CHAPTER ONE HUNDRED EIGHT

Beach and Dune Response to Severe Storms

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ABSTRACT

A numerical model is developed and applied to estimate the frequency distribution of severe erosion events. The proposed method is an extension of existing Monte Carlo storm surge simulation models. Hurricane and tropical storm meteorological parameters are randomly selected to generate a series of synthetic storms; the storm surge for each storm is estimated using a Bathystrophic storm surge model. The storm surge hydrograph is then used as input to a numerical erosion simulation model which determines beach profile response for each storm based on wave energy dissipation per unit volume as a general erosion forcing mechanism. Five 100-year random simulations are performed from which the return periods of storm surge and erosion, i.e. volume eroded and dune recession, are estimated.

INTRODUCTION

While major advances have been made in recent years in the development of frequency distributions for storm surge elevations, little progress has been made with regard to forecasting the probabilities of extreme erosion events. Detailed estimates of storm surge frequencies are now commonly made through numerical simulation of the governing equations based ultimately on historical probabilities of the meteorological characteristics of severe storms. For erosion events, on the other hand, it has not been possible to utilize this combined probabilistic-deterministic approach, since little is known concerning the equations or boundary conditions that govern storm erosion.

The goal of this study is to develop a general methodology to forecast the frequency distribution of severe erosion events based on severe storms expected over a wide range of return periods. The proposed methodology includes two phases: 1) the development of a computational method for predicting erosion due to a severe storm of given characteristics, and 2) the incorporation of this method into a larger model which accounts for the probabilities of occurrence of severe storm events. The results of the study are pertinent to current efforts to estimate the extent of erosion expected during a major storm, say with a 100-year return period, which may be required for coastal insurance, zoning, construction regulation, or structural

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design. Likewise, an estimate of the frequency distribution of erosion events will aid in the interpretation of the severity of particular erosion events relative to other possible erosion events.

The most widely used techniques for predicting single-storm erosion are schematic or geometric methods that are adaptations of the so-called Bruun's Rule (Bruun (1962)), which was originally proposed for estimating erosion due to sea level rise. The schematic method most often cited in the literature is that of Edelman (1968); although similar procedures have been proposed by Dean (1984) and others. Typical assumptions used by these methods for predicting storm-induced erosion include: 1) longshore transport gradients are spatially averaged, therefore, beach response is governed by a conservation of the sand volume perpendicular to shore, 2) offshore sand transport is effectively limited by the breakpoint of incident waves, and 3) the post-storm profile is in a dynamic state of equilibrium relative to the peak storm surge level. This last assumption implies that the profile has sufficient time to reach equilibrium during the peak surge. Comparisons of these methods to field data, however, suggest that these methods typically overpredict erosion in some cases by more than a factor of five. In effect, these methods predict the maximum erosion potential of the peak surge, a value that is seldom realized in nature due to the relatively slow response of beaches to changing water levels.

Several researchers, including Swart (1974), Vellinga (1983), and Hughes (1983) have developed more realistic predictive methods based on empirical results of small and large scale laboratory tests. The most useful computational methods, of Swart and Vellinga, use the general schematic arguments of Edelman's method; however, through derived model laws and experimental results, the effects of almost all of the most important parameters in the dune erosion process are quantified.

At present, the literature includes only two general methods for estimating erosion frequencies. Vallianos (1974) applied peak storm surge levels associated with various return periods to estimate beach fill requirements for the same return periods, based on a modified form of Edelman's methods. In a more detailed approach, van de Graaff (1983) used the computational method of Vellinga to predict dune erosion probabilities as the result of seven parameters, each with a known or assumed probability distribution. Two methods are presented for estimating these probabilities; one is a complete integration of seven probability distributions, the other is an approximate method in which mean dune recession is estimated based on water level and wave height distributions. Variability of this estimate is then given by a normal distribution with a standard deviation defined by the other five parameters.

The overall objectives of the present study are the same as those of van de Graaff, namely to obtain a rational estimate of the erosion frequency distribution by combining a computational erosion model with the probabilistic components of forcing parameters. However, the specific methods proposed in this study are quite different in several aspects. First, the erosion model proposed for estimating single-storm beach response is more deterministic and based on a numerical simulation of simplified governing equations including a proposed process-based sediment transport equation and the equation for continuity of sand. Therefore, the entire time-history of profile response is predicted directly, based on the time-history of the storm surge. The method is based on the equilibrium beach profile theory described by Dean (1984), and, like other methods, it is intended to be simple and schematic and does not attempt to represent many important surf zone processes. Finally, the estimation of erosion frequency distributions is accomplished through a Monte Carlo simulation procedure, which is a logical extension of existing methods for predicting storm surge frequencies. The Monte Carlo procedure has the advantages of simulating nature as realistically as possible and of being based on historical probabilities of meteorological parameters which are well defined in most areas.

