Su-Ao Harbor, Taiwan, ROC—R.L. Wiegel

PART IV

COASTAL, ESTUARINE, AND ENVIRONMENTAL PROBLEMS

Aerial View of Taipei City—H.S. Hou

CHAPTER 181

INNOVATIVE DETERMINATION OF NEARSHORE FLOOD FREQUENCY

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ABSTRACT

Reliable estimates of coastal flooding from tides and storm surges are required for making sound engineering decisions regarding the design, operation and maintenance of many coastal projects. A recent investigation of flood frequency along the coast and within the bays of southern Long Island, New York, produced new and optimal approaches to obtain meaningful statistical estimates of flood levels. This paper summarizes various elements of the study and concentrates on the problem of stage-frequency computations in the inland bay areas. Methods for optimizing the number of necessary storm/tide simulations and estimating the accuracy of results are presented.

INTRODUCTION

Efficiency in design of coastal protection is becoming more and more important. Development of coastal regions, costs of damages from storm induced water levels, and costs of protection from these waters are all increasing. Adequate protection for coastal regions is desired; however, due to financial constraints the amount of flood level protection that can be considered adequate becomes a question for which there is no easy answer. Therefore, inherent in any coastal protection project is a need to develop the most accurate possible stage-frequency (frequency of storm/tide induced still-water level above a fixed datum) relationship estimate for the project area, as well as an estimate of the error in this relationship.

The technique in widespread use for the development of coastal flood frequency, especially from hurricane induced water levels, is the joint probability method (JPM) (Myers, 1970). A method to develop error estimates from meteorological uncertainty for stage-frequency relationships derived through the JPM was presented by Prater, et al. (1984). However, a generally accepted method to judge the correctness of the produced flood frequency, or to estimate the error of these frequencies, is not available.

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A study to investigate the frequency of storm-plus-tide flood levels along the coast and within the bays of southern Long Island, New York, was recently completed at the U.S. Army Engineer Waterways Experiment Station (WES). The offshore study domain is the New York Bight whereas the nearshore area of interest covers a coastal reach of approximately 125 km and includes three inlet/bay systems (Great South, Moriches, and Shinnecock Bays) with interconnecting channels. The problem is further complicated by a variable height dune system along the bayfront barrier islands which is susceptible to overtopping and deterioration during a storm passage.

The approach adopted for estimating stage frequency due to storm-induced surge and wave effects involved conjunctive use of several models. A numerical storm surge model calculated the still water level. A dune breach model permitted an ad hoc determination of dune overtopping and destruction. Several probability models were used to choose events to simulate, assign probabilities to those events, and construct the stage-frequency relationships. Each element of the study is briefly discussed; however, attention here is focused on the optimal methods used for estimating nearshore and inland bay flood frequencies and errors in the development process. A complete report on the study is given in Prater, et al. (1987).

STORM SURGE MODELING

Simulations required in the Long Island study involved application of two numerical surge models, collection of field data for model calibration, and analysis of alternative barrier and inlet configurations. The primary model applied in the study is the WES Implicit Flooding Model (WIFM). The numerical and hydrodynamic features of WIFM are discussed in Butler (1978) and the application to coastal studies is documented in numerous reports including Butler (1980, 1983). WIFM solves the vertically integrated time-dependent shallow water wave equations of fluid motion using an alternating direction implicit finite difference algorithm. The code allows subgrid barriers to be exposed, submerged, or overtopped. An important feature of WIFM is the capability to create an exponentially stretched grid which permits concentration of grid resolution in areas of interest. Also included in the code is the capability to flood or dry individual low-lying cells during a simulation.

A coarse global grid (Figure 1) was constructed to cover the New York Bight from a point south of Atlantic City, New Jersey, to beyond Cape Cod, Massachusetts (and includes New York Harbor and Long Island Sound). The purpose of the global grid is to model large-scale tidal and meteorological events, providing results for input to a small, high-resolution nearshore grid of the main study area. The high-resolution nearshore grid stretches from near Jones Inlet to beyond Shinnecock Inlet (including all back-bay and channel systems) and has variable grid size resolution of 200 to 1200 m.

