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FORECASTING EXTRATROPICAL STORM-RELATED BEACH EROSION ALONG THE U.S. EAST COAST

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FOREWORD

This report is a summary of work by TDL on storm-related beach erosion. The background and development of a beach erosion forecast technique is described as well as verification of forecasts and operational considerations which include focusing of wave energy.

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1. INTRODUCTION

Our oceans have been changing our beaches for thousands of years. These changes are part of a natural process in which a dynamical balance between beaches and oceans is maintained. By advancing and retreating, beaches respond to winds, tides, waves, breakers, swell, and long-term changes in sea level. Rates of beach accretion (advancing beach) and beach erosion (retreating beach) may be measured over several time scales. Long-term changes are measured in years, seasonal changes in months, while changes related to storms are measured in days or even hours. This paper discusses a technique which can be used to forecast qualitative estimates (none, minor, moderate, major, and severe) of beach erosion measured over the shortest of these time scales, namely, that erosion related to extratropical storms.

2. BACKGROUND

The coastal storm of early March 1962 affected the entire Atlantic coast of the United States causing severe beach erosion at locations between Long Island and Cape Hatteras. This storm, the most devastating extratropical storm on record, caused property damage estimated in excess of $200 million (Cooperman and Rosendal, 1962). Storms with large erosion potential can occur each winter.

In November 1976, the National Weather Service implemented on a trial basis a qualitative beach erosion forecast technique for the oceanic coastlines of Maine, Massachusetts, Rhode Island, New York, New Jersey, Delaware-Maryland and Virginia (National Weather Service, 1976). In October 1978 these forecasts, which are valid out to 48 hours at 12-h intervals, were modified and expanded to provide forecasts for the coasts of North and South Carolina (National Weather Service, 1978b).

During the first year of the trial implementation there were few beach erosion events. However, the winter of 1977-78 (October 1977 through April 1978) more than made up for this with six extratropical storms which caused major to severe erosion along the U.S. east coast. Before discussing the verification of the beach erosion forecast technique with 1977-78 winter data, the causes of storm-related beach erosion and the development of a technique to forecast this erosion will be discussed.

3. CAUSES OF STORM-RELATED BEACH EROSION

Beach erosion is a complex process involving many oceanographic, meteologic, and geologic factors. Some of the more important factors are winds, tides, waves, breakers, and offshore topography. Most of these factors must be considered in combination with one another. For example, the phase of the astronomical tide at the time of the meteorologically produced water level (storm surge or storm tide) is important. If the storm surge occurs at high astronomical tide, the total water elevation will be higher and the nearshore slope (see Fig. 1) will have less refraction and shoaling effects on incoming waves. Steep wind-waves (large heights and small periods) will break high on the beach face because of the superelevated water level of the combined high astronomical tide and storm surge. Steep wind-waves place a large quantity of water on the beach in a short time. This large amount of water does not have enough time to percolate through the beach face. Thus, the backwash 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, as a steep slope is cut into the berm (Fig. 1).

The length of time (duration) that steep waves break high on the beach face is an important factor in the erosion process. The March 1962 storm with its large storm surge and steep waves remained in the same area for five successive high tides. Steep waves broke high on the beach face, and even landward of the beach in places, for a long duration and contributed significantly to the severe erosion associated with this storm.

Most storms move large amounts of sand from the beach to areas offshore, but after storm passage the lower, longer period waves and swell restore the sand to the beach face. Depending on the availability of updrift sand for restoration, a storm may result in only slight permanent change.

Storm path and wave direction are important factors in determining the amount of material moved alongshore. If a storm produces longshore transport opposite to the long-term direction of transport, then 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 long-term direction of transport, large amounts of material removed by the storm have little possibility of being restored (U.S. Army Coastal Engineering Research Center, 1973).

Storm-related beach erosion is further complicated by winter-summer beach cycles. East coast beach configurations vary seasonally and locally but not nearly as greatly as west coast beaches. The sand which migrates from the beach face will often be deposited as, or on, an offshore bar. A bar is nature's way of providing protection to a beach by acting as a cushion to absorb wave energy before it reaches the beach. During post-storm periods and in the summer months, long period swell will carry sand from the offshore bar back towards the beach, where it again becomes a part of the beach face.

4. DEVELOPMENT OF A FORECAST TECHNIQUE

An erosion forecast technique which predicts the transport of sand along or away from a beach in dimensions of volume per unit time would mean very little to the general public. A more useful prediction is a qualitative forecast of erosion such as minor, moderate, major, and severe as recommended by Harrison, et al. (1971) and Rush (1973).

A. Beach Erosion Intensity Scales (Predictands)

As a first step in developing a qualitative erosion forecast technique, a storm-related erosion intensity matrix was 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. The matrix was constructed by associating a numerical value with a qualitative term which reportedly describes 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 1977, all winter (November 1 through April 30) Storm Data volumes (Environmental Data and Information Service) 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 Fig. 2. Through this procedure, the storm-related erosion intensity matrix shown in Table 1 was constructed. This matrix was then used to formulate two sets of predictands. One set was based on a linear intensity scale, while a powers-of-two intensity scale served as a basis for the other set. The linear and powers-of-two erosion intensity scales are shown in Fig. 2.

The beach erosion intensity values for the March 1962 and February 1973 storms (Table 1) are illustrated with photographs (Fig. 3 through Fig. 8) taken before and after these storms. These photographs are of the oceanic coastlines of Delaware, Virginia, and North Carolina. The photographs shown in Figs. 3 and 4, 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 photographs show a great deal of erosion damage at Rehoboth Beach and Virginia Beach. The erosion intensity value was 4 (severe erosion) for each of these states for this storm (see Table 1).

The next set of photographs (Fig. 5 through Fig. 8) is of the Outer Banks, N.C. taken before and after the February 1973 storm. The photographs shown in Figs. 5 and 6, taken by U.S. Army Corps of Engineers, Coastal Engineering Research Center, show a great deal of erosion damage at Nags Head, N.C. which has caused the collapse of beach cottages. Photographs shown in Figs. 7 and 8 were taken by the National Aeronautics and Space Administration as part of their Chesapeake Bay Ecological Program. The photograph shown in Fig. 7 depicts the Outer Banks just north of Avon Pier. This photograph was taken about 2 hours before low tide on January 18, 1973, about 1 month before the February storm; it is an aerial photograph, from about 5,000 feet, showing a broad beach with little offshore wave activity. In contrast, the aerial photograph (Fig. 8), taken after the storm on February 13, 1976, depicts an entirely different scene for the same beach. This photograph, was also taken about 2 hours before low tide at 6,500 feet. Avon Pier can be seen in the lower left portion of the photograph. This photograph shows that water traveled far up on the backshore of the beach and threatened a number of coastal structures. Even though this photograph was taken 2 days after the storm, it shows swell advancing from the east-northeast. The white patches on the ocean surface are caused by strong west winds which are blowing the tops of breaking waves. The erosion intensity associated with this storm for the North Carolina coast was 3 (major erosion). Figs. 5, 6, and 8 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).

B. Predictors

The following is a list of potential beach erosion intensity predictors:

(1) maximum observed tide height (astronomical tide plus storm surge) above mean sea level
(2) maximum storm surge height
(3) generalized storm duration
(4) variable storm duration
(5) frequency of erosional storms
(6) observed winds and waves at east coast light stations
(7) wave height and period computed using Sverdrup-Munk-Bretschneider (SMB) hindcast equations for "deep" and "shallow" water
(8) breaking waves
(9) wave steepness
(10) mean amplitude of the spring tide
(11) type of beach material
(12) seasonal beach cycles

Since only the first four predictors were found to be significant in the erosion process, only they are discussed. For a discussion of the other predictors see Richardson (1977).

(1) Maximum Observed Tide Height - Tide is an important factor in beach erosion. However, areas with little tide do experience erosion. For example, erosion is a problem at the western end of Lake Erie, even through the tidal range on Lake Erie is only about 3 inches.

Since significant astronomical tides occur along the east coast of the United States, it is desirable to incorporate them in a beach erosion forecast model. National Ocean Survey (NOS) tide gage stations were selected for the states of Maine, Massachusetts, Rhode Island, New York, New Jersey, Delaware, Virginia, North Carolina, and South Carolina. The availability of tide data limited the derivation of the beach erosion forecast technique to these east coast states. Since there was no tide gage located along Maryland's outer coast, but 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 coast. Fig. 9 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, the mean tidal range (the difference in height between mean high water and mean low water) at Sewells Point, Va. is 2.5 feet. The tide gage at Sewell Point, the representative gage for the Virginia coast, is located within the Chesapeake Bay. At False Cape, Va. (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 1 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. For convenience only, one tide gage is used to represent the tide along a coastal state. The nine 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 nine representative tide gages.

