NOAA Technical Report NWS 18

Joint Probability Method of Tide Frequency Analysis Applied to Apalachicola Bay and St. George Sound, Florida

Francis P. Ho and Vance A. Myers

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(Continued on inside back cover)

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Rogers C. B. Morton, Secretary

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JOINT PROBABILITY METHOD OF TIDE FREQUENCY ANALYSIS APPLIED TO APALACHICOLA BAY AND ST. GEORGE SOUND, FLORIDA

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ABSTRACT. Storm-tide height frequency distributions are developed within Apalachicola Bay and St. George Sound, Florida, for the National Flood Insurance Program. This is accomplished by applying Overland's numerical bay model to a full set of climatologically representative hurricanes. Surge computations by the continental shelf SPLASH model are used as the boundary input from the Gulf of Mexico. Tide levels are shown in map form and as frequency distributions at selected points between annual frequencies of 0.10 and 0.002. The report illustrates the application of a joint probability method to assessing storm tides within a bay using a hydrodynamic model.

1. INTRODUCTION

1.1 National Flood Insurance Program

The National Flood Insurance Act of 1968 as amended and the Flood Disaster Act of 1973 provide for a National Flood Insurance Program to be administered by the Secretary of Housing and Urban Development. The purposes are to make flood insurance available to property owners on a nationwide basis through cooperative efforts of the Federal Government, private industry, and local government. Essential to establishing the flood insurance program in any community, whether on the coast or in a river valley, is a flood frequency analysis. The Secretary has delegated these responsibilities to the Federal Insurance Administration (FIA). Other Federal agencies cooperate under reimbursable agreements in areas related to their own expertise. The National Oceanic and Atmospheric Administration (NOAA) has collaborated by making the necessary tide frequency analyses in coastal regions exposed to hurricanes.

1.2 Objective of This Report

Tide frequencies have been evaluated on the coast for the Flood Insurance Program by NOAA for a number of coastal reaches using a joint probability and modeling approach. This method is covered in detail in a recent report (Myers 1975). The study method includes a) determining the climatological probability distribution of certain key hurricane characteristics, b) calculating tide levels produced on the coast from a large number of climatologically representative hurricanes by use of a hydrodynamic model available from other work (Jelesnianski 1967, 1972) and c) performing a frequency analysis of the resulting computed tides. This technology applies directly only to beach locations facing the open ocean, as the cited hydrodynamic model is a continental shelf model and does not calculate hurricane tide behavior within bays and estuaries.

A large fraction of the population and property in the coastal zone subject to attack by hurricane tides is located along shores of bays and estuaries. NOAA undertook a pilot project of extending the joint probability method to storm-tide assessment in bays and estuaries as a contribution to the Flood Insurance Program. Apalachicola Bay and St. George Sound, Fla., were selected for the pilot project. First, a hydrodynamic model had to be developed for routing storm tides into the bay. This was done and has been reported separately (Overland 1975). The present report illustrates the specific application of the bay model, together with the previous technology, to the assessment of hurricane tide frequencies in the selected bay, and summarizes factors that would need to be taken into account in such applications to bays and estuaries in general. This report also forms the technical basis for flood hazard boundary maps being prepared by the National Ocean Survey, NOAA, for the FIA for the portions of Franklin County subject to inundations from the sea.

1.3 Study Area

The study area is the portion of Franklin County, Fla., that is subject to storm tide inundation, mapped in figure 1. The coast of the county extends from Indian Pass to Ochlockonee Point and includes the Gulf of Mexico side of St. Vincent, St. George, Dog, and St. James Islands. Partially protected waters include Apalachicola Bay and its extensions, St. Vincent Sound and East Bay, and St. George Sound. All are rather shallow. Principal towns are Apalachicola and Carrabelle. Areas normally above high tide but subject to inundation from extreme storm tides include a portion of the mainland north of Apalachicola and East Bay, a region around Carrabelle, lower parts of the islands, and narrow regions along all shores.

The Franklin County area was selected for this pilot study because a Flood Insurance assignment (type 15) had been made to NOAA by the FIA and because the Apalachicola Bay, St. George Sound system is a semi-enclosed shallow body of water that would be expected to respond both to the influence of the storm surge from the gulf and wind setup over the bay. Figure 2 shows the locations in the bay selected for tide frequency computations.

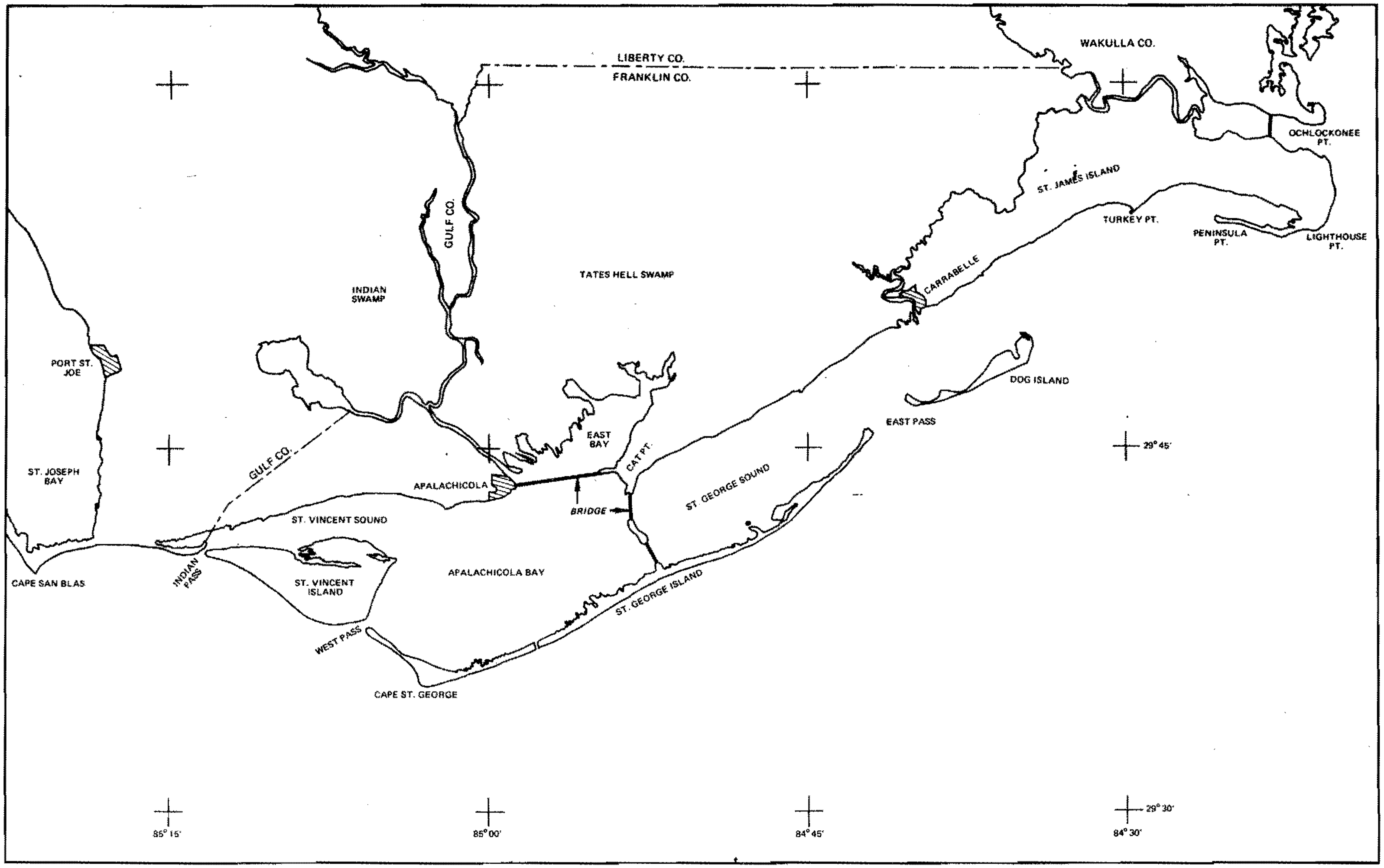

Figure 1.--Study area locator map.

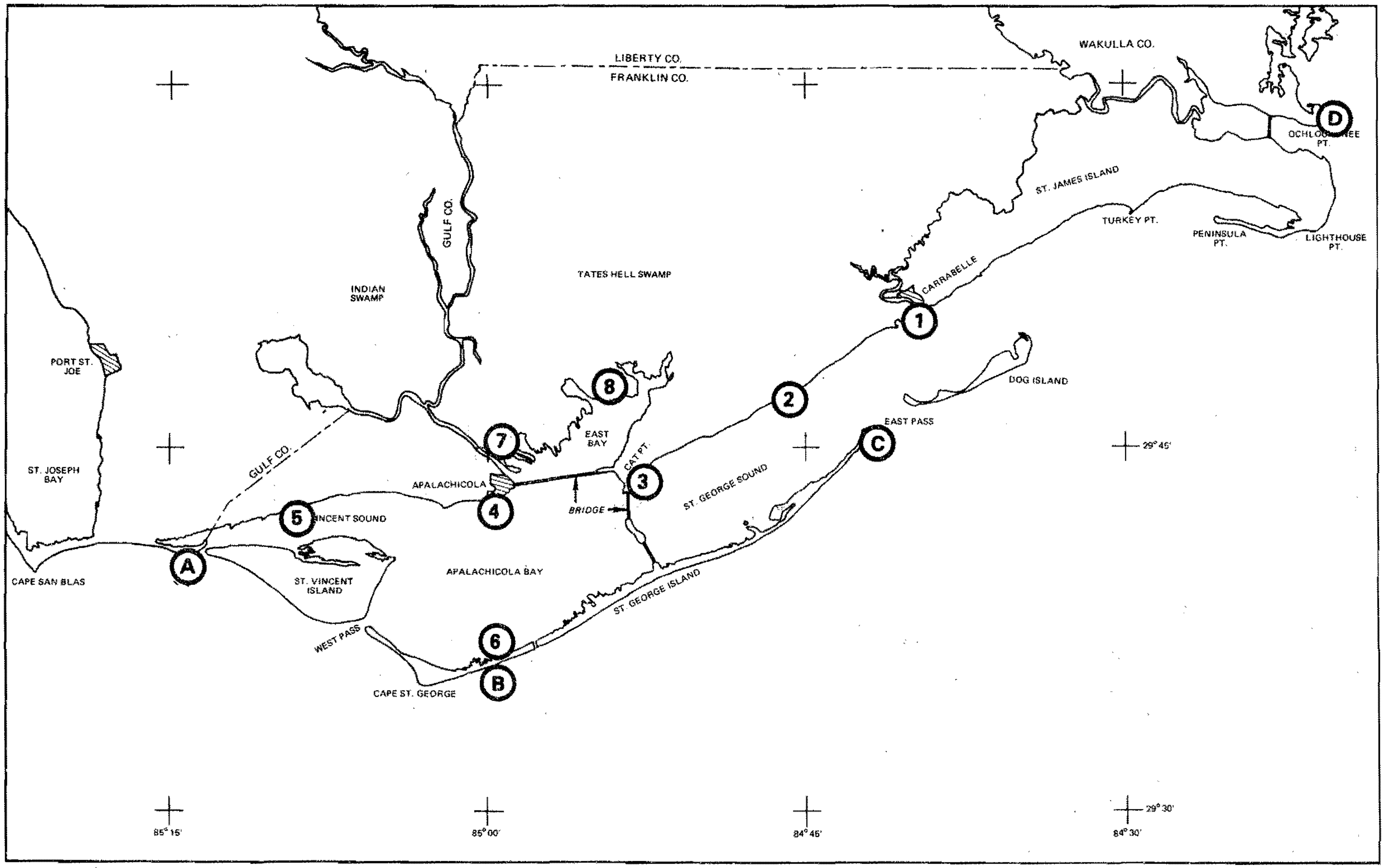

Figure 2.--Locator map for locations selected for storm tide frequency computations using the bay model (numbers). Letters identify coastal points in figure 4.

