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BUILDING RESEARCH ADVISORY BOARD

METHODOLOGY FOR ESTIMATING THE CHARACTERISTICS OF COASTAL SURGES FROM HURRICANES

Prepared by the
Panel on Coastal Surges
from
Hurricanes
of the
Science and Engineering Committee
on
Prevention and Mitigation of Flood Losses

Building Research Advisory Board
National Research Council

National Academy of Sciences
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PANEL ON COASTAL SURGES FROM HURRICANES

of the
Science and Engineering Committee
on
Prevention and Mitigation of Flood Losses

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FOREWORD

The Federal Insurance Administration (FIA) of the Department of Housing and Urban Development (HUD) is charged to promote the public welfare by providing insurance protection against the perils of flood and mud-slide losses and to stimulate the development of sound land-use practices by local communities. To obtain assistance in the effort to formulate and implement the most effective FIA programs possible for reducing the tremendous annual losses of property resulting from floods and mudslides, HUD entered into a contract with the National Academy of Sciences (NAS). Thus, the National Research Council (NRC), through its Science and Engineering Program on Prevention and Mitigation of Flood Losses, administered by the NRC Building Research Advisory Board, has provided the FIA with guidance and assistance on various aspects of FIA technical programs, practices, and plans.

This report has been prepared by the Panel on Coastal Surges from Hurricanes in response to one specific problem posed by the FIA--how best to estimate the height of coastal surges from hurricanes. The report has been reviewed by representatives of the Assembly of Mathematical and Physical Sciences and the Commission on Sociotechnical Systems as well as the Board and is approved for transmittal to HUD.

The Board gratefully acknowledges the work of the panel members and sincerely appreciates the contribution of the individuals to the total effort.

Herbert H. Swinburne, Chairman
Building Research Advisory Board

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I
INTRODUCTION

A. BACKGROUND

Established by the National Flood Insurance Act of 1968 (as amended), the Federal Insurance Administration (FIA) of the U.S. Department of Housing and Urban Development (HUD) is responsible for promoting the public welfare by ensuring the availability of insurance protection against the perils of flood and mudslide losses and by encouraging sound land-use practices by local communities as a condition for the insurance protection. In the context of its responsibilities, the FIA has considerable opportunity to formulate programs that will reduce the annual property loss resulting from floods and mudslides.

To aid it in making the maximum feasible technical and scientific input to disaster mitigation, the FIA requested that the National Academy of Sciences-National Academy of Engineering-National Research Council (NAS-NAE-NRC) provide it with continuous, objective review of and advice on its current technical programs, practices, and plans. In response to this request, the NAS entered into a contract with HUD and charged the Building Research Advisory Board (BRAB) with administration of the NRC Science and Engineering Program on Prevention and Mitigation of Flood Losses.

B. PURPOSE AND SCOPE OF THIS REPORT

This report was prepared in response to the FIA's request (Task 1, Contract No. H-3568) for an assessment of the adequacy, for National Flood Insurance Program purposes, of methods used by the National Oceanic and Atmospheric Administration (NOAA), Corps of Engineers (CE), U.S. Geological Survey (USGS), and others to determine the height of coastal surges from hurricanes. This report focuses only on hurricane-induced surges at the open coast or at the shores of bays and estuaries.[1] Specifically, it:

1. Reviews hurricane parameters and surge and coastal-water characteristics, in addition to height, that can influence the height and areal extent of inland flooding.
2. Describes various methods available for use in estimating the characteristics of hurricane-induced coastal surges.
3. Recommends a method for estimating the characteristics of coastal surges from hurricanes to be used for purposes of the National Flood Insurance Program during the immediate future.
4. Identifies fundamental areas in need for further study and research to improve the adequacy of the recommended methods for predicting the characteristics of coastal surges from hurricanes.

C. CONDUCT OF THE STUDY

This study was conducted by the Panel on Coastal Surges from Hurricanes under the NRC Science and Engineering Program on Prevention and Mitigation of Flood Losses. As part of its study, the Panel examined the available literature on methods for predicting characteristics of hurricane-induced coastal surges and considered state-of-the-art material presented to it by the NOAA, CE, and USGS. All information obtained was reviewed and discussed by the Panel as it developed the conclusions and recommendations presented in this report.

[1]While related, hurricane-induced surges that occur on enclosed lakes and reservoirs and coastal surges resulting from "northeasters," earthquakes, or any natural phenomenon other than hurricanes are beyond the scope of this report. Similarly, a number of topics significantly related to the problem of coastal-surge effects (e.g., how, to what extent, and at what height hurricane-induced storm waters run up and over dry land; the effects of waves associated with the storm waters; and the effects of rainfall accompanying hurricanes) are not considered here either because they are under study by others or because they are beyond the scope of the assigned task.

D. ORGANIZATION OF THE REPORT

The remainder of this report is divided into two major sections: Conclusions and Recommendations, in which the conclusions and recommendations of the Panel are presented without elaboration; and Discussion, in which the conclusions and recommendations of the Panel are supported and further substantiated.

II
CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. The current approach to determining the height and areal extent of inland flooding having probabilities of annual occurrence of 0.100, 0.020, 0.010, and 0.002--i.e., of determining the height of storm waters (the surge caused by a hurricane plus height of astronomical tide) having the same probabilities of annual occurrence at the coastline and of projecting these waters inland--is inadequate.
2. A more adequate approach involves establishing the areal extent and height of inland flooding having a given probability of annual occurrence on the basis of flooding that would be caused by individual hurricane-induced surges (with astronomical tide superimposed thereon) whose temporal and spatial (height and alongshore spread) characteristics and attendant wind fields are defined probabilistically.
3. The SPLASH models of the NOAA currently provide the soundest basis for determining the temporal and spatial (height and alongshore spread) characteristics of a hurricane-induced surge along open, unbroken coastlines of the Atlantic and Gulf coasts.[2]
4. The method of joint probabilities provides the soundest basis for assigning a probability of occurrence to the temporal and spatial characteristics of a surge produced by a hurricane and to the total height of the resulting storm waters (i.e., surge plus astronomical tide).

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[2]While beyond the scope of the Panel's study, it should be noted that the ability to model and predict hurricane-surge heights within estuaries, bays, lagoons, and other semienclosed tidal waters and in adjacent low-lying lands must be improved. Required are not only general models but specific ones for each separate body of water for which such a model would be needed.

5. Substantial improvement in the accuracy currently attainable by application of the SPLASH models and the joint probability approach in estimating the temporal and spatial characteristics of a hurricane-induced surge requires an expanded oceanographic and meteorological data base that can be used to gain better understanding of the relationship among hurricane parameters, surge characteristics, and on-shore and near-shore geographic features.