(2) 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; Hampton Roads, Virginia; Avon, North Carolina; and Charleston, South Carolina were obtained by subtracting the hourly astronomical tide heights from the hourly NOS measured 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).

(3) Generalized Storm Duration - This predictor is the number of consecutive high tides (approximately 12.4 hours apart) that a "critical value" (2.5 foot storm surge height plus the amplitude of the spring tide at the representative tide gage) is reached or exceeded. The 2.5-foot storm surge value was selected by screening all states together. 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 all tide gage locations except Avon, N.C. These ranges are shown in Table 2. Since the Tide Tables do not contain data for Avon, tidal data at the nearest tide gage to Avon (Cape Hatteras, N.C. oceanside tide gage, located 8 n mi south of Avon) were used. 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 the spring tide.

(4) Variable Storm Duration - In an attempt to construct a more localized storm duration predictor, a variable storm duration predictor was introduced. This predictor was constructed in a similar manner to the generalized duration term. However, the "critical value" for each state was not constrained to a 2.5-foot storm surge but enjoyed the freedom of being computed with a 1.0-, 1.5-, 2.0-, or 2.5-foot storm surge depending on which value was selected in separate screening runs for that state. "Critical values" used to determine generalized and variable durations for each state are shown in Table 2.

C. Derivation of Beach Erosion Equations

Because tidal range is similar on coastal segments, the states of Maine and Massachusetts (82 sets of data) were grouped together, while the states of Rhode Island, New York, New Jersey, Delaware-Maryland, Virginia, North Carolina, and South Carolina (213 sets of data) were placed into a second group. For each group, seperate beach erosion equations were derived for the predictand data in linear and powers-of-two forms. The groups were then combined (295 sets of data) and generalized equations were derived on the two forms of predictand data. In the derivations, predictand data were correlated with observed predictors. This is in contrast to the MOS approach where predictand data are correlated with forecasts from a model.

The six derived beach erosion equations were tested on dependent data separately and in combination with one another. These tests gave best results when the equations were applied as follows. The powers-of-two scale generalized equation is first used to compute the erosion intensity. If an intensity of moderate or greater is computed, the erosion intensity is based on this equation. If the computed intensity is less than moderate, then the linear scale erosion equations are used for their respective groups.

This selective use of the equations on dependent data specifies the more serious erosion events, without greatly overestimating the minor and no erosion events. The three equations are:

$$BE(Me.\ \&\ Ma.) = -1.34 + 0.24\ MT + 0.09\ MS^2 + 0.54\ D + 0.12\ VD, \quad (1)$$

$$BE(R.I.\ thru\ S.C) = -0.66 + 0.35\ D + 0.16\ MS + 0.23\ VD + 0.15\ MT, \quad (2)$$

$$BE2(ALL) = -0.23 + 1.44\ D + 0.13\ MS^2 + 0.70\ VD + 0.23\ MT, \quad (3)$$

where BE is beach erosion intensity (scale of 0 through 4), BE2 is beach intensity (scale of 1 through 16), D is generalized storm duration, MS is maximum storm surge height (feet), VD is variable storm duration, and MT is maximum tide height (feet) above mean sea level.

The multiple correlation coefficient and root mean square error associated with equations (1), (2), and (3) are 0.62 and 0.80 intensity units (IU), 0.68 and 0.80 (IU), and 0.70 and 2.34 (IU) respectively. All equations show the beach erosion intensity increases with increases in storm duration, maximum storm surge height, and maximum tide height. Note that the magnitude of the constant associated with the Maine-Massachusetts equation, (1), is twice the magnitude of the constant of equation (2), the Rhode Island through South Carolina equation. This is not surprising, since the range of the astronomical tide at Maine and Massachusetts is about twice the average range of the tide at the other seven east coast tide gage locations.

5. VERIFICATION

The six extratropical storms which caused major to severe erosion (see Fig. 10) along the east coast during the 1977-1978 winter season provided an excellent independent sample to test and compare the newly derived set of beach erosion equations (1), (2), and (3) with a beach erosion equation implemented in November 1976 (National Weather Service, 1976).

The old 1976 equation was derived on 1962-1973 winter season (November 1 through April 30) linear intensity data. This equation

$$[BE(ALL\ States) = -0.95 + 0.62D + 0.18\ MS + 0.20\ MT]$$

contains a generalized duration (D), maximum storm surge height (MS), and a maximum tide height (MT) predictor. In addition to these three predictors, the newly derived set of equations contains a variable duration predictor and was derived on 1962-1977 winter season linear and powers-of-two forms of predictand data.

Observed-forecast contingency tables were constructed with the 12- and 36-h beach erosion forecasts computed by the new set of equations and the equation implemented in 1976. Table 3 contains the contingency tables associated with the 12-h forecasts computed with the new set of equations (upper table) and the equation implemented in 1976 (lower table). The new set of equations improves the forecast of the major category but overforecasts the moderate category. The new set of equations and the 1976 equation do equally well forecasting the no erosion category, where 20 of the 28 events were forecast correctly. Table 4 shows contingency tables based on the 36-h forecasts which were computed with the new set of equations (upper table) and the 1976 equation (lower table). Again the new set of equations improves the forecast of the major category. However, the moderate category is overforecast.

Relative matrix scores, percent of correct forecasts, and threat scores were computed from the four contingency tables. The relative matrix scores (RS) were computed by the following formula.

$$RS = \sum_{i=1}^{5} \sum_{j=1}^{5} f_{ij} m_{ij} \Bigg/ \sum_{i=1}^{5} 0_i m_{ii}$$

, where: f_{ij} are elements in an observed-forecast (5x5) contingency table, m_{ij} are the elements of the scoring matrix shown in Table 5, and 0_i are the total number of elements in the observed categories.

The threat score $\left[\frac{\text{\# hits}}{\text{\# forecasts} + \text{\# observed} - \text{\# hits}}\right]$ is the relative frequency of correctly forecasting the event in which the event was a threat (Palmer and Allen, 1949). Threatening situations are those in which either severe, major, or moderate erosion occurred or was forecast to occur. Table 6 shows relative matrix scores, percent of correct forecasts, and threat scores associated with the 12-h forecasts computed with the new set of equations and the 1976 equation. Table 7 contains the scores associated with the 36-h forecasts.

The relative matrix scores and the percent of correct forecasts associated with the new set of equations are 20% to 30% higher than the scores associated with the 1976 equation. Threat scores associated with the new set of equations are much higher than the scores associated with the 1976 equation. Based upon this verification the new set of equations was implemented in October 1978.

6. OPERATIONAL CONSIDERATIONS

The beach erosion forecast message (second half of the FZUS3 message) is transmitted on Request/Reply out to 48 hours at 12-h intervals. Two sample FZUS3 messages are illustrated in Fig. 11. The first part of the message, "STORM SURGE FCST FEET", is explained in Technical Procedures Bulletin No. 226 (National Weather Service, 1978a). For those cases when minor ($1.5 \geq BE > 0.5$), moderate ($5.7 \geq BE2 > 2.8$), major ($11.3 \geq BE2 > 5.7$), or severe ($BE2 > 11.3$) erosion is forecast at any one of the coastal states (Maine, Massachusetts, Rhode Island, New York, Delaware and Maryland (Delmar), Virginia, North Carolina, and South Carolina), the beach erosion message will be as shown in the middle portion of Fig. 11. BE and BE2 are beach erosion intensity based on linear and powers-of-two scales respectively. These qualitative forecasts of erosion (National Weather Service, 1978b), which are based on the east coast storm surge forecasts (Pore, et al., 1974) and astronomical tide heights, can be related to past storms by Table 8. If no erosion is forecast at any coastal state, the erosion message will be as shown in the lower portion of Fig. 11.

The beach erosion forecast guidance only gives in qualitative terms a "regional erosion picture" for the oceanic coastline of an entire state. The erosion along the coastline of a state has great temporal and spatial variations due to both the inner continental shelf and the nearshore bathymetry, with the latter complicated by longshore and onshore-offshore bar migration.