Both numerical grids were calibrated for the primary M2 astronomical tidal constituent, and verified for a mixed tide condition. Typical results for comparing observed and computed surface elevations are

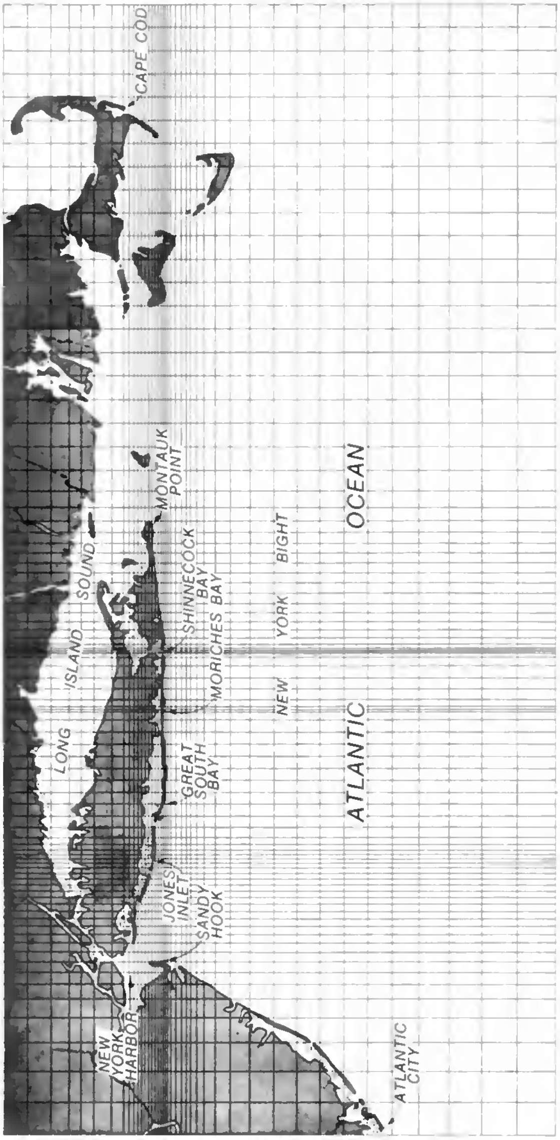
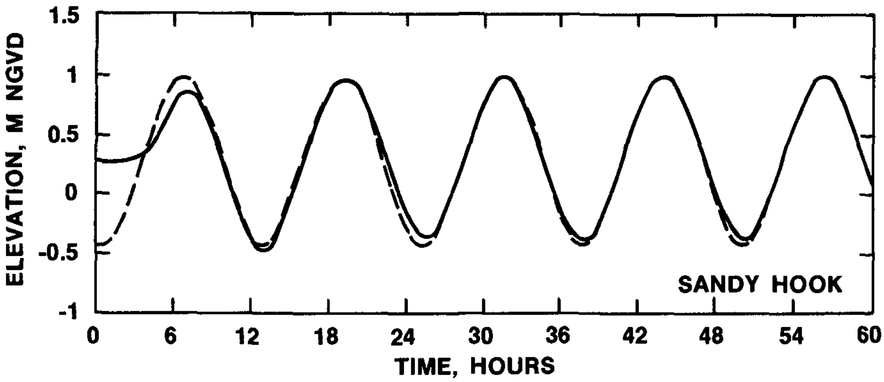


Figure 1. Global grid for storm tide simulations

displayed in Figure 2. Figure 2a shows a comparison of global results to measured data at Sandy Hook, New Jersey, and Figure 2b compares nearshore grid results to measured data at a gage within Great South Bay. Bathymetric and topographic data describing barrier island and inlet configurations for five severe historical storms (hurricanes of 1938, 1954 (Carol), and 1960 (Donna), and the extratropical storms (northeasters) of November 1950 and March 1962) were developed. These storms were hindcasted to verify both the global and nearshore numerical models for storm-plus-tide events.