B. RECOMMENDATIONS

1. To obtain the input needed for the conduct of a Federal Insurance Study implementing the approach involving establishing the height and areal extent of inland flooding on the basis of flooding caused by individual surges, the FIA should request the NOAA to:
    a. Publish, in the form of nomograms, the relationships among the temporal and spatial characteristics of surges and hurricane parameters for various reaches of the Atlantic and Gulf coasts. The surge characteristics to be considered are: peak surge height, position of peak surge on the shore relative to position of storm center, time of peak surge on the shore relative to time the storm center is closest to the point of peak surge, the standard deviation (distance spread parameter) of the surge profile alongshore at the time peak surge occurs, the standard deviation (time spread parameter) of the surge hydrograph at the position alongshore at which the peak surge occurs, and the trace speed of the surge crest alongshore. The hurricane parameters to be considered are: central pressure anomaly, radius to maximum winds, forward speed, and path (angle of incidence on coast of landfalling storms or distance from shore of alongshore-moving storms).
    b. Publish, in the form of graphs, the variation of the shoaling factor along the length of the reaches of the Atlantic and Gulf coasts for which nomograms are prepared.

c. Publish, in the form of tables or graphs, the probabilities of annual occurrence of various values of the above hurricane parameters in the reaches of the Atlantic and Gulf coasts for which the nomograms are prepared.

d. Publish, in the form of tables or graphs, the probabilities of annual occurrence of various heights of the astronomical tide above and below standard mean sea level for various communities selected by the FIA within the reaches of the Atlantic and Gulf coasts for which nomograms are prepared.

e. Document and publish the programs and subprograms of its SPLASH models.

2. To provide the basis for substantial improvement in the accuracy currently attainable in estimating the temporal and spatial characteristics of surges, the FIA should encourage the NOAA, CE, USGS, and other appropriate agencies and institutions to undertake an expanded meteorological and oceanographic data collection program in coastal areas in order that the engineering and scientific community can further study and research:

    a. The assumption of independence among storm parameters.

    b. The assumption of independence among surge, astronomical tide, and other initial water conditions.

    c. The "feedback" effect of flooding of low-lying coastal areas on surge height and growth at shore.

    d. The effect of the presence of bays and estuaries on the surge at points along the coast away from the entrance to the bays and estuaries.

III
DISCUSSION

A. BACKGROUND

Pursuant to the National Flood Insurance Act of 1968 (as amended) and the National Flood Disaster Protection Act of 1973, flood (including that resulting from hurricanes) and mudslide insurance protection is available to owners and occupiers of buildings in local communities choosing to participate in the National Flood Insurance Program administered by the FIA. To participate in the program, flood-prone communities must adopt and enforce land-use and control measures to avoid or reduce future losses. These measures are based on flood frequency, areal extent, and height data furnished and used by the FIA to determine which of the established insurance rate categories are applicable to buildings in the particular community.

To obtain these data for coastal communities subject to hurricane-induced flooding, the FIA contracts for conduct of Flood Insurance Studies (FIS) with either public or private organizations; however, only a few such studies actually have been completed and thus far the FIA has used mainly the Corps of Engineers (CE), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS). Among the tasks to be performed, in conducting a FIS of a hurricane-susceptible coastal community are: (1) determining surge heights having recurrence intervals of 10, 50, 100, and 500 years (i.e., surges having probabilities of annual occurrence of 0.100, 0.020, 0.010 and 0.002)[3]; (2) estimating the areal extent and height (flood elevations) of overland flows associated with these surge heights; and (3) computing the flood-hazard factors applicable to different parts of the community subject to flooding by the 100-year surge. The FIA does not specify what methodology should be used by the

[3]Rigorously speaking, the surge having a particular probability of annual occurrence is the surge height that has a particular probability of not being exceeded annually.

organization conducting a FIS to determine hurricane surges or areal extent and height of overland flooding, but it does require that the height of overland flooding be determined to an accuracy of ± 0.5 foot.

The results of an FIS are transmitted by the FIA to the community in a technical report that identifies and categorizes those areas potentially inundatable by tidal floods. The land areas in the community are designated as being in: (1) Zone V (i.e., an area of special flood hazard due to the potential for inundation by tidal floods with velocity) or Zone A (i.e., an area of special flood hazard due to the potential for inundation by tidal floods without velocity) if they are below the predicted 100-year surge flood elevation; (2) Zone B (i.e., an area of moderate flood hazard) if they lie between the flood elevation predicted for the 100-year surge and that predicted for the 500-year surge; (3) Zone C (i.e., an area of minimal flood hazard) if they lie above the predicted 500-year surge flood elevation. Zones V and A are further divided into 30 subcategories each depending upon the difference between the 10-year and 100-year flood elevation predicted for a particular area, the difference being determined to the nearest 0.5 foot when the difference is 10 feet or less and to the nearest 1 foot when the difference is more than 10 feet.

The areas designated as being in Zones A-1 through A-30 or V-1 through V-30 are of particular interest to the community since its participation in the National Flood Insurance Program (and thereby its access to flood insurance protection as well as any federal financial assistance for acquisition or construction purposes) requires that it enact and enforce land-use, construction, and other regulations for those areas to discourage further development and to encourage floodproofing of existing or permitted new development.[4] Additionally, property owners in those areas must purchase flood insurance for their buildings.

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[4] The height of the lowest floor (including the basement) of new buildings constructed in such areas must be at least equal to the predicted 100-year flood elevation, unless a specific variance is granted by the FIA. Even if a specific variance is granted, the premium for the compulsory flood insurance for the new building may be extremely high.

Given the significance to a community of the FIA designation of the areal extent and height of 100-year surge flooding, it is to be expected that a community will scrutinize the data resulting from an FIS. Indeed, although only relatively few studies of coastal communities susceptible to hurricane-induced surges have been completed, some already are being challenged. Particularly disturbing to the FIA is that in more than one case a community is contesting the FIA's designation of flood-prone lands either on the grounds that a study performed by a different organization than the one which conducted the official FIS resulted in a materially different estimate of the areal extent and height of 100-year surge flooding or on the grounds that the areal extent and height of historical storms suggest major departures from the official FIS estimates. Further compounding the situation is that in more than one instance when different organizations performed FIS on adjacent communities, the surge height predicted for a common boundary by one organization differed measurably from the height predicted by the other organization.

Even though the three organizations (CE, NOAA, and USGS) that have been conducting FIS of coastal communities for the FIA use substantially different methods to estimate the characteristics of the storm waters that could cause flooding, all three organizations focus on estimating the height of storm water (i.e., the combined height of hurricane surge and initial coastal water conditions) having a given probability of occurrence.[5]

The basic method used by the USGS to determine the total height of storm water along the open coast as well as behind barrier islands and in bays and estuaries is related to the agency's responsibility for recording historical natural phenomena and their effects and is essentially a statistical analysis of storm tides in the region of the area under investigation. It involves: (1) determining the height and frequency of occurrence of historical storm tides (astronomical plus surge) by examining available tidal gauge records in the subject area, identified

[5] Thus far, the USGS and CE have been the organizations principally involved in conducting FIS for bay and estuary communities.

high water marks, and other historical records (e.g., newspaper accounts and public documents); (2) reconstructing the historical surge heights (storm tide minus astronomical tide) by deducting the known or presumed astronomical tides at the time of the storms; and (3) extrapolating this historical surge height to the desired frequencies by combining the surge height of desired frequency with astronomical tides in a random manner and assuming a log-Pearson Type III distribution for the combination. The method assumes that: (1) storm-surge occurrence and effects are unrelated to astronomical tidal events and effects, and (2) historical data available only for a relatively short period from remotely located, often protectively situated tidal gauges (which in fact frequently do not function at the climax of storm effects) can be used as baseline data for the area under study.