1.4 Authorization

This study was funded by the Federal Insurance Administration under HUD-NOAA Annual Agreement IAA-H-5-73 and Project Order No. 5 relating to Franklin County.

1.5 Relation to Other Reports

The climatological characteristics of hurricanes in the region are taken from the compendium by Ho, Schwerdt, and Goodyear (1975). Storm-tide frequencies within the bay are tied into a separate determination of open coast tide frequencies on the Gulf of Mexico side of the barrier islands, carried out by the methods cited in the first part of par. 1.2 in the report "Storm Tide Frequency Analysis for the Gulf Coast of Florida from Cape San Blas to St. Petersburg Beach" (Ho and Tracey 1975). The hydrodynamic bay model developed for this project is described in the report by Overland (1975). Overland's work depends on using boundary values from Jelesnianski's SPLASH model (1967, 1972). As indicated, the information generated in this study is being used as the basis for flood hazard zone maps being prepared by NOAA for Franklin County. Coastal tide frequencies at the Franklin County-Gulf County boundary in this report are identical with the values for Gulf County in a separate NOAA report.

1.6 Historical Notes

The most severe known hurricanes to affect Franklin County struck in close succession in 1837, 1842, and 1851. The County has been affected by lesser or more distant hurricanes, of which the latest was AGNES in 1972, which entered the coast of Gulf County to the west. Historical notes on these and other storms are found in Ho and Tracey's report (1975).

1.7 Definitions

Astronomical tide is the normal daily or twice daily oscillation of the height of the ocean surface and adjacent waters occasioned by the gravitational attraction of the moon and sun acting on the rotating earth. The height and time of the high and low points of this astronomical tide is precomputed and published in annual volumes by the National Ocean Survey. The astronomical tide is also called the gravitational tide.

Surge is the name given to the increase or decrease of the height of the ocean surface and adjacent waters due to storms and wind. The surge at a particular time is calculated by subtracting the height of the precomputed astronomical tide for that particular time from the observed height of the water surface.

Storm tide is the name applied in this report to the total height of the ocean or adjacent water surfaces above local mean sea level in storms. In historical storms, the highest storm tide in a particular storm is the highest water level observed at a tide gage or indicated by a reliable high-water mark at a location where wave effects would not be prominent. In future or postulated storms the maximum storm tide is the maximum sum of the precomputed astronomical tide and the predicted surge.

Wind setup is the increase in water level in portions of bays or estuaries occasioned by the direct drive of the stress from strong winds that moves water from the upwind to the downwind shore. Wind setup is a portion of the surge.

Central pressure--the lowest value of sea-level pressure at the center of a hurricane at a particular time. The central pressure is an index of the overall intensity of the storm.

Radius of maximum winds. Radially outward from the center of a hurricane the wind increases rapidly from slight values to hurricane force then decreases more gradually. The distance from the hurricane center to the wind velocity maximum is called the radius of maximum winds, and is symbolized by R. The radius of maximum winds is used as a numerical index of the size or lateral extent of hurricanes.

Hurricane track--the path on a map of the center of a moving hurricane.

Landfall point--the intersection of a hurricane track and the coast.

Local mean sea level (local MSL). The arithmetic mean of hourly sea-level heights over a specific 19-yr series of observations. Nineteen years is required to complete principal lunar phase cycles. Details are given in the recent revised "Tide and Current Glossary" (Shureman 1949, rev. 1975). Storm tide levels in this report are referred to local MSL, 1941-59 epoch. Sea-level changes are monitored annually at tide control stations throughout the United States to observe the need for changing the reference epoch. Changes are expected about every 25 years.

The National Geodetic Vertical Datum (NGVD) of 1929 is a level surface to which elevation contours on current topographic maps are generally related. The position of this surface, which is everywhere perpendicular to the earth's gravity field, is defined by precise leveling between geodetic benchmarks throughout the United States. This datum is approximately but not exactly at the mean level of the sea on the coast. It cannot coincide exactly because of the facts that the sea is not a geopotential surface, and that sea level has risen by unequal amounts along the coast since the 1929 adjustment. Differences between NGVD and local MSL for this study are given in par. 3.6.1.

2. HURRICANE TIDE FREQUENCIES OUTSIDE BARRIER ISLANDS

Figure 3 shows profiles of tide frequencies along the open coast of Franklin County, from figure 6 of the cited regional study, "Storm Tide

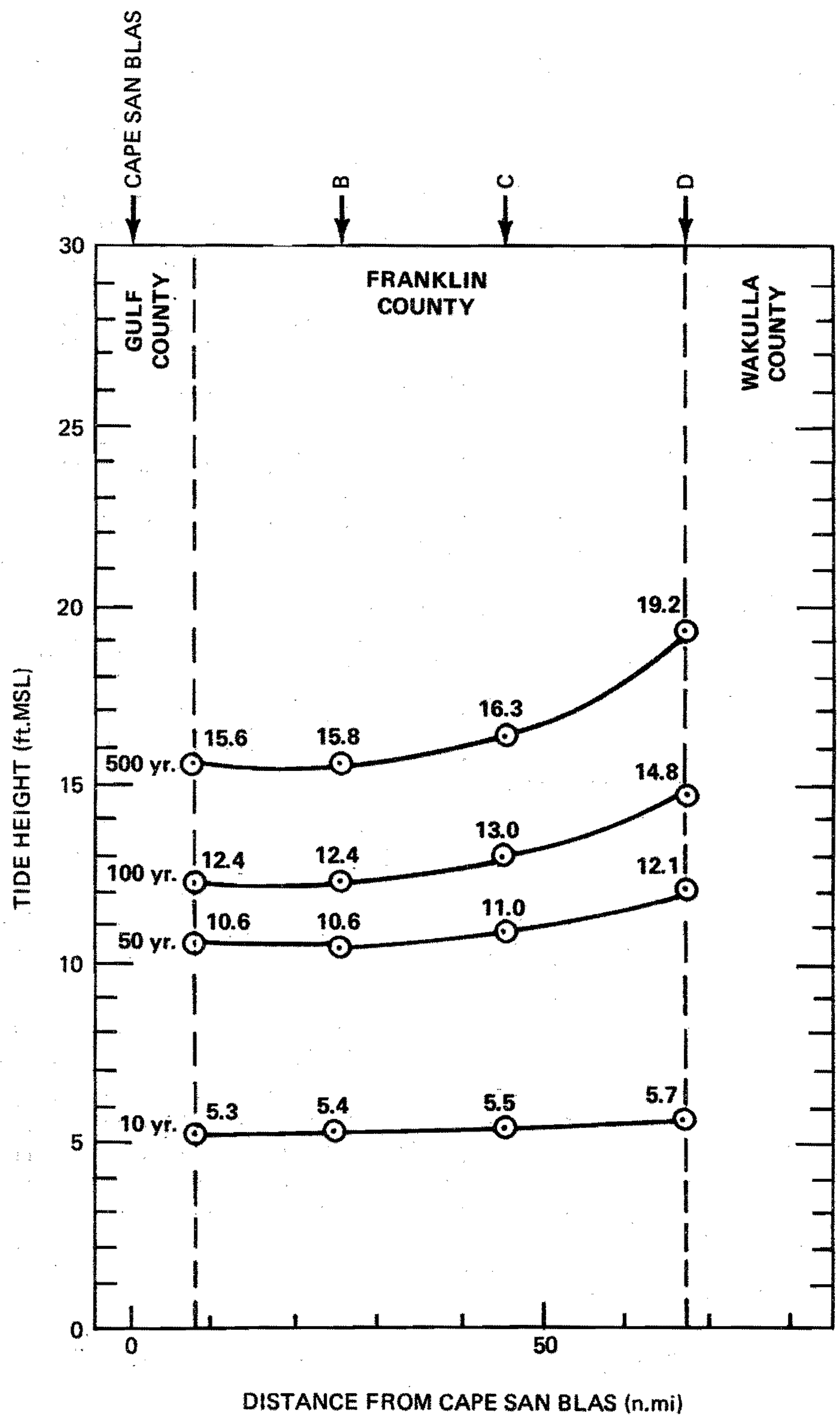

Figure 3.--Tide frequency profiles along open coast of Franklin County (open coast defined in section 2). Datum reference is local MSL, 1941-59 epoch. For differences from National Geodetic Vertical Datum of 1929 see par. 3.6.1.

Frequency Analysis for the Gulf Coast of Florida from Cape San Blas to St. Petersburg Beach" (Ho and Tracey 1975). These profiles pertain to the Gulf side of St. Vincent, St. George, and Dog Islands and, at the east end of the county, to a line connecting Turkey Point, Peninsula Point, Lighthouse Point, and Ochlockonee Point. Figure 4 shows the same information as storm tide frequency curves at Indian Pass, on St. George Island south of Apalachicola, at East Pass, and at Ochlockonee Point.

3. HURRICANE TIDE FREQUENCIES INSIDE BARRIER ISLANDS

3.1 Governing Physical Factors on Storm Tide

The response of bays and estuaries to hurricanes is a complex function of storm intensity and duration and local geography. The stage and phase of the astronomical tide may make appreciable modifications of the storm surge if the astronomical tide range is large.

The first factor in the bay response is the propagation of the open ocean surge into the bay. For this the width of the mouth of the bay is critical. Small bays with wide entrances will fill completely during most storms, while large bays with small openings from the sea will not fill to the ocean storm tide level during storms of short duration. The effective width of entrances may depend on the height of the storm tide, as high tides will overtop low barrier islands.

The second major factor in bay and estuary response is wind setup, defined in par. 1.7. Wind setup is more effective in shallow water than deep and is also related to the length of over-water fetch along the wind direction.

The atmospheric pressure gradient places an additional stress on the water and is important in the open sea but is small compared to other effects in bays.

Flooding of low-lying terrain is an important factor, as water that might otherwise contribute to a high surge at a particular location is effectively spread over a large area. However, strong local wind effects can be expected on these newly created shallow flats.

Converging channels distinctly raise water levels unless these are dissipated by flooding over adjacent flats.

