlation coefficient associated with the SMB shallow-water wave equation (0.52) is higher than the correlation coefficient associated with the SMB deepwater wave equation (0.45), the RMSE's associated with each equation is about the same (5 feet).

The wave height and period computed by the deeptwater and shallow-water SMB equations were offered to a multiple regression screening

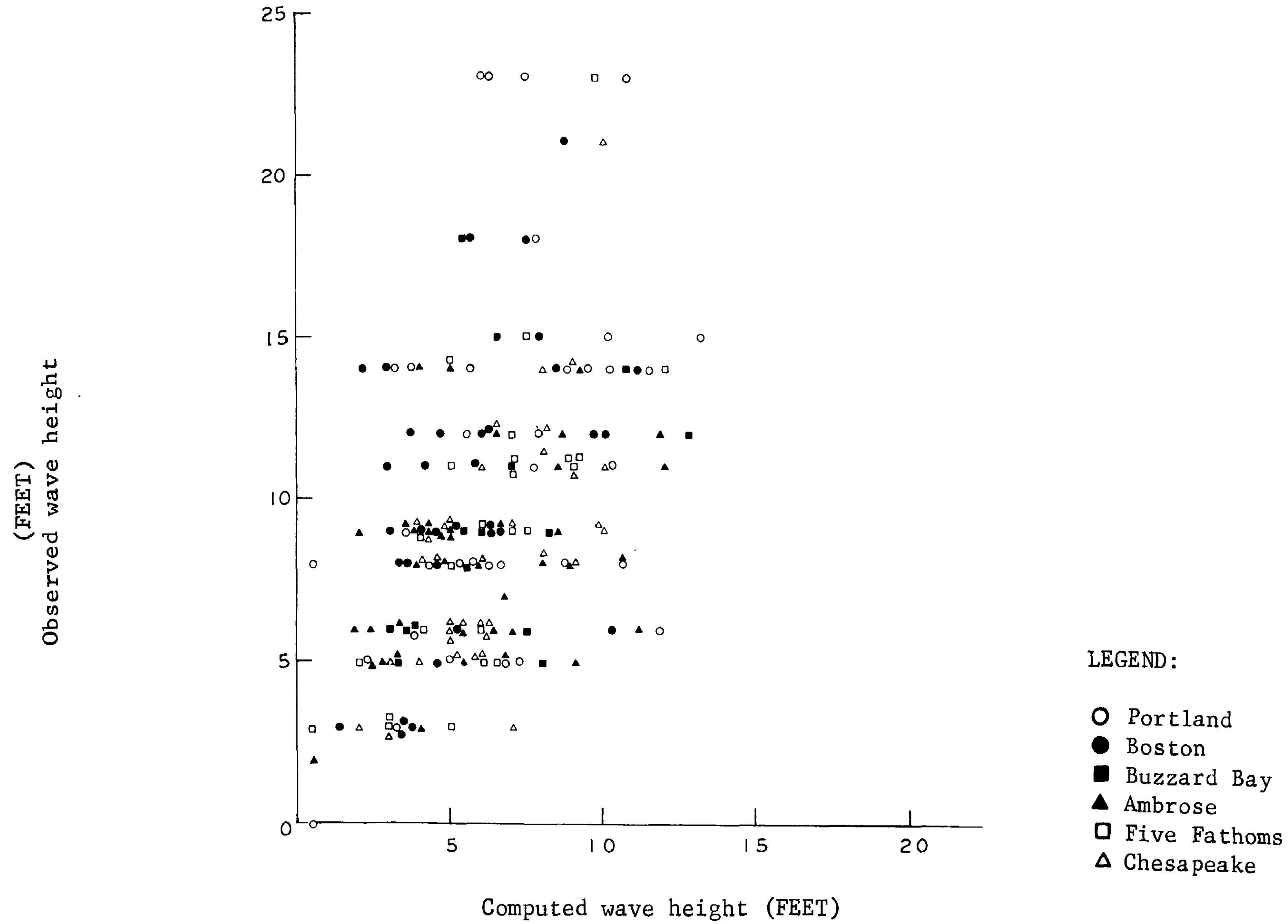


Figure 17. Observed wave heights and wave heights computed by the SMB deepwater wave equation at six light stations for 36 erosional storms. The correlation coefficient and RMSE for these data are 0.52 and 4.98 feet, respectively.

program as predictors of beach erosion. Wave equations of Wilson (1955) and the Pierson-Neumann-James method (Pierson, et al., 1955) could also have been used to compute the wave heights at the six light stations. However, it is concluded after looking at east coast light station wave data that the observed significant wave heights at the light stations are of such poor quality that they do not warrant further investigation by other wave hindcast methods.

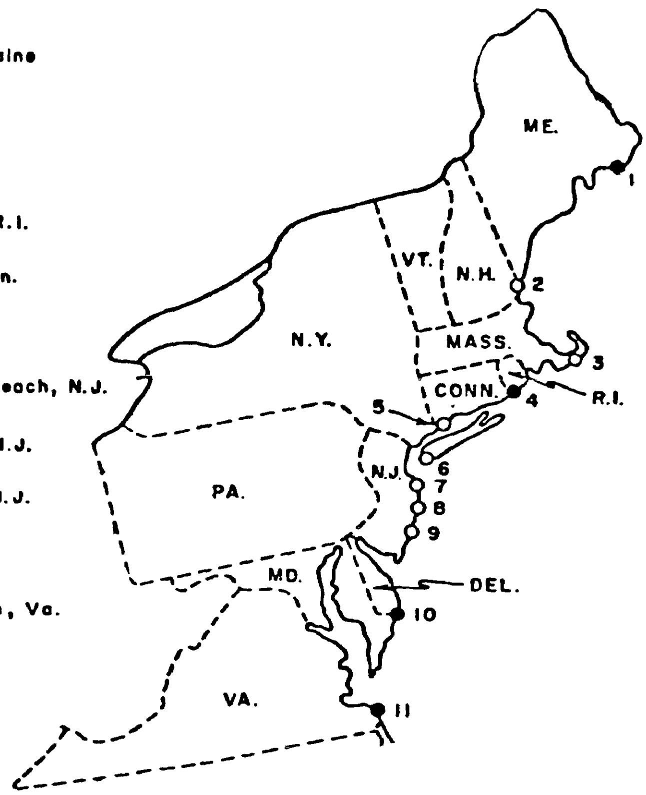
Breakers

Since breaker data (height and period) are unavailable for most of the erosional storm events, breakers are not used as predictors. However, since breakers are such an important factor in beach erosion, they are included in this discussion. Figure 18 shows the locations of northeast U.S. Coast Guard Stations which have been or are participating in a cooperative wave observation program. This Figure also indicates the time period over which stations have participated in the program. Only stations located along the coast of Maine, Rhode Island, Maryland, and Virginia have current programs. The breaker height, period, direction, and type are visually estimated every four hours by coastguardsmen. The observers were given the following instructions by CERC (personal correspondence with CERC):

(1) Write the average height, to nearest whole foot, for highest third of breakers.

(2) Write time in seconds for eleven breaker crests to pass a point. Eleven crests will include ten

1. Moose Peak Lifeboat Station, West Jonesport, Maine
(25 Sept. 1954 to Present)
2. Hampton Beach Lifeboat Station, Hampton, N.H.
(9 Sept. 1954 to 30 Nov. 1966)
3. Nauset Lifeboat Station, Eastham, Mass.
(27 Sept. 1954 to 21 June 1958)
4. Point Judith Lifeboat Station, Narragansett, R.I.
(25 Sept. 1954 to Present)
5. Stratford Point Light Station, Stratford, Conn.
(21 Sept. 1954 to 14 July 1960)
6. Short Beach Lifeboat Station, Freeport, N.Y.
(21 Sept. 1954 to 1 June 1959)
7. Monmouth Beach Lifeboat Station, Monmouth Beach, N.J.
(22 Sept. 1954 to 14 Oct. 1964)
8. Toms River Lifeboat Station, Seaside Height, N.J.
(22 Sept. 1954 to 15 Nov. 1957)
9. Atlantic City Lifeboat Station, Atlantic City, N.J.
(23 Sept. 1954 to 19 Sept. 1964)
10. Ocean City Lifeboat Station, Ocean City, Md.
(23 Sept. 1954 to Present)
11. Virginia Beach Lifeboat Station, Virginia Beach, Va.
(12 April 1954 to Present)



LEGEND:

● Active Stations

○ Inactive Stations

Figure 18. Location and status of northeast Coast Guard Stations that have, or are participating in, the Cooperative Wave Observation Program (personal correspondence with CERC).

(2) cont'd

complete breakers (crests plus troughs). Calm sea conditions are to be recorded as "000".

(3) Write one of five numbers (shown in Figure 19), to describe direction from which waves are coming just before they break. If the sea is calm, record "0". If there is more than one train of waves, write the direction of the most prominent waves, and mention the other directions in remarks.

(4) Write one of five numbers, given in Figure 20, to best describe the way waves are breaking.