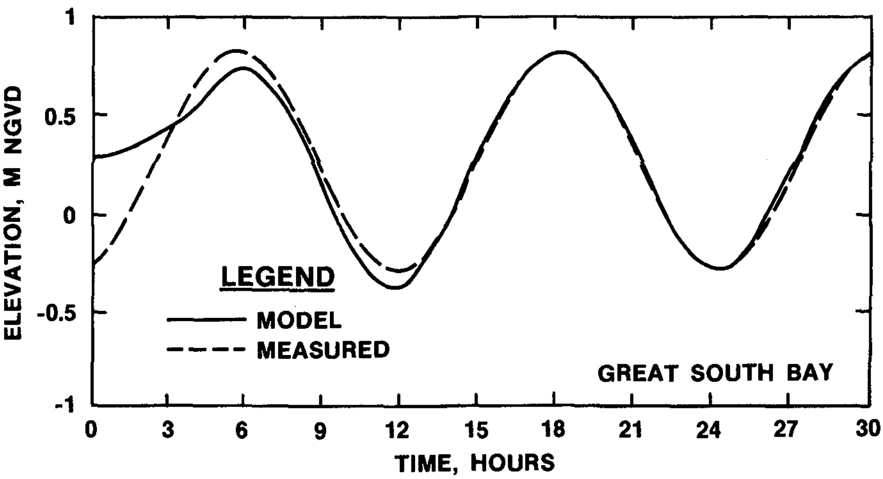


Figure 2. Comparison of global model results to measured data

To provide wind stress from hurricanes to the hydrodynamic model, a parametric model was used to represent the windfield as specified by the Standard Project Hurricane (SPH) criteria (NWS, 1979). Wind speed and direction computed by the SPH model are appropriate to open-coast conditions. The model version used in WIFM permits a reduction of the open-water wind speed at the land-water interface and inland over low-lying land and embayments. For historical northeasters, wind speed and direction and atmospheric pressure were available from archived data (Brooks and Corson, 1984).

Extreme water levels on the coast produce substantial dune destruction and breaching, contributing to higher embayment water levels. In order to simulate these extreme events it was necessary to develop a mechanism to account for dune destruction and breaching. A simple, but deterministic method was adopted to lower the barrier island dunes and permit more water to enter the bays. Using methods given in the Shore Protection Manual (SPM, 1984), an effective water level during wave attack of the dune system is computed and allowed to trigger the lowering (or breaching) of a dune on a cell-by-cell basis. The method was calibrated using historical data from several storms. Destruction/breaching was considered a function of the dune type, height, and base width.

Good comparisons between observed and computed water levels were obtained at open coast gages (Figure 3 displays sample comparisons for Sandy Hook for all five storms mentioned above). Comparison at inland bay gages involve contributions from wave effects and dune breaching as discussed above. Flood potential is increased by the capability of storm-induced waves to enter the inland bays through inlets or over breached dune systems and of waves to develop on shallow inland bays. A method devised by the National Academy of Science (1977) was used to estimate the maximum flood height at inland gages due to surge plus tide plus wave contributions. Table 1 gives an example of comparisons obtained for inland gages spanning the entire nearshore grid domain.

Table 1

Comparison of Meseaured and Computed (Estimated) Flood Levels (m)

	Hurricanes						Northeasters			
	1938		1954		1960		1950		1962	
Gage	M	C	M	C	M	C	M	C	M	C
Amityville	2.4	2.3	1.8	1.5	1.8	2.5	2.1	2.0	1.8	1.7
Patchogue	2.7	2.6	1.5	1.6	1.4*	1.8	1.5	2.0	1.5*	0.7
Moriches CGS	4.6	4.0	1.5*	2.0	1.4	2.1	1.5*	2.0	1.5*	1.1
Pine Neck	4.3	4.5	1.5*	2.4	1.5*	1.9	1.5*	1.8	1.5	1.0

