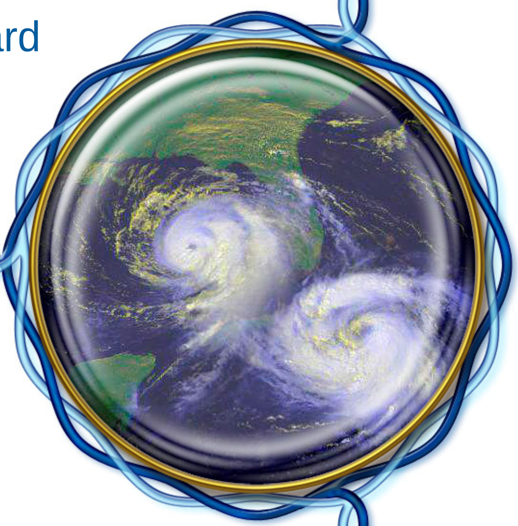
Storm Meteorology

FEMA Coastal Flood Hazard Analysis and Mapping Guidelines Focused Study Report

February 2005



Focused Study Leader

David Divoky

Team Members

Robert Battalio, P.E.
Bob Dean, Sc.D.
Ian Collins, Ph.D.
Darryl Hatheway, CFM
Norm Scheffner, Ph.D.

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Acronyms

1-D	one-dimensional
2-D	two-dimensional
ACES	he significant wave; the significant wave can be determined using the Shore Protection Manual or Automated Coastal Engineering System
DEP	State of Florida, Department of Environmental Protection
EST	Empirical Simulation Technique
FEMA	Federal Emergency Management Agency
FIS	Flood Insurance Study
FNWC	Fleet Numerical Weather Central
HRS	Hydraulic Research Station
HURDAT	digital file of storm data for all identified tropical storms in the North Atlantic
JPM	Joint Probability Method
MSL	Mean Seal Level
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Survey
PDF	probability distribution function
PWA	Philip Williams and Associates
RT	Return Time
WIS	Wave Information Studies
WL	water level

1 INTRODUCTION

1.1 CATEGORY AND TOPICS

This Focused Study describes a proposed approach for the development of new FEMA Guidelines for two topics:

- The first is the determination of storm meteorology (storm statistics) used in coastal storm surge flood studies.
- The second is the formulation of guidance for estimation of the 100-year flood when two or more flood-forcing mechanisms are important.

The particular topics addressed in this report were identified during Workshop 1 of the project and are described below.

Storm Meteorology Topics and Priorities					
Topic Number	Topic	Topic Description	Priority		
			Atlantic / Gulf Coast	Pacific Coast	Non-Open Coast
50	Modeling Procedures	Review and recommend storm surge statistical procedures (JPM, EST, Monte Carlo), and identify data sets for hurricanes, nor'easters, and Pacific storms	I	I	--
51	Combined Probability, Determinations of 1% Flood Elevations	Develop guidance on combined probability considerations for all processes; define procedure to determine the 100-year flood event	C	C	C
Key: C = critical; A = available; I = important; H = helpful					

Topic 50 is construed to be an effort to develop guidance regarding the statistical aspects of storm surge modeling, outlining procedures and data sources that are needed to implement procedures such as the Empirical Simulation Technique, Monte Carlo methods, and the Joint Probability Method. These methods are used to attach rates of occurrence to particular storms used in the hydrodynamic simulations, and to derive rates of occurrence of the resulting flood levels. The Joint Probability Method (JPM) has been used generally in past FEMA coastal surge studies, whereas the newer Empirical Simulation Technique (EST) has recently been approved by FEMA and is now coming into use.

Topic 51 is a more general task, extending to all mechanisms of coastal flooding, not just surge, but including, for example, astronomic tide, storm waves, and tsunamis, as well as the combined probability of coastal and riverine elevations in tidal waters. The goal is, given two or more such mechanisms affecting a site, to determine what the 1-percent-annual flood elevation is, as a function of the statistics of the several contributing mechanisms.

1.2. STORM METEOROLOGY FOCUSED STUDY GROUP

The Storm Meteorology Focused Study Group was made up of Robert Battalio, Ian Collins, Robert Dean, Darryl Hatheway, Norm Scheffner, and David Divoky, who served as Team Leader.

2 CRITICAL TOPICS

2.1 TOPIC 51: COMBINED PROBABILITY (FOR ALL GEOGRAPHIC REGIONS)

2.1.1 Description of the Topic and Suggested Improvement

The problem addressed in this topic is the determination of the total 1% flood elevation at a particular site that may be affected by multiple flood elevation processes or by processes with multiple components. High water levels accompanied by flooding may be the result of extreme astronomical tide; storm-induced tide; tsunamis; wave setup, runup, and overtopping; or riverine rainfall runoff (in estuaries). These may be affected by seasonal effects (El Niño conditions) and additional long-term factors such as changes in relative sea level (for example).

The goal is to provide guidance for determining the 1% flood event in such cases. Clearly, the total level reached during an extreme flood may be the result of a combination of many influences, each having its own associated probability or rate of occurrence. (Note: Strictly speaking, what we will loosely call “probability” is actually rate of occurrence measured in units of events per year; the 1% flood is the level occurring at an average rate of 0.01 times per year. This distinction between mathematical probability and temporal rate is occasionally quite important.)

The contributing events may be statistically independent or may be correlated in some manner. Furthermore, two (or more) events that do not occur together must still be statistically combined because the total rate of occurrence of a given flood height is influenced by both. Methods to handle the several possible combinations need to be summarized and guidelines developed.

2.1.2 Description of Procedures in the Existing Guidelines

Joint Probability Method

This Combined Probability topic does not address the combination of two or more processes, but is concerned with the total rate of occurrence of a storm defined by multiple parameters with individual probabilities. The Atlantic and Gulf Coast Guidelines suggest using the approach that was originally developed by the National Oceanic and Atmospheric Administration (NOAA), in which the governing hurricane parameters (i.e., central pressure index, radius to maximum winds, forward speed, and direction of travel) are examined for statistical independence and then the probabilities multiplied to derive the probability of occurrence of a particular storm. The required hurricane data are taken from *Hurricane Climatology for the Atlantic and Gulf Coasts of the United States* (National Weather Service, 1987). This item is discussed below, under Topic 50.

Tide and Surge

The Study Contractor is required to "Describe the method by which the tidal elevation data are convoluted with the surge data including tidal constants and tidal records." Refer to Benjamin and Cornell (1970) for the definition and use of "convolution integrals" in probability and statistics.

Storm Waves and Surge

The Study Contractor must use the "controlling" wave, defined in Appendix D, in Section D.2.2.6, as 1.6 times the significant wave; the significant wave can be determined using the Shore Protection Manual or Automated Coastal Engineering System (ACES). The waves are assumed to be coincident with the peak surge. There is little other specific (explicit) guidance for this topic in the current FEMA coastal guidelines. In many places, the guidelines refer to the need to choose a factor (deepwater wave height, for example) that somehow corresponds to another process with which it is to be combined (the 1% stillwater level, for example). It is generally not clear from the guidelines how this is to be done, and the matter is left to the judgment of the Study Contractor, along with the injunction that the assumptions be documented. Section D.2.2.6 of the Guidelines, for example, refers to "the meteorology of storms expected to provide approximate realizations of the 1-percent-annual-chance flood" and suggests that such storms would be useful in "assessing wave characteristics likely associated with" that flood. Subsequently, it is suggested that "the 1-percent-annual-chance flood is likely associated with central pressure deficits having exceedance probabilities between 5 and 10 percent," with the implication being that wave height and period estimated from hurricane formulas using pressures in this range would be appropriate (radius to maximum winds and forward speed are not mentioned, although median values might be assumed).

Similarly, there is no guidance regarding the combined probability of separate processes, such as storm surge and rainfall runoff in a tidal river.

Pacific Coast

There are no guidelines for the Pacific Coast.

2.1.3 Application of Existing Guidelines to Topic—History and/or Implications for the NFIP

Joint Probability for Hurricane Parameters

For hurricane flood studies on the East and Gulf Coasts, the original use of the JPM was proposed and developed by NOAA. The approach involves an assumption of independence of storm parameters so that the combined probability of a particular hurricane is the product of the probabilities of each of the governing parameters (i.e., forward speed, storm radius, central pressure depression, and storm position; a dependence on track angle is assumed and accounted for by separation of the storms into directional families). In the early studies by Tetra Tech, this assumption of statistical independence was investigated quite thoroughly by examining cross correlations and factor analysis for a multivariate sample. This aspect of combined probability is considered below as part of Topic 50.

Superposition of Surge and Waves

For applications that require determination of a wave estimate for superposition (through setup, runup, and overtopping) on a 1% stillwater surge level, two approaches have commonly been used. One approach has been to estimate a 1% deepwater wave condition from WIS data or other similar wave data. The second common approach has been to adopt a design-like storm, such as a storm with the 5–10% pressure deficit, and use this for computations based on hurricane wave formulas.

For the combination of overland wave propagation and surge (WHAFIS), the greatly simplifying assumption is made that depth-limited breaking waves occur at the shoreline during 100-year surge conditions (with an appropriate period), so that there is no need to attach a return period to wave height. The initial wave represents waves of all heights above the minimum necessary to produce breaking conditions.

Combination of Surge and Riverine Flood Profiles

In past studies, the combined probability of riverine runoff and coastal surge in tidal areas has been treated inconsistently by Study Contractors, including federal agencies. The correct treatment, if independence of the runoff and surge episodes at the mouth of a tidal river is assumed, is to simply add the rates of occurrence of specified flood elevations from each source, at several locations along the affected river reach. There is a great deal of inconsistency among existing studies in this common instance of combined probability, with many studies simply mapping the greater of the two levels (so that the level at the intersection of the two 100-year profiles would actually correspond to the 50-year level). As discussed below, however, the case of non-independence should also be considered. This issue is also discussed in Topic 19 of the Hazard Zone Mapping Focused Study.

Superposition of Tides and Tsunamis

The combination of tides and tsunamis is not specifically addressed in the Guidelines but has been considered in past FEMA studies, and so is included in this section. In the case where the total water level is the sum of two independent processes that combine in a linear manner, the probability of the expected sum is found by convolution. That is, if the probability density of the tide level is denoted by $p_a(Z)$ and the probability density of the tsunami water level is $p_t(Z)$, then the probability density of the sum of the two is given by:

$$p(Z) = \int_{-\infty}^{\infty} p_a(T)\, p_t(Z-T)\, dT \qquad (1)$$

The process is easily extended to the sum of three or more independent variables that add together. In the early Tetra Tech report (1982), the convolution theory was expanded to include cases where one component had a shorter duration than the other. In other words, it would include cases where, for example, the peak storm tide or tsunami could occur at tide levels other than the maximum.