Timing of events is critical. The most important open coast storm tide parameters are the maximum height and the duration that the water level remains high. As indicated, the open coast tide may or may not have time to fill the bay. The hurricane winds over a bay vary in speed and direction over a time scale of hours. Within the bay, propagation of the open coast surge and the wind setup can work together or in opposition. High water in back bays may be the result primarily of

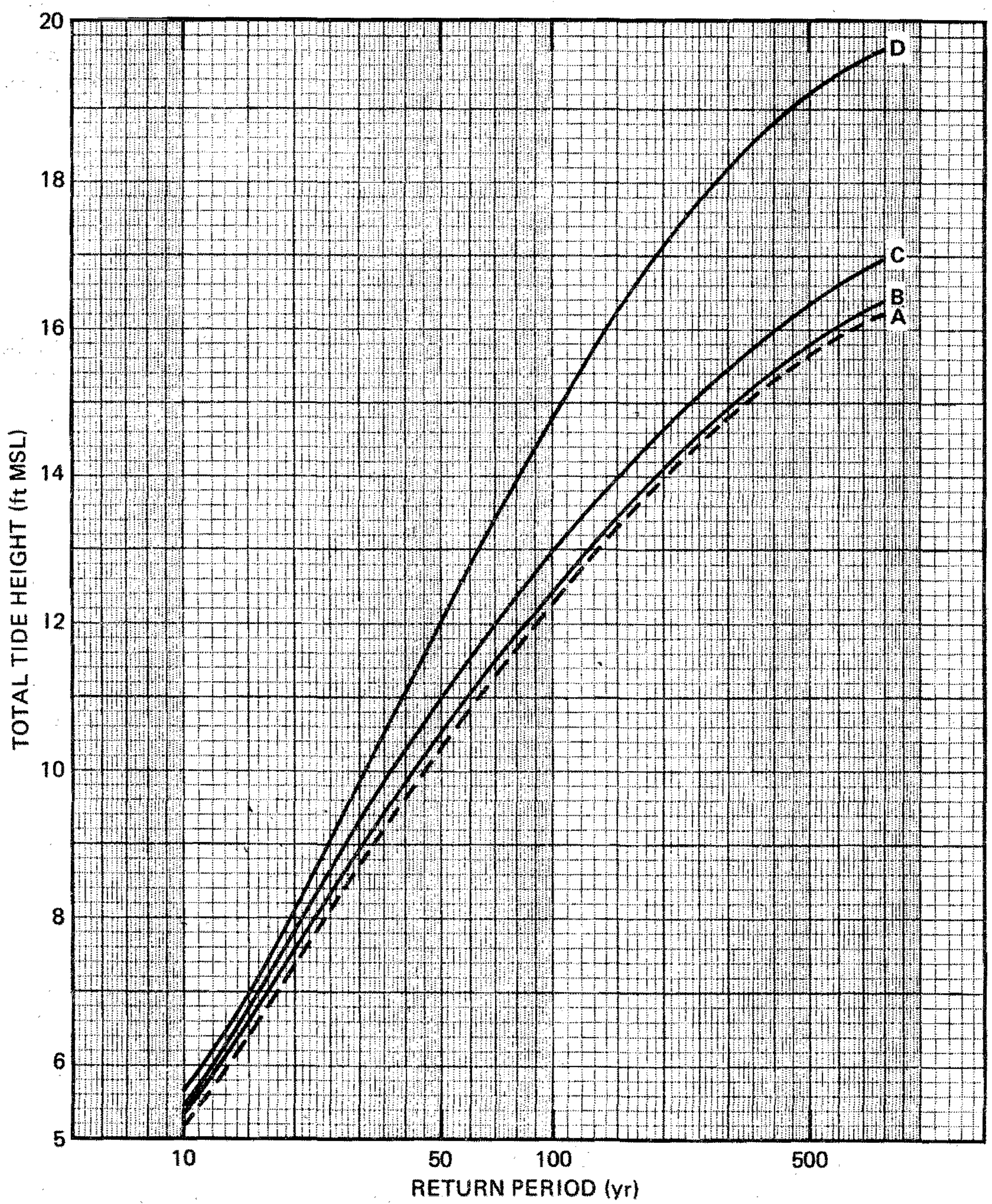

Figure 4.--Total tide frequency curves for the open coast of Franklin County, Fla., at selected locations: (A) Indian Pass, (B) St. George Island (south of Apalachicola), (C) East Pass, and (D) Ochlockonee Point. Locations in figure 2.

wind setup, or the propagation of the open coast surge or any combination. All of these effects are evident in the Apalachicola Bay results.

Nonlinear interaction between the surge and astronomical tide should be taken into account in systems with large tidal amplitudes, and long shallow water fetches. In the present study, because of the small astronomical tide amplitude, the interaction was neglected. Storm surge was computed on initial mean sea level and tidal effects added as a fixed correction (par. 3.6.2).

Heavy rain is a customary feature of hurricanes and can also fall in advance of the storm. In narrow estuaries with large drainage basins the water level can rise from runoff (as well as rain directly on the water surface) and thus alter the basin response to the storm surge. In the present study the ratio of drainage area to bay area is not large enough to produce a significant runoff effect. Runoff from rain was therefore neglected. Tropical storm rainfall in the region has been analyzed on a frequency basis by Goodyear (1968).

3.2 Governing Factors on Hurricane Wind Speed and Direction Over a Bay

3.2.1 Basic Hurricane Wind Pattern

A hurricane is a vast storm in which the wind spirals inward in a counterclockwise direction (Northern Hemisphere) in an approximately circularly symmetric pattern. The wind increases from the edges of the storm to the highest value at the radius of maximum winds, R, then decreases abruptly to low values near the center. There is usually some asymmetry to the pattern with the highest winds on the right side as the storm moves forward. The incurvature angle is generally less at the radius of maximum winds than at greater radial distances.

3.2.2 Storm Track Location with Respect to a Bay

A bay experiences the strongest winds from a hurricane of given intensity and lateral extent when the storm track is about at distance R to the left of the center of the bay, as viewed from the sea. This is also the track that gives the highest storm surge at bay entrances on straight uniform coasts.

3.2.3 Modifications by Adjacent Land Areas

Land areas modify the hurricane wind field in two ways. First, hurricanes weaken over land; that is, the pressure gradients that drive the wind become less. If the hurricane must progress some distance inland to affect a bay (for example, to move up the left side of Chesapeake Bay) then the whole storm will typically weaken progressively from its coastal intensity. The other effect is a local one. The greater surface roughness over land impedes the wind more than open water, for the same driving pressure gradient. The increased roughness means greater turbulence and perhaps a greater wind stress coefficient. To recover from the first effect, the whole hurricane must move from land to water, e.g., from the Florida Peninsula into the Gulf of Mexico. Recovery from the second effect is quite local. Off-shore winds increase to over-water values (corresponding to the existing pressure gradient) in a short distance; the precise distance is not known. Thus, only the portion of a bay immediately downwind of a large land surface will have the hurricane winds reduced somewhat. A possible third effect on long bays, estuaries, or lakes is a tendency for channeling of the wind along the long dimension of the water surface. Because of the size, shape, and location of Apalachicola Bay--immediately adjacent to the Gulf of Mexico with only narrow barrier islands between--no reduction for land effects on hurricane winds was made in this study.

3.2.4 Hurricane Wind Models

The SPLASH hydrodynamic model for hurricane surges on the continental shelf (Jelesnianski 1972, Jelesnianski and Taylor 1973) calculates a wind field instant-by-instant as the storm moves forward from specified depression of the central pressure, the radius of maximum winds, and forward motion. (In this discussion winds are understood to be 30 ft above open water.) This study uses Overland's (1975) model which in turn uses a simplification of the SPLASH wind procedure to calculate winds from specified hurricanes instant-by-instant at the grid points over the bay. Details are given in the cited report. Other wind models have been used by other investigators, for example Graham and Nunn (1959). Any differences between these models were not considered critical for Apalachicola Bay. For larger bays (e.g., Pamlico Sound or Chesapeake Bay) careful consideration would need to be given to modeling of the wind.

3.3 Hydrodynamic Model for Apalachicola Bay and St. George Sound

The two-dimensional vertically integrated numerical model for simulating hurricane surges in Apalachicola Bay and St. George Sound previously referred to and developed for this project is described in the report by Overland (1975). Limitations of the model and its verification are also described in the reference. For a given hurricane the open coast surge is calculated by the SPLASH model (Jelesnianski 1972, Ho and Tracey 1975). The bay model then calculates the propagation of this surge into the bay and the modifications by wind setup and over-land flooding. Topping of the barrier islands by the open coast surge is included. The needed winds are calculated by the bay model from the basic hurricane parameters as indicated in par. 3.2.4. The assumptions and procedures in numerically coupling the continental shelf SPLASH model and the bay model are given in Overland's report.

3.4 Variation of Hurricane Surge

3.4.1 The General Method

By using the hydrodynamic model described in par. 3.3, the maximum surge at any point inside the barrier islands can be computed by specifying a set of hurricane parameters, which are:

D = Depression of central pressure below ambient pressure
R = Radius of maximum wind, defined in par. 1.7
f = Speed of forward motion of the storm
θ = Track direction
L = Landfall point, defined in par. 1.7

Each hurricane is assumed to move forward in a straight line without change in size or intensity. As in the open coast tide frequency analysis, we need to simulate the effects of the variation of each of these parameters over the expected range, a total of hundreds of combinations. Rather than make hundreds of bay model calculations directly, the basic analysis design was to determine from selected bay model runs how surge height varies in the bay with each of the five meteorological parameters if the others are held constant, construct curves depicting these variations, then use these curves to adjust the surges from the selected runs to all the other representative hurricanes. Supports for applying such one-parameter-at-a-time surge variation curves to combinations of variations, neglecting interactions, include: (1) Such a procedure has been found valid for the open coast by multiple SPLASH runs. (2) The surge variation with forward speed is flat (par. 3.4.4), especially within Apalachicola Bay indicating refined treatment of this variable is not necessary. (3) The approximately linear variation of surge with D for the open coast (Jelesnianski 1972, fig. 1) also applies to Bay points.

Other criteria in the analysis design were that accuracy at the 100-yr return period would be optimized by grouping the selected bay model runs around hurricanes tending to give approximately 100-yr surges at the open coast, and that the analysis should proceed in sequence from the most influential to the least influential meteorological parameter. On this last criterion θ went to the bottom of the list. A "standard" hurricane was defined for the analysis having the parameters D = 62 mb, R = 26 n.mi., f = 13 kt, $\theta = 157^{\circ}$ relative to north (approximately normal to coast), and landfall point 38 n.mi. to the left of East Pass. Distance from East Pass is in terms of the bay model grid (Overland 1975) which is oriented parallel to the coast of St. George and Dog Islands. Such a hurricane gives a surge of 16.6 ft at East Pass (by the SPLASH model) compared to the 100-yr value there of 13.0 ft.

The variation of the hurricane surge in the bay due to each of the five parameters is discussed separately in the following paragraphs. This includes a qualitative discussion of the meteorological effects on the open coast surge since this has an important effect on the bay surge.

The surge height in these discussions is the water depth above local mean sea level; the astronomical tide is added later to estimate the total storm tide level (sec. 3.6).

3.4.2 With Landfall Point

The kinetic energy of the shoreward component of the wind is an important coastal surge causative factor. From the geometry of the hurricane wind field pattern (par. 3.2.1) it's evident that the maximum shoreward component is experienced at a given coastal site when the hurricane center landfalls approximately at distance R to the left. On straight coasts with uniform bathymetry, the highest surge along the coast will be experienced at this point of highest wind. Variable bathymetry (as in this study) modifies this location somewhat. Storms landfalling some distance to the right of a coastal site produce offshore winds and thereby negative surges. In the bay, the obvious connective sequence is that the wind setup is related to the strength and direction of the wind, which are related in turn to the storm track position, which is related in turn to landfall point.

In this study, the relation of maximum surge height at points in the bay to storm landfall point, L, was determined by applying the bay model to the "standard hurricane" (par. 3.4.1) landfalling at selected grid point locations: 83, 59, 38, 31 and 4 n.mi. left of East Pass and 7 n.mi. to the right. The resulting surge vs. L relations at selected control points in St. George Sound, Apalachicola Bay, and East Bay are depicted in figures 5, 6, and 7, respectively. The six computed surge values are shown on the point 1 curve as an example. Figure 2 is a locator map for the bay control points.