Figure 21 shows the location and status of CERC wave gages which are located along the northeast coast of the United States as of June, 1975. As can be seen from Figure 21, there are few active gages. Graphs of measured wave heights and period (measured with a Step Resistance Staff-Relay Type gage), and the observed breaker heights and periods (visually estimated by coastguardsmen) at Virginia Beach, Virginia, are shown in Figures 22 and 23. For these two Virginia Beach cases, the estimated peak breaker heights are much lower than the measured wave heights, although high breaker heights are observed at the same time that high waves are measured. The measured wave period varies between two and 14 seconds. The estimated breaker period remains constant at approximately six seconds. This constant breaker period is probably due to the fact that breaker observations

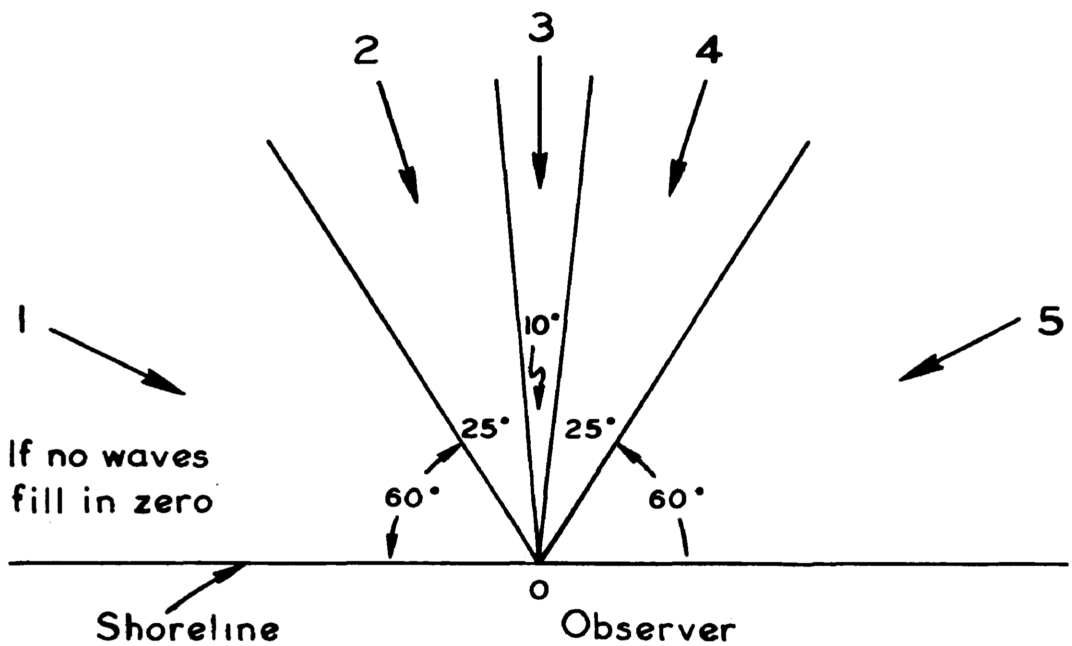


Figure 19. Wave direction code (personal correspondence with CERC).

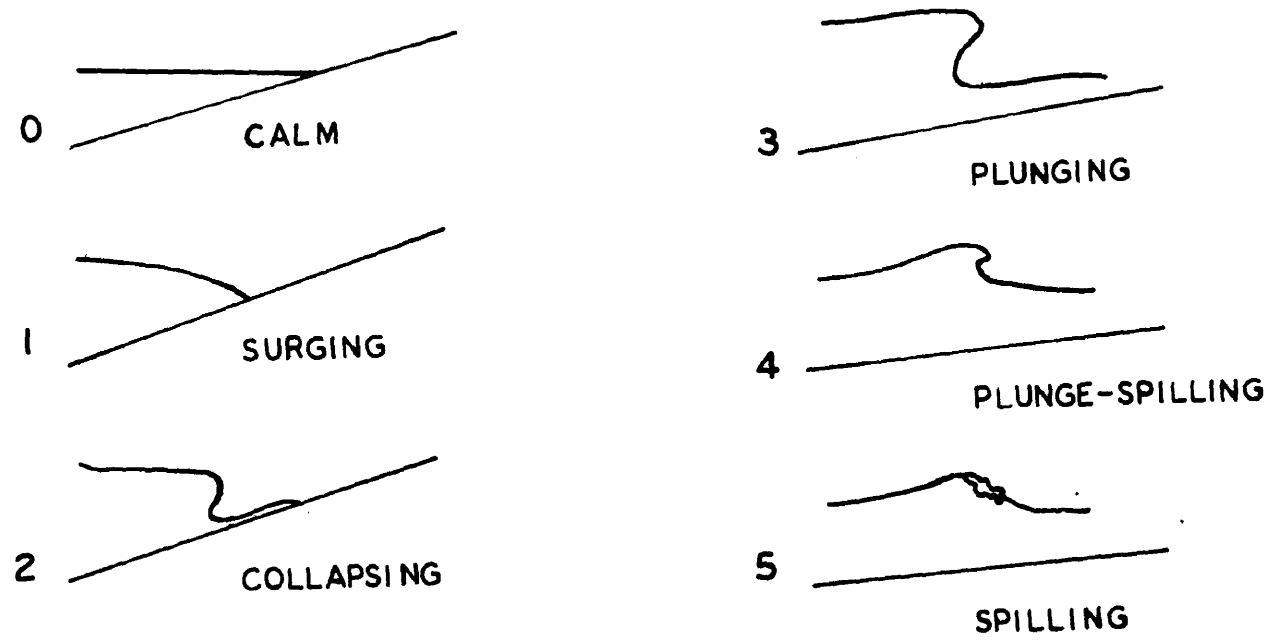


Figure 20. Breaker type code (personal correspondence with CERC).

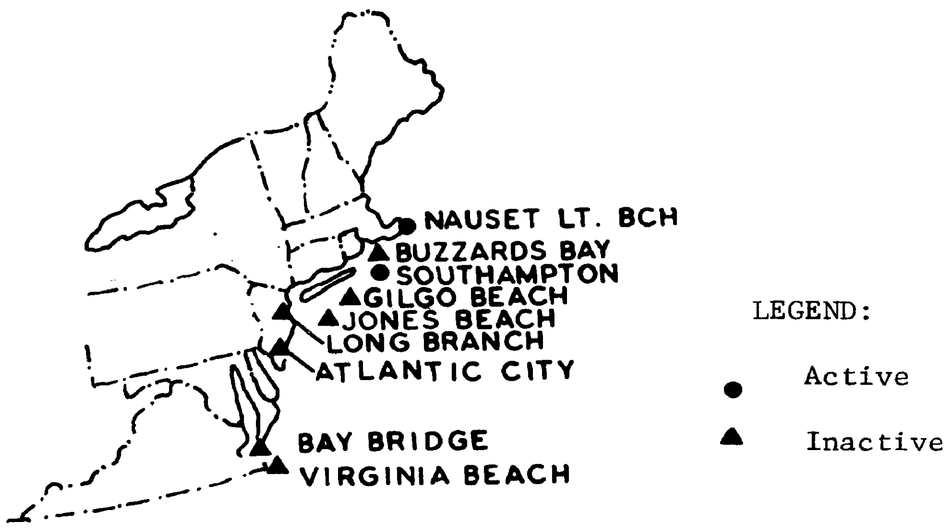
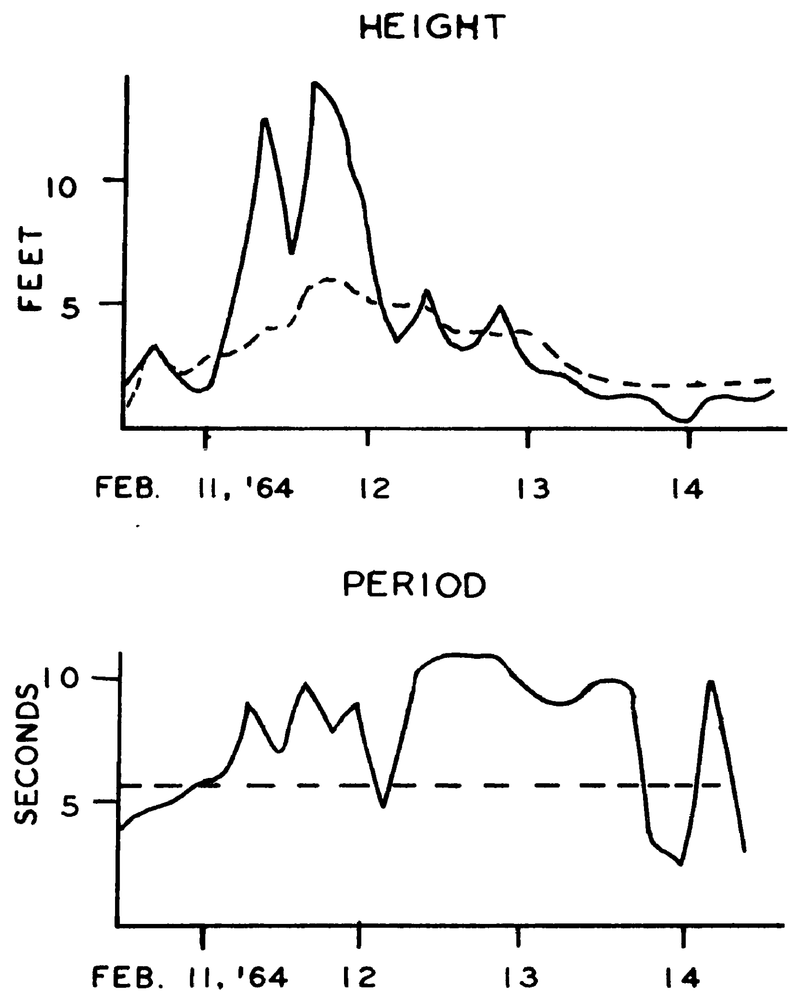


Figure 21. Location and status of CERC wave gages (Thompson, 1974).



LEGEND:

Measured ——

Estimated - - -

Figure 22. Measured wave height and period and estimated breaker height and period at Virginia Beach, Va. for February 11-14, 1964 (personal correspondence with CERC). The dates shown on these graphs are placed at the 1200 EST (1700 GMT) position for each day.