In the limit it is known that, for a process that has a Gaussian probability density function and is narrow banded in frequencies, the envelope will have a Rayleigh distribution. The Tetra Tech report (1982) showed that, if the storm tide or tsunami lasts for the duration of a half tide cycle (i.e., including a high tide event), the resulting level would be the sum of the two and would tend to a Rayleigh probability distribution. In practice, this may be questionable because, at the extremes, the tidal water levels have an asymptotic limit, whereas the Gaussian and Rayleigh functions are unbounded.

As an example, the “modified Rayleigh” distribution can be written in the form:

$$P = \exp\left(-\left(\frac{H - H_O}{H_C - H_O}\right)^{\gamma}\right) \qquad (2)$$

where H is the measured height, H_O is the minimum that is reported, H_C is a scaling factor, and γ is 2.0. (Often, the denominator is replaced with a single “scaling factor” and is referred to as the three-parameter Weibull distribution function.) Figure 1 shows an example from the predicted tides at San Diego. The 1-percent-annual-event would have a probability level of about 1/70,600 or $1.4\text{x}10^{-5}$ (assuming 706 high tides per year). The Rayleigh distribution function clearly overestimates the maximum tide elevation at this probability level. An alternative fit is shown that has $\gamma = 5.5$ and the values of H_O and H_C have been adjusted.

Other Approximations

In the early FEMA studies for the Southern Atlantic and Gulf coasts, the combined probability of storm surge and tide was approximated assuming that half of the peak water levels of the storm surge occurred at high tide and half at low tide. This approximation yielded a shift of about half the maximum tide level. With the typical tidal ranges in the Southern Atlantic and Gulf coasts, this approximation yields distributions that are close to those arrived at by the more exact methods.

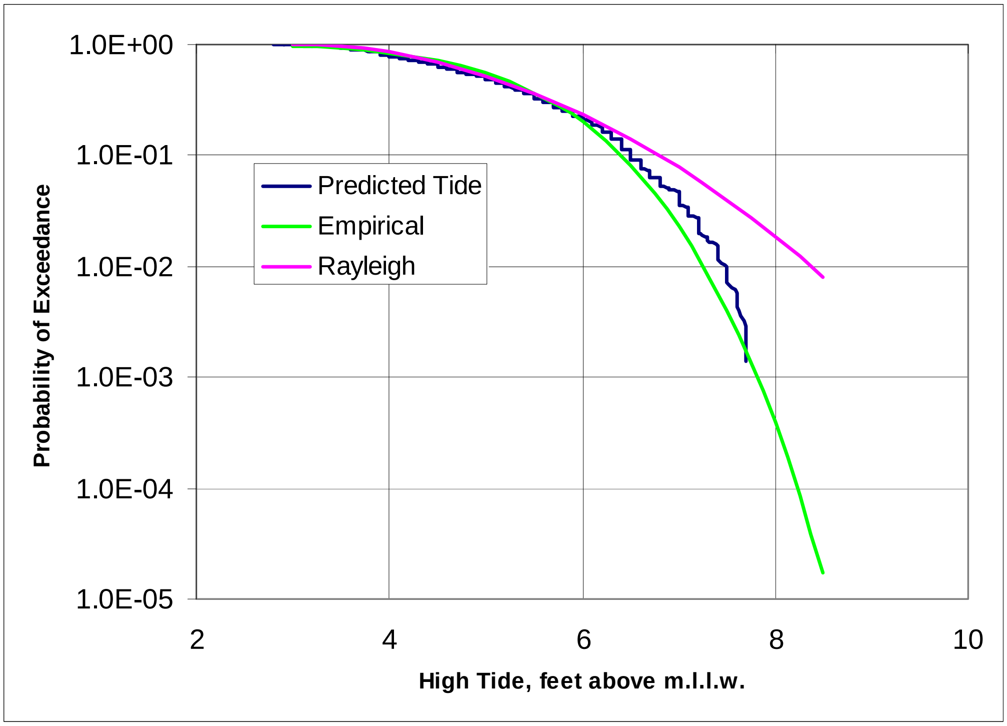


Figure 1. Probability distribution of high tide elevation at San Diego Bay.

In a recent study by Philip Williams and Associates (PWA, 2002), the potential for combined tides and waves was estimated by taking:

- the 1% water elevation with an average wave height,
- a 1% wave height with an average high tide (averaged from a set of water levels occurring at the time of high wind waves), and
- a third approximation as an intermediate case, calculated based on marginal joint probability.

The results (wave runup and overtopping) calculated for these three approximations were compared and the worst one was selected. This approach, discussed in more detail below, is very similar to what is recommended in this Focused Study, based on an extensive research effort by the Hydraulic Research Station at Wallingford, U.K.

2.1.4 Alternatives for Improvement

There are five major types of combinations of extreme water levels that result from the simultaneous occurrence of more than one event:

1. Two independent, simultaneous contributors that can be added in a linear manner (or nearly so)—In this case, the convolution process applies; the method can be extended to multiple independent contributors that contribute to the sum.

2. Two independent contributors that have major differences in their durations—In such cases, the modified convolution process developed by Tetra Tech may be appropriate, with the proviso that the integration limits must be confined to realistic bounds.

3. Two independently occurring contributors that interact with each other in a non-linear fashion—An example is wind setup in shallow water areas with large tidal ranges because, among other factors, the water response to wind stress is inversely proportional to the total water depth.

4. Two correlated or partially correlated processes—If the processes are completely correlated, these reduce to single events; if they are partially correlated, there are no simplified methods.

5. Three or more processes that are partially correlated—For example, tide level, wave height, wave period, and wave direction; wave overtopping is an example of a combination of processes of this type.

Astronomic tide occurs daily and everywhere, around the world. Therefore, methods must be developed to account for tidal effects in combination with everything else including storm surge, tsunamis, and all manner of wave effects, including wave crest elevation, runup, setup, and overtopping. In addition, the statistical combination of surge and riverine flooding must be accounted for.

Sample Combination Methods

The guideline methods to be developed must consider each significant combination of two or more factors chosen together. For illustration, consider two such combinations: surge plus tide and waves plus high water.

Surge Plus Tide

As mentioned earlier, one approximate method of combining surge plus tide that has been used in past studies. The method is based on the assumptions that it is equally likely for peak surge to occur at either high or low tide, and that the duration of the peak does not last long. For example, let S be a particular surge elevation computed from mid-tide, and let A be the tide amplitude around its mid-level. Then one simply reallocates the estimated rate (frequency) of occurrence of surge elevation S, assigning half of the total rate to elevation S+A and half to elevation S-A.

This reallocation of the probability-mass of the surge S (computed at mid-tide) to both higher and lower levels has the net effect of shifting the frequency curve slightly toward higher elevations. A more accurate statistical determination in the same spirit can be made using the convolution method. These statistical procedures, however, are not appropriate when the surge and tide interact physically, thus affecting each other's behavior.

An improvement over the linear approximation of surge plus tide assumes that the surge can occur at high tide, mid-tide ebb, low tide, and mid-tide flood. For high tide, the surge is simulated with tide; for the other three phases, it is assumed that the surge without tide can be added to the tide linearly. This approach helps identify maximum-interaction nonlinear effects. The assumption here is that combined-effect interactions are at their maximum level at high tide and are less important at mid-tide and low tide. This surge plus tide simulation procedure is generally used only for severe events for which the surge is significantly greater than high tide.

To account more fully for the interactions, more detailed hydrodynamic calculations are necessary. Two approaches will be described: the method adopted in FEMA's two-dimensional (2-D) storm surge model, and the approach used by the State of Florida Department of Environmental Protection (DEP).

FEMA Method

In the FEMA (1988) methodology, a large number of storms are simulated using the numerical surge model, and the computed water levels around the study area are recorded. These calculations are made with respect to the mean water level and do not account for tide. The large number of simulations is determined by taking all possible combinations of five parameters defining a storm: pressure depression, radius to maximum winds, storm forward speed, track angle, and track position. Tide could be included among these parameters and appropriately incorporated in the simulations through the boundary conditions. For example, both tide amplitude and tide phase could be taken as additional parameters, increasing the parameter set from five to seven types. If just a small number of values were chosen for each new tide parameter, say three values of amplitude and six values of phase, then the simulation costs would increase by a factor of 18. This was not an acceptable alternative when the surge methodology was developed, owing to the extremely high cost of computer time, although it might be considered acceptable today.

Instead, the FEMA methodology adopted a method by which simulations made around mean sea level (MSL), with no tide, are adjusted to approximate the levels that would be achieved with various tides. The first step is to perform a detailed simulation of a small set of storms, covering a range of peak surge elevations, with tide hydrodynamically added on the grid boundary; it is assumed that, in the offshore region, the tide will add linearly to the surge. For each storm, approximately 20–30 tide combinations are simulated, for a range of tide amplitudes and phases. These *combined* surge and tide simulations account for the interactions and provide the basis for the subsequent adjustment of the no-tide calculations.

The second step is to simulate each tide without surge, and then to linearly add the separately computed tide onto the tideless surge hydrographs computed for the small storm set. These *added* hydrographs will differ from the cases simulated with surge and tide *combined*. A simple regression expression is derived at each grid point, expressing the combined peaks as functions of the added peaks. Finally, these corrective expressions are applied to the very large data set computed without tide, to estimate what the surge would have been in each case for all of the selected tide conditions. Although this is a laborious procedure involving use of several intermediate utility programs, it is practical and far less costly than full 2-D simulations including tide.

Florida DEP method

The Florida DEP (see, for example, Dean et al., 1992) uses a different technique that is very simple in concept but relies partly on the use of a one-dimensional (1-D) surge model instead of a 2-D model. The DEP procedure, which is described in more detail under Topics 54 and 55 of the Stillwater Focused Study Report, begins with simulations of selected storms using a detailed 2-D model over the entire study area. This is followed by simulations of the same storms over several transects using a simpler 1-D model (Freeman et al., 1957). Of course, the 1-D model does not reproduce the 2-D results exactly, but—as with the FEMA approach relating added and combined tides described above—it is possible to perform both 2-D and 1-D simulations of a small set of storms and, from these, derive regression expressions relating the 2-D results and the 1-D results at all points along the transects. These expressions can then be used to adjust all subsequent 1-D calculations, thereby approximating 2-D calculations.

Using the very efficient 1-D model, the DEP procedure is to simulate a large number of storms with tide boundary conditions imposed at the seaward limits of the transects. The tide condition chosen is an actual tide history selected at random from the hurricane season. For example, if a storm is to be simulated for a total of three days, the procedure is to pick a starting time at random from within the hurricane season and use the following three days of tide predictions as the water elevation at the seaward boundary of the transect.

This procedure is repeated many hundreds or thousands of times, each time selecting a new storm (by Monte Carlo selection from the storm parameter cumulative distribution functions) and a new tide history segment for the 1-D boundary condition. In this way, the full range of possible tide conditions is automatically accounted for in a realistic, natural way because the physical interaction between surge and tide is implicit in the calculations.