Existing Monte Carlo storm surge simulation models, for example Fallah, et al. (1976), generally employ the following steps:

- Input consists of probability distributions of meteorological parameters and astronomical tide amplitudes.
- Artificial storms are assembled through random statistical sampling of the historical probability distributions.
- A deterministic model is used to generate hurricane, wind and pressure fields.
- A second deterministic model is used to generate storm surge.
- The storm surge and astronomical tide are randomly combined to give the total storm tide for each synthetic storm.
- When a sufficient number of storms have been simulated, the distribution of storm tide elevations is estimated through an extreme value analysis.

With the development of an efficient beach and dune erosion model, the methodology is easily extended as depicted in Figure 1. The storm tide for each storm is estimated based on a randomly assembled set of storm parameters. In this study, a simple Bathystrophic storm surge model initially proposed by Freeman, Baer, and Jung (1957) is used for efficiency. Breaking wave heights are also estimated for each storm. The deterministic erosion model is then used to generate the time-dependent erosion for each storm, relative to a common pre-storm profile, based on the time-histories of the storm tide and breaking wave heights. Finally, a frequency analysis is performed on the maximum erosion characteristics to give the frequency distribution of eroded volumes and dune recession.

EROSION MODEL - DEVELOPMENT

The beach erosion model is based on the premise that a beach profile will always move toward its most stable, equilibrium form in response to given input or forcing conditions. There is considerable empirical evidence to suggest that the general equilibrium form of beach profile may be approximated by a monotonic curve of the form

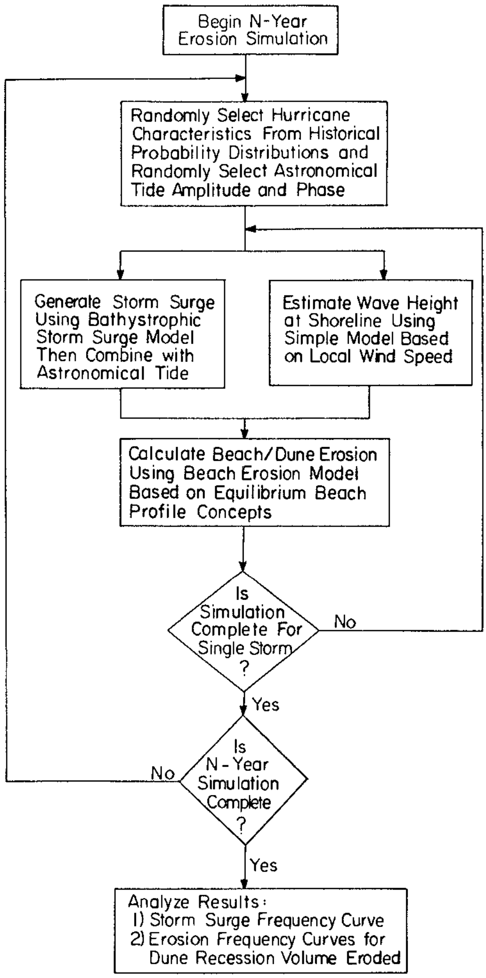
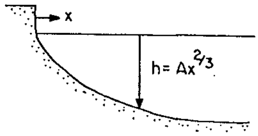


Figure 1. Flow Chart for Monte Carlo Storm Surge and Erosion Simulation.

$$h = Ax^{2/3} \tag{1}$$

which is the result of the uniform dissipation of wave energy per unit volume due to spilling breakers. As shown if Figure 2, the scaling parameter, A, may be theoretically related to a unique value of the energy dissipation per unit volume, D_*, which exists at all