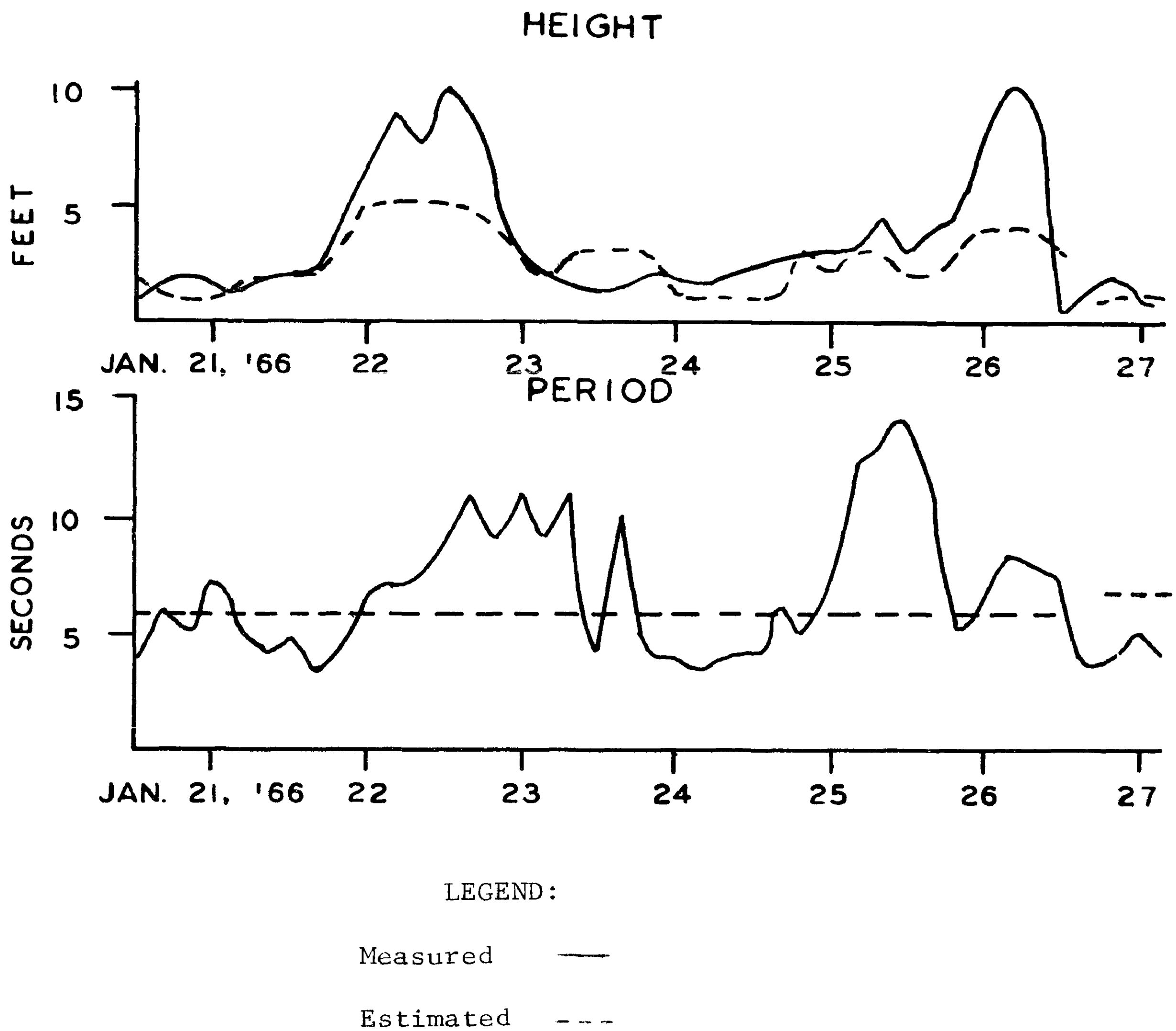


Figure 23. Measured wave height and period and estimated breaker height and period at Virginia Beach, Va. for January 21-27, 1966 (personal correspondence with CERC). The dates shown on these graphs are placed at the 1200 EST (1700 GMT) position for each day.

are visually estimated. Observed wave periods appear to be commonly about one-half that of measured wave periods (Gutman, 1977).

Wave Steepness

Between 1936 and 1956, laboratory experiments were made which led to the conclusion that beach profiles generally erode if deepwater wave steepness, H_o/L_o, (where H_o is deepwater wave height and L_o is deepwater wave length), exceeded 0.025, and accreted if H_o/L_o was less than about 0.025 (U.S. Army Coastal Engineering Research Center, 1973, p. 4-80). However, neither field data nor prototype-size laboratory experiments supported this widely used criterion (U.S. Army Coastal Engineering Research Center, 1973). Field and prototype-size laboratory data of Saville (1957) showed that beaches eroded at significantly lower deepwater wave steepness than the value of 0.025 derived from model laboratory experiments. Saville (1957) concluded that absolute wave height was probably as important as steepness in determining the beach profile.

Wave steepness predictors at light stations were computed from observed wave heights and periods at light stations. Steepness predictors at light stations were also computed from wave heights and periods which were computed by the SMB deepwater and shallow-water wave equations. The wave length (L), was computed as a function of wave period (T) and depth of water (D) at the light station. Light station water depths are shown in Table 4. One of three formulae was used to compute the wave length, depending upon the ratio D/L_o, where: L_o is the deepwater wave length $L_o = g/2\pi\, T^2$, (where g is the acceleration due to gravity). The three formulae and regions of validity according to Eagleson and Dean (1966), where L_o has been substituted for L, are as follows:

Wave type	Region of validity	Formula
Deepwater waves	$D/L_o \geq 1/2$	$L = L_o$
Transitional waves	$1/2 > D/L_o \geq 1/20$	$L = D/10^{(0.726 \log_{10}(D/L_o) - 0.081)}$
Shallow water waves	$1/20 > D/L_o$	$L = (2\pi D \quad L_o)^{1/2}$

Expressions for wave length (L) can be derived from the following equation:

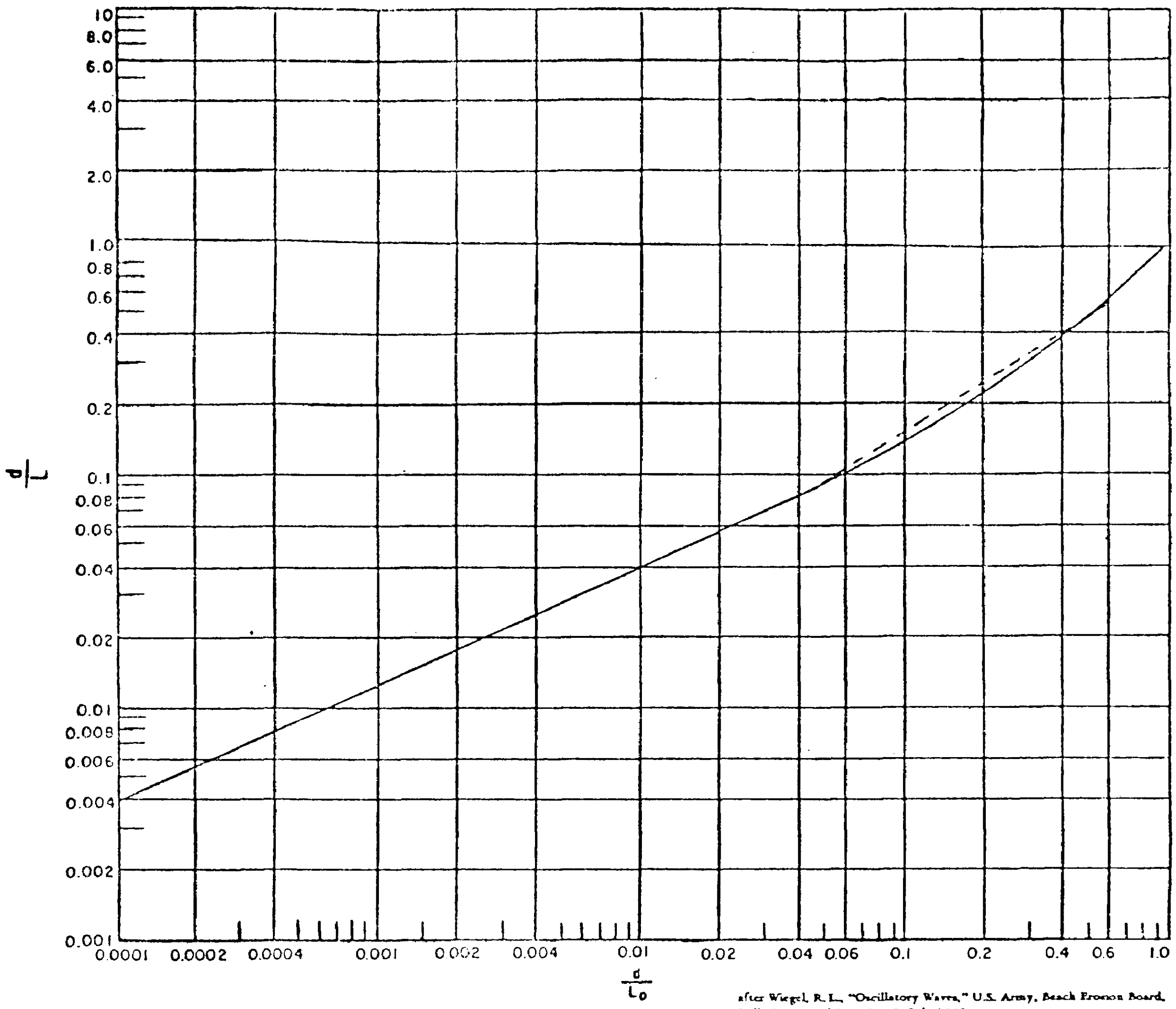
$$C^2 = L^2/T^2 = g\, L/2\pi \tanh (2\pi D/L),$$

where: C is phase velocity of the wave form at any depth (D). This equation is based on linear (Airy or small amplitude) wave theory. Since the period of the wave remains constant, $C^2/C_o^2 = L/L_o = \tanh (2\pi D/L)$, where C_o is deepwater phase velocity and L_o is deepwater wave length.