Comparing these several curves reveals the effects of some of the influences discussed in par. 3.1. The curves show that the maximum surge at Carrabelle (point 1) tends to be higher than at East Pass and decreases up the Sound to the east side of Cat Point (point 3) where it is less than at East Pass. In figure 6, comparing Lower Anchorage (point 6) with Apalachicola (point 4) shows the effect of wind setup in the bay. The wind is toward Apalachicola for landfall points to the left. For landfall points to the right this effect is reversed. As would be expected, the most critical landfall point for St. Vincent Sound (point 5) is farther to the west than for Apalachicola. The most critical landfall point for East Bay (fig. 7) is about the same as for Apalachicola. The difference between the two curves in figure 7 illustrates the effect of the additional wind setup in East Bay.

3.4.3 With Central Pressure

The open coast storm surge varies approximately with the kinetic energy of the wind that is putting stress on the water surface, other factors being held constant. The kinetic energy of the wind, other factors constant, is approximately proportional to the central pressure depression below a representative peripheral pressure. Thus, the coastal surge is

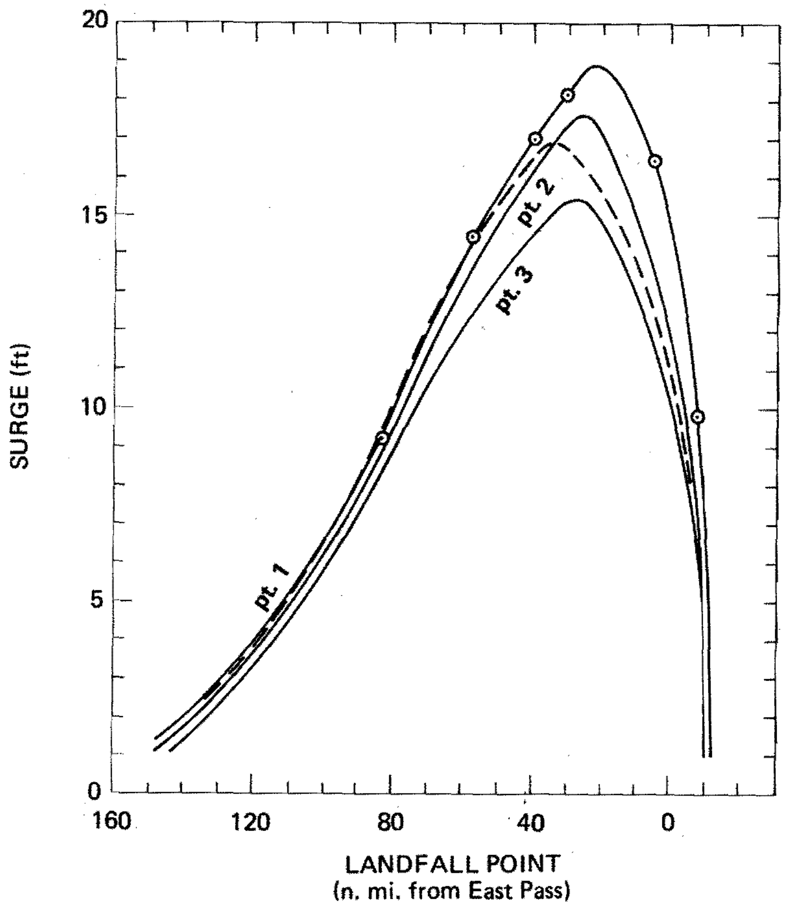

Figure 5.--Maximum surge height vs. storm landfall point at East Pass (dashed curve) and selected locations inside St. George Sound: Carrabelle (point 1), Cat Point (point 3), and about midway between (point 2). Hurricanes "standard" except for landfall point.

approximately proportional to the pressure depression. This was verified by Harris (1959) and by SPLASH model calculations by Jelesnianski (1972, fig. 1). The magnitude of the wind setup effect is also proportional to the kinetic energy of wind for given conditions and thus is also approximately proportional to the concurrent central pressure depression. Thus, both major bay tide-producing forces are proportional to the pressure depression. As pointed out in par. 3.1, however, these forces may not operate in phase, and the variation in surge height with respect to central pressure has to be examined for individual cases. Figure 8 shows the variation of maximum surge height at the control points in the sound and bay, respectively, computed by the bay model for the "standard hurricane" parameters specified in par. 3.4.1 except that D is varied. Model computations were made at four D's ranging from 32 to 72 mb. The variation at East Pass is also shown for comparison.

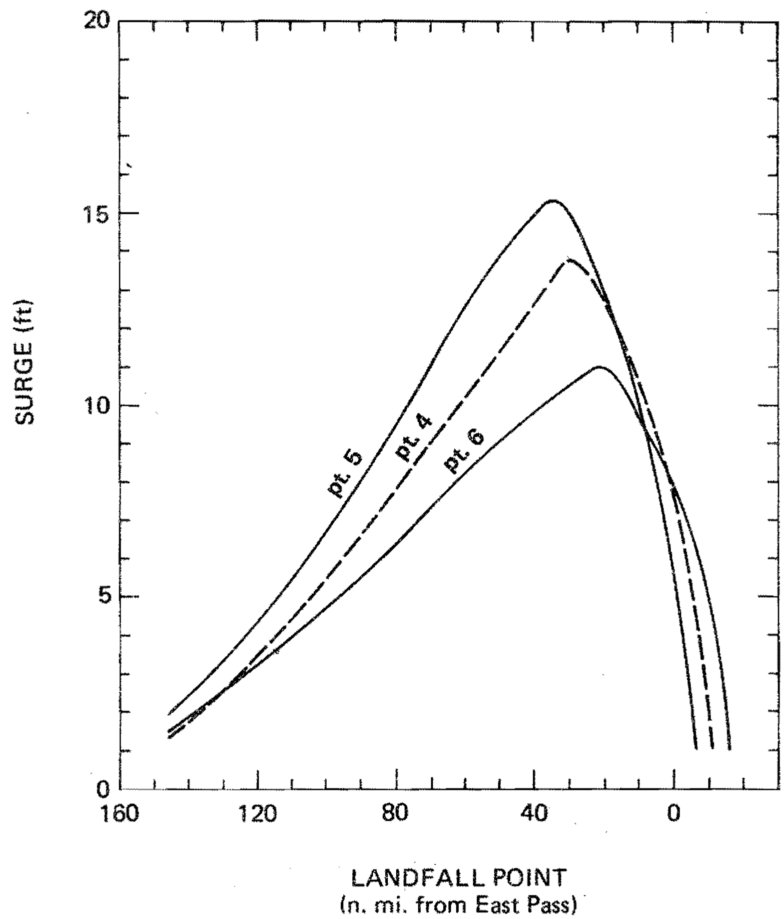

Figure 6.--Same as figure 5 for selected locations inside Apalachicola Bay: Apalachicola (point 4), St. Vincent Sound (point 5), and near Lower Anchorage (point 6).

3.4.4 With Forward Speed

The height of peak surge on the open coast increases with increasing storm forward speed up to a speed higher than that of any recorded hurricane in the study area. This is indicated by one of Jelesnianski's nomograms (1972, fig. 3). The speed of storm motion is also one of the factors that controls the time variation of the surge on the coast, which in turn influences the volume of water transported into a semi-enclosed area. The response of an open sound resembles that on the open coast while the response of a semi-enclosed bay is related to the size of the entrance and the storm speed. Thus a faster storm produces a higher ocean surge but may not have time to fill up a bay, depending on the constriction at the entrance. A slower storm produces a less severe coastal surge but this has more time to penetrate the bay.

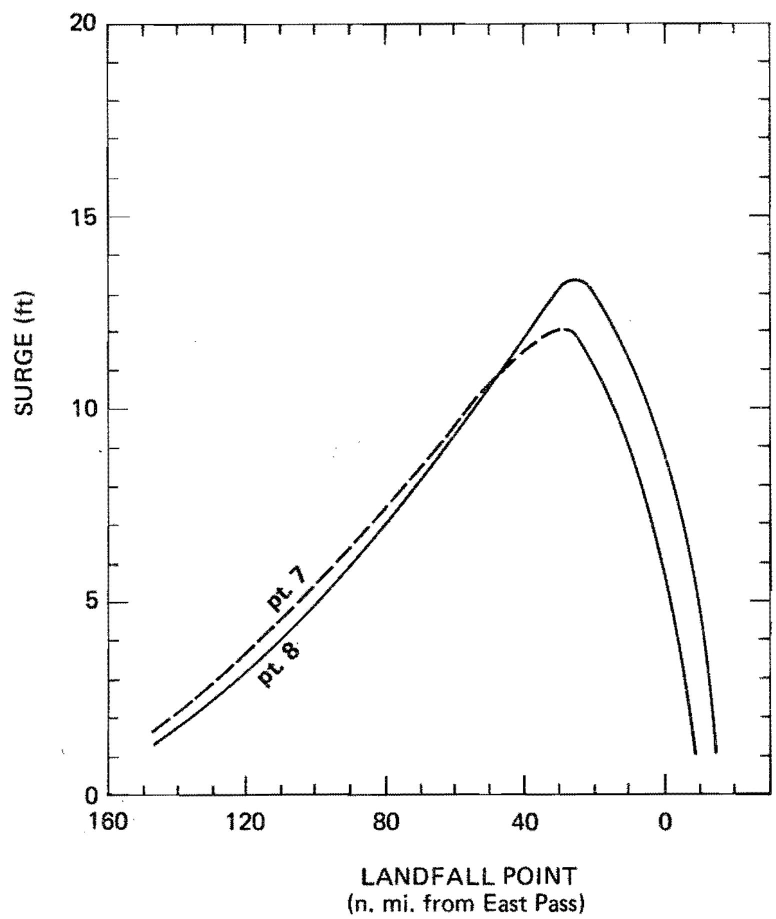

Figure 7.--Same as figure 5 for selected locations in East Bay.

Bay model runs were made as before with the "standard" hurricane except that speed was varied. The resulting variations of the surge with storm forward speed at the eight bay points are depicted in figure 9. Points 1 and 2, nearest the Gulf, behave like the open coast surge while the response is flat in Apalachicola Bay (points 4, 5, and 6); there the various effects tend to cancel. Point 8 at the head of East Bay is particularly sensitive to wind setup and shows an inverse variation of surge height with storm speed.

3.4.5 With Radius of Maximum Winds and Landfall Point

The surge variation with R cannot be divorced from landfall point, as is clear from the discussion in par. 3.4.2. Both influence the position of the band of strongest winds, a critical factor both for the location of the maximum surge on the coast and the maximum wind setup effect in the bay. The bay surge variation is related concurrently to these two parameters by curves developed in two steps.