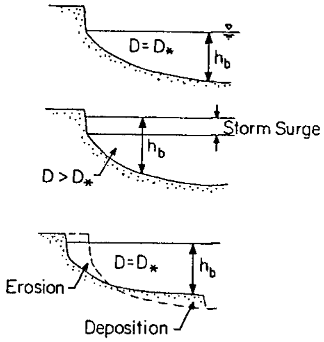
I. EQUILIBRIUM BEACH PROFILE FORM



based on uniform energy dissipation per unit volume where A is related empirically to sediment size and can be related to D_* by:

$$A = \left[\frac{24}{5} \frac{D_*}{\gamma \kappa^2 g^{1/2}} \right]^{2/3}$$

II. ENERGY DISSIPATION PER UNIT VOLUME $D = \frac{1}{h} \frac{\partial F}{\partial x}$



III. SEDIMENT TRANSPORT EQUATION $Q = K(D - D_*)$

Figure 2. Basic Concepts for Erosion Model.

points in the surf zone when the profile is in equilibrium. Analysis of over 700 beach profiles has provided an empirical relationship between sediment size and the equilibrium profile characteristics A and D_* as discussed by Dean (1984).

During a severe storm, the increased water level initially permits waves to break closer to shore. This effectively reduces the width of the surf zone and at the same time increases the energy dissipation per unit volume at all points in the surf zone. The profile is therefore "out of equilibrium" since actual energy dissipation levels are greater than the stable value, D_*. Based on the assumption that the profile will respond back toward equilibrium, the final result must be a widening of the surf zone until the actual energy dissipation equals D_*. This result can only be achieved by a net redistribution of sand over time, with erosion occurring nearshore and deposition pushing the breakpoint offshore.

Bakker (1968) and Swart (1974) have previously proposed that the net offshore sediment flux could be represented in terms of the disequilibrium of geometric profile lengths. In a similar fashion, if energy dissipation per unit volume is assumed to be the general forcing mechanism, then the offshore sediment transport rate may be related to the excess energy dissipation per unit volume as:

$$Q = K(D - D_*) \tag{2}$$

in which K is a proportionality factor to be determined. In a concurrent study, Moore (1982) found K to be on the order of 10^{-6} m^4/N.

For numerical simulation of time-dependent profile response, the equation for sediment flux is coupled with the equation for continuity of sand in the onshore-offshore direction

$$\frac{\partial x}{\partial t} = - \frac{\partial Q}{\partial h} \tag{3}$$

which is then solved numerically. Details of the numerical simulation are presented by Kriebel and Dean (1984). As a brief summary, the surf zone is represented by a series of elevation contours of uniform width, Δh, with the distance, x, defined from a reference baseline to the center of each contour. The solution proceeds by raising the water level and establishing the offshore limit of the active profile at the breakpoint of incident waves. The energy dissipation per unit volume, D, and the sediment transport rate, Q, are then calculated throughout the surf zone. An implicit, linearized finite-difference scheme is used which yields a tridiagonal matrix relating the change in position, Δx, of three adjacent contours. This system is then solved by the so-called double-sweep procedure to determine the change in contour location, Δx, over each time step.

EROSION MODEL - RESULTS

General characteristics of the numerical solution appear to be consistent with natural and laboratory beach profile response. If an initial equilibrium profile with linear beach face slope and a distinct berm is subjected to an instantaneous increase in water level which is held steady as the system responds toward equilibrium, then the general solution for either berm recession or volumetric erosion exhibits nearly exponential behavior, approaching equilibrium asymptotically. This behavior agrees quite well with laboratory results of Saville (1957), Swart (1974), Vellinga (1983), and Hughes (1983). Numerical results for 0.2 to 0.3 mm sand and wave heights of 1 to 5 meters indicate that natural erosion time scales are on the order of 10 to 100 hours, thus indicating that equilibrium is probably not attained during typical storm conditions.

For practical application to single storm erosion simulation, the time-history of erosion may be estimated simply by inputting new water level and wave height conditions at each time step over the duration of the storm surge. In the example in Figure 3, the time-dependent erosion is predicted for an idealized storm surge hydrograph applied to a representative beach profile as discussed by