For deepwater waves ($D/L_o \geq 1/2$), $\tanh (2\pi D/L) \simeq 1$, and $L = L_o$.

For shallow-water waves ($D/L_o < 1/20$), $\tanh (2\pi D/L) \simeq 2\pi D/L$, and $L/L_o = 2\pi D/L$, or $L = (2\pi D L_o)^{1/2}$.

For transitional waves ($1/2 > D/L_o \geq 1/20$), $\tanh (2\pi D/L)$ cannot be approximated. In order to compute the length of a transitional wave, the curve shown in Figure 24 has been approximated by a broken straight line, between the values $D/L_o = 1/20$, and $D/L_o = 1/2$. The



after Wiegel, R. L., "Oscillatory Waves," U.S. Army, Beach Erosion Board, Bulletin, Special Issue No. 1, July 1948.

Figure 24. The relationship of d/L_o to d/L where: d is water depth, L_o is wave length in deepwater, and L is wave length at any depth (U.S. Army Coastal Engineering Research Center, 1973, p. C-2). The broken line shows the approximate relationship of d/L_o to d/L for a transitional wave $(1/20 \leq d/L_o < 1/2)$.

following three wave steepness predictors (H/L, where H is wave height, and L is wave length) were computed:

(1) observed wave steepness at light stations

(2) computed wave steepness at light stations as a function of wave height and period computed by the SMB deepwater equation (without the water depth at the light station)

(3) computed wave steepness at light stations as a function of wave height and period computed by the SMB shallow-water equation (with the water depth at the light station).

It is important to note that refraction, shoaling, and bottom friction were not considered in computing the wave steepness.

Maximum Storm Surge Height

For an erosional storm, the storm surge heights for Portland, Maine; Boston, Massachusetts; Newport, Rhode Island; The Battery, New York; Atlantic City, New Jersey; Breakwater Harbor, Delaware; and Hampton Roads, Virginia were obtained by subtracting the hourly astronomical tide heights from the hourly NOS observed tide heights at these tide stations. These storm surge heights were then scanned for the maximum height which occurred during the erosional storm. At each of these locations, the National Weather Service makes storm surge forecasts to 48 hours in advance (Pore, et al., 1974). Therefore, maximum storm surge height can be used as a predictor.

Type of Beach Material

Three types of beaches are recognized along the northeast and mid-Atlantic coasts based on beach material: rocky, rocky/sandy, and sandy. Based upon this classification, values were assigned to a beach material predictor as shown in Table 5. This is a very generalized predictor.

Monthly Beach Cycles

The beach profile varies seasonally on the west coast. The berm is cut back or disappears entirely with erosional waves from storms, and the beach profile changes from convex-up to concave-up. Seasonal changes on southern California beaches (Shepard, 1950) are much more pronounced than are typical of Atlantic Coast beaches (Urban, et al., 1969; Zeigler, et al., 1961; Harrison, et al., 1971; Goldsmith, 1972; Goldsmith, et al., 1972). As pointed out by Galvin and Hayes (1969), the difference in the seasonal beach cycles between the east and west coast is probably due to the differences between the nearshore wave heights of the east and west coast. Mean wave height by month, for a number of visual observations by coastguardsmen at shore stations is plotted in Figure 25. These mean wave heights are average values of wave heights at stations within each of five coastal segments (U.S. Army Coastal Engineering Research Center, 1973). These data clearly show the contrasts between the sharp west coast wave climate seasons, and the smaller differences in the east coast wave climate seasons.

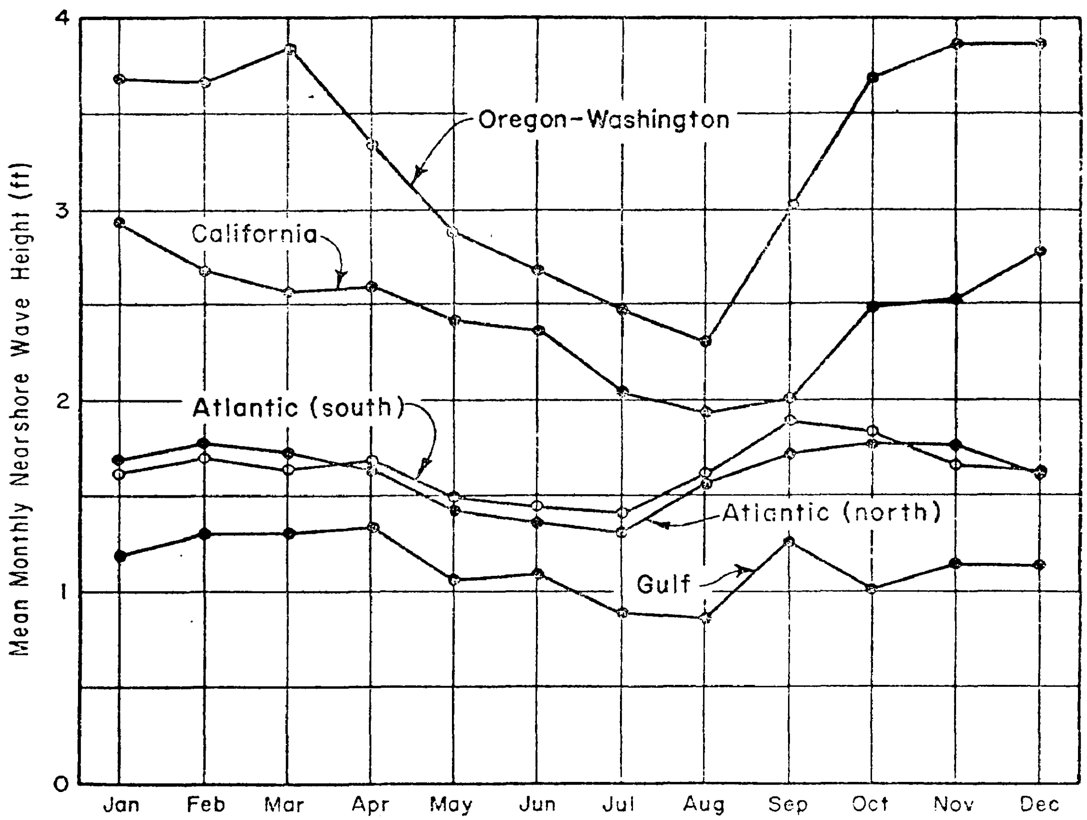


Figure 25. Mean monthly nearshore wave heights for five coastal segments (U.S. Army Coastal Engineering Research Center, 1973).

Table 5. Coastal states, type of beach material, and value of beach material predictor.

Coastal states	Type of beach material	Value of beach material predictor
Maine	Rocky	1.0
Massachusetts	Sandy/Rocky	0.5
Rhode Island	Sandy/Rocky	0.5
New York	Sandy	0.0
New Jersey	Sandy	0.0
Delaware	Sandy	0.0
Virginia	Sandy	0.0

Six beach cycle predictors were constructed in an attempt to determine which month has the highest correlation with erosion. There is one predictor for each month (November through April). The beach cycle predictor (BC(K)) is defined as $BC(K) = \cos(30^\circ [M-K])$, where: K = 1 (Jan.), 2 (Feb.), 3 (Mar.), 4 (Apr.), 11 (Nov.), and 12 (Dec.); and M is the month that the erosion event occurred. The beach cycle predictor was defined to have maximum weight for M = K. The beach cycle predictors and their assigned values are shown in Table 6.

Table 6. Monthly beach cycle predictors and their assigned values.
The beach cycle predictor (BC(K)) is defined as $BC(K) = \cos(30^{\circ}[M-K])$, where: K = 1 (Jan.), 2 (Feb.), ----, and M is the month in which the erosion event occurred.

Predictors BC(K)	Month (M) of Erosion Event (1) Jan.	(2) Feb.	(3) Mar.	(4) Apr.	(11) Nov.	(12) Dec.
BC(Jan.)	1.00	0.87	0.50	0.00	0.50	0.87
BC(Feb.)	0.87	1.00	0.87	0.50	0.00	0.50
BC(Mar.)	0.50	0.87	1.00	0.87	0.50	0.00
BC(Apr.)	0.00	0.50	0.87	1.00	-0.87	-0.50
BC(Nov.)	0.50	0.00	-0.50	-0.87	1.00	0.87
BC(Dec.)	0.87	0.50	0.00	-0.50	0.87	1.00

STATISTICALLY-DERIVED EQUATIONS

The sample of 36 erosional storms is too small to derive an erosion equation for each state. Therefore, the data for all seven states were pooled and one generalized equation was derived. This pooled method or generalized operator approach was used by Glahn and Lowry (1969) to forecast probability of precipitation and Barrientos (1970) to forecast wind. While the pooled method is advantageous in the sense that it increases the size of the developmental sample, the derived regression relationship is more general, with the result that some local effects are lost (Barrientos, 1970).

All-Predictors Equation

All predictors discussed in the previous sections were made available for selection to the screening procedure. Missing tide and light station data, primarily at Rhode Island, New Jersey, and Delaware, reduced the size of the developmental sample from 252 (36 x 7), to 206 pieces of data. The following beach erosion equation was derived by the screening procedure:

$$BE = -0.52 + 0.73\ (SD2.5) + 0.14\ (MT) + 0.45\ (SF) + 0.04\ (OH) - 0.30\ (BC(Feb.)), \qquad \text{Equation 1}$$

where: BE is beach erosion intensity (scale of 0 through 4), SD2.5 is storm duration (number of high tide cycles where the observed tide was greater than or equal to the mean spring amplitude of the tide plus 2.5 feet), MT is maximum tide height (feet), SF is storm frequency, OH is observed offshore wave height (feet) at a light station, and BC (Feb.) is monthly beach cycle where February is assigned a maximum value of 1.

The predictor terms were added one by one until the next term explained less than 1% of the variance. The terms are shown in their order of selection.