With regard to these temporal and spatial variations, there are localized coastal areas which appear to receive more than their "fair share" of erosion. During recent years, some of these areas along the east coast were; Plum Island, Mass., Charleston Beach, R.I., and Ocean City, Md. Wave refraction diagrams which depict the change of direction of waves as they move at an angle to the bottom contours in shallow water may help to delineate some of these erosion-prone areas. These refraction diagrams will be discussed in the next section. Goldsmith, et al. (1974) and Poole (1976) have published such diagrams for a number of wave conditions for the mid-Atlantic shelf area (Manasquan, N.J. to Cape Hatteras, N.C.). These diagrams, which are on file at a number of forecast offices, may be helpful in forecasting erosion for erosion-prone areas when used in conjunction with the qualitative erosion forecasts. When available, aerial photographs of the shoreline can also be helpful in pinpointing possible erosion-prone areas in newly developed communities.

When erosion is forecast for a coastal state, a good "rule of thumb" may be to note areas which have suffered erosion damage in previous years as locations which will again be erosion prone.

7. FOCUSING OF WAVE ENERGY

The near shore bathymetry acts as a complex system of lenses which can focus erosive waves at one location while disipating wave energy and even building the beach at an adjoining location. This uneven distribution of wave energy along coastlines has been investigated by Virginia Institute of Marine Science (VIMS) and TDL for two erosion events along the east coast. VIMS has provided wave refraction diagrams based on the nearshore bathymetry off Ocean City, N.J., and Ocean City, Md., using wave characteristics generated by two extratropical storms (March 9, 1976 and December 19, 1977).

For the March storm there was good agreement between the concentration of wave energy as depicted by a wave refraction diagram and reported erosion damage along the northern portion of Ocean City, N.J., (Fig. 12). The closely-spaced lines shown on the refraction diagram are wave rays, a family of curves everywhere perpendicular to the family of curves representing wave crests. Areas of high wave energy along the coast are depicted at areas where these rays converge. The wave refraction diagram shows wave rays converging just north of Ocean City, N.J., in about the same vicinity as the reported erosion damage. The wave refraction diagram was constructed with the observed wave condition (6-second waves from the east) which accompanied this March storm.

Wave refraction diagrams (Fig. 13), based on waves from the northeast (upper diagram) and east (lower diagram) associated with a December 19, 1977 storm for Ocean City, Md. area, show significant wave energy concentration in the Ocean City area just north of the inlet. Both diagrams are based on 10-second waves, the significant wave period which was recorded at the Environmental buoy which is located at 38.7°N, 73.6°W, approximately 70 n mi east-northeast of Ocean City, Md. In addition to wave rays, these diagrams also show the nearshore bathymetry. The shoals depicted in the diagrams are less than 20 feet below mean low water. It is interesting to note that except for the immediate area of Ocean City, waves from the east (Fig. 13, lower diagram) cause more areas of concentrated wave energy along the Maryland shore than waves from the northeast. For 10-second waves from the northeast, the offshore bathymetry, nearshore shoals (Fenwick and Isle of Wight), and "finger shoals" cause a divergence of wave energy along much of the coast. However the same offshore bathymetry and nearshore shoals caused 10-second waves from the east to converge at a number of locations (1 to 2 miles apart) along the coast.

Unfortunately wave refraction diagrams do not "tell" the entire story about the convergence-divergence of wave energy at or near the shoreline. For example, if a wave breaks before its crest is parallel to the shoreline, some of its energy will be transferred into generating longshore currents. The remaining energy will be absorbed by the nearshore slope and the beach face.

It is important to keep in mind that storms, because of their movement, generate wind waves from many directions. Therefore, the distribution of wave energy along a coast will more realistically be represented by a composite of wave refraction diagrams, or wave refraction diagrams based on wave spectra. Nevertheless, wave refraction diagrams when used in conjunction with the qualitative beach erosion forecasts may give additional guidance for forecasting more local beach erosion.

8. FUTURE PLANS

When observed tide data become available for the 1977-78 winter season, the beach erosion events for this season will be added to the dependent data and a new set of erosion equations will be derived. It may be possible to expand the erosion forecast method to the Connecticut coast by using observed tide and storm surge data at Stamford, Conn. After a storm surge forecast equation is derived for Ocean City, Md., it may be possible to make separate beach erosion forecasts for the Maryland and Delaware coasts, instead of the combined forecast for Delaware-Maryland.

TDL will continue to collect reports of beach erosion damage from forecast offices. These reports will be used to evaluate the beach erosion forecast technique.

When we are able to forecast nearshore and shallow-water waves, wave refraction information may be incorporated into the forecast technique. For example, if a refraction diagram based on wave forecasts for a particular storm shows a convergence of wave rays at Virginia Beach, Va. 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.

At some time in the future, TDL may produce computer-worded forecasts for coastal areas which could be similar to the computer-produced worded forecasts of Glahn (1978) 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 3 to 4 feet above normal during the next 12 hours. Nearshore wave heights of 8 to 10 feet from the northeast will result in high breakers. Moderate to major erosion is expected along the Virginia coast, except at Virginia Beach, where erosion is expected to be severe.

9. ACKNOWLEDGMENTS

A special thanks to Victor Goldsmith and Carolyn Sutton of VIMS for wave refraction diagrams. I would also like to thank the National Ocean Survey for tide data, the National Aeronautics and Space Administration for aerial photographs, and the Coastal Engineering Research Center for photographs of damage due to erosion. I am especially greatful to the forecasters of the Eastern Region Forecast Offices who provided reports of erosion damage.

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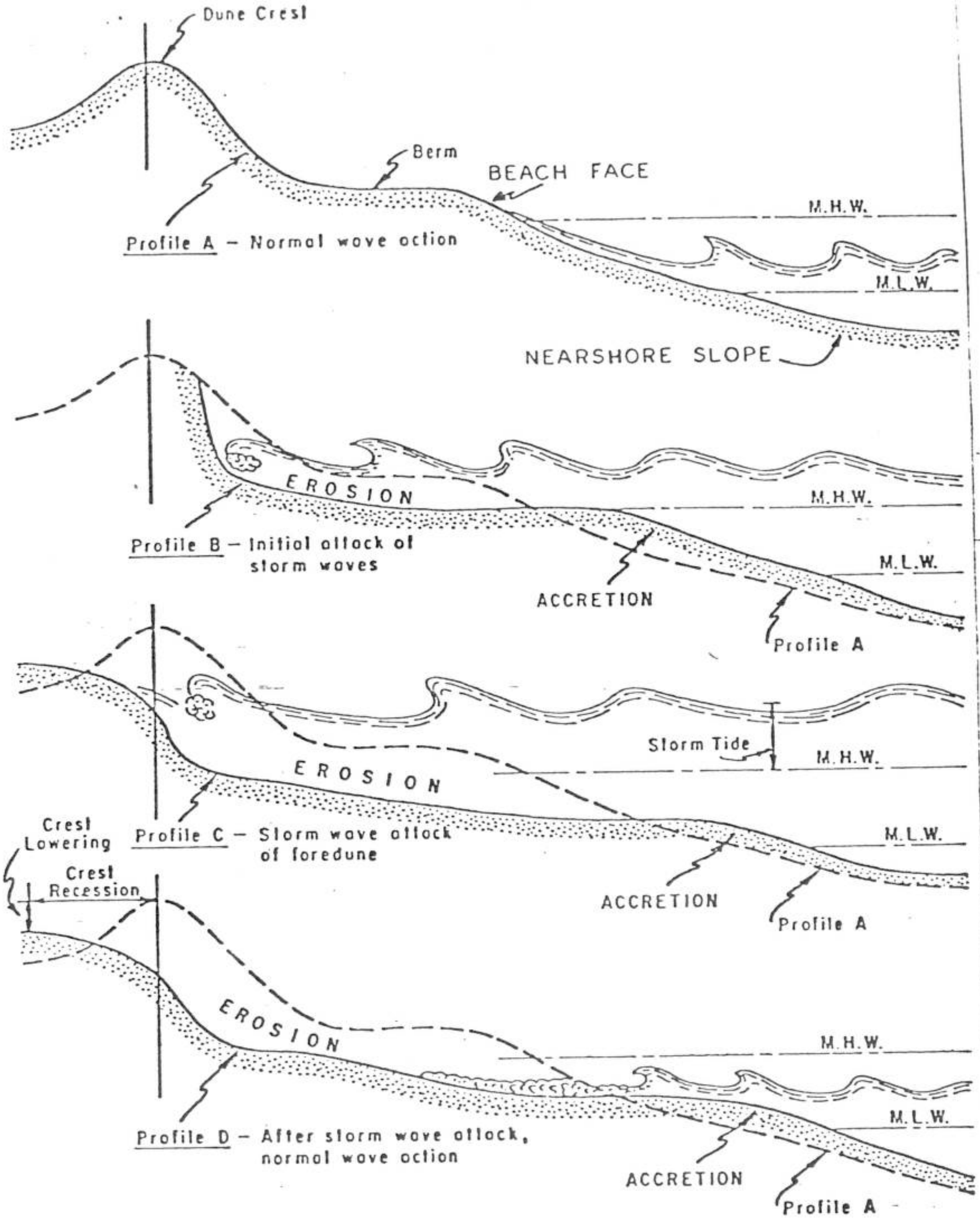


Figure 1. Schematic diagram of storm wave attack on a beach (modified from U.S. Army Coastal Engineering Research Center, 1973).