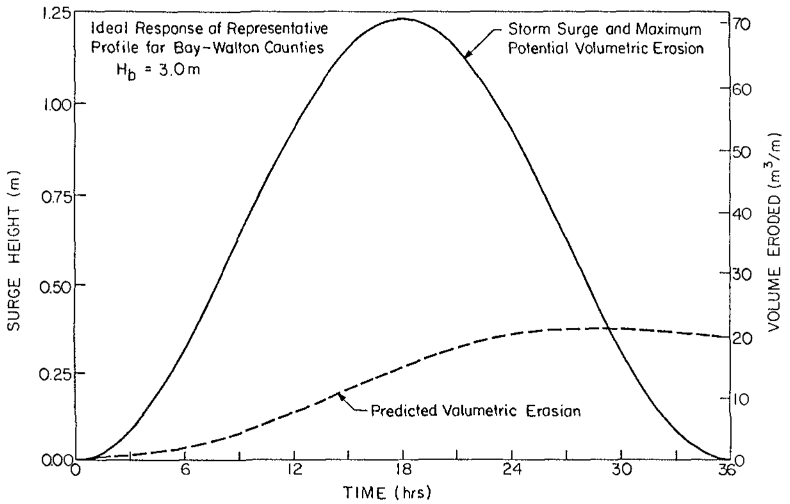


Figure 3. Time-Dependent Erosion Prediction for Idealized Storm Surge.

Kriebel and Dean (1984). In this case the right axis is scaled to the maximum erosion potential of the peak surge - a value that requires the peak surge level to be held steady for almost 300 hours.

This idealized example illustrates the general characteristics of the time-dependent erosion solution and reveals several features that seem representative of nature. First, the erosion potential of the peak surge is not realized during most storm events. Based on idealized cases with peak surge elevations of up to 3.6 m and 36 hour durations, only 14% to 36% of the maximum erosion potential is attained. Second, the erosion rate is maximum at about the time of the peak surge. Offshore transport processes respond at a slow rate relative to changing water levels, thus energy dissipation per unit volume, spatial gradients in sediment flux, and the erosion rate are all maximum at the time of the peak surge. Finally, the maximum erosion lags the peak storm surge. As the water level recedes, energy dissipation remains greater than equilibrium for some time causing erosion to continue.

A preliminary verification of the erosion model is obtained from a hindcast of erosion associated with Hurricane Eloise in the Florida Panhandle. The calibrated, Bathystrophic storm surge model is used to estimate the open coast storm surge and the predicted peak surge of 3.2 meters compares favorably to predictions of 3.2 meters by the National Weather Service (Burdin (1977)) and 2.9 m by Dean and Chiu (1982). This hydrograph is then applied to a schematic profile which is considered representative of the area of interest. A total of 20 test runs are made to simulate various combinations of beach slope, dune slope, wave heights, and water levels - both to test model sensitivity and since exact values cannot be specified for all parameters.

In a summary of results for all 20 test cases in Table 1, predicted volumetric erosion ranges from 20.8 to 38.4 m^3/m with best estimates of 27.1 to 30.1 m^3/m based on the parameters that best describe pre-storm and storm conditions. For comparison, Chiu (1977) gives average eroded volumes of 23.3 to 30.1 m^3/m. Both observed and predicted erosion are in close agreement, especially when compared to the maximum erosion potential of 113 to 289 m^3/m associated with steady-state peak surge levels.

Table 1. Comparison of Numerical Solution to Observed Erosion

	Volume Eroded m^3/m	Dune Recession m
Range Predicted	20.8 to 38.4	4.8 to 9.5
Best Estimates	27.1 to 30.1	6.8 to 7.0
Observed (Chiu)	23.3* to 30.1*	2.7 to 6.1 (4.6 m contour) 7.2 to 12.8 (3.0 m contour)
Maximum Potential	112.9 to 288.6	33.5 to 76.2

*Includes $5 m^3/m$ to reflect maximum erosion before recovery

As discussed by Kriebel and Dean (1984) dune steepening is not simulated in the model and this is evident in a comparison predicted and observed dune recession values. Predictions range from 4.8 to 9.5 m with best estimates of 6.8 to 7.0 m. Observed dune recession varies depending on the elevation contour and varies from 2 to 13 m with the 3.0 meter contour eroding about twice as far as the 4.6 m contour. However, predicted values are of the correct order of magnitude; this is further evidenced by the 33 to 76 m estimates of the maximum erosion potential of the same dunes.

It is emphasized that the predicted post-storm profiles such as shown in Figure 4 are not in equilibrium relative to the peak surge level and do not have the equilibrium $Ax^{2/3}$ shape consistent with the 0.26 mm sand in the profile. The true equilibrium profile is attained only after the peak storm surge is maintained for about 1,000 hours after which equilibrium erosion values are up to 10 times the erosion predicted by the time-dependent storm surge.