The multiple correlation coefficient and root mean square error (RMSE) for the all-predictors equation are 0.72 and 0.76, respectively. Since the range of beach erosion intensities is 0 through 4, an RMSE of 0.76 is slightly less than one category on the intensity scale.

Twenty-Six-Storms-Limited-Predictors-Linear Equation

Since the observed wave height at light stations is not readily available, and the storm frequency predictor is a very generalized-subjective predictor, they were not included in the remaining screening runs. By excluding light station data, the sample size was increased from 206 to 230 sets of data. This made it possible to divide the data sample into two parts. Erosion data from 1962 through 1971 (26 erosional storms, 174 sets of data) were used in the derivation of an erosion equation. These data were considered as dependent data, while data from 1972 through 1973 (10 erosional storms or 56 sets of data) were used as independent data to evaluate the derived erosion equation. The erosion equation which was derived from 174 sets of data is shown below:

$$BE = -0.62 + 0.60\ (SD2.5) + 0.17\ (MT) + 0.20\ (MS) - 0.46\ (BC(Feb.)), \qquad \text{Equation 2}$$

where: BE is beach erosion intensity (scale of 0 through 4), SD2.5 is storm duration, MT is maximum tide height (feet), MS is maximum storm surge height (feet), and BC(Feb.) is monthly beach cycle predictor where February is assigned the maximum value of 1.

The predictor terms, shown in their order of selection, were added in the same way as in the first screening run. The correlation coeficient and RMSE for this equation were 0.74 and 0.70, respectively.

As was mentioned earlier, the erosion intensity scale is a very subjective scale. It is much easier to make a distinction between no erosion and severe erosion, than to distinguish between minor, moderate, and major erosion. An attempt was made to remove some of the subjectivity from the intensity scale by combining the intermediate categories (minor, moderate, and major) into one category, moderate. The new 3-category scale (none, moderate, and severe) was used in the derivation of a 3-category erosion equation. However, there was very little difference between the 5-category and 3-category equations.

Twenty-Six-Storms-Limited-Predictors-Binary-Scale Equation

Since damage due to beach erosion is probably not a simple linear relationship, the linear erosion intensity scale was converted to a binary scale. Intensity scales based on powers of "e" and "10" were also tried, but the binary scale gave the best results. The five erosion intensity categories of the binary scale are: no erosion (2^0), minor erosion (2^1), moderate erosion (2^2), major erosion (2^3), and severe erosion (2^4). An erosion equation based on a binary scale was derived on 174 sets of data. This equation, which had a correlation coefficient of 0.81 and RMSE of 1.80, is of the following form:

$$BE2 = 1.37 + 2.32\ (SD2.5) + 0.13\ (MS)^2 - 1.12(BC(Feb.)) \qquad \text{Equation 3}$$

where: BE2 is beach erosion intensity (powers-of-2). The predictor terms are defined in the same way as in the previous equations.

The maximum-storm-surge-squared term $(MS)^2$ was included as a predictor in Equation 3 to take into account the suggested relationship between significant wave height and storm surge (Resio et al., 1973, p. 129).

Final Beach Erosion Equation

In order to determine which scale (linear or binary) should be used to derive a final beach erosion equation, both equations (2 and 3) were used to compute beach erosion intensity values for the 26 dependent and 10 independent storms. These computed values were placed in one of five categories (none, minor, moderate, major, and severe) as shown in observed-computed contingency Tables 7 through 10. Contingency Tables 7 and 8 were constructed using dependent and independent data in

Table 7. Observed-computed contingency table constructed with the twenty-six-storms-limited-predictors-linear-equation using dependent data. BE is the value of the computed erosion intensity.

OBSERVED CATEGORIES	COMPUTED CATEGORIES					Total	Percent of Total
	Severe ($3.5<BE$)	Major ($2.5<BE\leq3.5$)	Moderate ($1.5<BE\leq2.5$)	Minor ($0.5<BE\leq1.5$)	None ($BE\leq0.5$)		
Severe	4		2			6	3.4
Major			4	5		9	5.2
Moderate		2	7	2		11	6.3
Minor			3	20	9	32	18.4
None				28	88	116	66.7
Total	4	2	16	55	97	174	100.0

Table 8. Observed-computed contingency table constructed with the twenty-six-storms-limited-predictors-linear-equation using independent data. BE is the value of the computed erosion intensity.

OBSERVED CATEGORIES	COMPUTED CATEGORIES Severe (3.5 < BE)	Major (2.5<BE≤3.5)	Moderate (1.5<BE≤2.5)	Minor (0.5<BE≤1.5)	None (BE≤0.5)	Total	Percent of Total
Severe			2	2		4	7.1
Major			1	1		2	3.6
Moderate						0	0.0
Minor			1	9		10	17.9
None				16	24	40	71.4
Total	0	0	4	28	24	56	100.0

Table 9. Observed-computed contingency table constructed with the twenty-six-storms-limited-predictors-binary-scale equation using dependent data. BE2 is the value of the computed erosion intensity.

OBSERVED CATEGORIES	COMPUTED CATEGORIES					Total	Percent of Total
	Severe ($2^{3.5}<BE2$)	Major ($2^{2.5}<BE2\leq 2^{3.5}$)	Moderate ($2^{1.5}<BE2\leq 2^{2.5}$)	Minor ($2^{0.5}<BE2\leq 2^{1.5}$)	None ($BE2\leq 2^{0.5}$)		
Severe	4	2				6	3.4
Major		2	5	1	1	9	5.2
Moderate			5	4	2	11	6.3
Minor		1	7	13	11	32	18.4
None			7	50	59	116	66.7
Total	4	5	24	68	73	174	100.0

Table 10. Observed-computed contingency table constructed with the twenty-six-storms-limited-predictors-binary-scale equation using independent data. BE2 is the value of the computed erosion intensity.

OBSERVED CATEGORIES	COMPUTED CATEGORIES					Total	Percent of Total
	Severe ($2^{3.5} < BE2$)	Major ($2^{2.5} < BE2 \leq 2^{3.5}$)	Moderate ($2^{1.5} < BE2 \leq 2^{2.5}$)	Minor ($2^{0.5} < BE2 \leq 2^{1.5}$)	None ($BE2 \leq 2^{0.5}$)		
Severe			4			4	7.1
Major				2		2	3.6
Moderate						0	0.0
Minor			3	6	1	10	17.9
None			8	17	15	40	71.4
Total	0	0	15	25	16	56	100.0

Equation 2 (linear scale). Equation 3 (binary scale) was used to construct contingency Tables 9 and 10.

Tables 7 and 8 show that the linear-scale equation (Eq. 2) underestimated severe and major erosion events and overestimated minor and no erosion events for both dependent and independent data. The binary-scale equation (Eq. 3) did not underestimate severe and major erosion events as badly as the linear-scale equation, but the binary-scale equation greatly overestimated minor and no erosion events (Tables 9 and 10). The estimates of erosion intensity computed by the binary-scale equation are larger than the estimates computed by the linear-scale equation because in converting the predictand from a linear-scale value to a binary-scale value, the binary-scale values were increased. The mean of the erosion intensity values was increased from 0.60 (no erosion to minor erosion) for the linear-scale values to 2.25 (minor to moderate erosion) for the binary-scale values. The screening procedure (Appendix B) uses the mean of the predictand (erosion intensity) in the derivation of the beach erosion equation. Therefore, Equation 3 (binary scale) will generally estimate larger erosion intensity values than the linear-scale equation (Eq. 2). As expected, the erosion intensity values computed with dependent data (Tables 7 and 9) agreed more closely with observed estimates of erosion intensity values computed with independent data (Tables 8 and 10).

A matrix score (National Weather Service, 1973) was computed for each equation, for both dependent and independent data. The matrix score (S) was computed by the following formula:

$$S = \sum_{i=1}^{5} \sum_{j=1}^{5} f_{ij}\ m_{ij},$$ where: f_{ij} are elements in the observed-computed (5 by 5) contingency table and m_{ij} are the elements of the scoring matrix, shown in Table 11.

The scoring matrix contains a series of weighting factors which give heavier weights to the erosion categories which are more difficult to forecast. In order to make the matrix scores more meaningful when evaluating samples of different sizes, a relative matrix score (RS) was computed by the following formula:

$$RS = S/\sum_{i=1}^{5} 0_i\ m_{ii},$$ where: S is defined as above, 0_i are the total number of elements in observed categories and m_{ii} are elements along the main diagonal of the scoring matrix shown in Table 11.

The relative matrix scores and the percent of correct computations for the two equations (2 and 3) using dependent and independent data are tabulated in Table 12. For both the dependent and independent data, the relative matrix scores and percent of correct computations were higher for the linear-scale equation. Although the severity of erosion is underestimated, the erosion categories computed by both equations using independent data are in reasonable agreement with observed data. Klein, et al., (1959) have pointed out that the tendency to underestimate can be corrected by "inflating" the estimates so that the variability of the observed and estimated values is approximately

Table 11. Scoring matrix, which was designed to give heavier weights to erosion categories which are more difficult to forecast.

OBSERVED CATEGORIES	COMPUTED CATEGORIES				
	Severe	Major	Moderate	Minor	None
Severe	10	7	4	1	0
Major	7	8	5	2	0
Moderate	4	5	6	3	0
Minor	1	2	3	4	1
None	0	0	0	1	2

Table 12. Relative matrix scores and percent of correct computations for dependent and independent data.

Twenty-Six-Storms-Limited-Predictors-Linear-Equation (Eq. 2)		Twenty-Six-Storms-Limited-Predictors-Binary-Scale Equation (Eq. 3)	
DEPENDENT DATA		DEPENDENT DATA	
Relative Matrix Score	0.78	Relative Matrix Score	0.70
Percent Correct	68	Percent Correct	48
INDEPENDENT DATA		INDEPENDENT DATA	
Relative Matrix Score	0.68	Relative Matrix Score	0.57
Percent Correct	59	Percent Correct	38

the same. This adjustment ("inflation") can be made by multiplying the estimates by the reciprocal of the correlation coefficient between erosion intensity and the predictors.