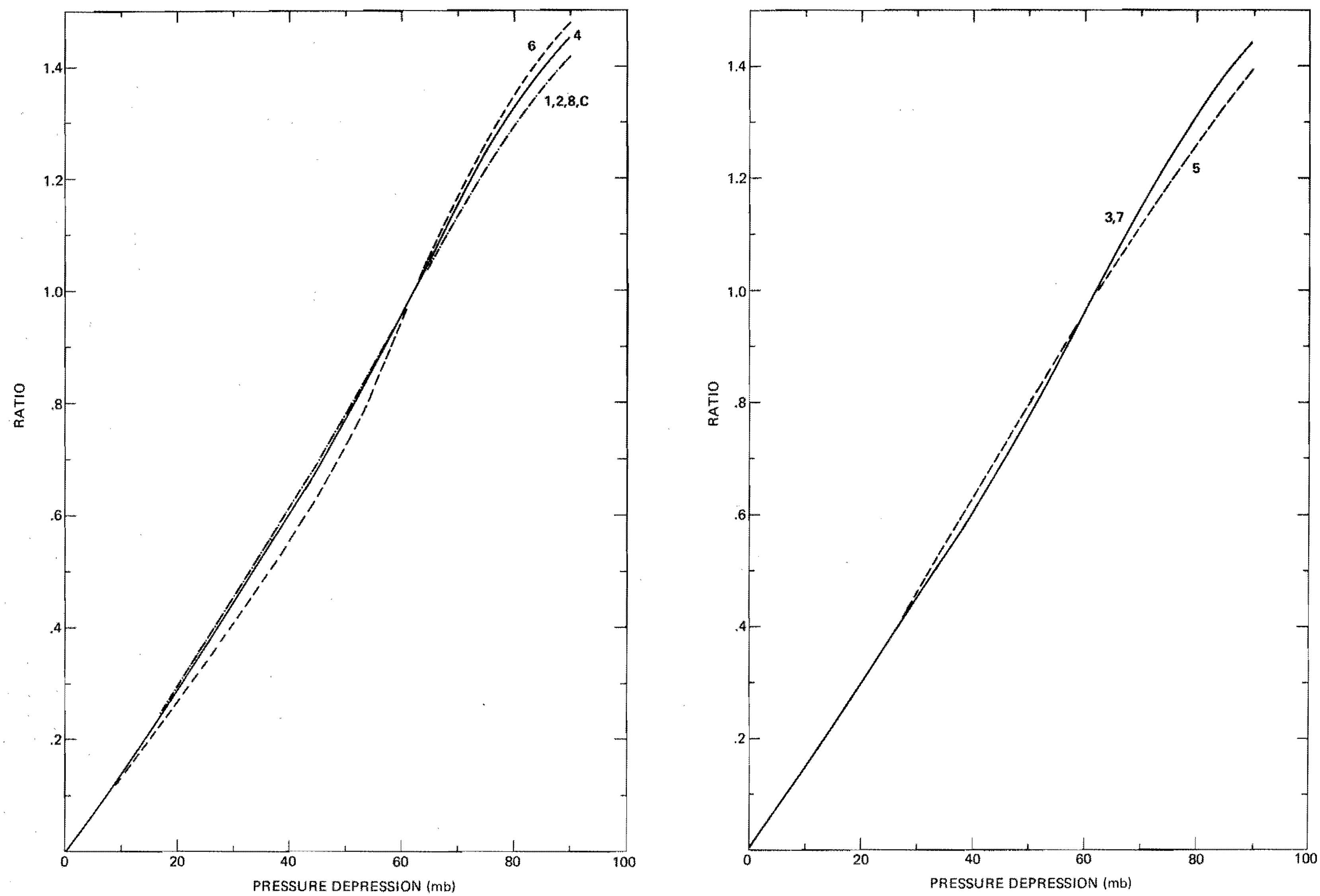

Figure 8.--Ratio of surge height at various pressure depressions (D) to height at D=62 mb. Hurricanes "standard" except for D. Left: bay locations 1, 2, 4, 6, and 8 (fig. 2) and East Pass (C). Right: bay locations 3, 5, and 7.

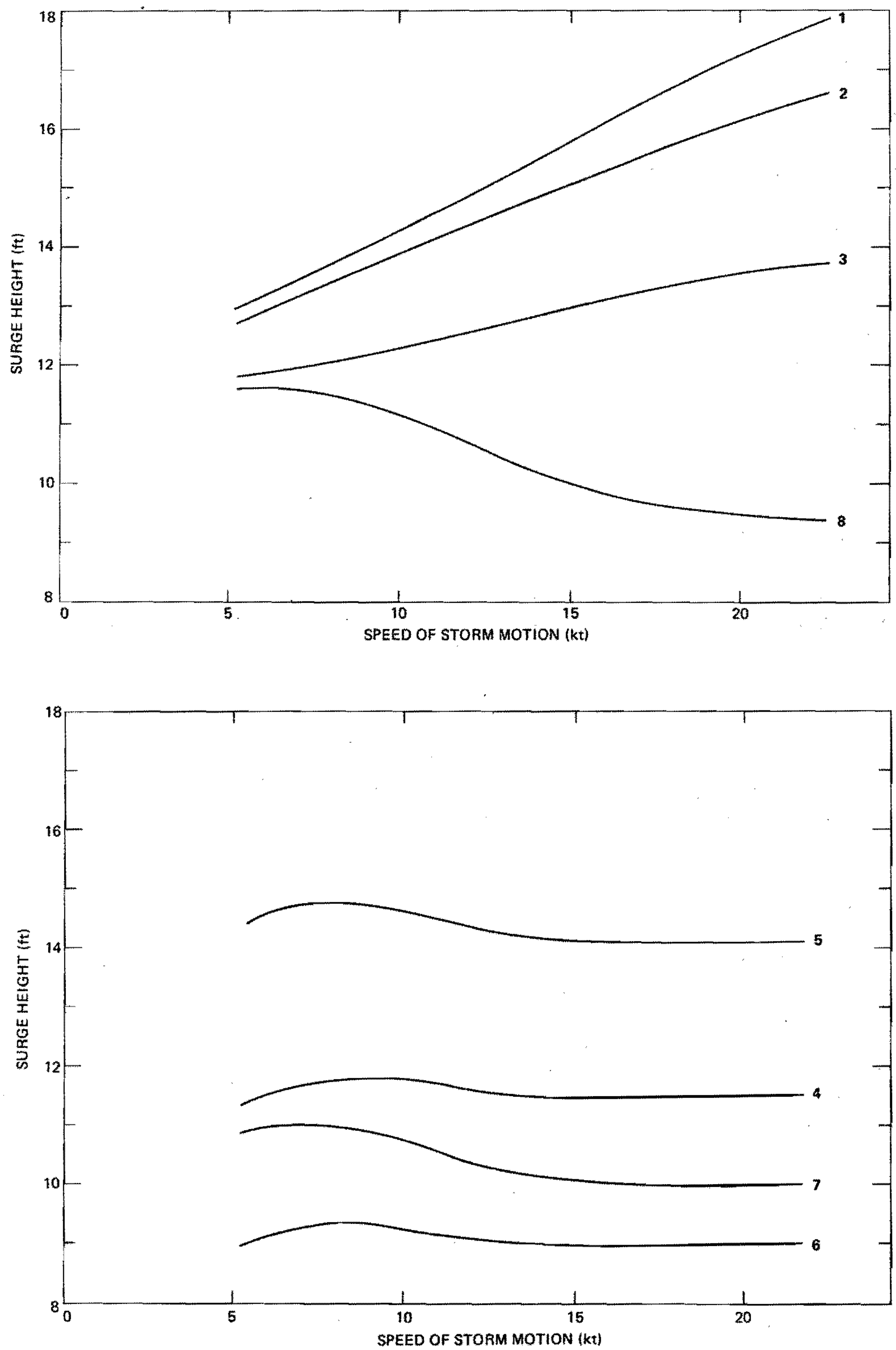

Figure 9.--Variation of surge height with respect to forward speed. Hurricanes "standard" except for forward speed. Upper: for locations 1, 2, 3, and 8. Lower: for locations 4, 5, 7, and 6.

First, this composite variation was analyzed for East Pass from the output of a large number of runs with the SPLASH model that had been made for the open coast tide frequency analysis (Ho and Tracey 1975). In these R and L was varied, while D, f, and θ were "standard." The resulting plot is shown in figure 10. It will be noticed that the maximum surge increases with R to about R = 26 n.mi. then decreases. This is consistent with the finding of Jelesnianski (1972, p. 6) for hurricanes in general. (The R = 26 curve is the same as the East Pass curve in figure 5.)

Next a set of maximum surge vs. L and R curves (at the standard D, f, and θ) like figure 10 was constructed for each of the eight bay control points. The surge vs. L curve at R = 26 was transcribed for each point from figures 5, 6, or 7. Using this as a guide, the curves for the other R's were constructed manually by spacing in proportion to the East Pass relationship in figure 10. The resulting curve sets are reproduced in figures 11-13.

3.4.6 With Direction of Approach

The maximum surge height at the coast for landfalling hurricanes varies with direction of approach of the storm. Other factors being equal, a storm approaching from the direction of 70° to 90° relative to the coast in general produces the highest surge [fig. 3 of Jelesnianski (1972)]. The direction of approach also affects the wind direction over the bay and its time changes and therefore the magnitude and time changes of the wind setup in various parts of the bay. If there is more than one major entrance to a bay, the time lag between maximum surge at the several entrances may be important and is sensitive to the storm approach direction, as is the shape of the surge hydrograph at each entrance. The results within a bay of combinations of all these factors can be replicated by matched runs of the continental shelf model and the bay model.

In the case of Apalachicola Bay, storm approach directions important for tide frequency analysis are restricted to SE through SSW. Storms from the ESE or E, unless curving sharply, would have been weakened by recent passage over land. Storms from the WSW are "alongshore" and contribute little to the storm tide frequency (Ho and Tracey 1975). The major entrances for hurricane tide flooding are East Pass and the east end of St. George Sound, nearby.

From these considerations, of the five hurricane parameters (D, R, f, θ, and L) θ was judged to be the least influential on tide frequencies in this particular bay. Its effects were approximated from the open coast surge behavior in lieu of model calculations.

Figure 14 (dashed curve) shows the surge frequency at East Pass calculated by the procedures described later in section 3.5 from the hurricane parameters in table 1, representing all hurricanes. The solid curves show the result of the same analysis with all storms held on a track direction of 157° (from north) rather than distributed over the several track directions. At the 100-yr return period the surge heights weighted for

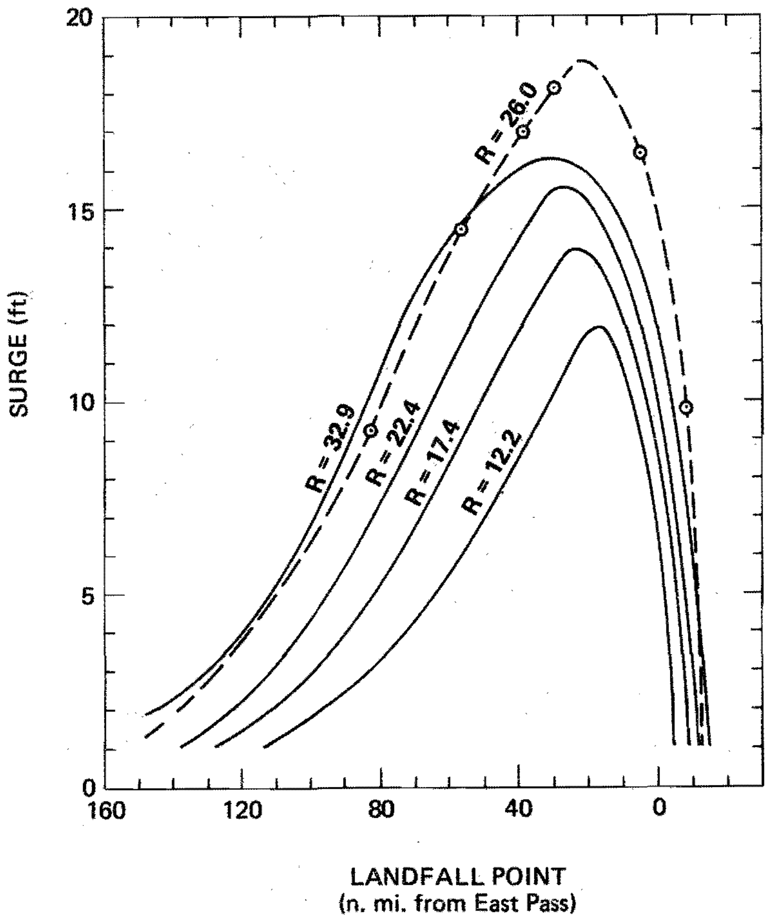

Figure 10.--Maximum surge height at East Pass vs. landfall point and R. Dashed curve for R = 26 n.mi. from figure 5. Hurricanes "standard" except for landfall point and R.

all directions and for $\theta = 157^{\circ}$ are 11.8 and 12.7 ft, respectively. The ratio 11.8/12.7 = 0.93 was adopted as a correction to adjust the 100-yr surge calculated with a fixed track direction of 157° to the corresponding surge level resulting from hurricanes from all directions, and was applied at each of the selected bay points. Similarly derived ratios of 0.94 and 0.90 were applied to adjust the single-direction 500-yr and 10-yr level frequencies, respectively.