ESTIMATION OF EROSION FREQUENCIES

As noted, the proposed erosion model is incorporated into a general Monte Carlo simulation model, as depicted in Figure 1, to obtain estimates of the frequency distribution of erosion events. Required input parameters include the probability of a hurricane or tropical storm occurring in a given year and the probability

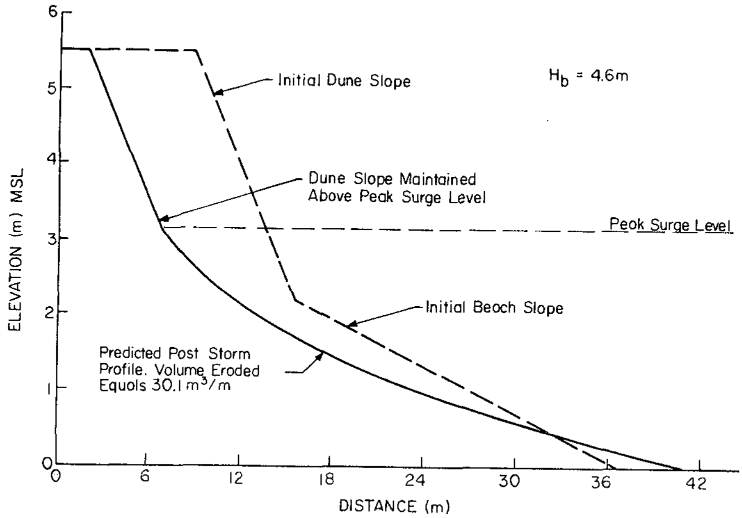


Figure 4. Example of Predicted Post Storm Profile, Hurricane Eloise.

distributions of various storm parameters which include the central pressure, radius of maximum wind, forward speed, direction of motion, and location of the storm track. Synthetic storms are assembled by selecting each parameter based on a separate uniformly distributed random number between 0 and 1. Once a storm is randomly assembled, the surface wind speed, pressure field, and storm surge are simulated at one-half hour time-steps. In this study, a one-dimensional Bathystropic storm surge model is chosen for simplicity and is calibrated through the bottom friction coefficient as described by Marinos and Woodward (1968), or Bodine (1971). The storm surge is then combined with a randomly-phased astronomical tide to produce the total storm tide.

While the storm tide serves as the principle driving mechanism in the numerical solution, an estimate of the breaking wave height is needed to serve as a boundary condition governing the surf zone width. A procedure similar to that used by Dean and Chiu (1982) is employed in which the maximum deepwater significant wave height of the hurricane is first determined according to the method of Bretschneider (1957). The local breaking wave height is then estimated by scaling the maximum deep water wave height according to the ratio of local wind speeds at the shoreline to maximum wind speeds in the storm. With the water surface elevation and breaking wave height at each time-step, the profile change over each time-step may then be determined with the erosion model. This is repeated for each synthetic storm over the N-year period. Results of the procedure include the peak storm surge, maximum volumetric erosion, and maximum dune recession for each storm. Frequency curves are then determined for each variable based on a simple plotting position formula.

APPLICATION OF MONTE CARLO STORM SURGE - EROSION MODEL

As an example of the Monte Carlo procedure, five 100-year simulations have been carried out for Bay County, Florida. The five simulations include 63, 74, 67, 69, and 70 hurricanes and tropical storms respectively for an average of nearly 69 storms per 100 years over the 300 nautical miles of coastline considered. For each storm, the initial profile, representative of pre-Eloise conditions, is re-established so results may then be compared to observed erosion from Hurricane Eloise.

In Figure 5, the storm surge frequency curves of all five runs are presented and show the expected natural variability obtained from the Monte Carlo procedure. Storm magnitudes for lower return periods are well-defined; however, the 100-year storm surge estimate varies by about 1 meter. In order to reduce this variability, the five individual curves are averaged in Figure 6. While this average curve could also be bounded by confidence limits based on observed variability between different Monte Carlo simulations, several more runs would be required to obtain stable estimates of the standard deviations of each return period. The predicted average frequency curve is compared to the results of two other numerical estimates for the same area, indicating the validity of the procedure for estimating storm surge frequencies.