Since the relative matrix scores and percent of correct computation were higher for the linear-scale equation, a final erosion equation was derived with a linear-intensity scale by combining dependent and independent data (230 sets of data). This equation, which has a correlation coefficient of 0.69 and an RMSE of 0.78, is shown below.

$$BE = -0.77 + 0.64\ (SD2.5) + 0.20\ (MT) + 0.18\ (MS) - 0.32\ (BC(Feb.)) \qquad \text{Equation 4}$$

where:

BE is beach erosion intensity (linear scale of 0 through 4), SD2.5 is storm duration, MT is maximum tide height (feet), MS is maximum storm surge height (feet), and BC (Feb.) is the monthly beach cycle predictor which gives maximum weight to the month of February.

This equation is very similar to the linear-scale equation (Eq.2) which was derived on 174 sets of data. The National Weather Service plans to use Equation 4 on a trial basis to make beach erosion forecasts.

For easy reference, all derived beach erosion equations are listed in Appendix C. The sample size, multiple correlation coefficient, and RMSE associated with each of these equations are also shown in Appendix C. The multiple correlation coefficients and RMSE's are based on dependent data.

DISCUSSION

Derived Beach Erosion Equations

In the derivation of all equations, the predictor terms were added one by one until the next term explained less than 1% of the variance. The terms are shown in their order of selection by the screening procedure.

Equation 1, $\left[BE = -0.52 + 0.73\ (SD2.5) + 0.14\ (MT) + 0.45\ (SF) + 0.04\ (OH) - 0.30\ (BC(FEB.))\right]$, shows that as the storm duration (SD2.5), maximum tide height (MT), storm frequency (SF), and offshore wave height (OH) increase, the erosion intensity increases. The first two predictors (storm duration and maximum tide height) were the same predictors that Darling (1964) used in constructing his "vulnerability curve" for Atlantic City, New Jersey.

The fifth predictor is the monthly beach cycle predictor (BC(Feb.)), which assigns maximum weight to February. However, this predictor is selected with a negative sign. As shown earlier in Figure 12, the greatest number of erosion events occurred in November, December, and February. January and February are the months in which maximum wave heights occur along the east coast (Galvin and Hayes, 1969). Therefore, by February, in general, the berm has already been cut back, and there is less sand to be eroded. This is in agreement with Equation 1 which shows that if two erosional storms struck the same coastal state (one in November and one in February), and if the four predictors (storm duration, maximum tide height, storm frequency, and offshore wave height) were the same for both storms, the November storm would have a higher (0.30 higher) erosion potential.

Table 13 contains the simple correlation coefficients of predictors and predictand computed during the derivation of Equation 1. The high correlation between the mean spring tide amplitude predictor and the type of beach material predictor is deceiving. Even though the beach material predictor and mean spring tide amplitude predictor both increase from Virginia to Maine, the high correlation between these two predictors is due to the fact that the beach material predictor is a very generalized predictor. Beach material has been typed by state, which does not allow for variability within a state. Both predictors are also independent of erosional storms. The wave height computed by the SMB deepwater method (independent of light station depth) is highly correlated with the wave height computed by the SMB shallow-water method (computed as a function of light station depth). There is a high correlation between these predictors because these predictors are both functions of the same trigometric function, the hyperbolic tangent.

The predictor which has the highest simple correlation with the predictand (beach erosion intensity) is storm duration (SD2.5). The simple correlation between these two variables is 0.59. The relatively high correlation between these two variables shows that erosion intensity is greatly dependent on the period of time that the superelevated water surface acts on the beach face. For example, if the Virginia coast, during the month of November, experienced a storm which lasted

Table 13. Simple correlation coefficients of predictors and predictand computed during the derivation of the all-predictor equation (Eq. 1).

PREDICTORS	Mean spring tide amplitude	Storm duration (SD2.5)	Frequency of erosional storms	Observed wave height	Observed wave steepness	Wave height computed by SMB deepwater method	Wave steepness computed by SMB deepwater method	Wave height computed by SMB shallow water method	Wave steepness computed by SMB shallow water method	Maximum storm surge height	Type of beach material	Monthly beach cycle (February)	Erosion intensity
Maximum tide height	.81	.28	.26	.37	.08	.13	-.01	.16	-.08	.25	.63	.03	.44
Mean spring tide amplitude		-.13	.19	.26	-.01	.00	-.21	.06	-.23	-.12	.80	-.01	.15
Storm duration (SD2.5)			.02	.19	.05	.23	.29	.14	.11	.50	-.13	.12	.59
Frequency of erosional storms				.13	.08	.05	.03	.05	.01	.15	.11	-.10	.29
Observed wave height					.33	.46	.38	.53	.40	.36	.29	-.06	.37
Observed wave steepness						.20	.20	.25	.24	.21	.02	.01	.10
Wave height computed by SMB deepwater method							.89	.93	.38	.35	.09	.02	.20
Wave steepness computed by SMB deepwater method								.76	.56	.39	-.15	.02	.21
Wave height computed by SMB shallow water method									.47	.33	.18	.01	.17
Wave steepness computed by SMB shallow water method										.24	-.14	.01	.16
Maximum storm surge height											-.18	.04	.46
Type of beach material												.03	.11
Monthly beach cycle (February)													-.07

through one high tide with a maximum tide of 4 feet above MSL, a storm frequency of 0, and an offshore wave height of 10 feet, the beach erosion intensity computed by Equation 1 would be 1.4. However, if this same storm remained in the same area for five high tides, as did the March 1962 storm, the erosion intensity would increase from 1.4 for one high tide to 4.3.

As can be seen in Appendix C, all four beach erosion equations contain a storm duration term (SD2.5), a maximum storm surge height term (MS), and a beach cycle term (BC(Feb.)). All of these equations show that as the storm duration and maximum storm surge height increases, the erosion intensity increases. The monthly beach cycle predictor, which gives February maximum weight, is always selected with a negative sign. While the order of selection is an indication of the importance of a predictor, the magnitude of the regression coefficient and the range of the predictor must also be considered. In all equations, the storm duration term was selected as the first predictor. The magnitude of the regression coefficient associated with this predictor, storm duration, is larger than the magnitude of any of the other regression coefficients. The range of the storm duration term (0 to 10) is also greater than the range of any of the other predictors. Therefore, it is safe to say that the most important predictor of erosion intensity in these equations is storm duration.

Application of Beach Erosion Forecast Equation

Equation 4, $\left[BE = -0.77 + 0.64\ (SD2.5) + 0.20\ (MT) + 0.18\ (MS) - 0.32\ (BC(Feb.))\right]$, was used during 1976 (January through April) to forecast qualitative estimates of erosion. Input to Equation 4 were forecasts of storm duration (SD2.5), maximum tide height above MSL (MT), and maximum storm surge height (MS). These predictors were forecast 36 hours in advance at 12-hour intervals by combining the east coast storm surge forecasts of the National Weather Service (Pore, et al., 1974) with forecasts of the astronomical tide. The qualitative beach erosion forecasts were compared with observed reports of erosion which were furnished by Forecast Offices of the Eastern Region of the National Weather Service. These comparisons indicated that the beach erosion equation provided meaningful forecast guidance as shown by the following documented erosion event.

Plum Island, Massachusetts (extreme northeast coast of Massachusetts) experienced the erosional damage shown by the photographs in Figure 26, as a result of a storm on March 16-17, 1976. Figure 27 contains three beach erosion forecasts which were made 36 hours in advance at 12-hour intervals. The top forecast was made at 0000 GMT on March 16, 1976 (1900 EST March 15, 1976). The 24- to 36-hour forecast calls for moderate to major erosion along the Massachusetts-Maine coasts (Plum Island area). Minor to moderate erosion is also forecast for Rhode Island, New York, and Delaware. Minor erosion was reported at New York and New Jersey. The forecasts made 12 hours later (middle forecasts) and 24 hours later (bottom forecasts) are consistent except

RETIREMENT COTTAGE of Mr. and Mrs. Walter Perkins, Main St., West Boxford, at Plum Island, Newbury, toppled during winter storm early Wednesday morning.

BASEMENT of Plum Island cottage was heavily damaged in the Tuesday-Wednesday wind-driven snowstorm. (Boisselle photos)

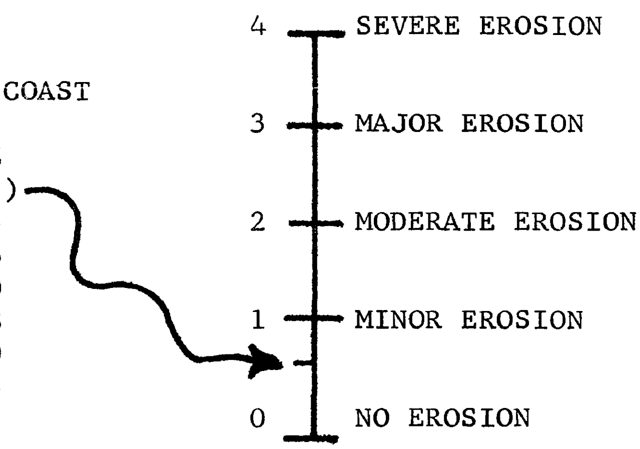
Figure 26. Photographs of property damage along Plum Island, Mass. following the March 16-17, 1976 storm.