Reported-
Descriptive Terms

SEVERE EROSION

Severe
Tremendous
Serious

MAJOR EROSION

Considerable
Widespread
Heavy
Markedly
Badly
Much

MODERATE EROSION

Erosion
Some Erosion
Erosion of Dunes
Beach Erosion
Coastal Erosion
Dunes Moved
Moderate Erosion

MINOR EROSION

Beach Change
Damage to Jetties and Piers
Some Loose Sand Moved
Light Erosion
Sea Wall Pounded
Heavy Surf
Limited Damage
Erosion Noted

NO EROSION

No Mention of Erosion

No Erosion

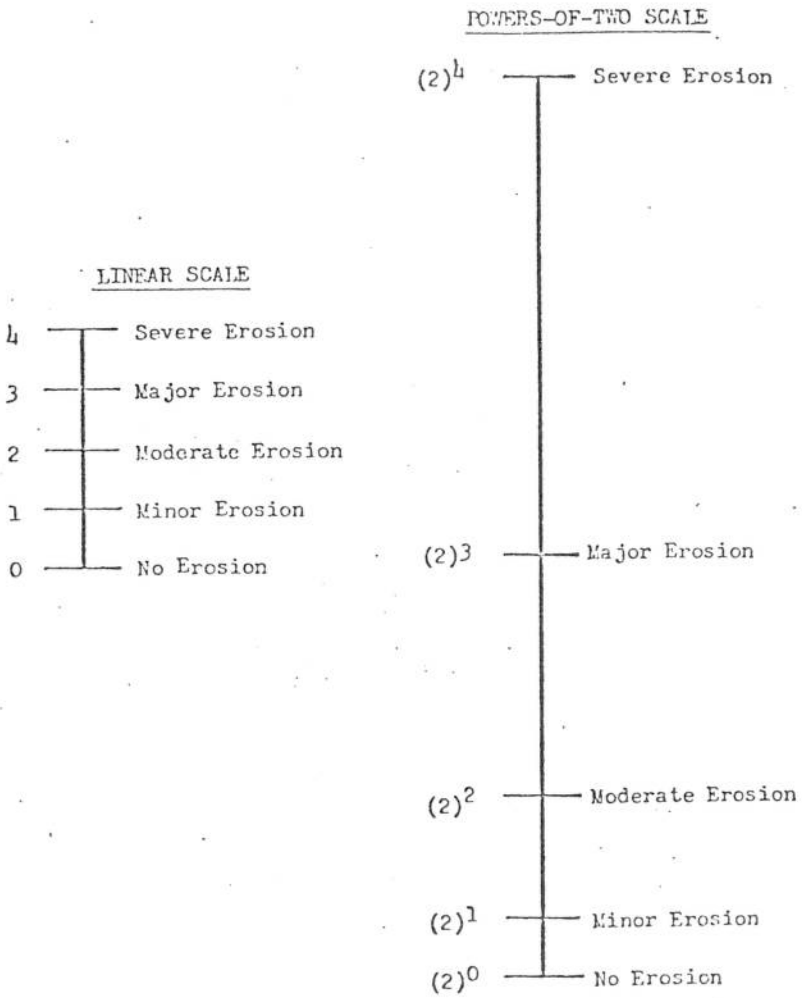


Figure 2. Storm-related erosion intensity scales and associated qualitative and reported-descriptive terms.

Figure 3. Photograph of property damage at Rehoboth Beach, Del. following the March 1962 storm.

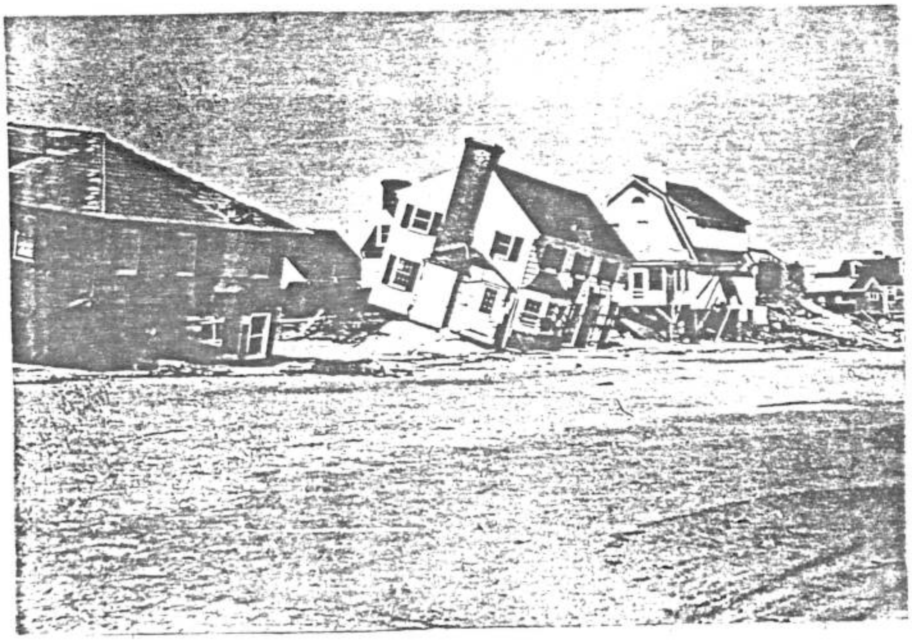


Figure 4. Photograph of property damage at Virginia Beach, Va. following the March 1962 storm.

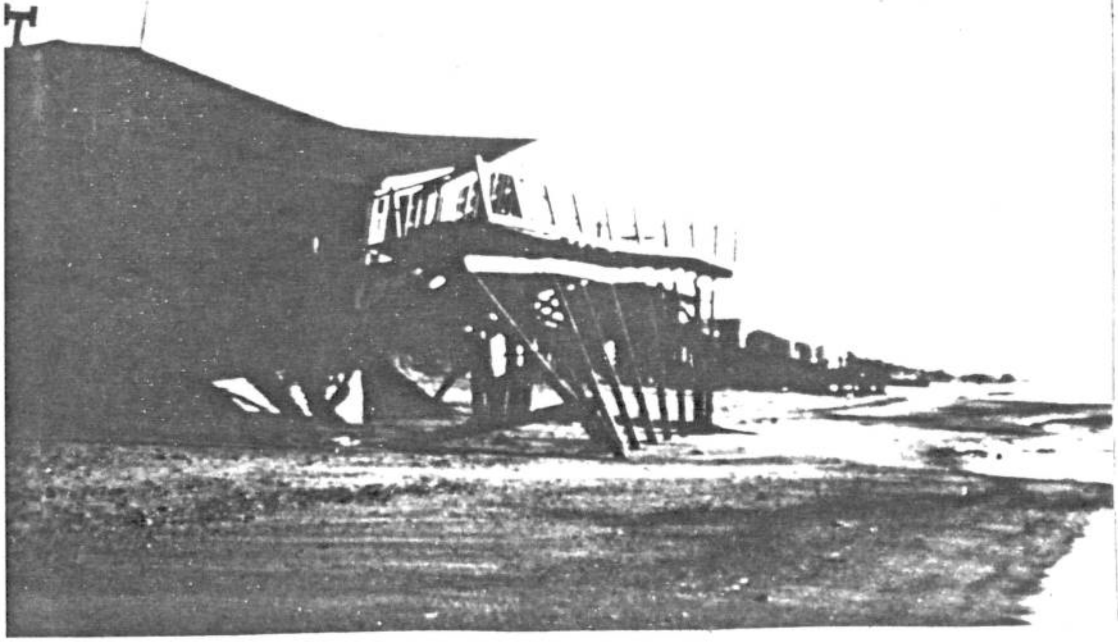


Figure 5. Photograph of property damage along the Outer Banks, N.C. following the February 1973 storm.