Waves plus High Water

A second major problem is the choice of waves to be associated with high water. The combination of waves and surge has been mentioned above with respect to overland propagation, for which the assumption of limit-height breaking at the shore eliminated all difficulty. However, in general the user is faced with the difficult problem of selecting a combination of wave and high water that will reasonably represent the1% total event. Three approaches are mentioned here.

1) Southern California Flood Insurance Study

The first approach, used by Tetra Tech in its 1982 flood insurance work for Southern California (Tetra Tech, 1982), was simply to consider all significant storms or wave and high water sources, and to follow their effects from source to shore, computing shoreline processes such as setup and runup. A limited number of extreme deepwater conditions were used.

The stillwater processes that were considered included astronomic tide and surge from local tropical cyclones. The wave sources included intense winter storms in the north Pacific; local storms; and tropical cyclones, both local and remote (off Baja California). Extratropical wave data were taken from Fleet Numerical Weather Central (FNWC) data for the period 1946–1974, summarized at three points off Southern California. These three points defined two connected offshore line segments along which wave heights, directions, and periods were specified by interpolation.

Wave rays were initiated along these lines, at very fine spacing, and were carried toward shore using a refraction algorithm developed specifically for the project to permit efficient handling of such large data sets. Wave setup and runup were determined for these waves, once they reached the coast, using practical engineering methods. The treatment of tropical cyclone wave generation and propagation was similarly straightforward. Locally generated storm surge was investigated by a numerical simulation of the 1939 storm, which was unusual for reaching as far as the Los Angeles area. It was found that the wind-driven component of high water from this storm was small compared to the inverse barometer contribution; consequently, the total surge component was simply approximated by the barometric component for each storm considered in the study.

Once the results from each factor, assumed to be independent, were determined, combinations with tide were determined by convolution calculations, and an extremal analysis was performed based on fitting multiple versions of the Gumbel and Weibull distributions. Correlations (joint probability) between high water levels and large swells (as related by El Niño conditions, for example) were not investigated.

2) Sandy Point Study

A second example is the more recent Sandy Point study referenced above (PWA, 2002). This study considered the joint probability of estuarine high stillwater levels and local wind waves. Stillwater levels were analyzed using tide gage data collected nearby, applying extreme-value analysis on the highest recorded tides and the largest residuals (residual equals the measured water level minus the predicted astronomic tide for the same time). The probability of high wind speed was used as a surrogate for the high seas generated by local winds (because the site was in sheltered waters, swell was not considered, but the approach is also applicable to swell). An attempt was made to define joint probability directly using a coincident time series of winds and water level data covering a period of 29 years. However, it was found that this period was not sufficiently long to define the low-probability events of interest. No attempt was made to fit the data to a bivariate extreme-value distribution and then estimate low-probability conditions by extrapolation, although this may be a viable alternative approach (see general discussion below). Consequently, an Averaging Method and a Marginal Probability Method were used to estimate the flood events, as described below. Three estimates of the 100-year probability event were made (Table 1), each of which consisted of a high stillwater level and high wind speed.

These events are shown graphically in Figure 2. The selected events are reasonably close to "rule of thumb" guidance used in other studies, as depicted in the figure (labeled "Standard Practice" in the legend).

Table 1. Wind Speeds and Total Stillwater Level Conditions with Return Periods

Event	Label	Wind Speed			Stillwater Level	
		km/h, 2-min avg	mph, 1-sec avg	RT (year)	ft NGVD	RT (year)
100-year WL, average simultaneous wind	A	69	57	6	8.14	100
Intermediate case (marginal probability)	B	110	90	37	6.75	2
100-year wind, average simultaneous WL	C	139	114	100	5.87	< 1

NGVD = National Geodetic Vertical Datum, RT = return time, WL = water level

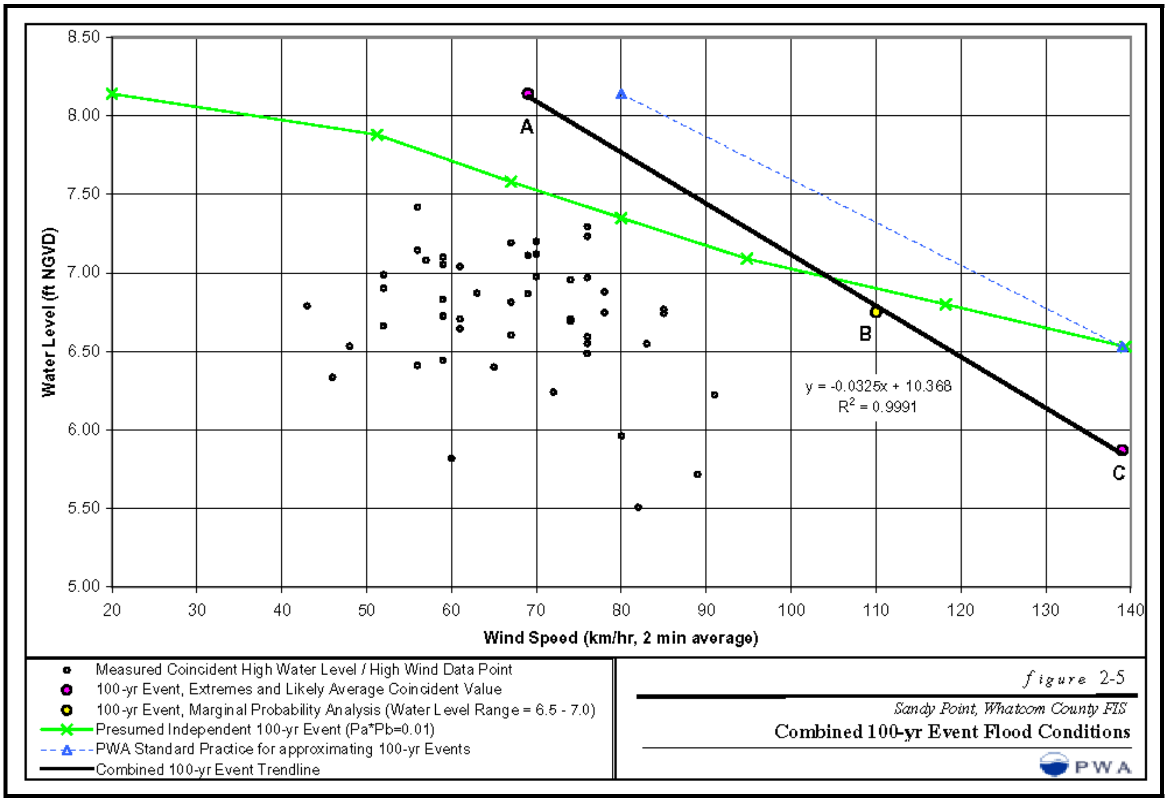


Figure 2. Combined 100-year event flood conditions from the Sandy Point Study.

2a) Averaging Method

The averaging method used standard extreme-value analysis to determine the 100-year event for one parameter. The other parameter was selected based on the average of values observed to occur at the same time as extreme values of the first parameter. Attempts to correlate wind speed with extreme high-water levels indicated no linear correlation with magnitude, but did indicate a narrow range of values from which an average wind speed could be selected as being likely to recur during a 100-year water level. Similarly, an average high-water level residual was selected as being likely to recur during a 100-year wind event. This resulted in two estimates of the 100-year event: a 100-year wind speed and a high water level of less than 1-year return period, and a 100-year water level and a wind speed with a 6-year return period.

2b) Marginal Probability Method

Besides the two estimates resulting from the averaging method, a third estimate used marginal probabilities. This estimate was arrived at by analyzing all wind speeds occurring coincidentally with water levels that fell within a certain range. A water level range from 6.5 to 7.0 ft NGVD was chosen because 13 measurements of extreme coincident wind and water level were within this range, allowing some confidence in the results. The median of this range corresponded to a two-year-return-period tide level (6.8 ft NGVD), based on the residual analysis (see below). An extremal analysis of wind speeds occurring coincidentally with water levels in this range was performed to determine the probability of wind speeds for a two-year-return-period tide. The rules of marginal probability defined the total probability as the quotient of the conditional probability and the probability for the condition to occur. In this case, the probability of the water level being within the 6.5–7.0 ft NGVD range was one time per two years (or P1 = 0.5). Therefore, the 50-year-return-period wind speed, which occurs one time per 50 years (P2 = 0.02), was determined so that the total probability would be equivalent to a 100-year event (P1 * P2 = 0.5 × 0.02 = 0.01). The selected wind speed had a 37-year return period based on the single-parameter return-period analysis conducted on the wind speed.

2c) Residual Water Level Analysis—Event Selection Method

Residuals were calculated by subtracting the predicted astronomic tide from the observed (recorded) water level at the tide gage for the 29-year period of record. Extreme-value analysis was applied to the residuals, allowing the residual values for different return periods to be estimated. An extreme-value analysis was also applied to the high tide data directly, providing an estimate of the high-water levels for different return periods. Subtracting the residuals from the extreme tide values for the same return periods provided an estimate of the astronomic tide likely to occur during the extreme event.

The above method was characterized as the Event Selection Method, which could involve various approaches. The implicit assumption was that the probability of coastal flooding caused by high wave runup or surge and overland wave propagation would be the same as the joint probability of occurrence of the environmental forcing parameters, namely water levels, winds, and waves. Comparison with observations of flooding during the Sandy Point study indicated that this approach may have underestimated the probability of flooding and that other approaches estimating the extreme value of the flood event directly, such as runup and overtopping, might have provided better estimates.

3) Wallingford JOIN-SEA Method

A series of directly pertinent reports have been prepared by the Hydraulic Research Station (HRS) at Wallingford, U.K., and the University of Lancaster, U.K. In these reports the joint occurrences of astronomical tide, storm tide, and waves were assessed to determine the risks, at different levels, of overtopping of seawalls; the quantity of overtopping; and other potential structural responses.

The method proceeded with the following steps:

1. Preparation of input data, consisting of many independent records (or hindcasts) of wave heights, wave periods, and water levels.
2. Fitting of statistical distributions separately to the wave heights, water levels, and wave steepnesses.