The method used by the CE to determine the total height of storm water on the open coast as well as in barrier island and bay and estuary situations is related to the agency's responsibility for efficiently designing safe coastal structures and relies on the use of a one-dimensional model predicated on the bathystrophic storm tide theory developed by Freeman, Baer, and Jung[6] and evolved by Bretschneider and Collins,[7] Marinos and Woodward,[8] and Bodine[9] to estimate the surge height on the open coast, seaward of barrier islands, and at the mouths of bays and estuaries. The method involves selecting the characteristics (central pressure index, radius of maximum winds, and forward speed) of a theoretical hurricane whose central pressure index has one half the frequency of occurrence in

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[6] J.C. Freeman, Jr., L. Baer, and G.H. Jung, "The Bathystrophic Storm Tide," Journal of Marine Research, XVI, 1 (1957).

[7] C.L. Bretschneider, and J.I. Collins, Prediction of Hurricane Surge: An Investigation for Corpus Christi, Texas and Vicinity, National Engineering Science Co. Technical Report SN-120 for U.S. Army Corps of Engineers Galvesto District (Pasadena, Calif.: National Engineering Science Co., 1963).

[8] C. Marinos, and J.W. Woodward, "Estimation of Hurricane Surge Hydrographs," ASCE Journal of the Waterways and Harbors Division, XCIV (1968): 189-216.

[9] B.R. Bodine, "Storm Surge on the Open Coast: Fundamentals and Simplified Prediction," U.S. Army Corps of Engineers Coastal Engineering Research Center Technical Memorandum 35, 1971.

the geographical region within which the study area lies as the frequency of hurricane desired (e.g., the 100-year hurricane).[10] The surge height resulting from the hypothetical hurricane--traveling shoreward from the Continental Shelf along a line perpendicular to the coast and offset to the left (facing land) from the point to be studied a distance equal to the radius of maximum winds--is calculated by the steady-state integration of the wind stress at discrete points along the locus of the radius of maximum winds using a one dimensional model. The method takes into account the initial rise of water level above mean sea level (which often occurs prior to the arrival of a hurricane and usually is taken from historical records), the astronomical tide, and atmospheric pressure setup. The CE method assumes that: (1) the surge height having the desired frequency of occurrence results from a slow-moving landfalling hurricane which strikes the coast to the left (facing land) of the land point under study; (2) on-shore water volume transport, advection of momentum, and precipitation can be neglected; (3) the alongshore sea surface is uniform and parallel to the bottom contours; and (4) astronomical tide and initial wave setup can be linearly superimposed on storm surge height.

The CE has, in addition, studied a number of specific bays and estuaries using either physical or two-dimensional mathematical hydrodynamic models to simulate wind and surge dynamics within the bays and estuaries under specified input water level variations at the mouths. Existing at

[10]The selection is made using National Weather Service (NOAA) Draft Memorandum HUR7-120 (Revised Standard Project Hurricane Criteria for the Atlantic and Gulf Coasts of the United States), June 1972. This draft document updates the results of statistical analyses of historical hurricanes experienced in various delineated zones along the Atlantic and Gulf coasts as reported by H.E. Graham and D.E. Nunn in <u>Meteorological Considerations Pertinent to Standard Project Hurricane, Atlantic and Gulf Coasts of the United States</u>, U.S. Weather Bureau and U.S. Army Corps of Engineers National Hurricane Research Project Report 33 (Washington: U.S. Department of Commerce, 1959). Although these references provide frequency distribution data about the other storm, parameters are given in representative (e.g., representative small radius of maximum winds, representative mean radius, and representative large radius) not probabilistic terms.

the CE Waterways Experiment Station, Vicksburg, Miss., are physical models for the following points on the Atlantic and Gulf Coasts: Newburyport Harbor, Mass.; Jamaica Bay (New York Harbor), N.Y.; Barnegat Inlet, N.J.; Delaware River, Del; James River, Va.; Masonboro Inlet and Bay, N.C.; Georgetown Harbor, S.C.; Charleston Harbor, S.C.; Savannah Harbor, Ga.; and Mobile Bay, Ala. Mathematical models have been created for the following points on the Atlantic and Gulf Coasts: Masonboro Inlet and Bay, N.C.;[11] Tampa Bay, Fla.;[12] Jamaica Bay, N.Y.;[13] Sarasota Bay and Lake Worth, Fla.[14] Further, the CE Coastal Engineering Research Center, Ft. Belvoir, Va., has been proceeding with calibration of the mathematical model developed by Reid and Bodine for Galveston Bay[15] for use in studies of Charleston Harbor and Bay, S.C., while the CE Galveston District has been proceeding with calibration of the same model for use in studies of Corpus Christi Bay, Copano Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, Lavaca Bay, Baffin Bay, Laguna Madre, and Sabine Lake, Texas.

The method used by the NOAA to determine the total height of storm water on the open coast is related to the agency's responsibility for predicting surge heights from specific hurricanes that are being tracked by the

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[11] This model was developed by Masch based on previous work reported in Frank D. Masch, et al., A Numerical Model for the Simulation of Tidal Hydrodynamics in Shallow Irregular Estuaries (Austin: The University of Texas, 1969).

[12] Two models were generated: One was developed by Ross and is described in Bernard E. Ross, Progress Report for U.S. Army Corps of Engineers Coastal Engineering Research Center Contract DACV 17-71-C-0001, Vol. 1 (Tampa: University of South Florida, 1973). The other was developed by Leenderste based on previous work reported in Jan Jacob Leenderste, Aspects of a Computational Model for Long-Period Water Wave Propagation (Santa Monica, Calif.: The Rand Corporation, 1967).

[13] This model was developed by Leenderste based on previous work reported in Leenderste, op. cit.

[14] This model was developed by Dean based on previous work reported in R.G. Dean, et al., Residence Times of Water Behind Barrier Islands (Gainesville: University of Florida, 1970).

[15] This modeling is proceeding based on the work reported by R.O. Reid, and B.R. Bodine, "Numerical Model for Storm Surges in Galveston Bay," ASCE Journal of the Waterways and Harbor Division, XCIV (1968).

National Hurricane Center and is based on application of the joint probability theory used by Myers in studying tide frequencies in Atlantic City and Long Beach Island, N.J.[16] The method involves: (1) analyzing the behavior and characteristics of historical landfalling and alongshore hurricanes near the area under study to determine the frequency of landfalling hurricanes, the probability distribution of forward speeds of all the hurricanes, the probability distribution of radius of maximum winds of all the hurricanes, the probability distribution of the central pressure anomaly of all the hurricanes, and the probability distribution of the direction of motion of the landfalling hurricanes; (2) calculating the frequency of occurrence of surge heights produced by theoretical hurricanes embracing all combinations of the characteristics of historical storms applying the method of joint probabilities and Jelesnianski's two-dimensional dynamic model using either precomputed nomograms or computational runs of specially written computer programs[17]; and (3) using the method of joint probabilities to calculate the frequency of occurrence of possible maximum total heights of hurricane surge and astronomical tide. The NOAA has, in addition, developed mathematical models for Apalachicola Bay and St. George Sound, Florida.[18]

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[16]V.A. Myers, "Joint Probability Method of Tide Frequency Analysis Applied to Atlantic City and Long Beach Island, N.J.," ESSA Technical Memorandum WBTM HYDRO 11, 1970.