M,C represent measured (M) and computed (C) values
* Limited data available

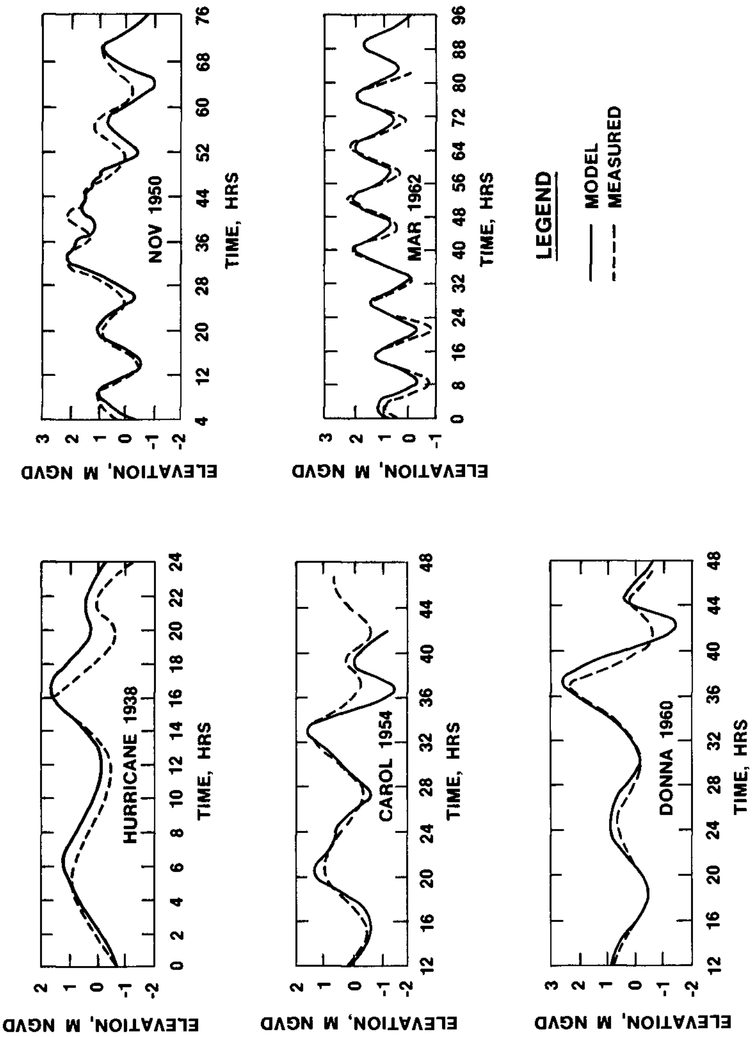


Figure 3. Comparisons of computed and measured water levels at Sandy Hook, New Jersey, for five historical storms

In Table 1, Amityville and Patchogue are located in Great South Bay, the Moriches Bay gage is at the Coast Guard Station, and Pine Neck is located in Shinnecock Bay.

STATISTICAL APPROACH

The two most common approaches to establish frequency curves are called the historical method and the JPM. In the historical method a series of historical events is recreated with pertinent data being saved at necessary grid locations. In effect, it is analogous to operating a "time machine" with the hindsight to know what data to collect and where to collect it. Probability is assigned to each event by a standard ranking method. For the JPM, the storm type is parameterized. For example, hurricane windfields can be defined by three parameters: central pressure deficit (DP), radius to maximum winds (R), and forward speed (F). Then an ensemble of synthethic events is simulated representing those events which are possible in the study area. Probability is assigned to individual events by assigning probabilities to parameter values which determine that event. If the parameters are independent, then the probability of the event will be the product of the probabilities of the component parameters. If dependency among parameters exist, the ensemble is subdivided into sets of events, each containing independent component parameters.

Hurricanes

The JPM approach was adopted to develop hurricane stage frequencies for this study. Five storm parameters were used to describe hurricanes: F, R, DP, track direction, and landfall point. Probability distributions for each parameter were obtained by a thorough review of the historical occurrence of hurricanes in the New York Bight. It was determined that three F's, three R's, six DP's, and five landfall points with three track directions and two track directions for bypassing storms were needed to represent the range of hurricane parameters which could occur. This selection gives a total ensemble of 918 hurricane events to be modeled, each with its own probability of occurrence. The actual number of storm events modeled was reduced. Sensitivity tests determined that water levels resulting from different pressure deficits could be linearly interpolated. Therefore, only two values of DP, values near the extremes of the DP probability distribution, were used in forming the actual computational ensemble of 306 hurricanes.

Northeasters

Because of the difficulty in parameterizing northeasters and the availability of data from frequent storm events, a historical approach was adopted. From previous studies performed for the New York Bight (Myers, 1970; and Camp Dresser and Mckee, 1980) and from historical records, a stage-frequency curve constructed from both northeaster- and hurricane induced water levels show northeasters dominate the higher frequency, lower magnitude events but are generally ineffective in producing the rarer, higher stage events. Consequently, the length of historical record chosen (the 41-year period from 1940 to 1980) is sufficient to adequately cover the area of dominance on the combined event stage-frequency curve.

Historical data from 101 storms over the 41-year span that produced at least a 0.7 m surge at Sandy Hook, New Jersey, were used to develop a partial duration exceedence (PDE) curve. Twenty-seven storms from this set were selected (storms representative of the entire set of 101 storms) and assigned probability masses in proportion to the amount of the PDE distribution each storm is to represent. The mean difference (for the 27 events) between simulated surge elevations and observed values was 8 cm at Sandy Hook and 9 cm at Montauk, New York.