The frequency distributions for volumetric erosion from each of the five 100-year simulations are plotted in Figure 7. As expected, there is some variation between the five curves at 50 to 100 year return periods; however, the erosion curves are closely grouped at all return periods. Again, the five curves are averaged and the mean volumetric erosion, as well as dune recession, are extended to 500-year levels in Figures 8 and 9. Without empirical data on historical storm related erosion events, it is difficult to verify these randomly generated erosion frequency curves. However, the predicted values are in general agreement with guidelines for storm-related erosion given by the U.S. Army Corps of Engineers (1977) where the severity of open coast erosion is broadly classified as:

moderate storm	10 - 25 m^3/m
extreme storm	25 - 25 m^3/m
rare storm	50 - 125 m^3/m

An interesting comparison can be made between the predicted frequency curves, in Figures 6, 8, and 9, and the observed storm surge and erosion characteristics of Hurricane Eloise. Although there is no data to firmly establish the peak storm surge level of Hurricane Eloise for the area of interest, if the predicted value of 3.2 m is accepted then it appears that Eloise may be associated with

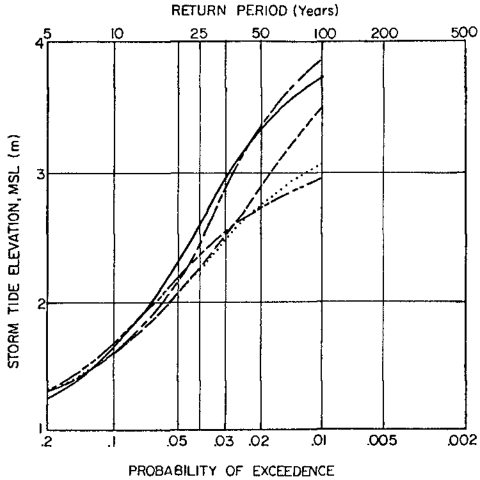


Figure 5. Results of Five 100-Year Simulations for Peak Storm Surge.

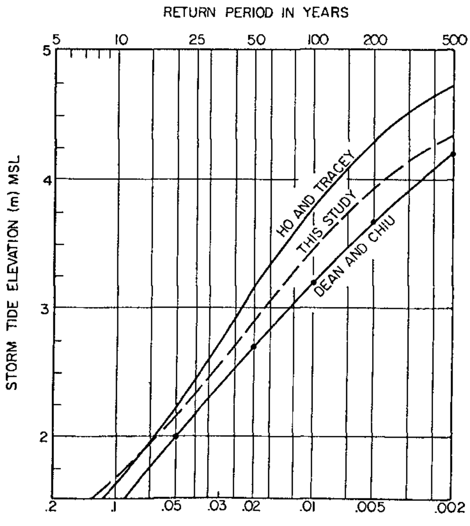


Figure 6. Comparison of Predicted Storm Surge Frequency Curves.

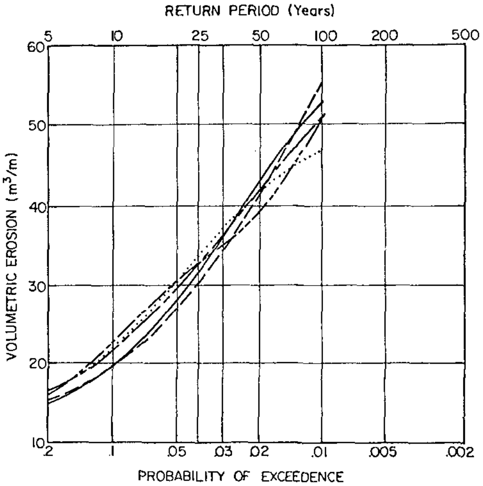


Figure 7. Results from Five 100-Year Simulations for Volume Eroded.

a return period of about 75 years. However, if observed erosion characteristics with a 9 m dune recession and an eroded volume of 30.1 m^3/m are considered, then from Figures 8 and 9, Hurricane Eloise should probably be classified as a 25 to 50 year storm in terms of its erosion damage. Since Hurricane Eloise was a rapidly moving storm of short duration, a relatively small percentage of its erosion potential was realized.

This conclusion is reinforced in Figure 10 where the peak storm surge is plotted against the predicted maximum volumetric erosion for all storms in one simulation run. It is evident that the largest storm surge levels do not always produce the greatest erosion. Likewise, several relatively small storms can produce significant erosion due to longer durations. The range of erosion values associated with Hurricane Eloise clearly fall below what would normally be expected for a storm of the same magnitude, i.e. peak surge. Certainly, storm duration and magnitude, not just magnitude alone, are important considerations when estimating erosion frequencies.