3.5 Joint Probability Assessment of Surge Frequencies

3.5.1 The General Method

The essentials of the joint probability assessment of tide frequencies at a point on the open coast (Myers 1975, Ho and Tracey 1975) are:

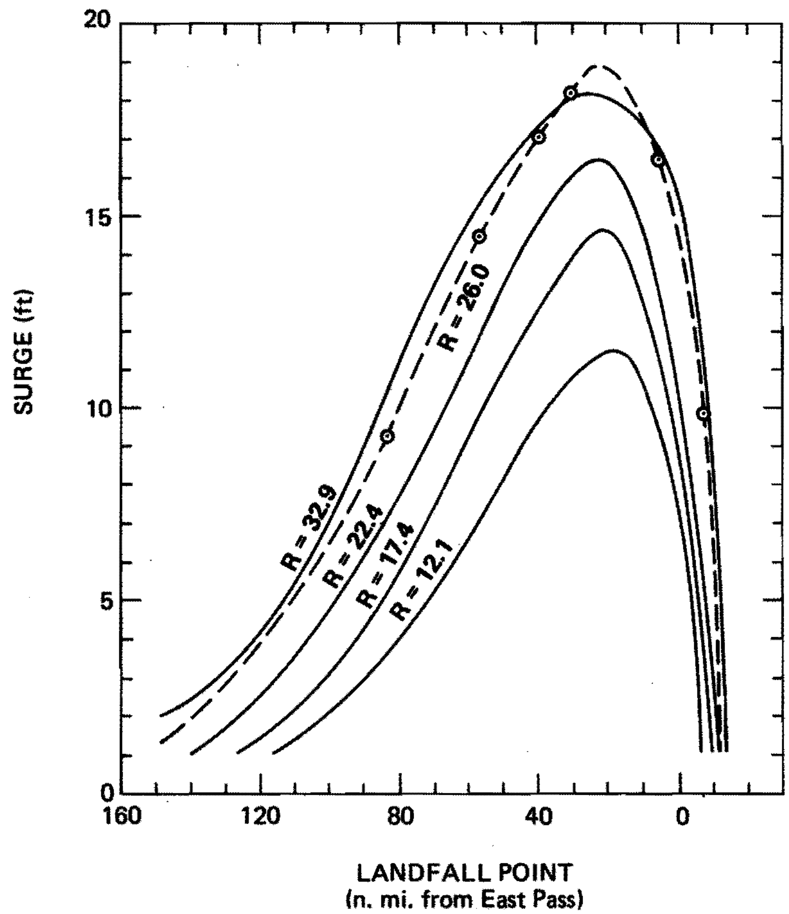

Figure 11.--Maximum surge height at Carrabelle (point 1) vs. storm landfall point and R. Same D, θ, and f as figure 10. Dashed curve for R = 26 n.mi. from figure 5.

a. Define the climatological probability distribution of each of the key hurricane parameters listed in par. 3.4.1. Include any significant contingent probabilities between any two parameters.

b. Specify a set of representative hurricanes covering the full range of these parameters in all combinations. Each specified hurricane is close enough to any adjacent neighbor in the set that linear variation of the storm surge between the two may be presumed.

c. Compute the storm surge at the coastal point from each of the representative hurricanes with a hydrodynamic model. The SPLASH model for the continental shelf is used for this.

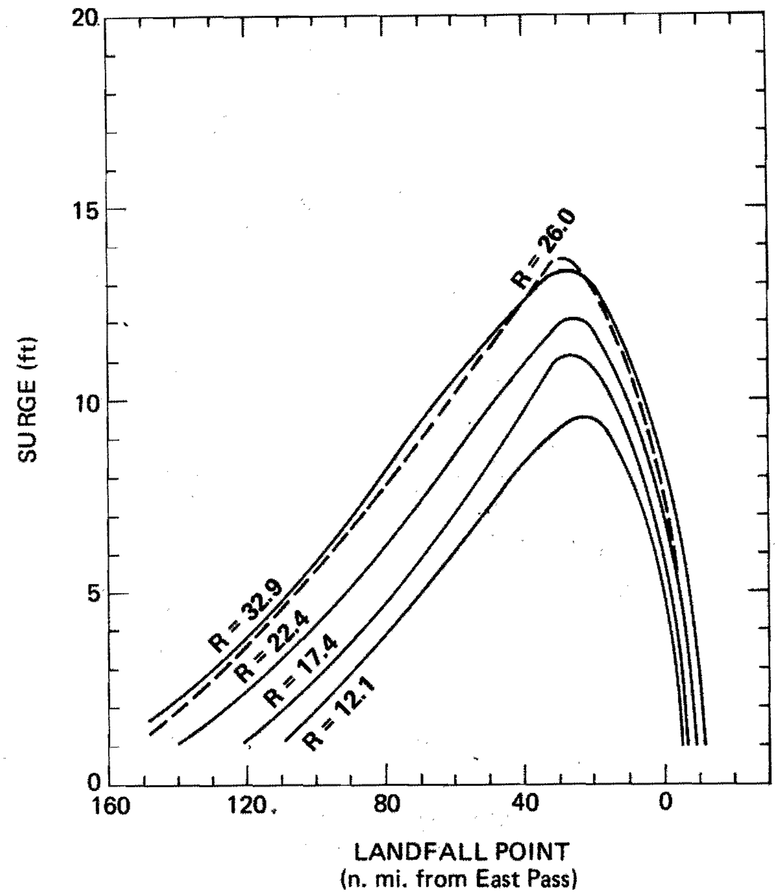

Figure 12.--Same as figure 11 but for Apalachicola (point 4). Dashed curve from figure 6.

d. Calculate the annual frequency of each coastal surge derived in step c. This is equal to the annual frequency of the producing hurricane, calculated from the parameter probabilities. Each representative hurricane stands for all hurricanes within certain parameter class-interval bounds.

e. Combine all the coastal storm surges with the astronomical tide on a probability basis.

f. Having calculated a large number of storm tides and the annual probability of each, form the frequency distribution.

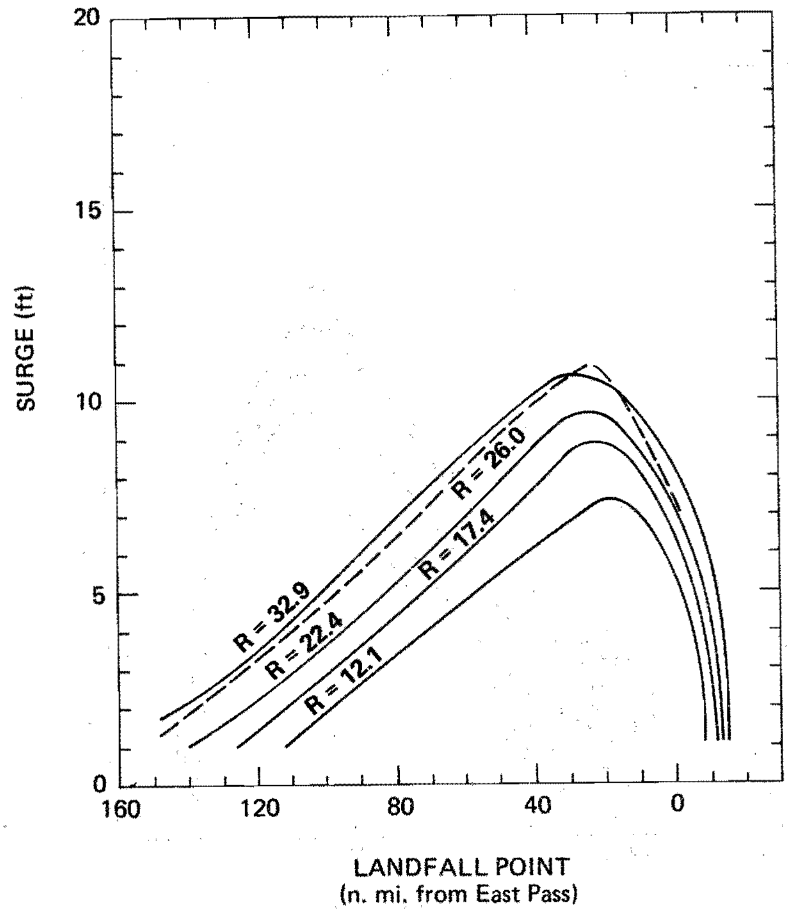

Figure 13.--Same as figure 11 but for Lower Anchorage (point 6). Dashed curve from figure 6.