Tide Convolution

Global grid simulations were carried out for surge without tide. Tides were incorporated through the convolution of tidal values with output of the surge-only numerical simulation. This procedure is valid in the open Bight where nonlinear effects of combining surge and tide are negligible. The convolution procedure produced more than 600,000 possible hurricane surge-tide combinations and over 18,000 northeaster surge-tide combinations. These storm-tide event sets were ranked by elevation, and through the use of their probabilities, stage-frequency relationships were developed for open-coast locations throughout the study area.

COASTAL STAGE FREQUENCIES

The surge-tide convolution was performed at all locations in the global grid where a frequency relationship was desired. From these data a probability of exceedence distribution for water levels was developed, from which stage frequencies could be deduced. By adding exceedence probabilities from the hurricane and northeaster curves, the return period between occurrences of water levels equal to or exceeding the specified level from either hurricanes or northeasters were computed. The northeaster storm of record (November 1950) was an outlier for the events chosen. Sensitivity tests on assignment of probability of occurrence for this rare event indicated insignificant impact on the combined stage-frequency curve above the 50-year return period due to the dominance of hurricane events on the longer return periods. Hence, the uncertainty of the return period of the 1950 event will not affect the combined stage-frequency curves in the study area. Figure 4 displays sample combined stage-frequency curves for open-coast locations at Sandy Hook, on the coast fronting Great South Bay, and for the eastern end of the study area (Montauk). Prior to this investigation, a single frequency curve similar to that for Sandy Hook was used for evaluating coastal projects on southern Long Island. These results can reduce costs of future projects by being a yardstick for accurately assessing risk associated with different protection levels. Figure 5 compares stage-frequency curves computed from model results with curves deduced from measurements at Sandy Hook. Historical data used to produce Figure 5 only provide a combined frequency curve out to the 25-year return period.

As stated above, adequately monitored hurricane occurrences are scarce in the north Atlantic Ocean and the development of accurate parameter distributions with limited data becomes difficult. By using a bootstrap technique (Prater, et al., 1984), error estimates on the stage-frequency curve were obtained from the uncertainty of these

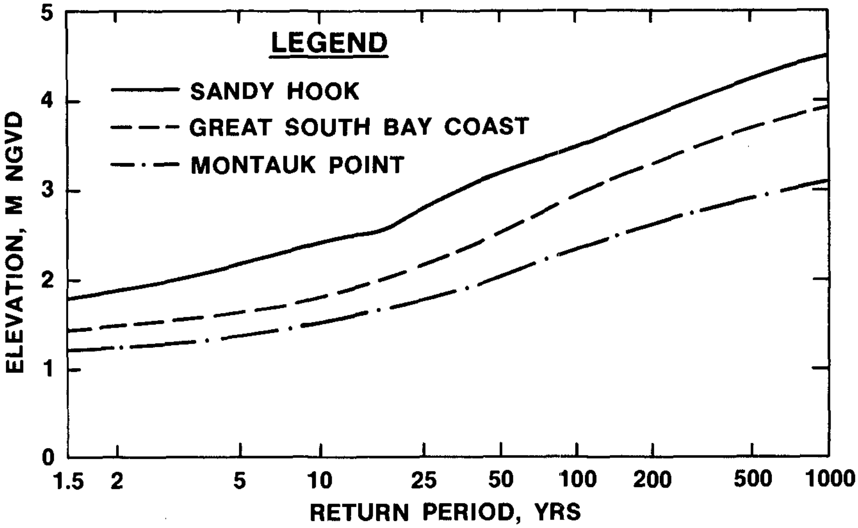


Figure 4. Computed JPM curves for three locations along coastal reach of southern Long Island