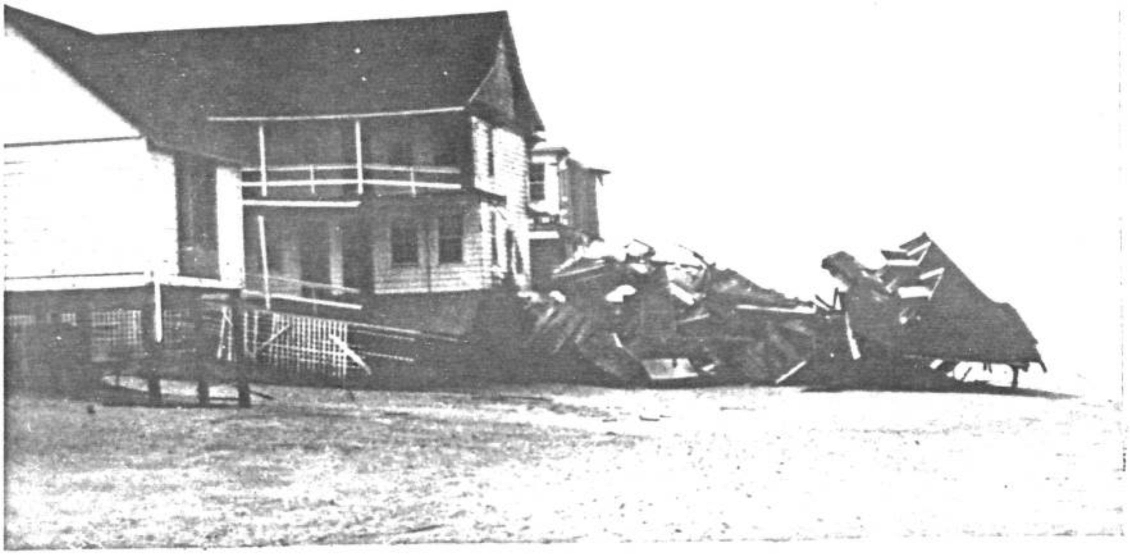


Figure 6. Photograph of property damage along the Outer Banks, N.C. following the February 1973 storm.

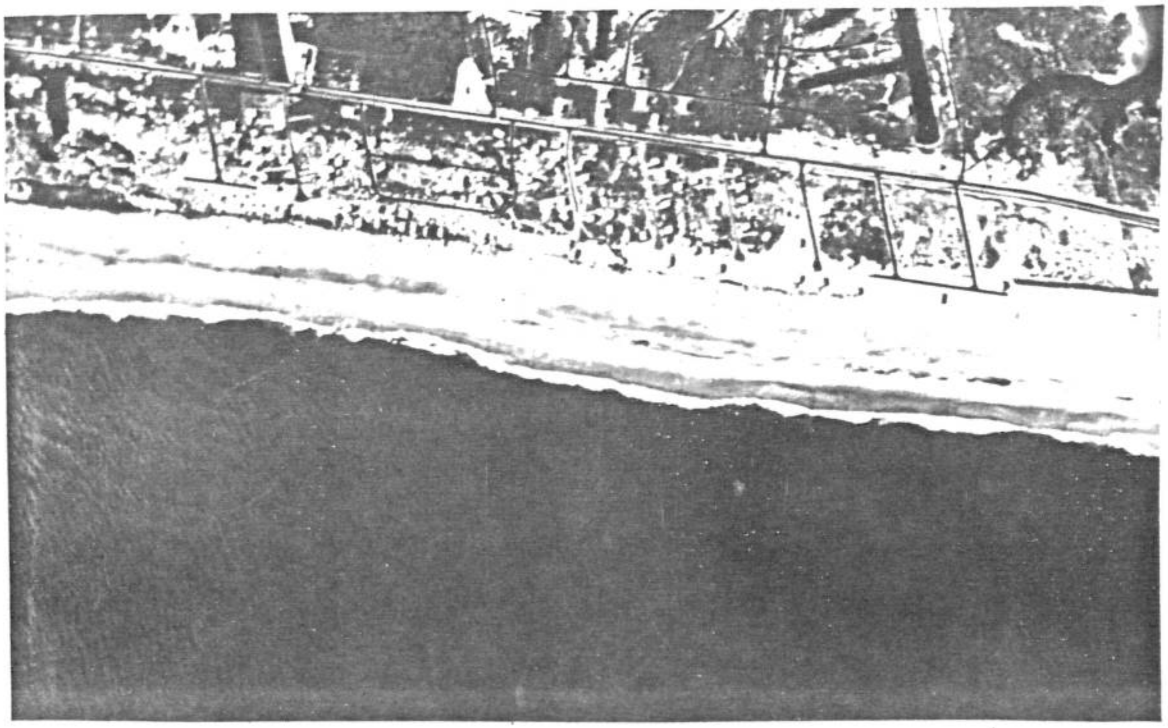


Figure 7. Aerial photograph of the beach north of Avon Pier, N.C. on January 18, 1973, before the strom.

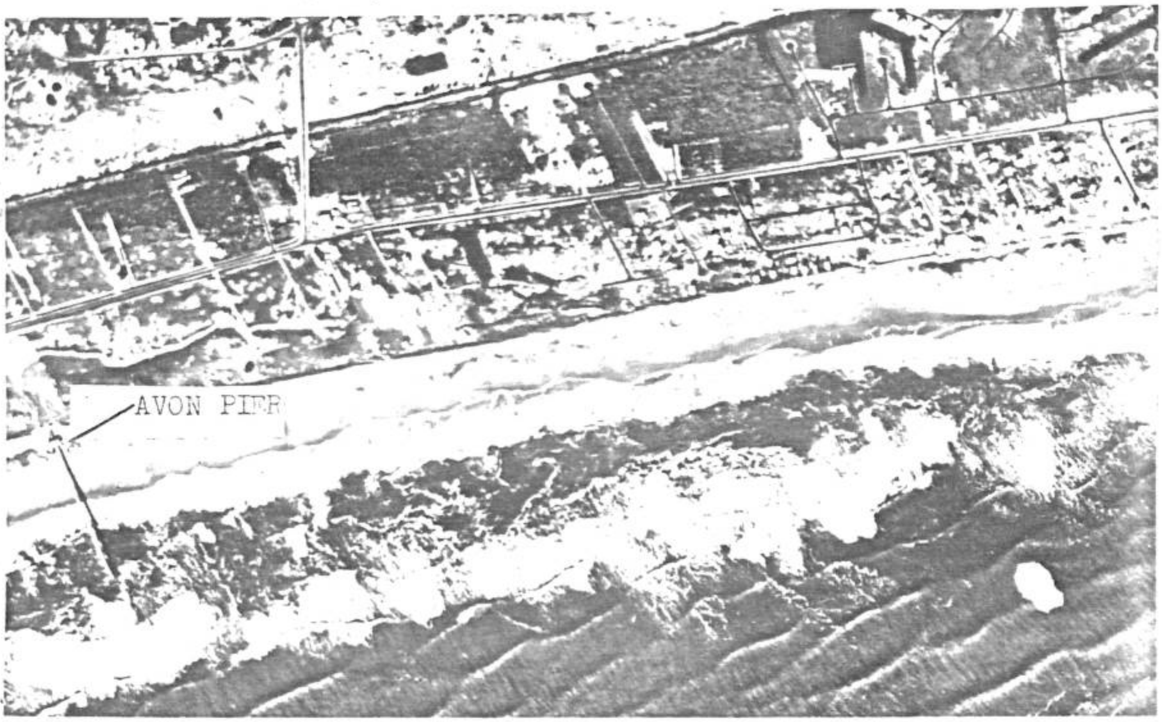


Figure 8. Aerial photograph of the beach north of Avon Pier, N.C. on February 13, 1973, after the storm.