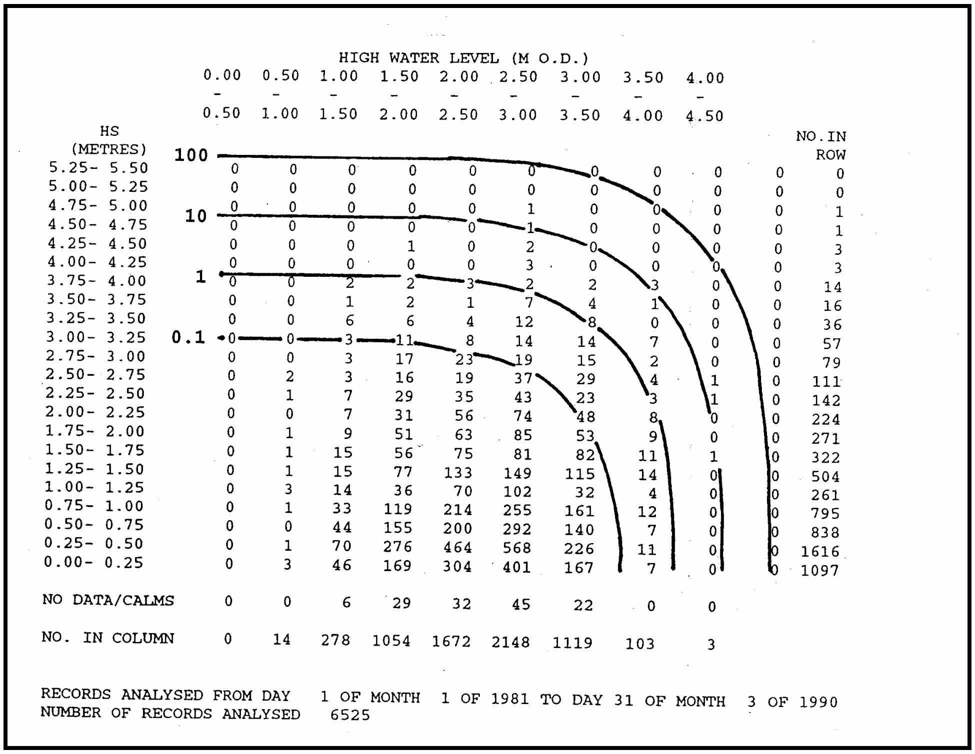
3. Fitting of the dependence between wave heights and water levels, and between wave heights and steepnesses.
4. Statistical simulation of a large sample of data on wave height, wave period, and water level using the fitted distributions and Monte Carlo simulations.
5. Extremal analysis of the range of response variables based on the simulated data.

The methods in the reports were supported by a set of FORTRAN programs that were used to fit the statistical databases and to derive "objective" estimates of the desired extremes. The principal reports included:

1. *Validation of Joint Probability Methods for Large Waves and High Water Levels*, by P. Hawkes and R. Hague, Report SR 347, November 1994.
2. *The Joint Probability of Waves and Water Levels: JOIN-SEA*, H.R. Wallingford Report SR 537, November 1998 with minor amendments, May 2000.
3. *The joint probability of waves and water levels in coastal engineering design*, by P.J. Hawkes, B.P. Gouldby, J.A. Twain, and M. W. Owen, in Journal of Hydraulic Research, Vol. 40, April 2002.

The reports include examples in which the individual contributing processes (wave height, wave period, wave direction, tide, and storm surge anomalies) were both correlated and uncorrelated. The analysis started with wave conditions and water levels on a common time database. Scatter plots of wave heights versus wave periods, wave heights versus storm surge, wave heights versus directions, and so forth, were made to identify the degree of independence of the contributors. If and when these relationships were identified, the appropriate computation method was chosen to make the simulations of long-term records. The reports indicate that a three-year database is sufficient, but this will probably not be the case for any of the U.S. coastal regions. Atlantic and Gulf Coast hurricanes will not be properly represented in a three-year period, and the Pacific Coast, particularly the southern part, will have longer term variability owing to El Niño effects. The 30-year database for waves and swells that is available from Oceanweather (see the Focused Study Report for Storm Wave Characteristics) would provide a more useful source, and long-term tide gauge records from NOS would provide water level data (see discussion of Topics 54 and 55 in the Stillwater Focused Study Report).

Figures 3 and 4 show a sample result for wave height and surge based on recorded data and a summary of the final estimates of extremes. The special cases of "independent" and "dependent" are compared.



HIGH WATER LEVEL (M O.D.)

HS (METRES)	0.00 - 0.50	0.50 - 1.00	1.00 - 1.50	1.50 - 2.00	2.00 - 2.50	2.50 - 3.00	3.00 - 3.50	3.50 - 4.00	4.00 - 4.50		NO. IN ROW
5.25- 5.50	0	0	0	0	0	0	0	0	0	0	0
5.00- 5.25	0	0	0	0	0	0	0	0	0	0	0
4.75- 5.00	0	0	0	0	0	1	0	0	0	0	1
4.50- 4.75	0	0	0	0	0	1	0	0	0	0	1
4.25- 4.50	0	0	0	1	0	2	0	0	0	0	3
4.00- 4.25	0	0	0	0	0	3	0	0	0	0	3
3.75- 4.00	0	0	2	2	3	2	2	3	0	0	14
3.50- 3.75	0	0	1	2	1	7	4	1	0	0	16
3.25- 3.50	0	0	6	6	4	12	8	0	0	0	36
3.00- 3.25	0	0	3	11	8	14	14	7	0	0	57
2.75- 3.00	0	0	3	17	23	19	15	2	0	0	79
2.50- 2.75	0	2	3	16	19	37	29	4	1	0	111
2.25- 2.50	0	1	7	29	35	43	23	3	1	0	142
2.00- 2.25	0	0	7	31	56	74	48	8	0	0	224
1.75- 2.00	0	1	9	51	63	85	53	9	0	0	271
1.50- 1.75	0	1	15	56	75	81	82	11	1	0	322
1.25- 1.50	0	1	15	77	133	149	115	14	0	0	504
1.00- 1.25	0	3	14	36	70	102	32	4	0	0	261
0.75- 1.00	0	1	33	119	214	255	161	12	0	0	795
0.50- 0.75	0	0	44	155	200	292	140	7	0	0	838
0.25- 0.50	0	1	70	276	464	568	226	11	0	0	1616
0.00- 0.25	0	3	46	169	304	401	167	7	0	0	1097
NO DATA/CALMS	0	0	6	29	32	45	22	0	0		
NO. IN COLUMN	0	14	278	1054	1672	2148	1119	103	3		

RECORDS ANALYSED FROM DAY 1 OF MONTH 1 OF 1981 TO DAY 31 OF MONTH 3 OF 1990
NUMBER OF RECORDS ANALYSED 6525

Figure 3. Example of joint occurrences from recorded data (after HRS Report SR-347).

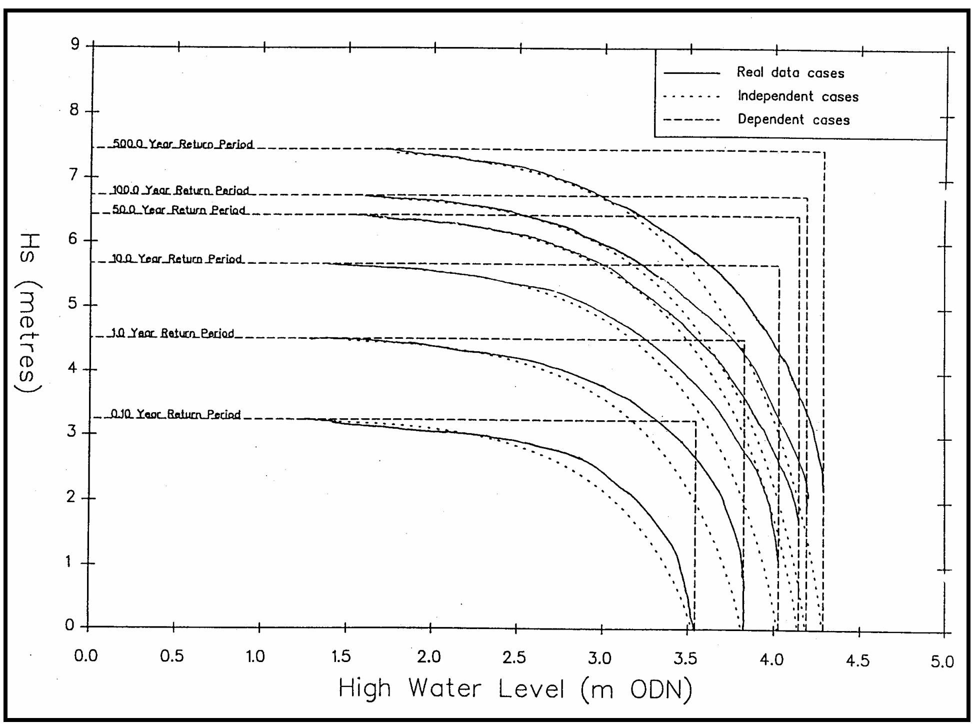


Figure 4. Example of Final Estimated Extremes (after HRS Report SR-347).

It is noted that the "worst" 100-year event may not be the same for all responses, as illustrated in Figure 5. Differing water level and wave height combinations may be the most critical determinants for different responses. For example, the 1% erosion will tend to depend strongly on the duration of high water levels in the event that it occurs for slow-moving storms that cause high water to persist for long periods. Thus, the 1% storm surge levels and the 1% erosion may be caused by different hurricane events. For example, Hurricane Andrew (1992) crossed the east Florida coast rapidly and caused little erosion of the nourished Miami Beach.

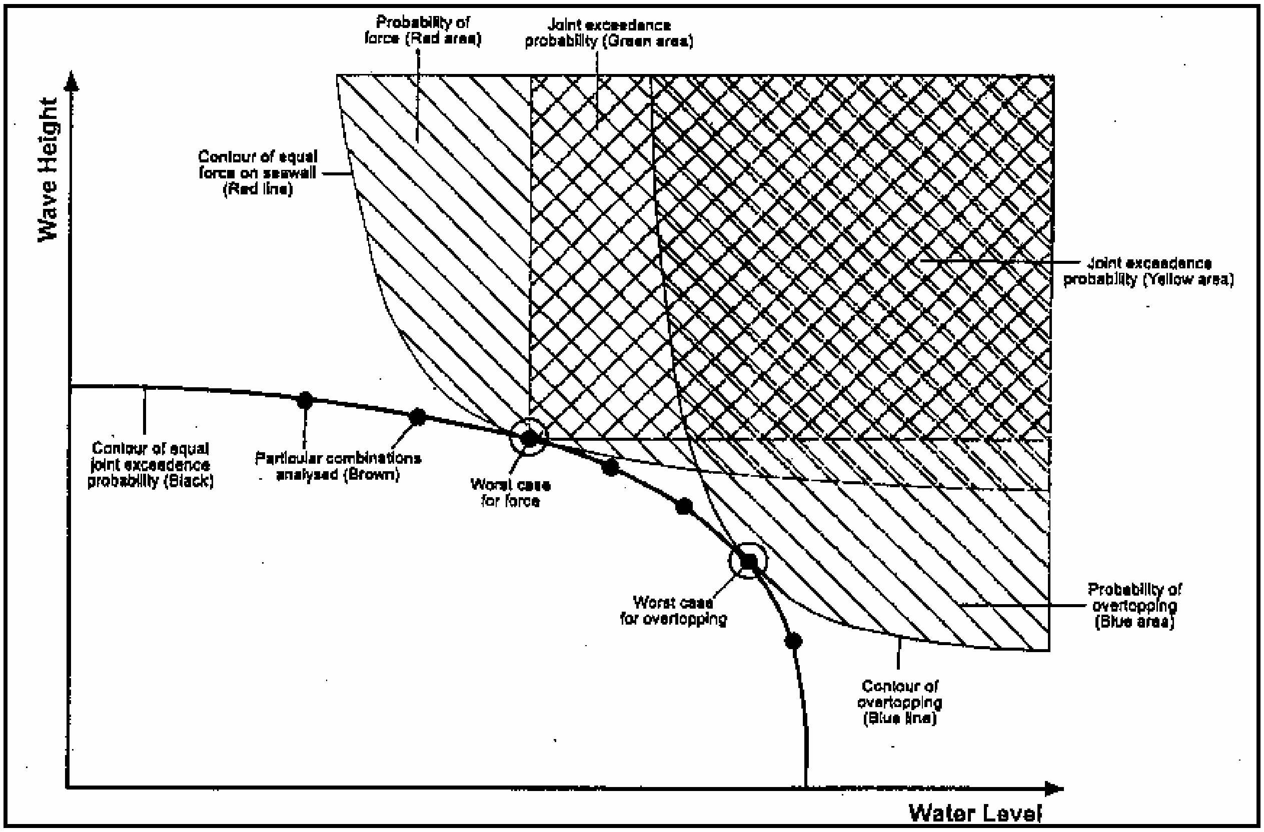


Figure 5. Illustration of differing combinations of waves and water levels governing different design cases.