EROSN KWBC 160000
BEACH EROSION FCST FOR U.S. NE COAST

	00Z	12Z	00Z	12Z
ME.	0.1	0.6	2.0	2.4
MASS.	0.1	0.8	2.1	2.3
R.I.	-0.4	0.0	1.2	0.1
N.Y.	-0.3	0.3	1.3	-0.2
N.J.	-0.3	0.3	0.4	-0.1
DELMAR.	-0.3	0.2	1.0	-0.3
VA.	-0.3	-0.3	-0.5	-0.5

EROSN KWBC 1612000
BEACH EROSION FCST FOR U.S. NE COAST

	12Z	00Z	12Z	00Z
ME.	0.7	2.1	2.2	(0.6)
MASS.	0.9	2.1	2.2	0.5
R.I.	0.1	1.2	-0.1	-0.3
N.Y.	0.3	1.3	-0.6	-1.0
N.J.	0.3	1.1	-0.4	-0.8
DELMAR.	0.3	0.3	-0.8	-1.0
VA.	-0.2	-0.7	-0.6	-0.5



EROSN KWBC 170000
BEACH EROSION FCST FOR U.S. NE COAST

	00Z	12Z	00Z	12Z
ME.	1.9	2.6	0.2	0.5
MASS.	1.9	0.8	0.2	0.5
R.I.	1.1	-0.2	-0.4	-0.5
N.Y.	1.4	-0.5	-0.6	-0.5
N.J.	1.1	-0.6	-0.6	-0.6
DELMAR.	0.4	-0.8	-0.6	-0.6
VA.	-0.5	-0.4	-0.4	-0.9

Figure 27. Automated beach erosion forecasts for March 16-18, 1976.

for the forecasts for Delmar, in that moderate to major is forecast for Maine and Massachusetts, while minor to moderate erosion is forecast for Rhode Island, New York, and New Jersey. The reported erosion for this documented erosion event is in good agreement with the erosion forecasts shown in Figure 27.

In order to determine the effectiveness of the erosion forecasts, Equation 4 is being used operationally by the National Weather Service to forecast beach erosion twice each day. These forecasts are made out to 48 hours in advance at 12-hour intervals. For those cases when minor, moderate, major, or severe erosion is forecast at any one of the coastal states, (Maine, Massachusetts, Rhode Island, New York, New Jersey, Delaware and Maryland (Delmar), and Virginia), the beach erosion message will be as shown in the top portion of Figure 28. These qualitative forecasts of erosion can be related to past storms in Table 14. If no erosion is forecast at all coastal states, the erosion message will be as shown in the lower portion of Figure 28.

Fine Scale Studies

In order to include such predictors as angle of wave approach relative to the coastline and breaker heights, an erosion study for a very small segment of the coast would have to be undertaken. Such studies have been made by Davis and Fox (1972), and Harrison, et al., (1971).

The correlation study of Harrison, et al., (1971) did not yield completely reliable beach-change predictor equations. Perhaps they

FZUS3 KWBC 160000
BEACH EROSION FCST FOR N.E. COAST OF THE U.S.
FCST NOT VALID FOR TROPICAL STORMS

	00Z	12Z	00Z	12Z	00Z
ME.	NONE	MINOR	MODERATE	MAJOR	NONE
MASS.	NONE	MINOR	MODERATE	MAJOR	NONE
R.I.	NONE	NONE	MINOR	NONE	NONE
N.Y.	NONE	NONE	MINOR	NONE	NONE
N.J.	NONE	NONE	NONE	NONE	NONE
DELMAR.	NONE	NONE	MINOR	NONE	NONE
VA.	NONE	NONE	NONE	NONE	NONE

FZUS3 KWBC 160000
BEACH EROSION FCST FOR N.E. COAST OF THE U.S.
FCST NOT VALID FOR TROPICAL STORMS
NO EROSION IS FCST FOR THE NEXT 48 HOURS

Figure 28. Beach erosion forecast messages which are being transmitted by teletypewriter twice each day to National Weather Service Forecast Offices. The message shown in the upper portion of this figure is transmitted when minor ($1.5 \geq BE > 0.5$), moderate ($2.5 \geq BE > 1.5$), major ($3.5 \geq BE > 2.5$), or severe erosion ($BE > 3.5$) is forecast at any one of the northeast coastal states. BE is the forecast of the beach erosion intensity. These forecasts, which are made out to 48 hours in advance at 12-hour intervals, are based on the east coast extratropical storm surge forecasts of the National Weather Service and astronomical tide heights. The beach erosion forecasts shown in this figure are based on 00 Greenwich Mean Time data on the 16th of the month. If no erosion ($BE \leq 0.5$) is forecast at all of the northeast coastal states, the beach erosion forecast message is as shown in the lower portion of this figure.

Table 14. Qualitative erosion terms associated with past storms.

STORM DATES	ME.	MASS.	R.I.	N.Y.	N.J.	DELMAR	VA.
Mar. 6-9, 1962	MINOR	MINOR	MAJOR	SEVERE	SEVERE	SEVERE	SEVERE
Nov. 26-30, 1962	NONE	NONE	NONE	NONE	MODERATE	MODERATE	MAJOR
Nov. 29-30, 1963	MAJOR	MODERATE	MODERATE	MAJOR	NONE	NONE	NONE
Nov. 11-13, 1968	MINOR	MAJOR	MAJOR	SEVERE	SEVERE	NONE	MINOR
Apr. 6-7, 1971	NONE	NONE	NONE	NONE	NONE	MAJOR	MODERATE
Feb. 19-20, 1972	SEVERE	SEVERE	SEVERE	MINOR	NONE	NONE	NONE

could have obtained better results if, in addition to 1000 millibar U- and V-wind components, they had included tide height, wave height, period, and direction (before and after refraction). The inclusion of these predictors would be expensive because tide gages and wave recorders would have to be installed at beach profile locations. Nevertheless, a fine scale study with observed tides and waves before and after refraction may further delineate some of the "grey area" between offshore waves and sand movement on the beach. In the future, an array of buoys may furnish some of this much-needed information.

Implicit Wave Predictor Term

Waves are an important factor in causing erosion. Although observed and SMB computed wave height and steepness predictors were offered to the screening program, only the observed light station wave height predictor was selected. In screening runs where observed wave height was not offered as a predictor (Equations 2, 3, and 4), the maximum storm surge height was selected. Because of the relationship between significant wave height and storm surge height (Tancreto, 1958 and Resio, et al., 1973, p. 129), Equations 2, 3, and 4 do contain an implicit wave height predictor term in the form of maximum storm surge height.

In order for wave data to become an important predictor in a beach erosion forecast scheme, the wave data must be measured locally by wave gages. Visually observed wave data at offshore light stations are no substitute for measured wave data near the coast! Wave gages located near the coast would measure waves after they have undergone the effects of refraction, shoaling, and friction. These are the waves that are important in the beach erosion process (Mason, 1942).

Application of Forecast Technique to Other Coastal Areas

Before the final beach erosion equation (Eq. 4) is applied to other coastal areas (South Atlantic, Gulf or West Coasts), the equation should be tested with data from these coasts. It is concluded here that if the beach material and storm surge on other coasts are similar to the beach material and storm surge along the coast of the northeast and middle Atlantic States, and if the astronomical tides are of the semidiurnal type, then the beach erosion equation should be valid for these coasts. Since the tides along the Gulf Coast are diurnal and the tides on the West Coast are mixed, the storm duration term in the erosion equation would have to be modified before the equation could be applied to these two coasts. Because tides along the entire Atlantic Coast are predominately semidiurnal, Equation 4 should be applicable to the South Atlantic Coast (North Carolina, South Carolina, Georgia, and the east coast of Florida). In any case, the equation is only applicable for extratropical storms which occur during the six-month period, November through April, because the equation was derived from a data set covering this period.

Localized Beach Erosion Forecasts

Qualitative beach erosion forecast can be localized by including wave refraction information. Figure 29 shows that wave orthogonals converge on headlands and diverge at bays. Fisher, et al., (1975a) have found a good correlation between areas of overwash, severe erosion, and the convergence of wave orthogonals. Therefore, if the offshore bathymetry is known and the angle of wave approach and wave period are forecast, shoaling coefficients, refraction coefficients and areas of wave convergence can be forecast (Goldsmith, et al., 1974). By forecasting this wave refraction information, a generalized forecast of erosion can be localized. For example, if a refraction diagram based on wave forecasts for a particular storm shows a convergence of wave orthogonals at Virginia Beach, Virginia, and if moderate beach erosion is forecast for the Virginia coast, then a generalized forecast of erosion such as, "Moderate erosion along the Virginia coast", could be localized and changed to "Moderate erosion along the Virginia coast, except in the Virginia Beach area, where erosion is expected to be severe." Wave refraction information would make it possible to make more detailed erosion forecasts.

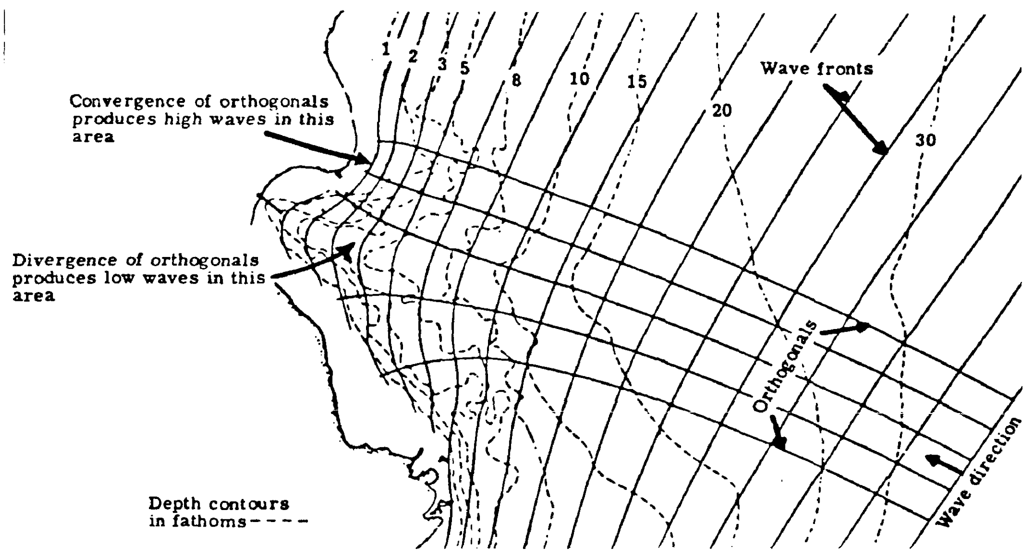


Figure 29. A wave refraction diagram depicting depth contours, wave direction, wave fronts, and wave orthogonals, (Goldsmith, et al., 1974).