The same procedure is extended in this project to Apalachicola Bay and St. George Sound as follows:

a & b. The hurricane climatology and the selection of representative hurricanes are the same as for the open coast tide frequencies. The specification of hurricane parameters in Ho and Tracey's open coast report, for East Pass (labeled "Carrabelle" in that report) is adopted and applied to the study area. This is reproduced in table 1. The explanation of the dependence of the radius of maximum winds, R, on the pressure depression, D, depicted in the table is found in the parent report. Other parameters for landfalling hurricanes are statistically independent.

c. The storm surge at each of eight bay control points in the Bay and the Sound is calculated for each representative hurricane. Calculations are made directly with the bay model (Overland

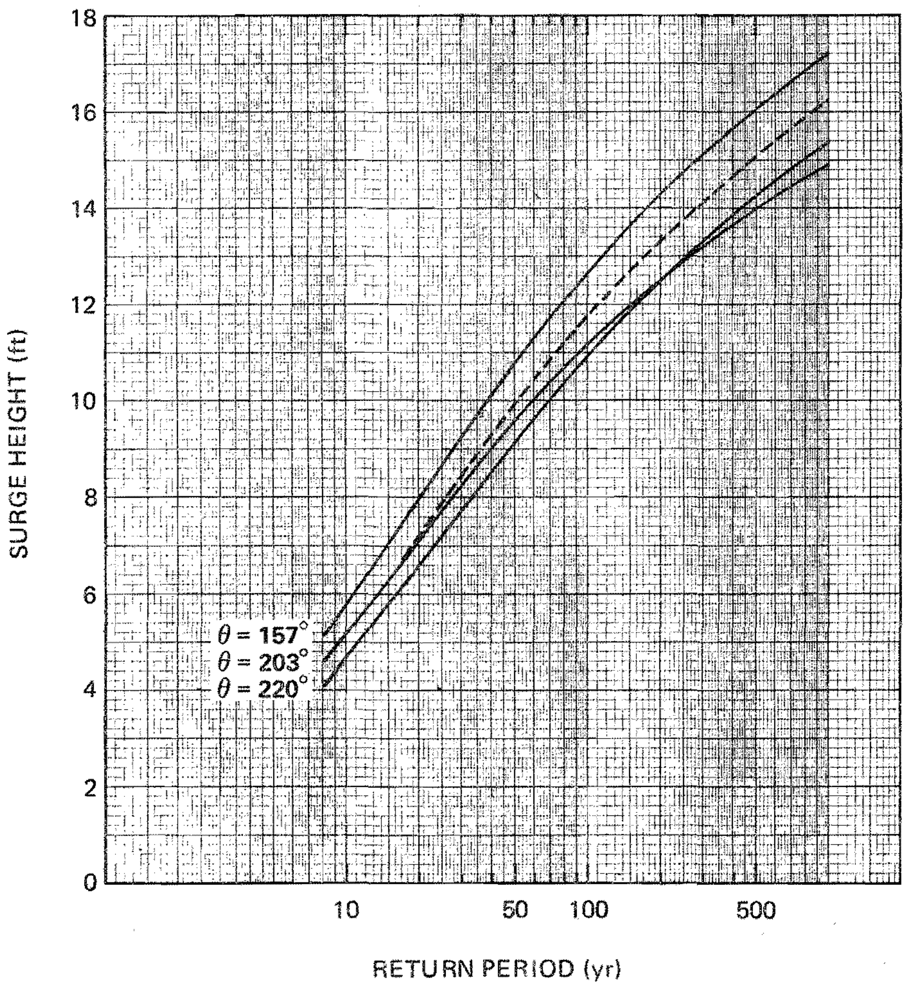

Figure 14.--Surge frequency curves at East Pass for three directions of storm motion (solid lines) and the combined surge frequency curve (dashed line). See text.

1975) for a subset of the representative hurricanes, using the open coast surge from the continental shelf model as boundary input. The surges at the control points for the remainder of the representative hurricanes are obtained by adjustments based on the relations developed in section 3.4.

d. The frequency of each hurricane surge is calculated in the same manner as for the open coast. This is illustrated later in this section.

e. At each control point a surge frequency graph is constructed from the surges from step c and their frequencies from step d.

Table 1.--Hurricane and tropical storm parameters--Franklin County, Fla.

Landfalling storms
F_n = .00222

D	P_i	P_{rD}				f	P_f	θ	θ_L	P_θ
		R								
		12.1	17.4	22.4	32.9					
83.2	0.01	0.33	0.33	0.33	0					
74.6	.03	.25	.25	.25	0.25	5.3	0.10			
62.7	.06	0	.33	.33	.33	6.9	.20	157	097	0.40
51.4	.10	0	.33	.33	.33	9.2	.20	203	143	.26
37.2	.20	0	.33	.33	.33	11.7	.20	220	160	.34
26.4	.20	0	.33	.33	.33	15.0	.20			
20.6	.20	0	.33	.33	.33	21.0	.10			
15.7	.20	0	.33	.33	.33					

Legend

D = central pressure deficit (mb).

P_i = Proportion of total storms with indicated D value.

f = Forward speed of storm (kt).

P_f = Proportion of storms with indicated f value.

R = Distance from center of storm to principal belt of maximum winds (n.mi.).

P_{rD} = Proportion of storms in D class with indicated R value.

θ = Direction of entry, measured clockwise from north (deg.).

θ_L = Direction of entry, measured clockwise from the coast (deg.).

P_θ = Proportion of storms with indicated θ_L value.

F_n = Frequency of landfalling storm tracks crossing coast (storm tracks per n.mi. of coast per year).

f. The surge frequency graph is adjusted for astronomical tide and "pre-storm setup" effects as explained in section 3.6.

3.5.2 Example of Computation of Bay Surge From Representative Hurricane

Consider the combination of hurricane parameters from table 1:

$D = 51.4$ mb
$R = 17.4$ n.mi.
$f = 21.0$ kt
$\theta = 157°$

Let the landfall point be 34 n.mi. to the left of East Pass.

Steps in computation of surge at Apalachicola (point 4):

a.	Surge height for "standard" D, f, and θ (par. 3.4.1), and R and L as indicated above (read from fig. 12):	10.4 ft
b.	Adjustment factor from $D = 62$ to $D = 51.4$ mb (read ratio from curve B, fig. 8):	0.785
c.	Adjustment factor from $f = 13$ to $f = 21$ kt (ratio of values from point 4 curve, fig. 9): 11.5 ft/11.5 ft:	1.0
d.	No adjustment for direction of approach since this is "standard." (An adjustment factor could be obtained for other directions by ratios from fig. 14.)	
e.	Adjusted surge height = a x b x c = 10.4 x 0.785 x 1.0 =	8.16 ft

3.5.3 Frequency of Surge From Example Representative Hurricane

The example storm represents a definite fraction of all storms, obtained by multiplying the parameter probabilities from the table. These values are:

a.	Fraction of storms represented by D value:	0.10
b.	Fraction of storms represented by R value:	0.33
c.	Fraction of storms represented by f value:	0.10

We are letting all storms approach from 157° temporarily (par. 3.4.6) and do not use P_θ in the table:

d.	Fraction of storms represented by θ value:	1.0

We need one more factor, the landfalling frequency within a coastal interval. Following the practice of the open coast analysis, which is related to the grid of the SPLASH model, storms are allowed to landfall at 8-statute mile (6.9 n.mi.) intervals along the coast. Here, this means read a new value at 6.9-n.mi. intervals of L (for each R value) from figure 13. Thus:

e. Coastal interval landfall frequency = 6.9 n.mi. x 0.00222 storms $n.mi.^{-1}$ x yr^{-1} = 0.015318 yr^{-1}

The final step is to multiply this coastal interval frequency by the parameter probabilities:

f. 0.1 x 0.333 x 0.1 x 0.015318 = 0.00005106 yr^{-1}

3.5.4 Frequency of all Surges

Table 1 groups hurricanes and tropical storms affecting Franklin County into eight D classes, three R classes, and six f classes, 8 x 3 x 6 = 144 combinations. The surges at each of the eight bay control points and at East Pass for each of the 144 storms landfalling at a succession of 6.9-n.mi. intervals along the coast, and the frequency of each such event, were worked out as illustrated in paragraphs 3.5.1 and 3.5.2. θ was fixed at 157° for this process. The surge frequency curves were formed and adjusted for direction of approach by the factors given in par. 3.4.6. The landfalling range was extended sufficiently for east and west of the study area to obtain computed surges down to the 10-yr level.

Figure 15 shows the resulting surge frequency curves for three of the Bay points, Carrabelle (point 1), Apalachicola (point 4), and Lower Anchorage (point 6). These frequency curves reveal lower surge levels in the Bay than in the Sound (Carrabelle) as expected.

As a test of the various approximations, the 100-yr surge frequency at East Pass was computed both by the procedures and nomograms of this report and by the procedures of the open coast report (Ho and Tracey 1975). Both start with the same hurricane climatology (table 1) and apply the same joint probability concepts and surge generation model but apply different short cuts in adjusting computed surges of selected hurricanes to other representative hurricanes. 11.7 ft was obtained by both methods.

3.6 Tidal Adjustments

3.6.1 Reference Datum

Storm tide elevations in this study are referred to local MSL. The National Ocean Survey has determined the deviations of local MSL from the National Geodetic Vertical Datum of 1929 at primary tidal stations by precise leveling. These datum planes are defined in par. 1.6. These differences, adjusted to the 1941-59 tidal epoch, at stations in or closest to Franklin County are:

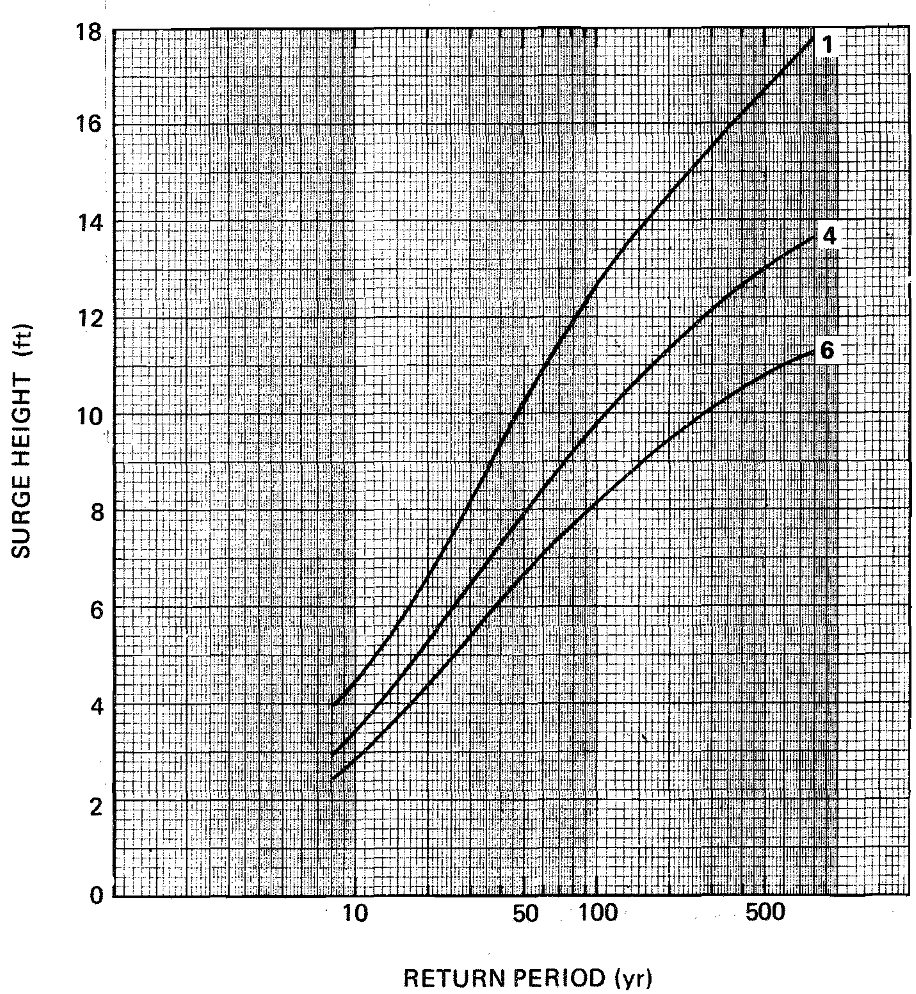

Figure 15.--Surge frequency curves for selected locations: Carrabelle (1), Apalachicola (4) and Lower Anchorage (6).

Apalachicola, Fla.:	Local MSL 0.54 ft above NGVD
St. Marks, Fla.:	Local MSL 0.39 ft above NGVD
Pensacola, Fla.:	Local MSL 0.30 ft above NGVD

If conversions of the storm tide levels in this report to height above NGVD are required, add the Apalachicola factor in Apalachicola Bay. For the eastern part of Franklin County, interpolate between Apalachicola and St. Marks. The latest information on tidal datum planes may be secured from the National Ocean Survey, Rockville, Md., 20852, Attention C331.