Figure 5 presents results for a two-parameter process (probability of force on a seawall and probability of overtopping). In principle, the processes could be extended to include separate inputs for waves, swells, river flows in estuaries, wave heights, wave periods, and wave directions. However, presentation of multiple combinations of results for each input would become multidimensional and very complex.

2.2 COMBINATION OF SURGE AND RIVERINE FLOODS

The common case of combined surge and riverine flood near the mouth of a tidal river was considered in the early FEMA methodology but is missing from the latest Guidelines. As noted above, the recommended approach has been to assume a mismatch between the times of surge and runoff peaks, so that the two floods are effectively separate events (even if sometimes correlated by being derived from the same storm). With this assumption, one simply adds the rates of occurrence of a given flood level, Z, to obtain the total rate:

$$R_{TOTAL}(Z) = R_{RIV}(Z) + R_{SURGE}(Z) \quad (3)$$

However, the assumption of independence may not always be appropriate, and the question then is whether practical methods can be found to account for interdependence. There are two major difficulties that must be overcome to accomplish this: First, one would require knowledge of rainfall characteristics of the hurricanes and tropical storms that contribute to the 100-year surge, as well as how those rains are incorporated in the rainfall data upon which the riverine flood profile is based. Second, the riverine (HEC-RAS) modeling would have to be repeated many times to account for physical interactions that would occur over the entire range of possible surge-runoff combinations. One might also look at historical data for simultaneous surge level and stream discharge and, from those data, develop a mean relationship between surge and directly related runoff. To this must still be added the truly separate rainfall events, determined from hurricane-free rainfall data.

This appears to be a daunting task and might require a major investment with little significant return for the flood insurance program. Certainly, it could not be classified as *Critical*, but would instead become *Important*, requiring a much longer period of effort. In other words, the simple addition of rates, while approximate, may remain the most suitable approach. This issue is also discussed under Topic 19 in the Hazard Zone Mapping Focused Study Report.

2.3 EST POST-PROCESSED APPROACH

A related Empirical Simulation Technique (EST) approach, briefly described in the following paragraphs, uses an input database of total surge that results from simulating (generally) all recorded events at a specific location. A full discussion of this approach is found in Scheffner et al. (1999). These surge-only values are combined in a linear manner with a finite combination of tides, computed historic wave distributions, computed historic setups, computed historic runup, and so forth, to generate a database of total surge, that is, surge plus tide, waves, setup, and so forth. The EST uses this input data to generate n repetitions of T years of simulated storm activity that includes those processes; a study might involve, say, n=100 repetitions of a T=200-year sequence of storm activity. From the output database of life-cycle simulations, frequency-of-occurrence relationships are computed. An empirical estimate of the cumulative probability distribution function (PDF) $F_X\left(x_{(r)}\right)$, denoted by $\hat{F}_X\left(x_{(r)}\right)$, and is given by the plotting position formula

$$\hat{F}_X\left(x_{(r)}\right) = \frac{r}{(n+1)} \quad (4)$$

for $\{x_{(r)}, r=1,2,3,\ldots,n\}$. This form of the estimate satisfies Gumbel's requirements, allowing future values of x to be less than the smallest observation $x_{(1)}$ with a cumulative PDF of $1/(n+1)$, and to be larger than the largest value $x_{(n)}$ with cumulative PDF of $n/(n+1)$. In the example approach, the 100-year total surge elevation can be determined for each of the 100 simulations of 200 years of simulated storm activity. Mean value and standard deviation analyses can then be used to determine any return-year elevation estimate with an estimate of error based on (for example) the standard deviation. An example of 100 stage-frequency plots and the computed average determined in this way are shown in Figure 6 (see, for example, Borgman and Scheffner, 1991; Scheffner and Borgman, 1992). In a sense, this method is a numerical simulation substitute for convolution methods.

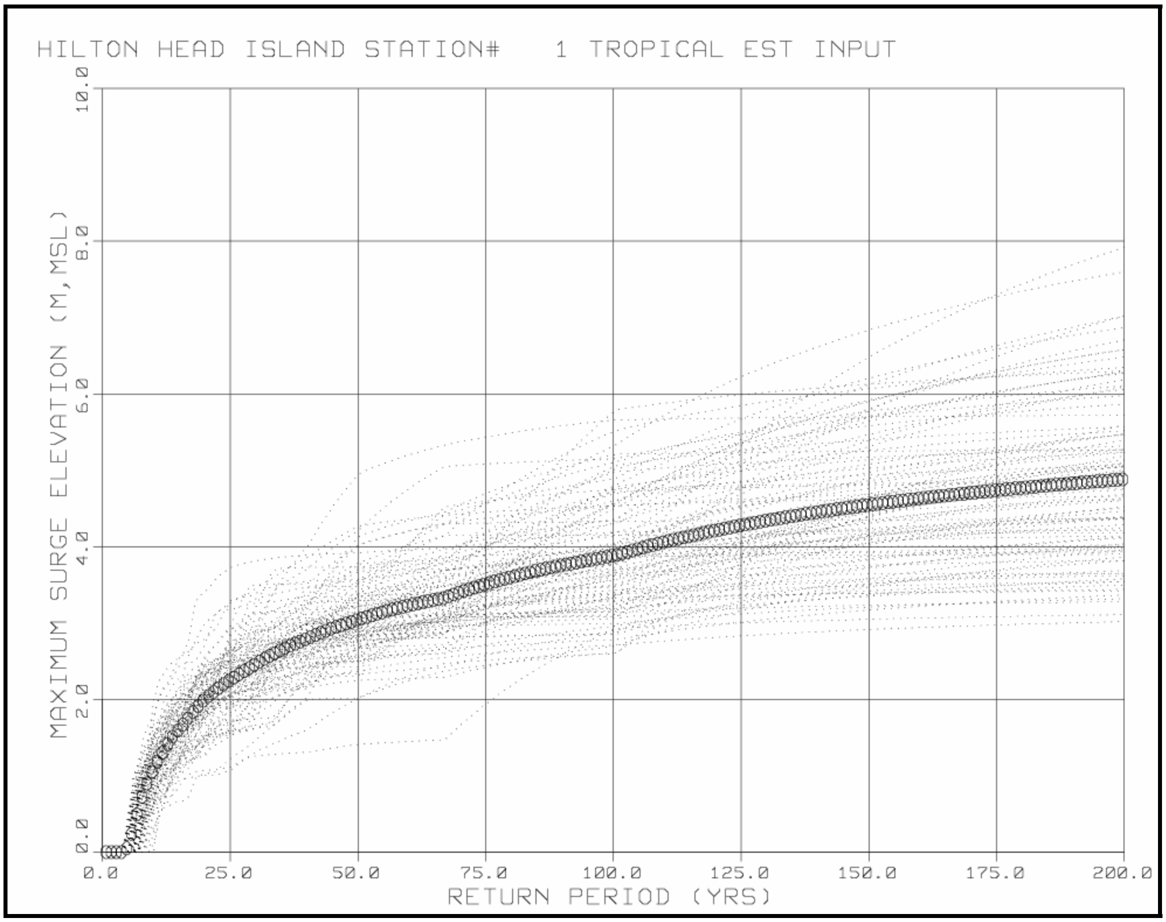


Figure 6. Distributions derived from 100 simulations of 200-year periods.

2.4 RECOMMENDATIONS

It is recommended that each important variety of flood combination—waves plus high water, tsunami plus tide, and so forth—be included as topics in the new Guidelines, along with a suggested methodology and illustrative examples derived from test studies and/or hypothetical cases. Performing a small set of test studies in typical environments will permit detailed evaluation and comparison of alternatives, as well as development of suitable approximations and practical advice for flood insurance applications.

For example, an approach such as that presented in the HRS (U.K.) reports, which shares features with the PWA (2002) approach, appears to be the most comprehensive and suitable for addressing combinations of water levels and wave conditions, subject to the proviso that a period of record longer than 3 years would probably be required for the initial statistical summaries. The technique can be adapted to consider joint occurrences of both dependent and independent contributors to flood levels. A test study using this approach is recommended at a site (or sites) on the Pacific Coast. More than 10 years of water level data can be obtained from a NOS tide gage, with a corresponding record from a NOAA wave buoy. Within the available time constraint for critical studies, however, an effort separating swell heights and periods, wave heights and periods, and tides might not be feasible.

A test study using data from the recent Sandy Point flood insurance study (FIS) is recommended. The test study would include the HRS Monte Carlo, Tetra Tech, and time series approaches. The results would be compared to the EST results used in the Sandy Point FIS for a limited range of parameters selected for use with the other approaches. Applying the test to Sandy Point allows use of a 29-year data set that has already been analyzed. Additionally, Sandy Point is a simple, two-variable case—water level and locally generated wind waves—with actual flood data available for verification purposes. The output will be 100-year wave runup elevations calculated with each method for selected shore profiles and common input data. It would also be advantageous to apply these methodologies to an Open Coast situation, which would include several variables (e.g., water level variables; heights, periods, and directions of swell and storm seas).

The combination of tsunami and tide levels can probably be handled as a straightforward application of the convolution theorem because these are independent events and the resulting water levels are likely to approximate the simple sum of the two processes. Where the environment might indicate important physical interactions between the two processes, there may be no good alternative to hydrodynamic modeling of numerous joint probability cases.

On the Atlantic and Gulf Coasts in hurricane-dominated areas, the system presently in use is acceptable, with the possible exception of the Atlantic Coast north of Long Island. The latter region could be addressed using the HRS Monte Carlo process.

2.5 PRELIMINARY TIME ESTIMATE FOR GUIDELINE IMPROVEMENT PREPARATION

Table 3 in section 6.0 Summary, summarizes the preliminary estimates of time required for Critical Topic 51. These time estimates do not include responding to comments and suggestions associated with the review of the Guideline improvements.