CONCLUSIONS

A numerical model has been developed which allows a first-order estimate of: 1) the time-dependent beach and dune erosion associated with tropical or extra-tropical storm surge and 2) the frequency distribution of extreme erosion events based ultimately on historical meteorological parameters of severe storms. The proposed erosion model is certainly in the developmental stages. Current research is being directed toward incorporating wave runup, variable beach slopes, and the formation of dune scarps. Also, a detailed

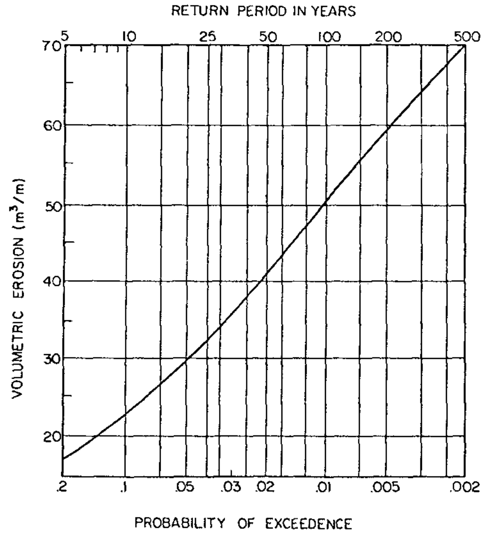


Figure 8. Predicted Frequency Curve for Volume Eroded.

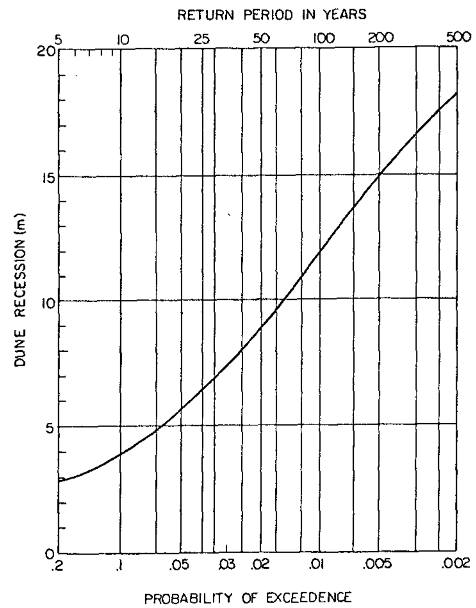


Figure 9. Predicted Frequency Curve for Dune Recession.

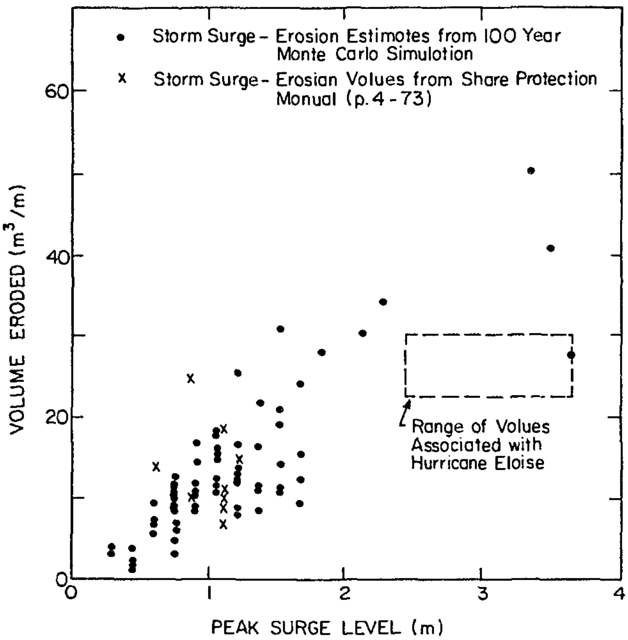


Figure 10. Comparison of Predicted Storm Surge and Volume Eroded for One 100-Year Monte Carlo Simulation.

calibration and verification of the model is being performed based on available field data on pre- and post-storm beach profiles from Hurricane Eloise.

Numerical estimates of erosion frequency distributions appear reasonable although verification is impossible without extensive field data on storm erosion. In general, however, the Monte Carlo procedure is well-verified for predicting storm surge probabilities. The method presented is a logical extension of the Monte Carlo technique that may permit the development of erosion frequency distributions for any open coast location in which historical meteorological parameters of severe storms are available.

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