FUTURE PLANS

In order to evaluate and improve the beach erosion forecast technique, accurate reports of erosion are needed. Hopefully, the cooperative erosion and data gathering program which has been set up with the Eastern Region of the National Weather Service will provide some of this much-needed information. Erosion data from the Forecast Offices of the Eastern Region will be supplemented with newspaper articles, beach profile data from CERC and aerial photography. To make better use of aerial photography, a baseline flight should be flown each year. Photographs from the baseline flights could then be compared to photographs of the beach after storms. After a large sample of data has been obtained through this cooperative erosion reporting program, the final beach erosion equation (Eq. 4) will be re-evaluated.

At some time in the future, the National Weather Service may produce computer worded forecasts for coastal areas which could be similar to the computer-produced worded forecasts of Glahn (1970) for U. S. cities. Beach erosion forecasts could then become a part of the computer-produced worded forecast for a coastal area. The computer-produced worded forecast for a coastal area might be as follows:

Virginia Coast

> Tides are expected to be three to four feet above normal during the next 12 hours. Nearshore wave heights of eight to 10 feet from the northeast will result in high

breakers. Moderate to major erosion is expected along the coast of Virginia, except at Virginia Beach, where erosion is expected to be severe.

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APPENDIX A

Glossary of "Beach Terms" according to

U. S. Army Coastal Engineering Research Center (1973)

BACKSHORE - That zone of the shore or beach lying between the foreshore and the coastline and acted upon by waves only during severe storms, especially when combined with exceptionally high water. Also BACKBEACH. It comprises the BERM or BERMS.

BACKRUSH - The seaward return of the water following the uprush of the waves. For any given tide stage, the point of farthest return seaward of the backrush is known as the LIMIT of BACKRUSH or LIMIT BACKWASH.

BAR - A submerged or emerged embankment of sand, gravel, or other unconsolidated material built on the sea floor in shallow water by waves and currents.

BEACH BERM - A nearly horizontal part of the beach or backshore formed by the deposit of material by wave action. Some beaches have no berms, others have one or several.

BEACH FACE - The section of the beach normally exposed to the action of the wave uprush. The FORESHORE of a BEACH.

CREST OF BERM - The seaward limit of a berm. Also BERM EDGE.

FORESHORE - The part of the shore lying between the crest of the seaward berm (or upper limit of wave wash at high tide) and the ordinary low water mark that is ordinarily traversed by the uprush and backrush of the waves as the tides rise and fall.

LITTORAL CURRENT - Any current in the zone extending seaward from the shoreline to just beyond the breaker zone, caused primarily by wave action, e.g., longshore current, rip current.

LONGSHORE BAR - A bar running roughly parallel to the shoreline.

LONGSHORE TROUGH - An elongate depression formed in the foreshore or in the bottom just offshore by waves or tidal currents.

OFFSHORE - The comparatively flat zone of variable width, extending from the breaker zone to the seaward edge of the Continental Shelf.

OVERWASH - That portion of the uprush that carries over the crest of a berm or of a structure.

RIP CURRENT - A strong surface current flowing seaward from the shore. It usually appears as a visible band of agitated water and is the return movement of water piled up on the shore by incoming waves and wind. With the seaward movement concentrated in a limited band, its velocity is somewhat accentuated. A rip consists of three parts: the FEEDER CURRENTS flowing parallel to the shore inside the breakers; the NECK, where the feeder currents converge and flow through the breakers in a narrow band or "rip"; and the HEAD, where the current widens and slackens outside the breaker line.

SURF ZONE - The area between the outermost breaker and the limit of wave uprush.

UPRUSH - The rush of water up onto the beach following the breaking of a wave. Also SWASH, RUNUP.

APPENDIX B

Excerpts from a detailed description of the selection of predictors by screening according to Miller (1958)

In multiple regression analysis, a predictand, Y, is expressed as a linear function of a number of predictors, $X_i (i = 1,2,...,n)$, where the coefficients, a_i, are determined using the method of least squares,

$$Y = a_0 + a_1 X_1 + a_2 X_2 + \ldots + a_n X_n \qquad (1)$$

Although there are a number of different screening procedures (Draper and Smith, 1966), the "forward selection" procedure will be discussed. This procedure selects significant predictors in a step-wise fashion. In order to select the first significant predictor, it is necessary to determine the following variances and covariances:

$$\mathrm{Var}(Y) = \sum_{t=1}^{N} (Y_t - \overline{Y})^2 / N \qquad (2)$$

$$\mathrm{Var}(X_i) = \sum_{t=1}^{N} (X_{it} - \overline{X}_i)^2 / N \ , \ i = 1,2,\ldots,n \qquad (3)$$

$$\mathrm{Cov}(YX_i) = \sum_{t=1}^{N} (Y_t - \overline{Y})(X_{it} - \overline{X}_i) / N \ , \ 1 = 1,2,\ldots,n \ , \qquad (4)$$

where: (2) is the variance of the predictand, (3) are the variances of the n possible predictors, and (4) are the covariances between the predictand and each of the predictors. N is the sample size.

The first selected predictor, X_j, must satisfy

$$R_{YX_j}{}^2 > R_{YX_i}{}^2 \quad , \quad \begin{matrix} i,j = 1,2,\ldots,n \; , \\ i \neq j \end{matrix} \tag{5}$$

where:

$$R_{YX_i}{}^2 = \frac{\mathrm{Cov}(YX_i)^{\;2}}{\mathrm{Var}(Y)\ \mathrm{Var}(X_i)} \quad . \tag{6}$$

$R_{YX_i}{}^2$ is the square of the correlation coefficient between Y and X_i.

The second step in the screening procedure is to find X_k such that the square of the partial correlation coefficient satisfies the following:

$$R_{YX_k \circ X_j}{}^2 > R_{YX_i \cdot X_j}{}^2 \quad , \quad \begin{matrix} i,j = 1,2,\ldots,n \\ k \neq i,j \end{matrix} \tag{7}$$

where:

$$R_{YX_i \cdot X_j}{}^2 = \frac{(R_{YX_i} - R_{YX_j} R_{X_i X_j})}{(1 - R_{YX_j}{}^2)(1 - R_{X_i X_j}{}^2)} \tag{8}$$

and

$$R_{X_i X_j} = \frac{\mathrm{Cov}(X_i X_j)}{\mathrm{Var}(X_i)\ \mathrm{Var}(X_j)} \tag{9}$$

The repetitive character of this procedure permits the following general description:

1. Select X_s such that

$$R^2_{YX_s \cdot X_j X_k \ldots X_q X_p} > R^2_{YX_i \cdot X_j X_k \ldots X_q X_p} \quad , \qquad (10)$$

$$(i, s = 1, 2, \ldots, n)$$
$$(s \neq i, j, k, \ldots q, p)$$

where:

$$R^2_{YX_i \cdot X_j X_k \ldots X_q X_p}$$

$$= \frac{(R_{YX_i \cdot X_j X_k \ldots X_q} - R_{YX_p \cdot X_j X_k \ldots X_q} \, R_{X_i X_p \ X_j X_k \ldots X_q})^2}{(1 - R^2_{YX_p \cdot X_j X_k \ldots X_q})\ (1 - R^2_{X_i X_p \cdot X_j X_k \ldots X_q})} \quad , \qquad (11)$$

and where: $R_{X_i X_p \cdot X_j X_k \ldots X_q}$ is determined by repetitive solution of the partial correlation coefficient, equation (8).

Finally, it is necessary to point out that variables not selected by this procedure may contain additional significant information when taken in combination with <u>other</u> non-selected variables. This suggests that the set of significant selected variables may not be the unique "best set". This shortcoming appears to be common in all forward type predictor selecting schemes (Efroymson, 1955).

APPENDIX C

Beach erosion equations and associated sample sizes, multiple correlation coefficients and RMSE's

Equation	Sample Size	Multiple Correlation Coefficient	RMSE
All - Predictors Equation (Eq. 1)			
$BE = -0.52 + 0.73\ (SD2.5) + 0.14(MT) + 0.45(SF) + 0.04(OH) - 0.30\ (BC(Feb.))$	206	0.72	0.76
Twenty-Six-Storms-Limited-Predictors-Linear Equation (Eq. 2)			
$BE = -0.62 + 0.60(SD2.5) + 0.17(MT) + 0.20(MS) - 0.46(BC(Feb.))$	174	0.74	0.70
Twenty-Six-Storms-Limited-Predictors-Binary-Scale Equation (Eq. 3)			
$BE2 = 1.37 + 2.32(SD2.5) + 0.13(MS)^2 - 1.12(BC(Feb.))$	174	0.81	1.80
Final Equation (Eq. 4)			
$BE = -0.77 + 0.64(SD2.5) + 0.20(MT) + 0.18(MS) - 0.32(BC(Feb.))$	230	0.69	0.78

In the above equations, BE is beach erosion intensity, while BE2 is beach erosion intensity expressed in powers of 2 (2^0 through 2^4). SD2.5 is storm duration, MT is maximum observed tide height (Feet), SF is storm frequency, OH is observed wave height (Feet) at light stations, BC(Feb.) is monthly beach cycle which gives a maximum weight of 1 to February, and MS is maximum storm surge height (Feet).

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