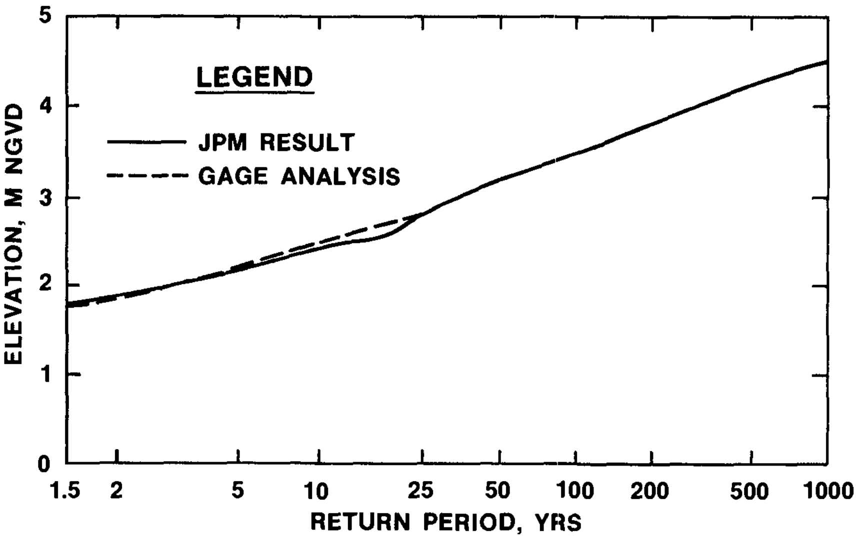


Figure 5. Comparison of computed JPM curve and gage analysis at Sandy Hook, New Jersey

parameter distributions. The procedure consists of assuming the unknown storm population distribution for each hurricane parameter is the same as the parameter distribution obtained from historical information. Synthetic parameter distributions are created by repeated sampling from this assumed population. The variation in the synthtic parameter distributions is due to the small sample sizes. Synthetic stage-frequency curves are then generated by randomly selecting a synthetic distribution for each parameter. About 1000 such curves gave very stable results (little change in final result with increased number of bootstrapped samples) and provided an estimate of error in the selection process. When the process is examined for each return period, an estimate of the uncertainty (due to limited size of sample population) of a stage-frequency curve is obtained (Figure 6).

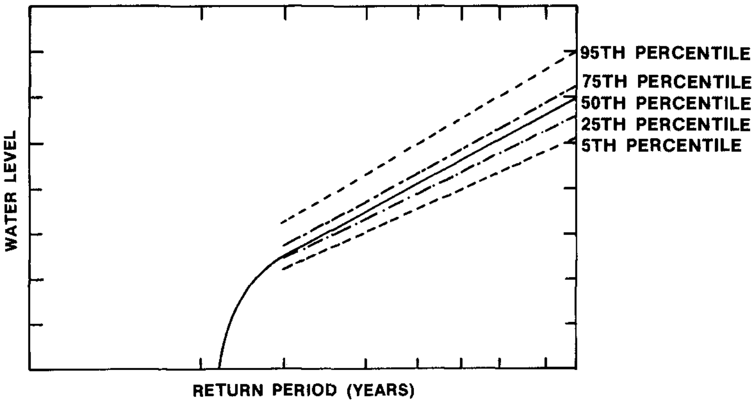


Figure 6. Bootstrapped stage-frequency confidence intervals

INLAND STAGE FREQUENCIES

For nearshore grid simulations, it was necessary to represent the statistics of the thousands of possible global surge-tide events with a much smaller ensemble of events for nearshore simulation. A random sampling of roughly 6000 hurricane-plus-tide events was further reduced to three sets of 17 storm-tide events, with each set chosen to represent a range of storms from moderate to very severe. Weaker events were not emphasized due to the dominance of northeasters for return periods below 50 years. Tests showed that 40 northeaster-plus-tide simulations could reliably represent the full set of extratropical events. Statistical justification in the selection process involves the concept of reduction in dimensionality. Probabilities of each nearshore event were assigned according to what portion of the nearest open-coast stage-frequency curve each event represented. Stage frequencies were developed from results of these simulations. This procedure replaced the typical approach of routing all the open-coast surge events into the back-bay areas. It provided a clean statistical method to account for the nonlinear effects involved in routing flood waters through inlets and over the barrier islands.

As for the historical storm simulations, the contribution to flood water potential from wave effects was taken into account. Wave set-up estimates were made by applying standard practices in the SPM (SPM, 1984). A procedure was developed which would process previously generated storm simulation output and compute additional bay elevations on a storm-by-storm basis. The accuracy of these results suffers because of the simplifying assumptions made as well as a lack of information available as to the physical processes involved. The results give a good indication of the size of the influence wave setup has on the back-bay stage frequencies. At the 100-year return period, maximum additional water elevation in back-bay areas from influence of wave effects is on the order of 1 m.