[17]Chester P. Jelesnianski, "SPLASH (Special Program to List Amplitudes of Surges from Hurricanes), Part I--Landfall Storms," NOAA Technical Memorandum NWS TDL-46, 1972 and "SPLASH (Special Program to List Amplitudes of Surges from Hurricanes), Part II--General Track and Varient Storm Conditions," NOAA Memorandum NWS TDL-52, Mar. 1974. These works are a refinement of the following two publications initially used by Myers: C.P. Jelesnianski, "Numerical Computations of Storm Surges Without Bottom Stress," Monthly Weather Review, XCIV (June 1966): 379-94, and "Numerical Computations of Storm Surges with Bottom Stress," Monthly Weather Review, XCIV, (Nov. 1967): 740-56. The computer program for Jelesnianski's method is specifically written for the NOAA CDC 6600 computer, makes extensive use of other NOAA program subroutines, is not compatible with the software of other computers, and has not been documented.

[18]James Overland, Estimation of Hurricane Storm Surge in Apalachicola Bay, Florida, NOAA Technical Report NWS 17 (in press); F.P. Ho and V.A. Myers, Joint Probability Method of Tide Frequency Analysis Applied to Apalachicola Bay and St. George Sound, Fla., January 1975 draft of a NOAA Office of Hydrology Report.

B. METEOROLOGICAL AND OCEANOGRAPHIC BASIS OF FLOOD INSURANCE STUDIES

Hurricanes are spawned over the oceans near the equatorial zones, usually during the period from June through October, and are migratory cyclones having maximum sustained wind speeds equal to or greater than 75 miles per hour. Of the eight or so hurricanes spawned each year in the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea, about 50 percent are landfalling hurricanes (i.e., they cross the Atlantic or Gulf coasts of the United States), and of the six hurricanes spawned each year off the west coast of Central America, about 1 percent cross the Pacific coast of the United States and then only in California. While there is little likelihood of a hurricane landfalling at any one specific location given the infrequency of occurrence and the thousands of miles of coastline, a hurricane is a major meteorological phenomenon (measuring as much as 500 miles across to the gale force winds of 40 miles per hour and 100 miles across to the hurricane force winds) and, therefore, can affect a large number of coastal communities no matter whether or where it landfalls.

A hurricane moving over the Continental Shelf produces a buildup of water at the coast that can inundate near-shore dry lands. For a given set of near-shore geographic features (e.g., bottom topography [bathymetry] and roughness of the Continental Shelf and coastline curvature), the nature of the storm waters depends upon the characteristics of the surge produced by the hurricane and the initial coastal water conditions prevailing at the time of the hurricane. The initial coastal water conditions are an important determinant of the total height of storm waters above mean sea level because a surge arriving in phase with high tide obviously would result in a total storm water height greater than would a surge arriving in phase with low tide.

The storm surge characteristics of height, duration, and spatial spread along the shore are affected to various degrees by different parameters of the hurricane (e.g., central pressure anomaly, radius of maximum winds, forward speed, maximum sustained winds, direction of the storm relative to the coast). The surge height resulting from a landfalling hurricane is most closely related to the central pressure anomaly but is also influenced by the forward speed of propagation and duration of the storm; however, the duration and spatial spread alongshore of the storm waters depend mainly on the forward speed, direction of the storm relative to the coast (i.e., angle of approach), and radius of the maximum winds of the storm. In the case of a hurricane moving alongshore, the surge height, in addition to being strongly related to the central pressure anomaly alone, is quite sensitive to the speed of the storm and its distance from the coast relative to the radius of maximum winds (e.g., the surge height rapidly decreases when the distance from the shore is more than twice the radius of maximum winds). Surge duration for the alongshore-moving hurricane is again closely related to the forward speed and radius of maximum winds.

A hurricane with given parametric values approaching the coastline normally creates the highest surge height at a point on the coast to the right (facing land) of its landfall. The distance of this point from the location of the landfall of the storm center is about equal to the radius of maximum winds of the hurricane. However, the peak surge height of a landfalling storm usually is experienced only over a relatively short distance along the coast (the height of surge is reduced significantly within several times the radius of maximum winds to the right and within a couple of radii to the left of the storm center) and all but disappears within 10 times the radius to the right and a third of that distance to the left of the storm center. On the other hand, an alongshore-moving hurricane with the same parametric values as a landfalling hurricane may produce at the same point on the coast a surge only about 50 percent as high as that produced by the landfalling hurricane[19] but that height extends over a substantially greater distance along the coast.

The areal extent and height of flooding that will occur inland from a surge on the open, unbroken coastline with known characteristics is

[19]A possible exception to this is the hurricane generating resonance while moving southward on the Atlantic coast or northward off the west coast of Florida. The former circumstance is all but impossible to envision, the latter would be exceedingly rare.

influenced by the wind field attendant the hurricane. It is possible, for example, for a greater degree of inland flooding to result from a surge having a relatively low height and a strong wind field than from a higher surge having a weaker wind field or a wind field acting in a direction opposite the flow of the storm waters. The interaction and effects of the wind field are even greater as the open coast surge crosses barrier islands or funnels through bays and estuaries to inundate normally dry lands beyond. In these instances, as in a lake, local winds can induce a surface current in the general direction of the wind movement, thus causing an increase or decrease in water level above or below that anticipated by consideration of surge characteristics alone. This current results principally from tangential stresses at the water surface between wind and water, and it produces a piling up of water at the leeward side and a lowering of water level at the windward side with a return flow along the bottom. Haurowitz, Saville, Sibul, and Tickner draw attention to this effect in their studies of the passage of the hurricane of August 26-27, 1949 over the northern part of Lake Okeechobee.[20] During this hurricane, after the lake level was inclined by the wind, the wind direction shifted 180° in a period of three hours. This turning of the wind resulted in a turning of the height contours of the lake surface, but the turning of the contours lagged behind the turning of the wind so that for a period of time the wind blew parallel to, rather than perpendicular to the water level contours.

The implication of these comments on oceanographic and meteorological considerations is that the degree to which a hurricane affects a coastal community (i.e., the extent of and height to which low-lying lands are

[20] B. Haurowitz, "The Slope of Lake Surfaces Under Various Wind Stresses," U.S. Army Corps of Engineers Beach Erosion Board Technical Memorandum 25, Nov. 1951; T. Saville, Jr., "Wind Set-Up and Waves in Shallow Water," U.S. Army Corps of Engineers Beach Erosion Board Technical Memorandum 27, June 1952; O. Sibul, "Laboratory Study of Wind Tides in Shallow Water," U.S. Army Corps of Engineers Beach Erosion Board Technical Memorandum 61, Aug. 1955; E.G. Tickner, "Effect of Bottom Roughness on Wind Tide in Shallow Water," U.S. Army Corps of Engineers Beach Erosion Board Technical Memorandum 95, May 1957.

flooded) is a function not only of the several characteristics of the surge at the coastline, but also of the action of the storm's wind on this water as it is driven inland. The current approach used by the FIA for determining the height of a surge having a given probability of annual occurrence at the coastline and of projecting the associated water inland to determine the height and areal extent of flooding having the same probability of occurrence does not take into account the effect of wind field on extent and height of inland flooding nor any characteristic of the surge other than height. Thus, it is concluded that such an approach is inadequate for purposes of the FIA and that a more adequate approach involves establishing the areal extent and height of inland flooding having a given probability of annual occurrence on the basis of flooding that would be caused by individual hurricane-induced surges (with astronomical tide superimposed thereon) whose temporal and spatial (height and alongshore spread) characteristics and attendant wind fields are defined probabilistically.