PWM	Portland, Maine
BOS	Boston, Massachusetts
NWP	Newport, Rhode Island
NYC	New York (The Battery), New York
ACY	Atlantic City, New Jersey
BWH	Breakwater Harbor, Delaware
ORF	Hampton Roads, Virginia
AVN	Avon, North Carolina
CHS	Charleston, South Carolina

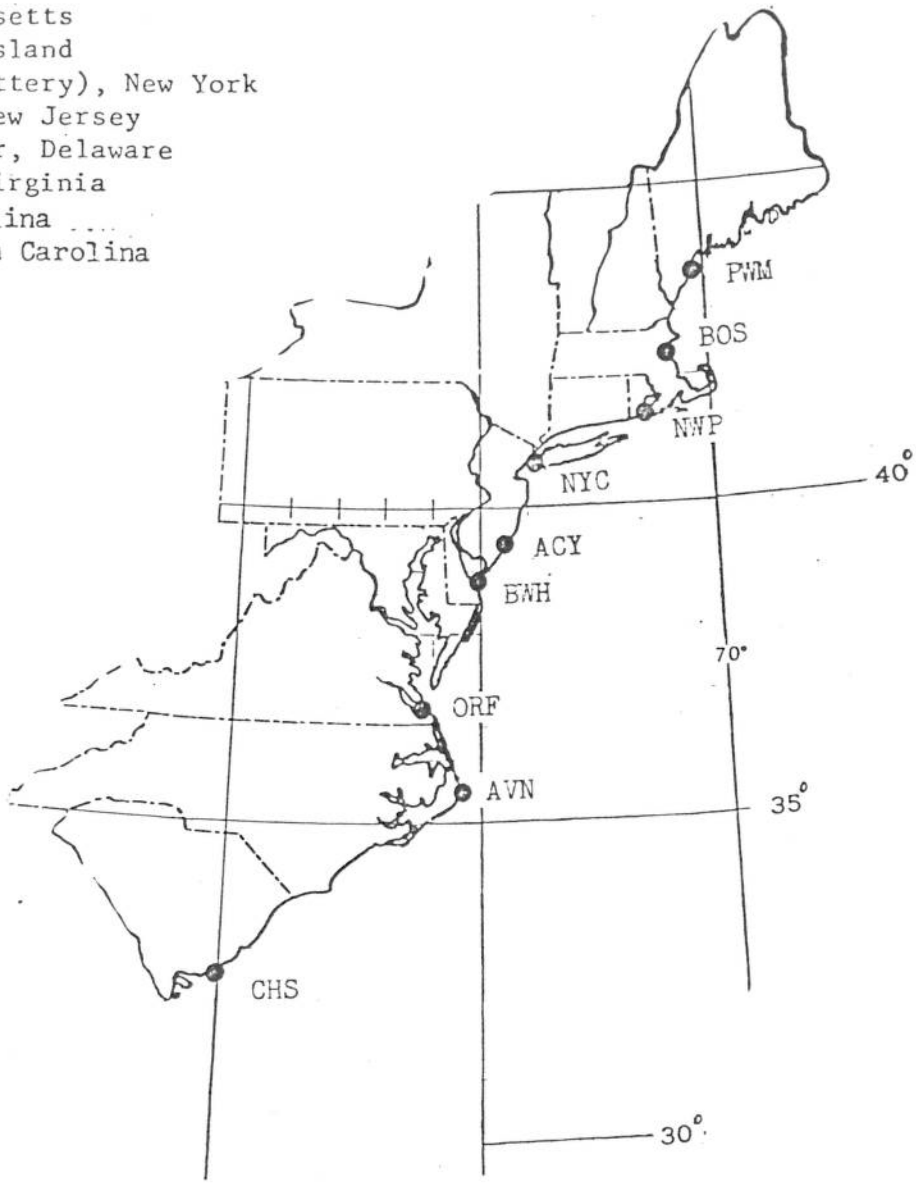


Figure 9. Locations (●) of National Ocean Survey tide gages.

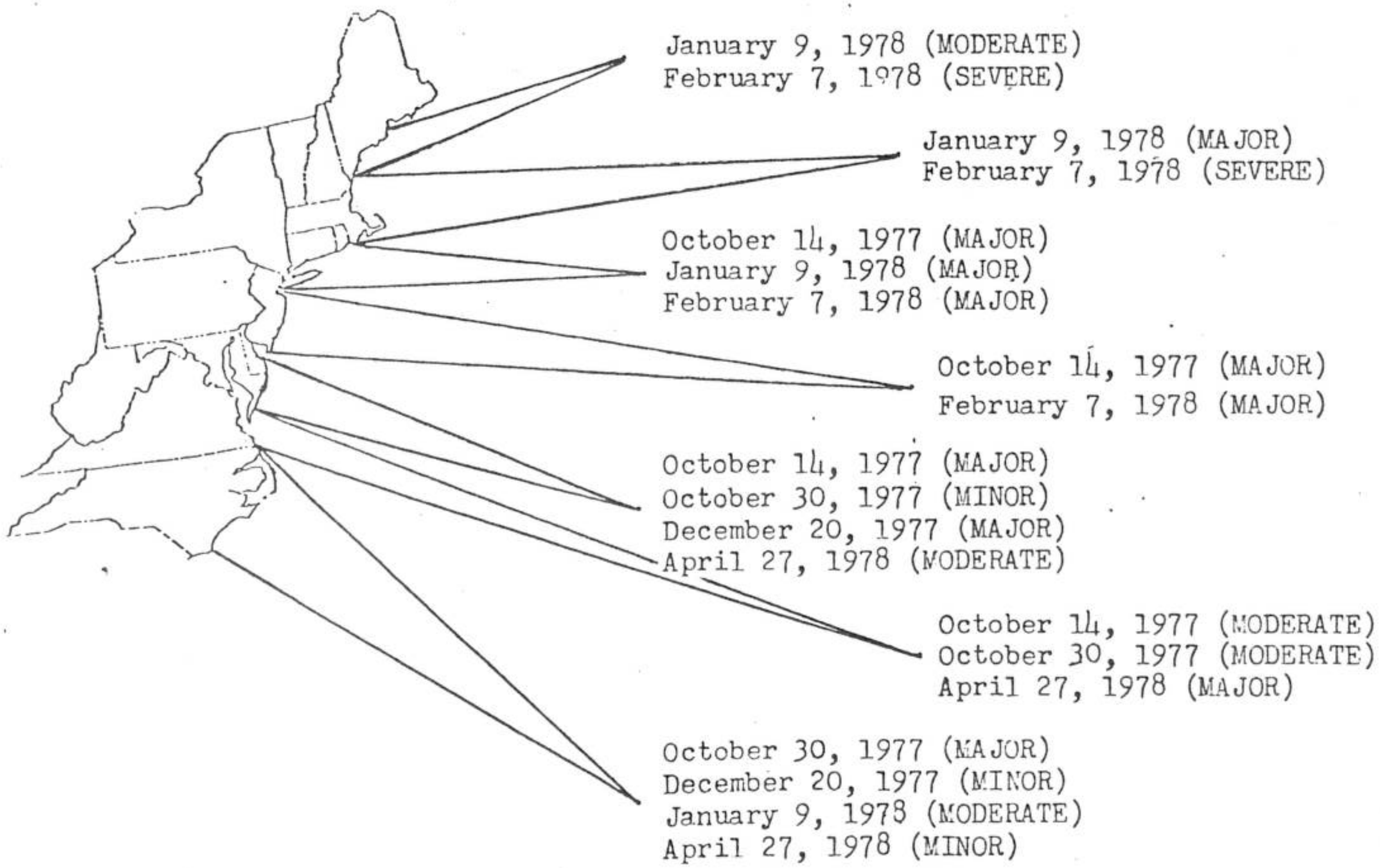


Figure 10. The intensity of beach erosion suffered by east states from Maine to North Carolina during the 1977 - 1978 winter season.

SAMPLE 1

```
FZUS3 KWBC 160000
STORM SURGE FCST FEET (INVALID FOR TROPICAL STORMS)

PWM    -0.2    -0.4    -0.3    0.8    2.2    2.9    2.4
BOS    -0.6    -0.3    -0.3    1.3    2.4    3.0    2.0
NWP    -0.0     0.0     0.8    1.2    2.5    2.6    1.5
SFD    -0.7     0.5     0.9    3.8    4.4    4.0    2.4
LGA    -0.1    -0.3     1.4    1.6    3.3    1.2   -0.5
NYC     0.1     0.2     1.8    1.6    2.7    1.8    0.6
ACY     0.0     0.3     1.2    1.9    2.0    1.6    0.7
BWH     0.3     0.3     1.6    1.6    2.1    1.1    0.4
BAL    -0.1     0.6     1.1    1.1    1.3    1.2    0.1
ORF     0.7     0.8     0.8    0.8   -0.1    0.2   -0.2
AVN     0.4     0.5    -0.1   -0.1   -0.5   -1.0   -0.8
CHS     0.4     0.7    -0.5   -0.5   -1.1   -1.3   -0.7

BEACH EROSION FCST FOR EAST COAST STATES
INVALID 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
N.C.      NONE     NONE     NONE       NONE     NONE
S.C.      NONE     NONE     NONE       NONE     NONE
```