CONFIDENCE INTERVALS

Confidence limits on the upper portion of nearshore stage-frequency curves were estimated by observing variability in stage frequencies generated by each of three nearshore sets of 17 hurricane-plus-tide events. The stage frequency curves from these sets were regressed and compared with each other. Assuming for any given return period the calculated stage is a normally distributed random variable, an estimate of the probable error can be calculated using the three stage-frequency curves generated independently from the three sets of selected events. The accepted stage-frequency curve with error bands is formed by processing all 51 events as one set. Figure 7 shows an example of the results obtained for a typical open-coast gage location. Results were presented for specified regions rather than for specific model gage locations. Thus a given stage-frequency curve is applicable, within a specified tolerance level, for a region defined by two endpoints. Regional averages were determined by a weighted average of nearby model gage results. Figure 8 presents an example regional stage-frequency curve for the far eastern region (one of 16 regions) showing the minimum and maximum stages of the data used to develop the curve.

PROJECT ALTERNATIVES

Various project dune heights and other structural alternatives were examined for impact on stage-frequency within the inland bays. Among these were included the 1979 dune configuration, non-overtopping dunes (conservatively built), variable height dune systems design to offer 25-, 50-, 100-, 200-, and 500-year protection, leeved back-bay areas, and inlet and channel surge barriers. Stage-frequency curves for the 1979 dune congiguration were used as a baseline for comparing alternative plan impacts. The non-overtopping dune alternative provided information on the highest level of protection to be obtained in the back bays. A basic result from examining all plan tests is that back-bay flood levels are more effectively minimized by increasing heights of the barrier dune system. Interior channel gates tend to increase flood levels in areas local to the gate. Inlet barriers will reduce surge levels within the gated bay, but unless dune heights are raised inlet gates will not give much protection against severe events. Inlet gates

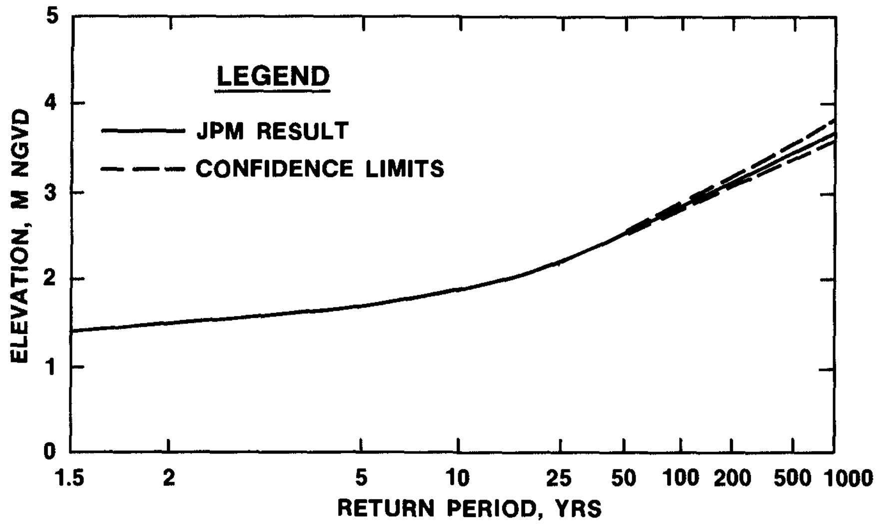


Figure 7. Confidence intervals for the hurricane selection process for a typical open-coast model result

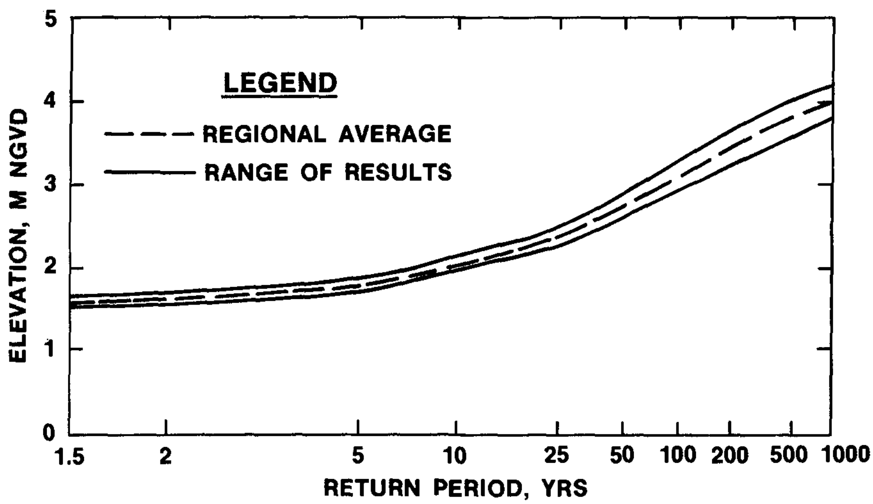


Figure 8. Regional JPM result for southeastern Long Island

do protect against the lower energy events because flood waters are primarily transmitted through the inlets during these events. A plan to levee back-bay areas did not significantly increase bay flood levels.