C. APPLICATION OF THE SPLASH MODELS

The approach discussed above to predicting the areal extent and height of inland flooding of a coastal community having a given probability of occurrence requires studying the potential effects of a large number of water and wind conditions of individual storms as contrasted with the current procedure of studying the potential effect of a surge having a given probability of occurrence. To study the potential effects of individual storms requires that the characteristics of a particular surge and wind field of a hurricane be relatable in time and space. One way this can be achieved is to describe the temporal and spatial (height and alongshore spread) characteristics of the surge in terms of various parameters that, in turn, can be correlated with the parameters characterizing the hurricane producing the surge at a given location. The surge parameters to consider are: (1) peak surge height, (2) position alongshore at which the peak surge occurs, (3) the time at which the peak surge occurs, (4) the standard deviation (distance spread parameter) of the surge profile alongshore at the time the peak surge occurs, (5) the standard deviation (time spread parameter) of the surge hydrograph at the position alongshore where the peak surge occurs, and (6) the trace speed of the surge crest alongshore.

A reasonable approximation of the temporal and spatial distribution of the surge elevation at the shore can be achieved by assuming a bi-variate Gaussian (normal) distribution characterized by the six parameters identified above. The general bi-variate Gaussian distribution for the surge elevation (S) at a position (x) alongshore at a time (t) can be represented as:

$$S(x,t) = S_p \exp\left\{-\frac{1}{2}\left[\left(\frac{x-x_p}{\sigma_x}\right)^2 - 2\rho\left(\frac{x-x_p}{\sigma_x}\right)\left(\frac{t-t_p}{\sigma_t}\right) + \left(\frac{t-t_p}{\sigma_t}\right)^2\right]\right\}, \qquad (1)$$

where

- S_p is the peak surge height,
- x_p is the position alongshore at which the peak surge occurs (measured positive to the right facing shore),
- t_p is the time at which the peak surge occurs,
- σ_x is the standard deviation (distance spread parameter) of the surge profile alongshore at $t = t_p$,
- σ_t is the standard deviation (time spread parameter) of the surge hydrograph at $x = x_p$, and
- ρ is the ratio $\sigma_x/C\sigma_t$ where C is the trace speed of the surge crest alongshore.

The reference points for x and t are the same as those for x_p and t_p. For landfalling hurricanes, x_p is relative to the position of landfall of the hurricane eye, while t_p is relative to the time of landfall. For non-landfalling hurricanes, x_p is relative to an arbitrary reference point (P) on shore and t_p is relative to the time when the hurricane eye is closest to and abeam of the point (P).

The maximum surge at any x occurs at time t_m, which can be determined from:

$$t_m = t_p + \frac{(x-x_p)}{C}. \qquad (2)$$

The corresponding local maximum surge at x can be determined from:

$$S_m(x) = S_p \exp\left[-(1-\rho^2)\frac{(x-x_p)^2}{2\sigma_x^2}\right]. \qquad (3)$$

Figure 1 illustrates both the distribution of surge height vs. x and t as would be approximated by Eq. (1) for a landfalling hurricane and the corresponding envelope of maximum surge height along the coast. The envelope of maximum surge heights alongshore has a wider spread than the alongshore profile of surge heights at any specific time t; the profile of surge heights alongshore at $t = t_\rho$ is illustrated on the figure. The envelope standard deviation is given by $\sigma_x/(1-\rho^2)^{0.5}$.

For a non-landfalling hurricane moving parallel to the shore, $\sigma_x = C\sigma_t$ (i.e., $\rho = 1$), and Eq (1) reduces to the form:

$$S(x,t) = S_p \exp\left[-\frac{1}{2\sigma_t^2}\left(t-t_p-\frac{x^1}{C}\right)^2\right], \qquad (4)$$

where $x^1 = (x-x_p)$ and t_p is the time of maximum surge following the passage of the eye abeam of $x^1 = 0$. Thus, there are only four surge parameters required in the case of a non-landfalling hurricane (S_p, σ_t, t_p, and C) and C must equal the storm speed. Figure 2 illustrates the distribution of the surge height vs. x and t as would be approximated by Eq. (4) and the corresponding envelope of maximum surge heights along the coast.

The six parameters characterizing the surge can be related to the following specific parameters characterizing a hurricane from which it is possible to define the prevailing wind field: central pressure depression (D), radius to maximum wind (R), forward speed (U), and path in the region of concern. For landfalling hurricanes, the path can be characterized by the position on the coast of landfall of the eye and the angle (Θ) of the path measured clockwise from the coast. For non-landfalling hurricanes, the path can be characterized by the distance (L) of the hurricane measured seawards from the coast.

Neither the USGS statistical method nor the one-dimensional model that is basic to the CE method can generate the time- and space-related descriptions of the hurricane and its surge as just discussed. The former treats the hurricane as an exogenous variable, and the latter's mathematics confine