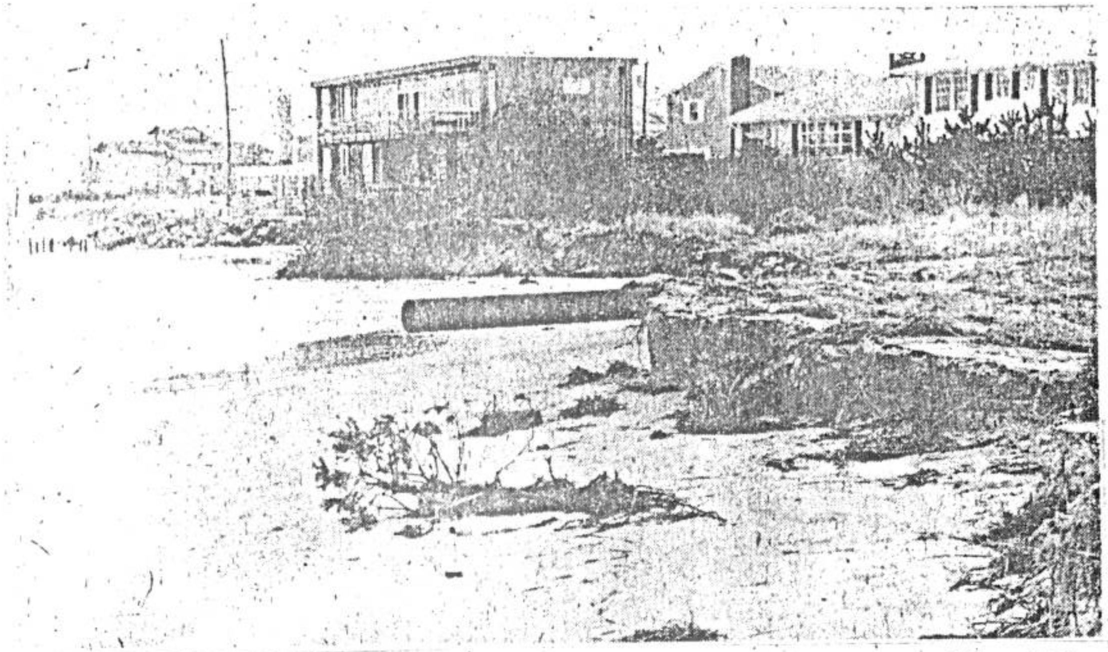
SAMPLE 2

```
FZUS3 KWBC 160000
STORM SURGE FCST FEET (INVALID FOR TROPICAL STORMS)

PWM     0.4     0.2     0.5    0.4    0.2   -0.2   -0.6
BOS     0.4     0.1     0.2   -0.0   -0.3   -0.6   -0.8
NWP    -0.4     0.4     0.7    0.4    0.4   -0.2   -0.4
SFD     0.2     0.4     0.8    0.2   -0.3   -1.0   -0.9
LGA    -2.3    -0.1     0.1   -0.3   -0.3   -1.1   -1.2
NYC    -0.9     0.6     0.6    0.2   -0.1   -0.5   -0.7
ACY    -0.8     0.1     0.4    0.2   -0.1   -0.4   -0.3
BWH    -1.2     0.5     0.4   -0.1   -0.3   -0.5   -0.3
BAL    -0.5    -1.3     0.0    0.0    0.4   -0.2   -0.1
ORF    -0.2    -0.6    -0.6   -1.7    0.0    0.0    0.5
AVH     0.0     0.3    -0.1   -0.5    0.0    0.1    0.3
CHS     0.5     0.6     0.4    0.2    0.1    0.4    1.0

BEACH EROSION FCST FOR EAST COAST STATES
INVALID FOR TROPICAL STORMS
NO SIGNIFICANT EROSION IS FCST FOR THE NEXT 48 HOURS
```

Figure 11. Two sample FZUS3 messages transmitted on Request/Reply twice each day. The message shown in the upper portion of this figure is transmitted when minor, moderate, major, or severe erosion is forecast at any one of the east coast states. These forecasts, which are made out to 48 hours in advance at 12-h intervals, are based upon 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 0000 Greenwich Mean Time data on the 16th of the month. If no erosion is forecast at any of the east coast states, the FZUS3 message will be as shown in the second sample.



ON THE ROCKS. During storm tides earlier this week the waters of Great Egg Harbor Inlet finally uncovered the rocks of the master jetty protecting the north end of the island for the first time in 20 years. At center is an extension of storm sewer pipe that has been uncovered as the sand dunes washed away. Photo courtsey of Ocean City, (N.J.) Sentinel-Ledger.

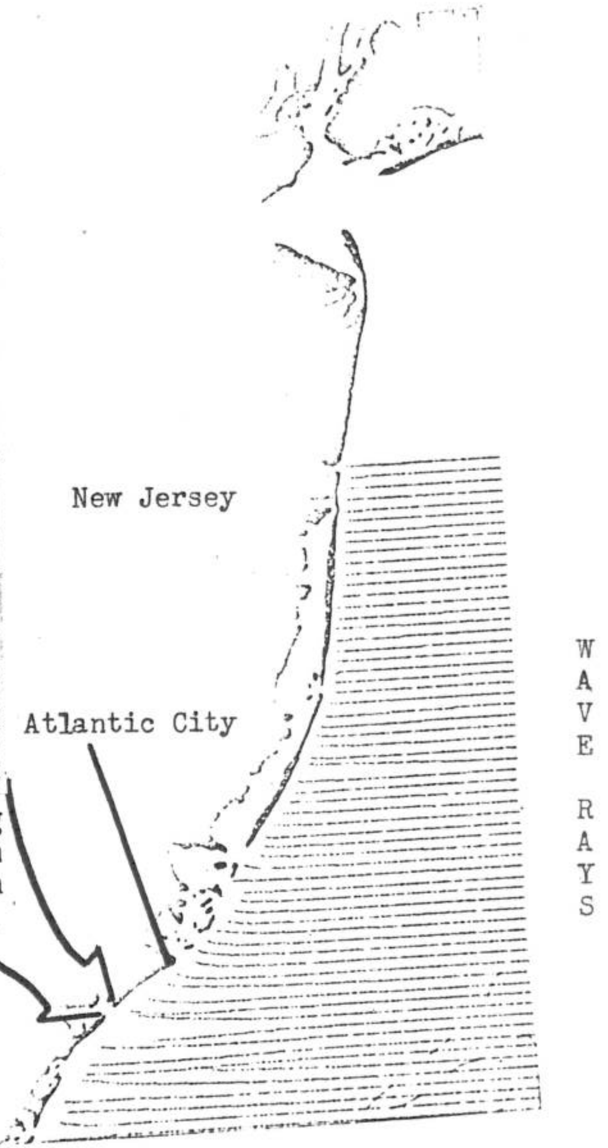
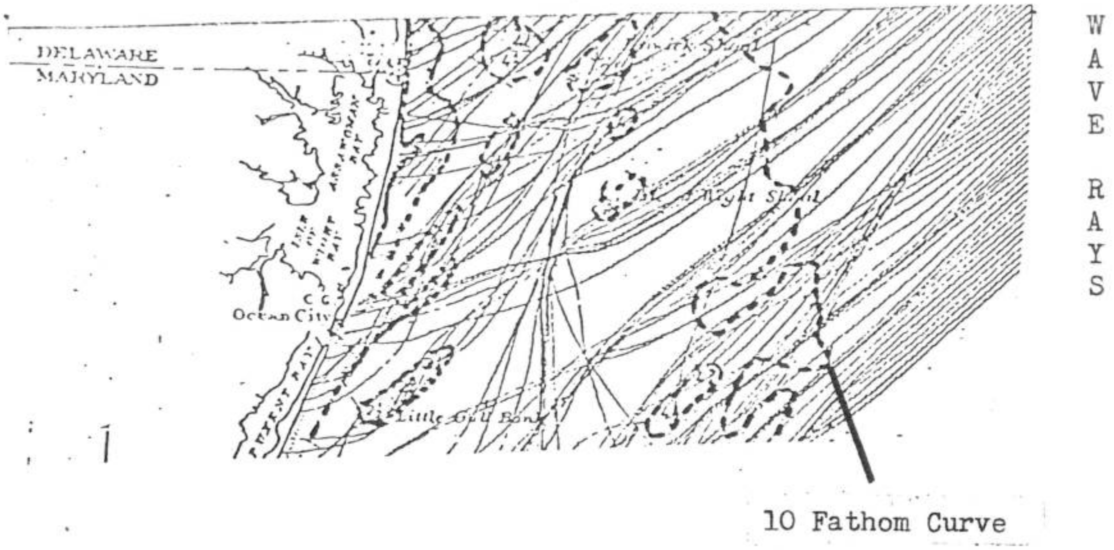


Figure 12. Photograph depicting beach erosion damage near Great Egg Harbor Inlet, N.J. on March 9, 1976. To the right of the photo is the wave refraction diagram based on the wave observations associated with this March 9, 1976 storm, indicating wave energy concentration (wave ray convergence) at the inlet (arrow).