3 AVAILABLE TOPICS

None identified.

4 IMPORTANT TOPICS

4.1 TOPIC 50: STATISTICAL METHODS FOR SURGE MODELING (FOR BOTH ATLANTIC/GULF COASTS AND PACIFIC COAST)

4.1.1 Description of the Topic and Suggested Improvement

The basic approach to estimating storm surge frequency, as implemented in FEMA coastal surge model studies, assumes two sorts of knowledge for a given study region. First, the approach assumes that if the characteristics of a particular storm are specified, then modeling tools exist to determine the flood elevations that would occur everywhere within the study area as a consequence of that storm. The storm characteristics might include direction of forward motion, location of the shoreline crossing point, speed of travel, and measures of storm size and intensity. The modeling tool is the storm surge hydrodynamic model, implemented for the local bathymetry, topography, and terrain.

The second assumption is a method for attaching a frequency to the simulated storm, which is then also attached to the computed flood levels for that one storm simulation. This requires knowledge of the storm history for the area, from which the frequency information can be derived. By simulating numerous storms in this manner, one effectively simulates a long period of record at the site, from which flood statistics can be derived. Topic 50 is concerned with the methods by which this process can be achieved.

4.1.2 Description of Potential Alternatives

Joint Probability and Monte Carlo Methods

The primary method used in past FEMA coastal surge model studies has been the so-called Joint Probability Method (JPM), pioneered for coastal surge applications by NOAA (e.g., Myers, 1970). In the JPM method, a hurricane has usually been defined by five parameters. Track angle, track position, and forward speed are the three kinematic parameters; storm radius to maximum winds and central pressure depression are the two dynamic parameters.

By defining a sample window around the study area, one identifies all recorded storms that have passed within the site vicinity, and from those storms one establishes empirical probability distribution functions for each of the five storm parameters. Each of those distributions can then be discretized into a small number of representative values and probabilities, say, on the order of five each. Taking one value from each set defines a storm; all possible combinations represent all possible storms. In the event that even only five values were selected for each of the five discrete approximations, all possible storms would be represented by a set of more than 3,000 combinations (in practice, the actual simulation set is usually on the order of a few hundred storms).

The frequency represented by one particular storm is calculated as the rate of storm occurrence (events per year obtained from the count of storms caught during a known number of years within the sample window of known size) multiplied by the product of the probabilities assigned to the five parameters (if independence is assumed). This storm rate is attached to each surge elevation computed throughout the basin for that one particular storm. As each storm in the simulation set is run, a histogram is developed at each location in the grid, with rate being accumulated into bins defined by small flood-elevation ranges. For example, if a particular storm with rate R produces a flood elevation of S at point P, then bin 10S (if elevations are resolved to the nearest tenth of a foot) in histogram H(P) is incremented by R. At the conclusion of the entire set of runs, the histogram at any point constitutes a discrete density function. By summing such histograms from the top down, one obtains a cumulative distribution from which the elevation corresponding to an exceedance rate of 0.01 can be read.

An objection to this procedure is the independence assumption, which permits simple multiplication of individual parameter probabilities. This objection is only partly justified, however, because usual practice has been to divide the storm sample into three families: storms that approach land from the sea; those that exit from land to the sea; and those that travel more or less parallel to the local mean coast. A dependence between track angle and the other parameters is clear (storms exiting land, for example, may be less intense than those that make landfall), and this separation into subfamilies accounts for that dependence.

Another lack of independence frequently cited as a point of special concern is the possible dependence between central pressure and radius to maximum winds. The intense Labor Day storm of 1935, for example, had both a very small radius (6 nm) and a very large central pressure depression (3.6 inches Hg). It is sometimes asserted that a storm of this intensity cannot exist with a significantly larger radius, owing to energy limitations. However, this lack of independence, if it exists as a practical matter, has not been well demonstrated using standard statistical tests, and energy calculations show that the radius could be made much larger without exceeding energies frequently encountered in other storms.

A related approach is the Monte Carlo Method, in which continuous distributions are used instead of discretized distributions. Individual storms are constructed by choosing a value randomly from each of the parameter distributions. In general, the questions of independence raised concerning the JPM apply equally to the Monte Carlo Method, although it should be noted that if a correlation between parameters can be specified, then it can also be accounted for in both Monte Carlo and JPM applications. The Monte Carlo Method has an advantage over JPM; because the distributions are not separated, the set of possible storms is not limited to a finite set, as with JPM. The Monte Carlo Method has the potential disadvantage that a greater number of simulations may be necessary to ensure that the tails of the distributions are adequately sampled.

Both the JPM and Monte Carlo approaches require distribution functions for each of the storm parameters and an estimate of the corresponding storm density (number of storms per nautical mile per year at the study site). Two data sources in particular have been relied on in past FEMA work: first, publications of the NWS (currently, NWS 38); and second, storm data files from NOAA (currently, NOAA Hurricane Research Division, data file *HURDAT*). HURDAT is a digital file of storm data for all identified tropical storms in the North Atlantic (now including storms since as early as 1851). In addition to storm tracks (position at six-hour intervals), HURDAT also contains wind and pressure information (although central pressure data are scattered for storms before the 1960s), but no information regarding storm radius. From its storm track information, HURDAT provides a complete data source for three of the five storm parameters that are needed for JPM and Monte Carlo studies: forward speed, track direction, and track position.

NWS 38 (National Weather Service, 1987) was commissioned by FEMA as a comprehensive source of the data needed in a hurricane surge flood study. NWS presents an atlas of the required data in graphical format for all locations along the Atlantic and Gulf Coasts (although northeasters are not included). Track information is based on HURDAT data, whereas pressure and radius data are based on a reevaluation of the available data from NOAA sources. Figure 7 shows the coastline coordinate system used in NWS 38.

Figures are provided in NWS 38 showing the necessary storm parameters as functions of the coastal coordinate. For example, Figures 8 and 9 show the storm frequency for entering and exiting storms. Figure 10 shows the manner in which a cumulative distribution is displayed (this example is for central pressure on the East Coast).

HURDAT is relatively current, at present including storms through the 2002 season. In fact, the data contained in HURDAT have been updated throughout during the past few years as part of a major reanalysis.

NWS 38, however, is almost 20 years old, which is significant in that a large proportion of the high-quality pressure and radius data that are now available may postdate the study. Consideration should be given, therefore, to recommending more up-to-date data sources to replace or supplement NWS 38.

There is a second difficulty with NWS 38 that is not widely recognized: Data are developed and presented with respect to the shoreline-based coordinate system instead of natural geographic coordinates. The reason for this is historical. The pioneering numerical surge model developed by NOAA, the SPLASH model (Jelesnianski, 1972) originally assumed a straight shoreline with a fixed offshore bottom slope. Three sorts of storms were allowed: entering perpendicular to the straight shoreline, exiting similarly, or running parallel to the shoreline. In developing storm data for the early coastal flood studies performed with the SPLASH model, statistics were naturally specified in the same manner. Storm data categorized in this way was published in NWS 15, the predecessor of NWS 38.

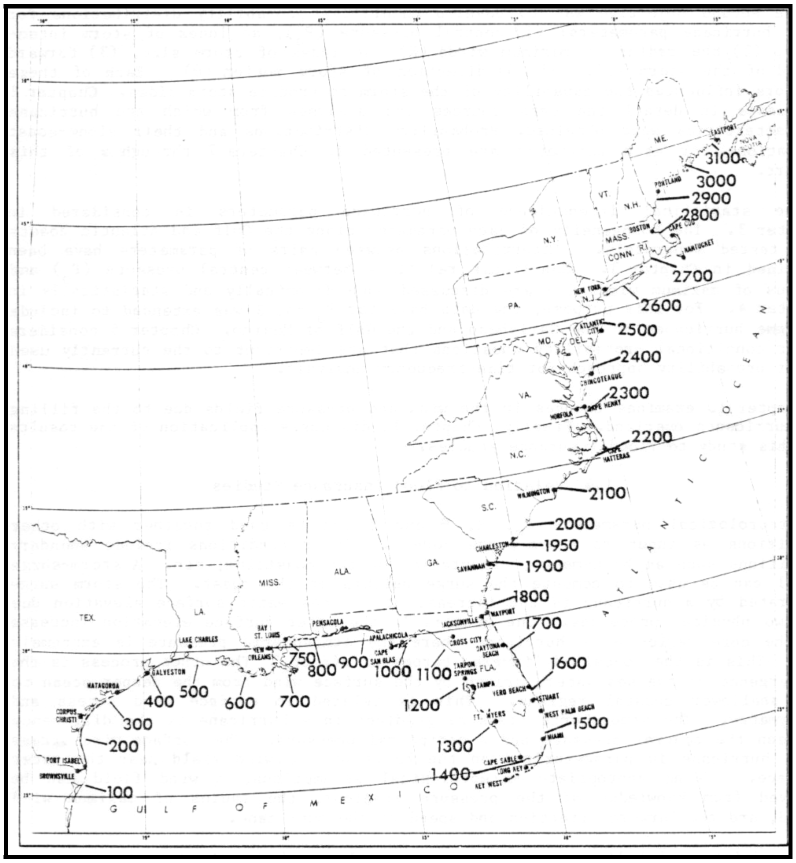


Figure 7. Coastline coordinate system from NWS 38.

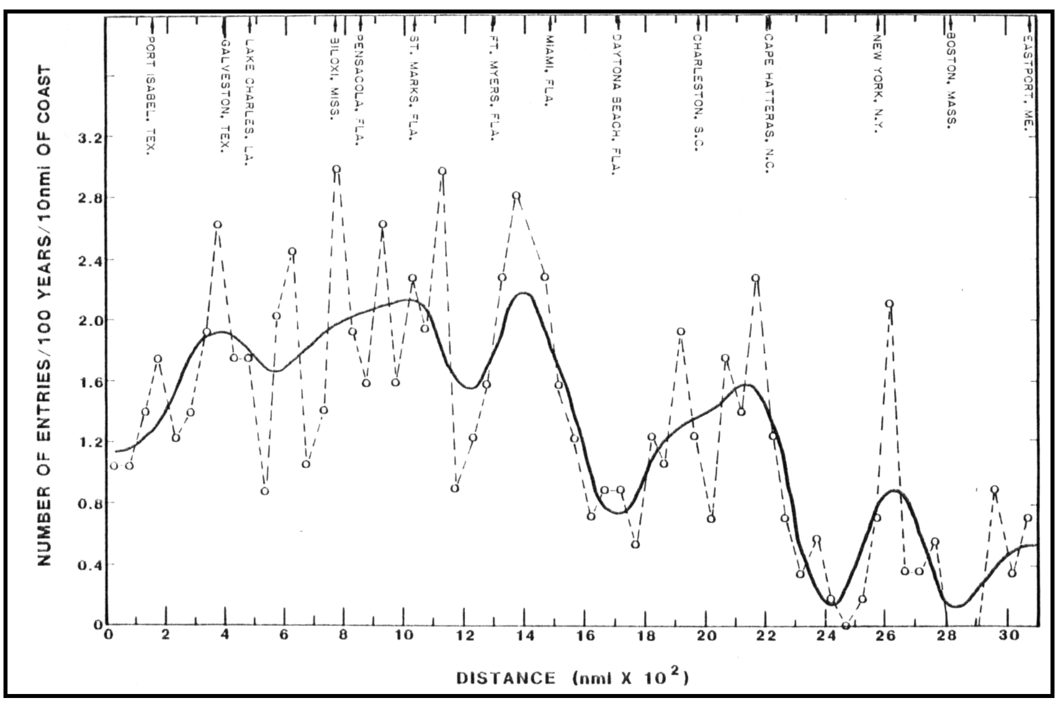


Figure 8. Storm frequency for entering storms from NWS 38.