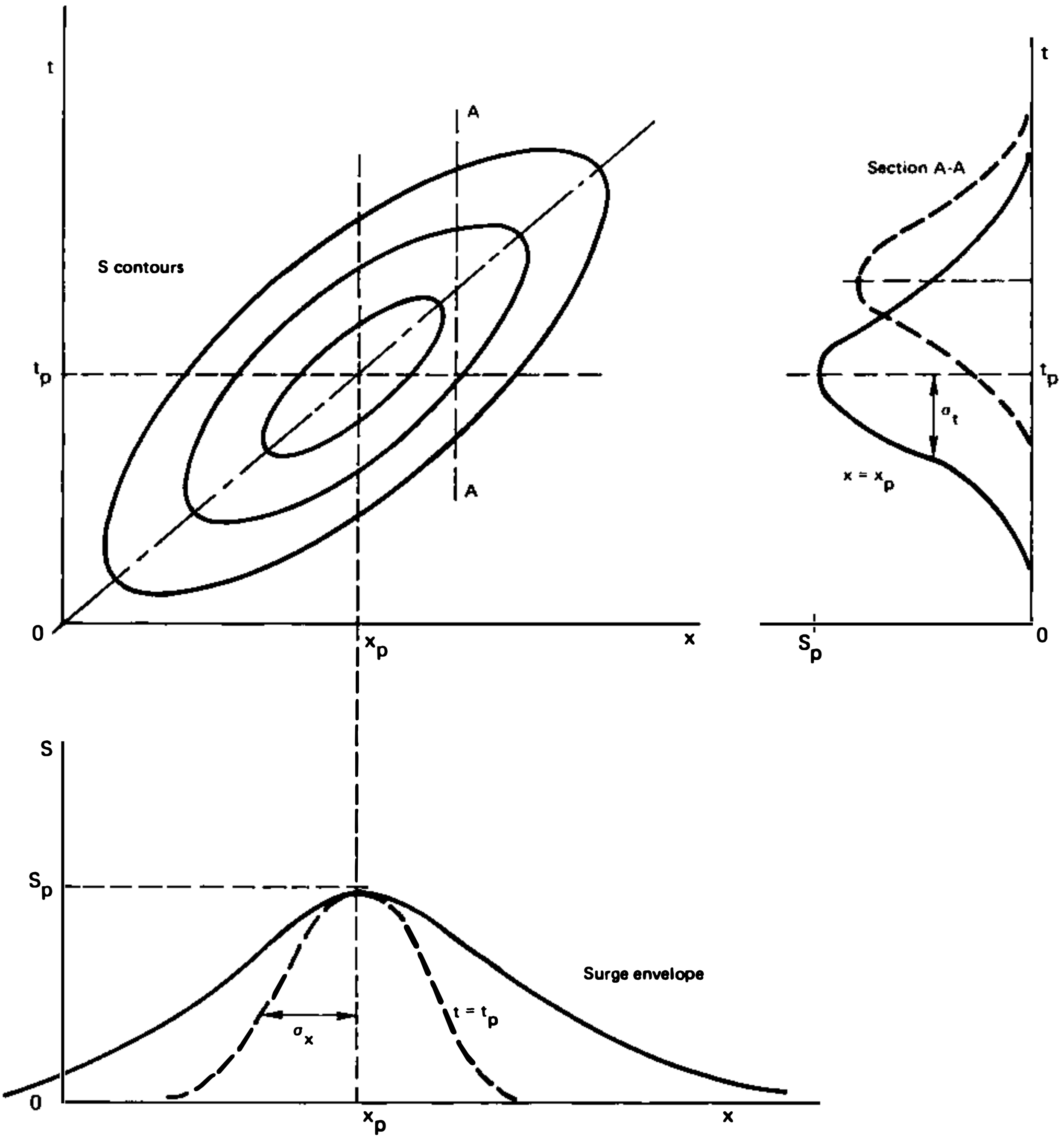

FIGURE 1 Distribution of surge height vs. x and t and the corresponding envelope of maximum surge height along the coast for a landfalling hurricane.

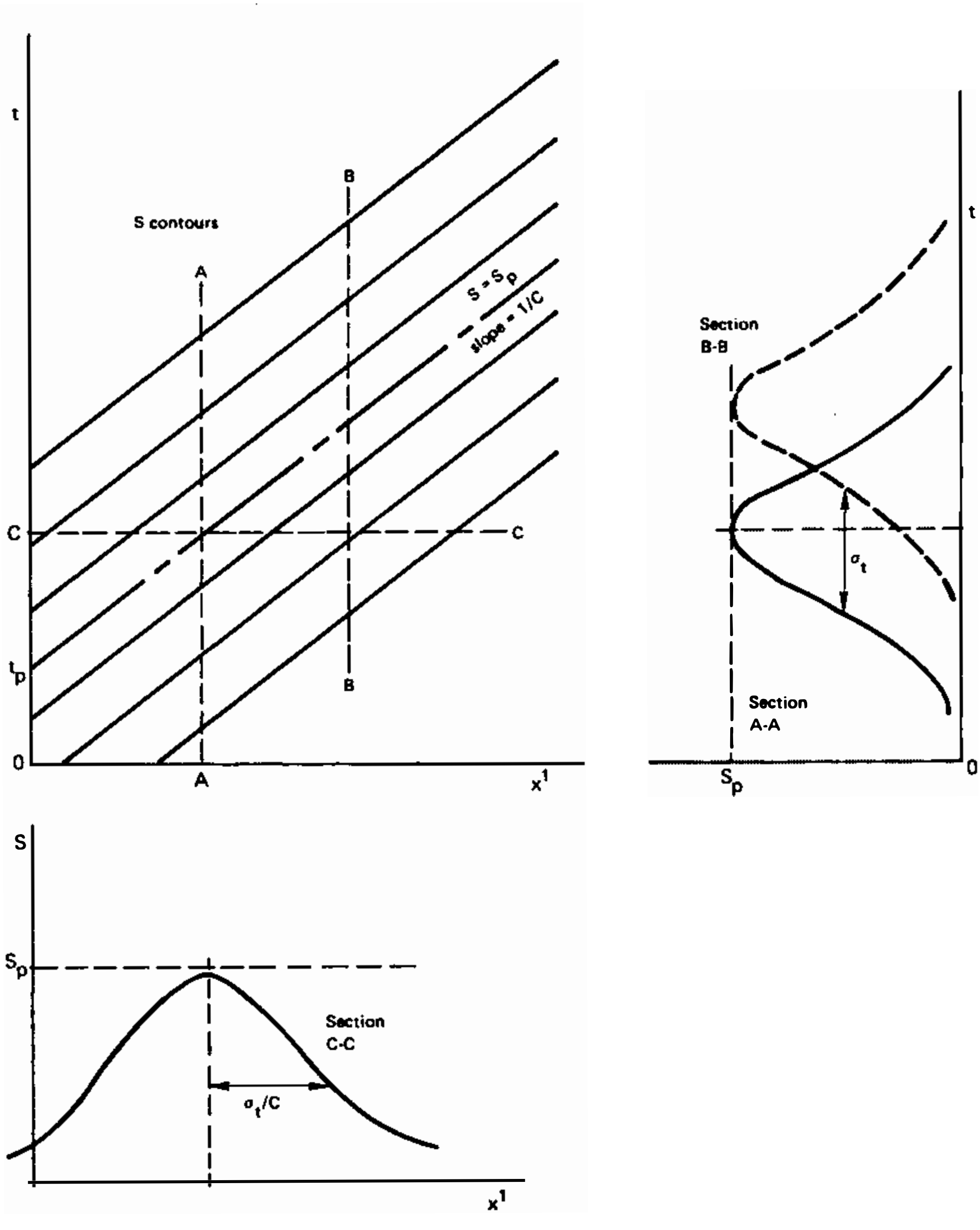

FIGURE 2 Distribution of surge height vs. x and t and the corresponding envelope of maximum surge height along the coast for a non-landfalling hurricane.

it to dealing with storms that landfall perpendicular to the coast. On the other hand, however, the feasibility of producing this kind of information is demonstrated by Jelesnianski's work with the NOAA SPLASH models resulting in nomograms that relate S_p to D, R, U, and Θ for what Jelesnianski defined as a "standard" landfalling hurricane moving across a "standard" basin.[21] The same types of nomogram (i.e., relating S_p to D, R, U, and Θ or L) can be developed for different reaches of the Atlantic and Gulf coasts, assuming a standard or idealized basin, without any reprogramming of the SPLASH models. With only a little reprogramming--and that confined to the output stages of the models as contrasted with the mathematical stages of the models--the SPLASH models offer the capability of being able to provide the information necessary to create nomograms that relate the other needed characteristics of the surge (x_p, t_p, σ_x, σ_t and C) to D, R, U, and Θ or L.[22] This capability derives from the fact that the SPLASH models are developed to "track" hurricanes in both real time and space and to display information about the peak surge heights resulting alongshore as the storm traverses the basin.