10 Fathom Curve

"Finger Shoals"

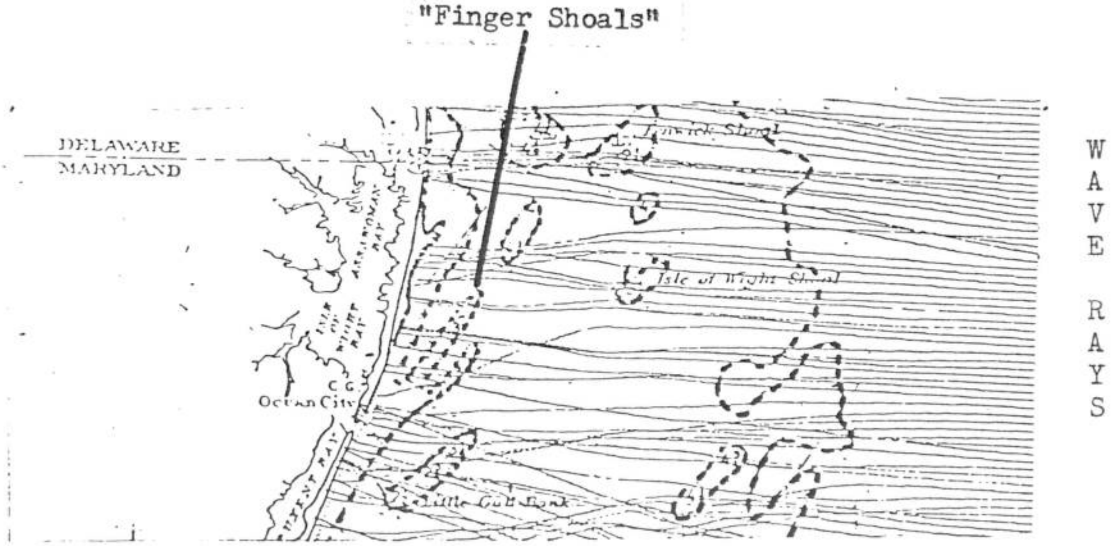


Figure 13. Wave refraction diagrams based on bathymetry off Ocean City, Md. and wave conditions associated with a December 19, 1977 storm. The upper diagram shows the rays generated by 10 second waves from the northeast, while the lower diagram depicts the ray pattern of 10 second waves from the east. Note that the easterly rays converge at more locations along the Maryland shore than the northeasterly ones.

Table 1. Storm-related erosion intensity matrix for the 14 states which border the Atlantic Ocean. Missing reports are denoted by "M".

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	M	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	1	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	M	0	0	0	0	0	0	0
Dec. 3-4, 1967	0	0	2	0	0	0	M	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	3	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	M	0	0	0	0	0	0	0
Feb. 12-13, 1972	1	1	0	0	0	0	M	2	0	0	0	0	0	0
Feb. 19-20, 1972	4	1	4	1	4	1	M	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	1	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	M	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	M	3	0	0	0
Apr. 1-3, 1973	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Dec. 9, 1973	0	0	0	0	0	2	2	0	0	0	0	0	0	0
Apr. 9-10, 1974	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Dec. 1-2, 1974	0	1	0	0	0	4	4	4	2	0	1	0	0	0
Apr. 2-5, 1975	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Feb. 1-2, 1976	3	1	1	0	0	0	0	0	0	0	0	0	0	0
Mar. 17, 1976	3	0	3	0	0	0	0	0	0	0	0	0	0	0
Jan. 10, 1977	3	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb. 24-25, 1977	2	2	0	0	0	0	0	0	0	0	0	0	0	0
Mar. 22-23, 1977	3	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2. Coastal states, associated tide gages, mean spring range of the tide at these gages, and "critical values" used in determining generalized and variable duration terms.

Coastal States	Associated Tide Gage	Mean Spring Tide Range (feet)	"critical value" used to determine Generalized Duration	"critical value" used to determine Variable Duration
Maine	Portland, Me.	10.4	7.7	6.2
Massachusetts	Boston, Mass.	11.0	8.0	8.0
Rhode Island	Newport, R.I.	4.4	4.7	4.7
New York	New York, N.Y.	5.4	5.2	5.2
New Jersey	Atlantic City, N.J.	5.0	5.0	4.5
Delaware	Breakwater Harbor, Del.	4.9	5.0	4.5
Virginia	Hampton Roads, Va.	3.0	4.0	3.0
North Carolina	Avon, N.C.	*4.1	4.5	3.5
South Carolina	Charleston, S.C.	6.1	5.5	5.0

* Spring tide range at Cape Hatteras, N.C. (Ocean side)

Table 3. Observed-forecast contingency tables based on six independent erosion events which occurred during the 1977-78 winter season. The upper table is for the 12-h forecasts based on the new set of equations. The lower table, also for the same forecast period, was computed with the 1976 equation.

NEW SET OF EQUATIONS

	FORECAST CATEGORIES						
OBSERVED CATEGORIES	SEVERE	MAJOR	MODERATE	MINOR	NONE	TOTAL	PERCENT OF TOTAL
Severe	0	2	0	0	0	2	4.3
Major	0	5	4	0	1	10	21.3
Moderate	0	2	3	0	0	5	10.6
Minor	0	0	0	1	1	2	4.3
None	0	0	6	2	20	28	59.6
Total	0	9	13	3	22	47	100.0

1976 EQUATION

	FORECAST CATEGORIES						
OBSERVED CATEGORIES	SEVERE	MAJOR	MODERATE	MINOR	NONE	TOTAL	PERCENT OF TOTAL
Severe	0	1	1	0	0	2	4.3
Major	0	0	3	6	1	10	21.3
Moderate	0	0	1	4	0	5	10.6
Minor	0	0	0	1	1	2	4.3
None	0	0	1	7	20	28	59.6
Total	0	1	6	18	22	47	100.0

Table 4. Same as Table 3 but for 36-h forecasts.

NEW SET OF EQUATIONS

OBSERVED CATEGORIES	FORECAST CATEGORIES SEVERE	MAJOR	MODERATE	MINOR	NONE	TOTAL	PERCENT OF TOTAL
Severe	0	2	0	0	0	2	4.3
Major	0	3	5	0	2	10	21.3
Moderate	0	1	3	0	1	5	10.6
Minor	0	0	0	2	0	2	4.3
None	0	0	2	2	24	28	59.6
Total	0	6	10	4	27	47	100.0

1976 EQUATION

OBSERVED CATEGORIES	FORECAST CATEGORIES SEVERE	MAJOR	MODERATE	MINOR	NONE	TOTAL	PERCENT OF TOTAL
Severe	0	1	1	0	0	2	4.3
Major	0	0	2	7	1	10	21.3
Moderate	0	0	1	3	1	5	10.6
Minor	0	0	0	0	2	2	4.3
None	0	0	0	2	26	28	59.6
Total	0	1	4	12	30	47	100.0

Table 5. Scoring matrix, which was designed to give heavier weights to erosion categories which are more difficult to forecast. The score for a correct forecast of severe erosion is given five times more weight than a correct forecast for no erosion.

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

Table 6. Relative matrix scores, percent of correct forecasts, and threat scores associated with the 12-h forecasts computed with the new set of equations and the 1976 equation.

Verification Scores	New Set of Equations	1976 Equation
Relative matrix score	0.60	0.46
Percent of correct forecasts	0.62	0.47
Threat score	0.26	0.04

Table 7. Same as Table 6 but for 36-h forecasts.

Verification Scores	New Set of Equations	1976 Equation
Relative matrix score	0.67	0.52
Percent of correct forecasts	0.68	0.57
Threat Score	0.22	0.05

Table 8. Qualitative erosion terms associated with past storms.

Storm Dates	ME.	MASS.	R.I.	N.Y.	N.J.	DELMAR	VA.	N.C.	S.C.
Mar. 6-9, 1962	Minor	Minor	Major	Severe	Severe	Severe	Severe	Severe	Minor
Nov. 26-30, 1962	None	None	None	None	Moderate	Moderate	Major	Major	Moderate
Nov. 29-30, 1963	Major	Moderate	Moderate	Major	None	None	None	None	None
Nov. 11-13, 1968	Minor	Major	Major	Severe	Severe	None	Minor	None	None
Dec. 31, 1970	None	None	None	None	None	None	None	Moderate	Severe
Apr. 6-7, 1971	None	None	None	None	None	Major	Moderate	None	None
Feb. 19-20, 1972	Severe	Severe	Severe	Minor	None	None	None	None	None
Feb. 7, 1978	Severe	Severe	Major	Major	Major	None	None	None	None