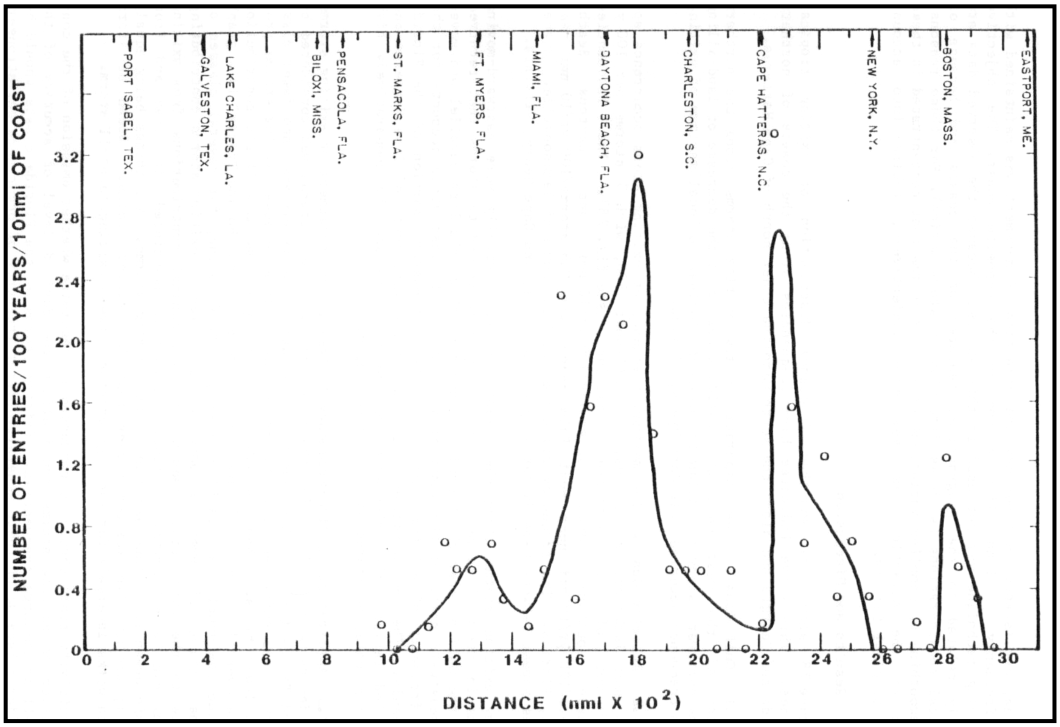


Figure 9. Storm frequency for exiting storms from NWS 38.

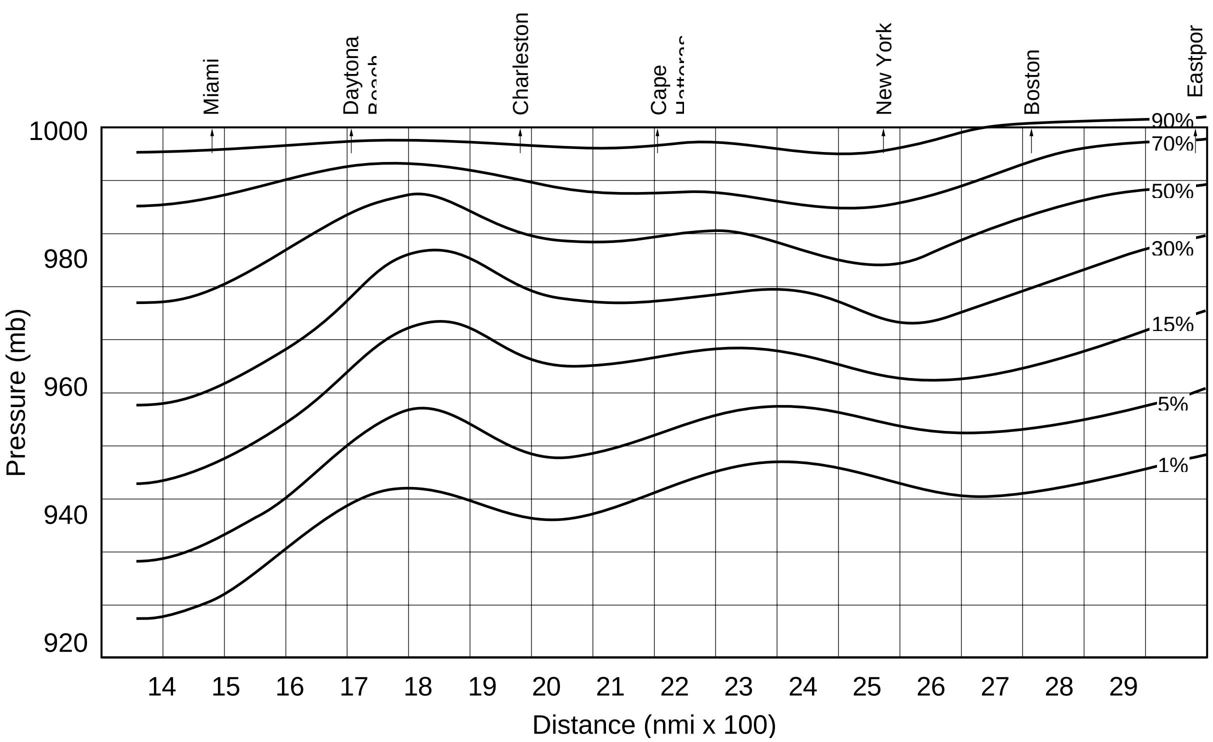


Figure 10. Cumulative distribution of central pressure on the East Coast from NWS 38.

The difficulty is that, by dividing storms into three relative path categories and then smoothing data alongshore as shown in the figures above, one inevitably combines the three storm families in an unknown way in the vicinity of every change in coastline orientation. For example, consider points below and above the right-angle coastal bend at Cape Hatteras. Entering storms below the cape belong primarily to the alongshore family above the cape, and vice versa. It is unclear what the practical implication of this is, and has been, for FEMA coastal studies. It should be noted that the objective smoothing procedure used in NWS 38 involves points as far distant as 250 nautical miles on each side of a given point. It should also be noted that a smoothing operation has the one-way effect of reducing all peaks and troughs; fluctuations in direction-family storm counts that are solely caused by bends in the coastline should be retained in the data (because they do not represent undesirable sample variation, which could, legitimately, be smoothed) and should not be reduced by smoothing. Current storm surge models, such as the FEMA surge model, ADCIRC; NOAA's SLOSH; DHI's Mike models, have no coastal orientation restrictions. The most natural way to provide the necessary storm data for these models is simply in terms of natural geographic coordinates.

Consequently, as part of the proposed effort, the appropriate storm data sources for coastal studies should be reviewed and recommendations made. The methods for developing the kinematic parameters (track and forward speed) may be relatively simple, using HURDAT as a source. The appropriate radius and pressure data may be more difficult to specify, requiring the participation of appropriate NOAA specialists. It would be extremely useful if the best available estimates of both R and ΔP, as functions of track position, could be added to HURDAT or summarized in a similar format. Existing data on these parameters are scattered through many sources, and some are unpublished; bringing these data together in HURDAT form would be of substantial value for coastal flood insurance studies.

Empirical Simulation Technique

A newer technique, the Empirical Simulation Technique (EST), has been developed for the U.S. Army Corps of Engineers and has recently been approved for flood insurance applications by FEMA. EST is a statistical technique that simulates long-period sequences of cyclic but non-deterministic multi-parameter systems such as storm events and their corresponding impacts (Scheffner et al., 1999; Scheffner and Borgman, 1992). The approach is based on bootstrap resampling-with-replacement, random-neighbor walk, and subsequent smoothing techniques in which a random sampling of a finite-length historical event database is used to generate a larger, long-period database. The only assumption is that future events will be statistically similar in magnitude and frequency to past events.

The EST begins with an analysis of historical storm events that have affected the study area. Characteristics of these events can be extracted from the HURDAT database and other sources. The selected events are then broken down to define the following components: relevant input parameters that are used to define the dynamics of the storms (the components of the so-called input vectors); factors that may contribute to the total response of the storm (i.e., surge), such as tidal phase, waves, and setup; and response vectors, which define storm-generated effects, such as total surge. Input vectors are simply sets of selected parameters that define the total storm; response vectors are sets of values that summarize the effects. Basic response vectors are determined by simulating historical storms with a suitable hydrodynamic model (ADCIRC has been adopted for surge). These input and response vectors are then used as the basis for the estimations of long-term surge history.

The recent South Carolina Storm Surge Study (Scheffner and Carson, 2001) is a typical example of a surge study, involving the following general sequence of steps:

- First, input vectors were developed for the base historical storms, including as components flood/ebb/slack tidal phase, spring-neap phase of the lunar month, minimum distance from the eye of the storm to the station location of interest, central pressure deficit, maximum wind speed, and forward speed of the eye of the hurricane.

- Next, corresponding response vectors were determined by simulating each historical event with ADCIRC. Each of 24 historic surges was combined with tide at four phases to generate a 96-event input database for the EST.

- The EST then generates multiple life cycles of surge-plus-tide activity. A total of 100 repetitions of 200 years was used for the South Carolina study. The large number of generated events is consistent with the local history (chosen by random sampling of the input vector space with random near-neighbor walk) in both frequency and magnitude.

- The long-period simulation was then post-processed (rank ordering and frequency analysis) to establish surge frequency relationships.

In this way, the EST uses observed and/or computed parameters associated with site-specific historical events and does not rely on assumed parameter independence, but rather uses the joint probability relationships inherent in the local data. Consequently, probabilities are site specific, do not depend on fixed parametric relationships, and do not assume parameter independence; the EST is distribution-free and nonparametric.

However, it is noted that owing to the extremely sporadic nature of hurricanes, the recorded experience at a site may not always adequately represent the range of events actually possible at that site; this is why it frequently happens that a new coastal flood is reported to be of unprecedented magnitude.