The SPLASH models are not applicable everywhere, however, because the models assume: (1) an ideal basin having a straight unbroken coastline; (2) a vertical land mass on the coast with a finite sea depth at the

[21]Chester P. Jelesnianski, "SPLASH (Special Programs to List Amplitudes of Surges from Hurricanes) Part I--Landfall Storms," op. cit., pp. 4, 6, and 11.

[22]Using the SPLASH models, NOAA already has developed relationships for peak surge at shore in terms of height of these hurricane parameters; and has published resulting nomograms for a landfalling hurricane at different locations along the Gulf and Atlantic coasts. NOAA's work indicates that, for a given location, S_p is most sensitive to changes of the hurricane parameters D, U, and Θ or L and only slightly dependent on R. It is evident that the other five parameters characterizing the surge can be related to these same hurricane parameters, and it is anticipated that the dependence of the other parameters describing the surge characteristics of these hurricane parameters would be as follows: x_p and σ_x ought to depend primarily on R and Θ; t_p and σ_t ought to depend primarily on R/U and Θ; and C ought to depend primarily on U and Θ with C being larger than U for a landfalling hurricane and equal to U for a hurricane moving parallel to the coast.

coast; (3) a wide shallow Continental Shelf, the width of which is greater than but of the same order of magnitude as the radius of maximum winds of the hurricane; and (4) linear wind-water dynamics. Thus, while the SPLASH models are directly applicable on the Atlantic and Gulf coasts when the radius of curvature of the land mass is an order of magnitude larger than the radius of maximum winds of the hurricane, they are marginally applicable when the radius of curvature is larger but of the same order of magnitude as the radius of maximum winds and are inapplicable when the radius of curvature is less than the radius of maximum winds (a condition that prevails for virtually all bays and estuaries and some deltas and capes).

Notwithstanding these limitations, the SPLASH models of the NOAA currently provide the soundest basis for determining, along unbroken coastlines of the Atlantic and Gulf coasts, the temporal and spatial characteristics of a hurricane-induced surge that must be related to hurricane parameters for use in the conduct of a FIS. Unfortunately even though the NOAA SPLASH models are nonproprietary, they cannot be applied by other public or private engineering organizations because, for example, the required computer programs are written specifically for the NOAA CDC6600 computer, make use of other special NOAA program subroutines, and have not been documented. More important, although the programs are reasonably straightforward, confident interpretation of the computer results requires substantial briefings and extensive study. This is particularly true with the SPLASH II model (used in connection with alongshore hurricanes) whose computer program requires that surge computations begin 12 hours before and end 12 hours after the storm passes the midpoint of the length of coast to which the model is being applied, resulting in spurious waves being predicted at the beginning and at the end of the computational run for rapid-moving storms and from the beginning of the computational run for slow-moving storms because of artificial reflections at the lateral boundaries of the basin.

In view of this situation and inasmuch as the Federal Insurance Program cannot be delayed until the NOAA can study each of the large number of coastal communities requiring a FIS, the immediate solution is to have the NOAA use its models to generate information on storm-water characteristics that can be used in the conduct of a FIS by other professional organizations. To this end, it is recommended that the FIA request the NOAA to publish, in the form of nomograms, the relationships among the temporal and spatial characteristics of surges and hurricane parameters for various reaches of the Atlantic and Gulf coasts. The surge characteristics to be considered are: peak surge height, position of peak surge on land relative to position of storm center, time of peak surge on land relative to the time the storm center is closest to the point of peak surge, the standard deviation (distance spread parameter) of the surge profile alongshore at the time peak surge occurs, the standard deviation (time spread parameter) of the surge hydrograph at the position alongshore at the point the peak surge occurs, and the trace speed at the surge crest alongshore. The hurricane parameters to be considered are: central pressure anomaly, radius to maximum winds, forward speed, and path (angle of incidence on coast of landfalling storms or distance from shore of alongshore-moving storms). It is expected that, in the implementation of this recommendation, the NOAA will have to conduct certain statistical analyses and that the FIA and the NOAA would resolve between them the length of and order in which reaches are to be studied, due consideration being given to the order in which FIS are to be made and the quality of oceanographic and meteorological data available for the reaches.

As mentioned earlier, the characteristics of the surge produced by a hurricane with given characteristics depend on various near-shore geographic features. This is particularly true in the case of the profile of water depth near shore (the shallower the coastal water the higher the surge). To account for this variation, NOAA has developed "shoaling factors" defined as the ratio of the height of the surge that would be produced at a point along the coast having a specific profile of water depth near shore by the standardized hurricane to the height that would be produced in the standard or idealized basin by the standardized hurricane. Because the nomograms to be developed by NOAA are to be based on consideration of a standard or idealized basin, shoaling factors will be required to apply the nomograms to specific points within the reaches. Thus, it is recommended that FIA request NOAA to publish, in the form of graphs, the variation of the shoaling factor along the reaches of the Atlantic and Gulf coasts for which nomograms are produced.

D. APPLICATION OF THE NOAA NOMOGRAMS

Since the new approach for determining the areal extent and height of overland flooding having a given probability of occurrence requires studying the inland effects of a number of storm water and wind conditions of individual hurricanes, it is anticipated that the organization conducting a FIS will need to consider a number of hurricanes (each having a particular D, R, U, and Θ or L) and will derive a number of corresponding surges (each having a particular S_p, x_p, t_p, σ_x, σ_t, and C).

The nomograms to be produced by NOAA are intended merely to supplant the need for each organization conducting a FIS to have direct access to the SPLASH models to derive the surge characteristics of a hurricane. The organization performing a FIS still will be required to choose the parameters of individual hurricanes to be used in conjunction with the nomograms and shoaling factor information in order to derive the corresponding surge characteristics applicable to the community under study and to relate the surge characteristics obtained to astronomical tide and wind field information derived from the parameters of the corresponding hurricane in order to study the flow of the storm waters from the coast to inland regions.

The organization conducting a FIS also will have to derive the probabilities of occurrences of the surge parameters. This can be done by assuming that the probability of occurrence of a particular set of S_p, x_p, t_p, σ_x, σ_t, and C values is the same as the probability of occurrence of a particular set of D, R, U, and Θ or L values. Then, given the probability of occurrence of the individual hurricane parameters (and knowledge about whether the hurricane parameters are independent or interdependent variables in the reach), by mathematical theory, the method of joint probabilities provides the soundest basis for assigning a probability of occurrence to a particular set of surge characteristics. Accordingly, it is recommended that the FIA request the NOAA to publish, in the form of tables or graphs, the probabilities of annual occurrence of various values for each hurricane parameter in each reach for which nomograms are produced by NOAA. It is anticipated that statistical analyses conducted to produce this information will provide the basis for a discussion in the NOAA publication of the independence or interdependence of the hurricane parameters in the reach studied. In the absence of such discussion, the parameters can be assumed to be independent.