Variable height dunes were examined by simulating the effect of barrier islands whose protective dune heights are designed according to elevations corresponding to the above mentioned return periods. The design heights include the effect of wave setup. To minimize computational effort, two sets of 17 hurricanes and one set of 13 northeasters (representative storms) were simulated for each of the five alternative barrier conditions. After processing the 25- and 50-year barrier simulations, the number of storms simulated was decreased because the northeaster and several moderate hurricane events have no effect on the higher return period plans. All results were presented in a regional format as exemplified in Figure 8.

SUMMARY AND CONCLUSIONS

A comprehensive investigation of storm-induced flood levels on the southern coast of Long Island, New York was successively completed. Efficient global and nearshore storm surge models were developed to simulate selected storm events. A dune breach model was used to more realistically simulate severe storm events. The most significant development in the progress of the study was the procedure to minimize the computational effort to predict nearshore and inland bay stage frequencies. This procedure permitted economical testing of various alternatives including variable-height dune systems and gated interior channels and inlets. The procedure also permits an estimation of confidence limits in the results. The methods used in this investigation require additonal research, particularly in delineating all sources of error in the estimation of confidence bands. Substantial research is required to accurately simulate contribution of wave setup, wave transmission, and inland bay wave effects. The results from this study also point to the importance of accurately modeling dune erosion and breaching.

ACKNOWLEDGMENTS

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REFERENCES

Brooks, R.M., and Corson, W.D., "Summary of Archived Atlantic Coast Wave Information Study Pressure, Wind, Wave, and Water Level Data," Technical Report WIS Report 13, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS, 1984.

Butler, H.L., "Coastal Flood Simulation in Stretched Coordinates," 16th International Conference on Coastal Engineering, ASCE, Hamburg, Germany, 27 Aug-1 Sep 1978.

Butler, H.L., "Evolution of a Numerical Model for Simulating Long-Period Wave Behavior in Ocean-Estuarine Systems," Estuarine and Wetland Processes with Emphasis on Modeling, Marine Science Series, Vol. 11, Plenum Press, New York, NY, 1980.

Butler, H.L., "Lake Pontchartrain and Vicinity Hurricane Protection Plan, Report 3, Numerical Model Investigation of Plan lmpact on the Tidal Prism of Lake Pontchartrain," Technical Report HL-82-2, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS, 1983.

Camp Dresser and McKee, "New York City Flood lnsurance Study," Reports 1-8, Annandale, VA, 1983.

Myers, V. A., "Joint Probability Method of Tide Frequency Analysis Applied to Atlantic City and Long Beach lsland, N.J.," ESSA Technical Memorandum WBTM HYDRO 11, U.S. Department of Commerce, Environmental Science Services Administration, Weather Bureau, Silver Springs, MD, 1970.

National Academy of Sciences, "Methodology for Calculating Wave Action Effects Associated with Storm Surges," National Research Council, NAS, Washington, DC, 1977.

National Weather Service, "Meteorological Criteria for Standard Project Hurricane and Probable Maximum Hurricane Windfields, Culf and East Coasts of the United States," NOAA Technical Report NWS 23, U.S. Dept. of Commerce, Washington, DC, 1979.

Prater, M.D., Hardy, T.A., and Butler, H.L., "Fire Island to Montauk Point, New York, Storm Surge Model Study," Technical Report in publication, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, MS, 1987.

Prater, M.D., Hardy, T.A., Butler, H.L., and Borgman, L.E., "Estimating Error of Coastal Stage Frequency Curves," 19th lnternational Conference on Coastal Engineering, ASCE, Houston, TX, 3-7 September 1984.

Shore Protection Manual, 4th ed., 2 Vols., U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, CE, U.S. Covernment Printing Office, Washington, DC, 1984.