4.1.3 Recommendations

To better gauge the strengths and weaknesses of the three approaches discussed here for determination of storm surge frequency estimation—JPM, Monte Carlo, and EST—it is recommended that all three methods be implemented in a test study using a common hydrodynamic surge model. The particular model and coastal location used for this study may not be a critical matter. However, it is noted that studies using the ADCIRC/EST combination have been performed for the following sites, from which one might be selected:

- Coast of Delaware
- American Samoa
- Brunswick, SC
- Ponce and Guaynilla, Puerto Rico
- Long Island, Raritan Bay (unpublished)
- New Orleans/Morganza Flood Plain (unpublished)
- Galveston, TX
- Hilton Head, SC
- Guam

The modeling information for studies performed with the FEMA surge model (model grids and storm parameters) has largely been lost or discarded since completion of those studies in the 1980s.

It is important also that NOS water-level time series (or similar data) be available as a benchmark to assist in the interpretation of the statistical results for the three methods. By using a single surge model, differences are isolated to the statistical procedure formulated into the model and the quality of the storm data.

To address such issues as unaccounted-for parameter interdependence and sensitivity to sample error from a finite sample window, it would be desirable to perform numerical experiments using storm parameter distributions specified *a priori* (but mimicking the observed data at the test site) and including specified parameter correlations. From these *a priori* distributions, representing known “true” conditions, one could draw, say, a set of 100-year samples and perform the statistical studies using each of the alternative approaches.

This test effort should use both NWS 38 data and alternative data newly developed from HURDAT and other sources. This would permit an assessment of the suitability of NWS 38 for future use by FEMA and would provide some insight into the impact of storm data coastal smoothing in existing studies. To achieve this, the test site should be selected from a coastal region included in NWS 38 (eliminating three of the ADCIRC/EST sites listed above) that is near a significant coastal bend.

As a longer term effort, a data compendium similar in spirit to NWS 38 might be developed or recommended, or very specific procedures might be devised that would permit Study Contractors to determine parameters in an objective, reliable, and reproducible way.

4.1.4 Preliminary Time Estimate for Guideline Improvement Preparation

Table 3 summarizes the preliminary estimates of time required for Critical Topic 50. These time estimates do not include responding to comments and suggestions associated with the review of the Guideline improvements.

5 ADDITIONAL OBSERVATIONS

Storm surge simulations rely critically upon knowledge of a storm's wind field and the surface stress created by the wind. These factors are appropriately considered here under the umbrella of Storm Meteorology, although they might equally well be addressed under the category of Stillwater. The following additional observations are made, and corresponding additional tasks are identified in the time and cost estimate above. These tasks will be applicable to all settings, including the Pacific Coast.

5.1 WIND FIELDS

Work performed at NOAA's Hurricane Research Division (HRD) has included the reconstruction of several hurricane wind fields using all available data. HRD has identified systematic differences between those reconstructions and the hypothetical descriptions given by planetary boundary layer models currently used in storm surge models. Systematic differences are important because they may lead to a systematic bias in surge predictions and would compromise calibrations that assume accurate storm knowledge. A task to review the available wind models and to suggest a model for flood insurance applications is recommended. This review should cover not only tropical storms, but also northeasters and Pacific storms, from the standpoint of storm surge modeling.

5.2 WIND STRESS

Recent dropsonde observations made by HRD indicate that wind stress on the ocean surface may decrease at high wind speeds. This can occur if extreme winds blow the crests off waves, creating a smoother surface that offers less traction to the wind. Current representations of the wind stress in storm surge models do not include such an effect. Consequently, it is recommended that an additional task be undertaken to review the many wind stress formulations available, and to suggest an appropriate treatment for flood insurance studies.

6 SUMMARY

The Storm Meteorology Focused Study Report addresses two broad topics: the specification of the 100-year (or 1%) event (Topic 51) and methods to determine storm surge flood frequency (Topic 50). The specification of the 1% flood is categorized as *Critical* for all regions, whereas surge frequency methodology is categorized as *Important* for the Atlantic and Gulf Coasts.

The specification of the 1% flood requires consideration of combinations of processes that may be independent or correlated, and that may combine in a linear or nonlinear manner. Important examples are the combinations of surge and tsunami with astronomic tide, the combination of surge with riverine rainfall flood profiles, and the combination of waves and high water.

The primary effort will be to perform test studies using the well-documented HRS joint probability approach to the problem of waves and high water, and, from these, to derive general guidance for flood insurance studies. Other methods and simplifications will also be considered, although the HRS procedures, which have been developed over many years, appear to be comprehensive and appropriate. Simpler tasks will include preparation of guidelines for the other identified combinations.

The recommendations for surge frequency determination include a comparison of the JPM and EST methods and the preparation of guidelines for the use of each. Appropriate data sets will be recommended, including not only sets for hurricanes and tropical storms, but also for northeasters. Consideration will be given to the applicability of NWS 38 for continued FEMA use.

Two additional tasks beyond the initial scope are suggested, dealing with the representation of wind fields and wind stresses in storm surge models.

Table 2 summarizes the Topics and recommendations of the Storm Meteorology Focused Study report.

Table 2. Summary of Findings and Recommendations for Storm Meteorology

Topic Number	Topic	Coastal Area	Priority Class	Availability Adequacy	Recommended Approach	Related Topics
50	Modeling Procedures	AC	I	PRODAT	Identify and summarize data sources for storm parameters, and compare storm surge statistical methods (EST, JPM, Monte Carlo approaches may all be valuable); prepare guidelines describing the use of each alternative; revisit treatment of storm wind fields and wind stress formulation	53-55
		GC	I	PRODAT		
		PC	--	--		
		SW	--	--		
51	Combined Probabilities, Determinatio n of the 1% Flood	AC	C	MAJ	For each major process combination, prepare Guidelines with recommended methodology and illustrative examples. For wave-plus-high-water perform (2 open/sheltered) case studies for Pacific sites to: (1) Implement Wallingford approach, (2) use NOS tide gage data, (3) use NOAA wave buoy data. Develop practical Guidelines from study findings, with examples	All
		GC	C	MAJ		
		PC	C	MAJ		
		SW	C	MAJ		

Key:
Coastal Area
AC = Atlantic Coast; GC = Gulf Coast; PC = Pacific Coast; SW = Sheltered Waters
Priority Class
C = critical; A = available; I = important; H = helpful
Availability/Adequacy
"Critical" Items: MIN = needed revisions are relatively minor; MAJ = needed revisions are major
"Available" Items: Y = availability confirmed; N = data or methods are not readily available
"Important" Items: PRO = procedures or methods must be developed; DAT = new data are required;
PRODAT = both new procedures and data are required

Table 3. Preliminary Time Estimate for Guideline Improvement Preparation		
Topic Number	Item	Time (Person months)
50	**Statistical Methods for Surge Modeling (for both Atlantic/Gulf Coasts and Pacific Coast)**	
	Identify and analyze historical long-term gage data	2
	Identify and analyze storm parameter data sources	1
	Establish procedures for methodology comparisons	3
	Apply and compare methodologies (JPM, EST, Monte Carlo) using a common hydrodynamic model and storm data set	4
	Analyze results; summarize and prepare new guidelines with examples of application drawn from test studies, and including recommended data sources	2
	Additional Topic: Review best available data regarding wind fields and compare with fields used in storm surge models; recommend the most appropriate models for FIS use (tropical storms, northeasters, and Pacific storms)	2
	Additional Topic: Review best available data for wind stress and compare with formulations used in storm surge models; recommend the most appropriate formulation for FIS use	2
	Total	16
51	**Combined Probability (for all geographic regions)**	
	Develop guidelines for the combination of tsunami and tide, including a worked hypothetical example	1
	Develop guidelines for the combination of surge and tide, including examples drawn from past studies (with consideration of FEMA surge studies, ADCIRC/EST, and the FL-DEP Monte Carlo method)	1
	Prepare recommendations for the combination of surge and a riverine runoff profile	1
	Plan test studies (2) for Pacific Coast wave and high water combination; obtain necessary data	2
	Sandy Point, Pacific Coast Sheltered Waters test study	2
	Perform and evaluate Pacific Coast test studies	6
	Prepare guidelines based on findings, including illustrative examples	2
	TOTAL	15

7 REFERENCES

Benjamin, J.R., and C.A. Cornell, 1970. *Probability, Statistics, and Decision for Civil Engineers.* McGraw-Hill Book Company, NY, 684pgs.

Borgman, L.E., and N.W. Scheffner. 1991. *The Simulation of Time Sequences of Wave Height, Period, and Direction.* (TR-DRP-91-2.) U.S. Army Corps of Engineers, Coastal Engineering Research Center, Waterways Experiment Station.

Dean, R.G., T.Y. Chiu, and S.Y. Wang. 1992. *Combined Total Storm Tide Frequency Analysis for Palm Beach County, Florida.* Florida Department of Natural Resources.

Federal Emergency Management Agency (FEMA). 1988 (August). *Coastal Flooding Hurricane Storm Surge Model*. Volumes 1, 2, and 3. Washington, D.C.

Freeman, Baer, and Jung. 1957. The Bathystrophic Storm Tide. *J. Marine Res* 16(1):12–22.

Hawkes, P.J, and R.C. Hague. 1994 (November). *Validation of Joint Probability Methods for Large Waves and High Water Levels*. H.R. Wallingford Report SR 347.

Hawkes, P.J., B.P. Gouldby, J.A. Twain, and M.W. Owen. 2002 (April). The Joint Probability of Waves and Water Levels in Coastal Engineering Design. *Journal of Hydraulic Research* 40(3):241–251.

Jelesnianski, C. 1972. *SPLASH.* (NOAA Tech Memo NWS TDL-46.)

H.R. Wallingford. 1998 (November). *The Joint Probability of Waves and Water Levels: JOIN-SEA.* (Report SR 537.) With minor amendments, May 2000.

Myers, V. 1970. *Joint Probability of Tide Frequency Analysis Applied to Atlantic City and Long Beach Island, NJ.* (ESSA Tech Memo WBTM Hydro-11.)

National Weather Service. 1987. *Hurricane Climatology for the Atlantic and Gulf Coasts of the United States.* (NWS 38.) U.S. Department of Commerce. Prepared for FEMA.

Philip Williams and Associates (PWA). 2002. *Coastal Hydraulics Phase Report for a Coastal Flood Insurance Study, Sandy Point, Whatcom County, Washington.* Prepared for Whatcom County Public Works.

Scheffner, N.W., and L.E. Borgman. 1992. A Stochastic Time-Series Representation of Wave Data. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 118(4):337–351.

Scheffner, N.W., and F.C. Carson. 2001. *Coast of South Carolina Storm Surge Study.* (USACE Technical Report ERDC/CHL TR-01-11.)

Scheffner, N.W., J.E. Clausner, A. Militello, L.E. Borgman, and B.L. Edge. 1999. *Use and Application of the Empirical Simulation Technique: User's Guide.* (USACE Technical Report ERDC/CHL-99-10).

Tetra Tech. 1982. *Methodology for Computing Coastal Flood Statistics in Southern California*. (Tetra Tech Report TC-3205.) Prepared for Federal Emergency Management Agency, Washington, DC.