In using the nomograms, which are to be prepared on a reach basis, to characterize the storm waters and winds occurring at a particular community within the reach, it should be recognized that implicit in the recommendation that NOAA provide probabilistic meteorological data on a reach basis is the idea that this meteorological data can be applied throughout the reach. In other words, there is an equal probability that the meteorological data provided by NOAA is applicable to a particular community or to any point on the coast above or below a community within the reach. This being the case, the nomograms can be applied at any point within the reach. The organization conducting the FIS can thus assume that the position alongshore of the peak surge (x_p) for any particular hurricane occurs at any point on the coast relative to the community under study. Then, by using the nomograms and the probabilistic hurricane data, the organization can derive the balance of the surge characteristics and the probabilities associated with this set of surge characteristics and also position the particular storm relative to the community.

To characterize fully the storm waters at a particular point, the peak surge height (S_p) and the time spread parameter of the surge hydrograph (σ_t) derived must be combined in some fashion with the oscillations of astronomical tide about standard mean sea level. Again, the method of joint probabilities provides the soundest basis for assigning a probability of occurrence to a particular algebraic addition of surge height and astronomical tide, given the probability of occurrence of the surge height and various heights of astronomical tide. To facilitate this computation, it is recommended that the FIA request the NOAA to publish, in the form of tables or graphs, the probabilities of annual occurrence of various heights of astronomical tide above or below standard mean sea level at various points within the reaches for which nomograms and meteorological data on hurricanes are to be published by the NOAA. It is anticipated that the FIA and the NOAA will cooperatively select the points within the reaches based on the availability of oceanographic data and the needs of the FIA with regard to future FIS.

E. FURTHER STUDY AND RESEARCH NEEDS

Notwithstanding the advisability of using the SPLASH models during the immediate future to generate information about the temporal and spatial characteristics of coastal surges from hurricanes for the purposes of Flood Insurance Studies, the SPLASH models do not provide estimates of surge height within $\pm$ 0.5 feet. Even when the meteorology of a particular hurricane is well defined (e.g., when the National Hurricane Center is tracking an ongoing hurricane), the predicted maximum surge height at a community on the open coast using the SPLASH models seems to lie rather consistently within a range of $\pm$ 2 feet of observed maximum surge height at the point. Moreover, the difference between the surge hydrograph predicted for a community on the open coast using these models and the surge hydrograph observed at the community could introduce significant uncertainty in subsequent estimates of the areal extent and height to which inland areas are flooded by a hurricane.

This situation largely arises because the SPLASH models--as well as other existing empirical, one-dimensional, and two-dimensional computational methods used to characterize the surge caused by hurricanes[23]--were developed on the basis of available historical data. They have only

[23]See, for example, W.C. Connor, R.H. Draft, and D. Lee Harris, "Empirical Methods for Forecasting the Maximum Storm Tide Due to Hurricanes and Other Tropical Storms," Monthly Weather Review, DXXXV, (April 1957): 113-16; D. Lee Harris, An Interim Hurricane Storm Surge Forecasting Guide, U.S. Weather Bureau National Hurricane Research Project Report 32, (Washington: U.S. Department of Commerce, 1959); M. Miyazake, A Numerical Computation of the Storm Surge of Hurricane Carla 1961 in the Gulf of Mexico, University of Chicago Department of Geophysical Sciences Technical Report 10, (Chicago, Ill.: University of Chicago, 1963); and Leenderste, op. cit.

been subjected to the necessary test of verification by hindcasting surges produced by particular historical storms. Note must be taken that both the development of the models and the verification tests of the models have suffered from the paucity and quality of data available about historical hurricanes and their effects. The number of wind and tide gauges in most coastal areas has been inadequate to specify the wind field and surge distribution of individual hurricanes. Additionally, most tide gauges have been located in bays and estuaries, rather than on the open coast, and most of these gauges, as well as the anemometers, have been located on structures incapable of withstanding even a moderate hurricane. As a result, the statistical correlations used to develop the models have entailed substantial sampling errors and, thus, the fit to the record experience used to verify models really have been checks on the arithmetic of the models and not checks against how well the properties of a given hurricane surge represent the total population. Even so, in the verification tests, the resulting fit to the record experience by any one model has not been close enough to assure capability to predict height or other characteristics of the surge with the accuracy that may be be required to subsequently estimate the areal extent and height of inland flooding to the accuracy desired in a FIS. The accuracy of the joint probability approach recommended herein for estimating the probability of the temporal and spatial characteristics of coastal surges also would be enhanced if certain assumptions inherent in the approach were studied to determine their appropriateness. For example, while available evidence, such as that presented by Graham and Nunn,[24] seems to support the assumption of independence among storm parameters, the assumption is not necessarily valid for all possible combinations of storm parameters. Indeed, severe storms may arise because of significant combinations of parameters. In any event, study of available literature indicates that sensitivity tests with implicit intercorrelations to determine whether weak interactions could have significant effects on rare combinations have not been run. Additionally, the approach recommended herein assumes independence among surge, tide, and other secondary effects of storms. Despite the

[24]H.E. Graham and D.E. Nunn, Op. cit.

fact that present knowledge does not permit consideration of these factors in a more sophisticated fashion, it is to be appreciated that surge dynamics cannot only be greatly affected by such factors as variations in local mean sea level, surf, swell, and the break of short gravity waves but that the effects of these factors on surge dynamics do not necessarily lend themselves to treatment by simple superposition of water effects.

One of the reasons a more comprehensive approach to dealing with surges or irregular coastlines does not exist is that little research has been addressed to the "feedback" effect of flooding of low-lying coastal areas on the surge height at shore (one example of a location where this could be important is the region of the Mississippi delta). Another reason is that little is understood about how the presence of bays and estuaries affects the surge at points along the coast away from the entrance to the bays and estuaries. Observations suggest, for example, that the presence of the Chesapeake Bay can have a very significant influence on the coastal surge some distance away from the entrance.

Thus, it is concluded that substantial improvement in the accuracy currently obtainable by application of the SPLASH models and the joint probability approach requires an expanded oceanographic and meteorological data base that can be used to gain better understanding of the relationship among hurricane parameters, surge characteristics, and on-shore and near-shore geographic features. Therefore, it is recommended that the FIA encourage the NOAA, CE, USGS, and other appropriate agencies and institutions to undertake an expanded meteorological and oceanographic data collection program in coastal areas in order that the engineering and scientific community can further study and research: (1) the assumption of independence among storm parameters; (2) the assumption of independence among surge, astronomical tide, and other initial water conditions; (3) the "feedback" effect of flooding of low-lying coastal areas on surge height and growth at shore; and (4) the effect of the presence of bays and estuaries on the surge at points along the coast away from the entrance to the bays and estuaries. In connection with expansion of the oceanographic and meteorological data collection program, it may be desirable for the agencies to use the SPLASH models to estimate the sensitivity of coastal-surge prediction to open ocean wind, air pressure, and initial elevation parameters as part of the basis for evaluating the extent of the need for more detailed open ocean data.[25] To facilitate this, and to create a greater chance for improving the SPLASH models by giving a wider spectrum of the engineering and scientific community an opportunity for "hands on" experience, the FIA should request the NOAA to document and publish the programs and subprograms of its SPLASH models.

[25] In any event, at a minimum the NOAA, CE, and USGS should make a reasonable effort to increase the probability of obtaining continuous records during storms by reinforcing instrument platforms and augmenting instrumentation in those regions with a history of instrument failures or washouts during storm events.

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