3.6.2 Combination of Hurricane Surge and Astronomical Tide

Figure 16 shows comparative storm surge and storm tide (surge plus normal tide) frequency curves by the joint probability method for the

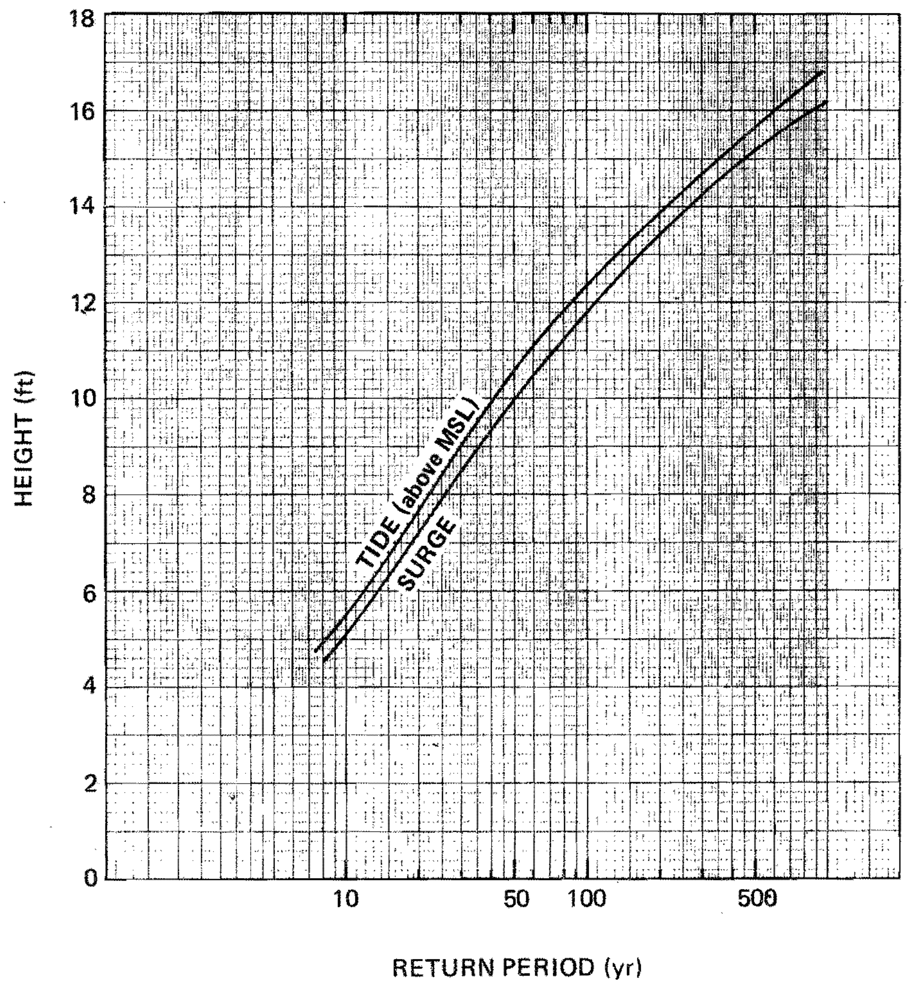

Figure 16.--Surge and tide frequency curves for East Pass.

open coast at East Pass. These are from the data sheets of the open coast study. This total tide curve was obtained by adding the astronomical tide to individual storm surges in a random manner as described in the open coast report. Comparing the curves, the astronomical tide contributes only 0.5 ft to the total tide frequency at the 100-yr return period (fig. 16) in this region of small astronomical tide range. Since the variation of the astronomical tide range in the bay is also small, and since the astronomical tide has plenty of time to fill the bay on each tide cycle, the factor of 0.5 ft was added to the calculated bay surge frequencies to adjust for net astronomical tide effects. This adjustment was applied at all the bay control points at the 100-yr and 500-yr return periods. The 10-yr return period is discussed later.

More complex coastal topography than in the present study area and a larger astronomical tide range might require the full random combination of surge and astronomical tide in storm tide frequency analysis within a bay as well as including the astronomical tide as a dynamic variable in the model. In a semi-enclosed body of shallow water the speed of propagation of the gravitational wave is dependent on water depth and is thereby influenced by tide height.

3.6.3 Pre-storm Setup

Some hurricanes in the Gulf of Mexico raise the water level on the gulf coast while the storm is still far from shore. In the regional study for the open coast (Ho and Tracey 1975), the magnitude of this effect was evaluated to average 0.7 ft at Cedar Key, Fla., and an adjustment of this amount was included in the Franklin County portion of the open coast tide frequencies except at the lower end of the frequency distribution where the adjustment was reduced. In the present study the same +0.7-ft adjustment is added to all tide frequencies at the 50-yr return period and beyond. The 10-yr return period is discussed below.

3.6.4 Comparison to Historical Gage Record

The basic tide frequency analysis includes only storm surges produced by hurricanes and tropical storms. Any effects of other weaker storms (such as extratropical storms that occur mostly during the winter months) on the tide would be reflected in long-period tide gage records in the affected area.

Yearly highest tides recorded at the Apalachicola tide station since 1941 were furnished by the Mobile District, U.S. Army Corps of Engineers, table 2. These values are plotted in figure 17 using the plotting position formula of Beard (1962),

$$P = (M-0.3)/(N+0.4)$$

where P = probability, M = serial number of event, N = length of record (1941-1973 or 33 yr).

The curve on the figure is the final tide frequency curve for Apalachicola. The upper portion is calculated by the joint probability method as just described, and includes the adjustments of par. 3.6.2 and 3.6.3. The curve at the 10-yr return period and below is drawn to the data.

In doing this there is an implicit adjustment of 0.9 ft from the 10-yr hurricane and tropical storm surge at Apalachicola (fig. 15) to the 10-yr all-storm tide. This is an unidentified combination of astronomical tide contribution, pre-storm setup, and any contribution from winter-type storms. This overall adjustment is consistent with the adjustments at the 100-yr return period (+0.5 ft for astronomical tide, +0.7 for pre-storm setup). This same factor of 0.9 ft was applied at all control points to adjust from computed 10-yr hurricane and tropical storm surge by the model computations to 10-yr all-storm tide.

Table 2.--Frequency analysis of maximum annual tides at Apalachicola, Fla., 1941-1973 ϕ

Year	Rank	Annual highest tide, ft. MSL*	Plotting position #
1950	1	6.32	0.021
1972	2	5.56	.051
1947	3	4.68	.081
1953	4	4.25	.111
1965	5	3.60	.141
1956	6	3.24	.171
1948	7	3.04	.201
1973	8	2.91	.230
1952	9	2.86	.260
1970	10	2.84	.290
1969	11	2.78	.320
1961	12	2.74	.350
1964	13	2.74	.380
1943	14	2.59	.410
1960	15	2.46	.440
1957	16	2.44	.470
1942	17	2.41	.500
1941	18	2.36	.530
1945	19	2.31	.560
1967	20	2.25	.590
1962	21	2.14	.620
1971	22	2.08	.650
1946	23	2.06	.680
1959	24	2.04	.710
1963	25	2.00	.740
1951	26	1.97	.770
1949	27	1.94	.799
1955	28	1.89	.829
1958	29	1.84	.859
1968	30	1.84	.889
1966	31	1.80	.919
1944	32	1.72	.949
1954	33	1.64	.979

ϕ Maximum annual tide heights furnished by Mobile, Ala., District, U.S. Army Corps of Engineers.

* Local mean sea level, 1941-1959 epoch. Add 0.54 ft to obtain height above National Geodetic Vertical Datum of 1929. See par. 3.6.1.

\# Beard's formula (Beard 1962).

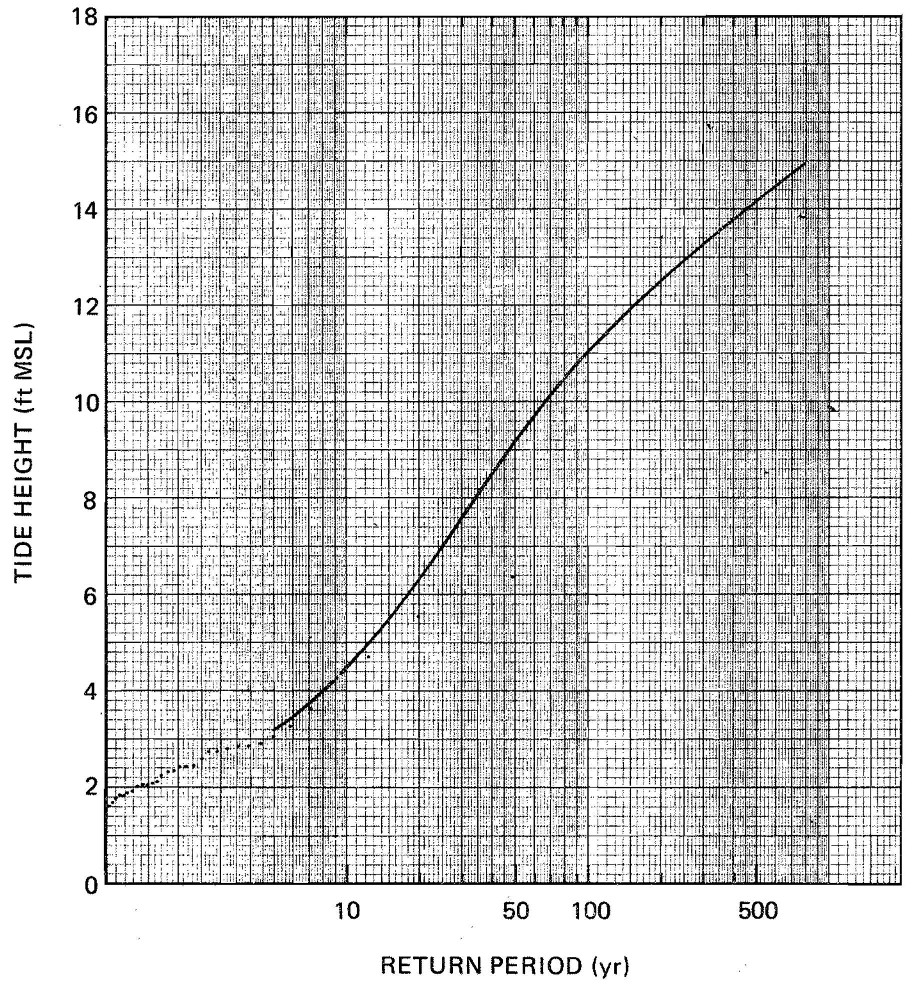

Figure 17.--Annual highest tides at Corps of Engineers gage, Apalachicola (1941-73), plotted as an annual series with adopted total tide frequency curve for Apalachicola.

3.7 Results

3.7.1 Tide Frequency Graphs for Selected Points

Figures 18, 19, and 20 show the resulting total tide frequency curves for selected locations in St. George Sound, Apalachicola Bay, and East Bay, respectively, derived by computing surge frequencies as detailed in section 3.5 and applying the tidal adjustments described in section 3.6.

It should be emphasized that these frequency values are of still-water levels that would be measured in a tide gage house or other enclosure, excluding wave action. The destructive effects of waves must be taken

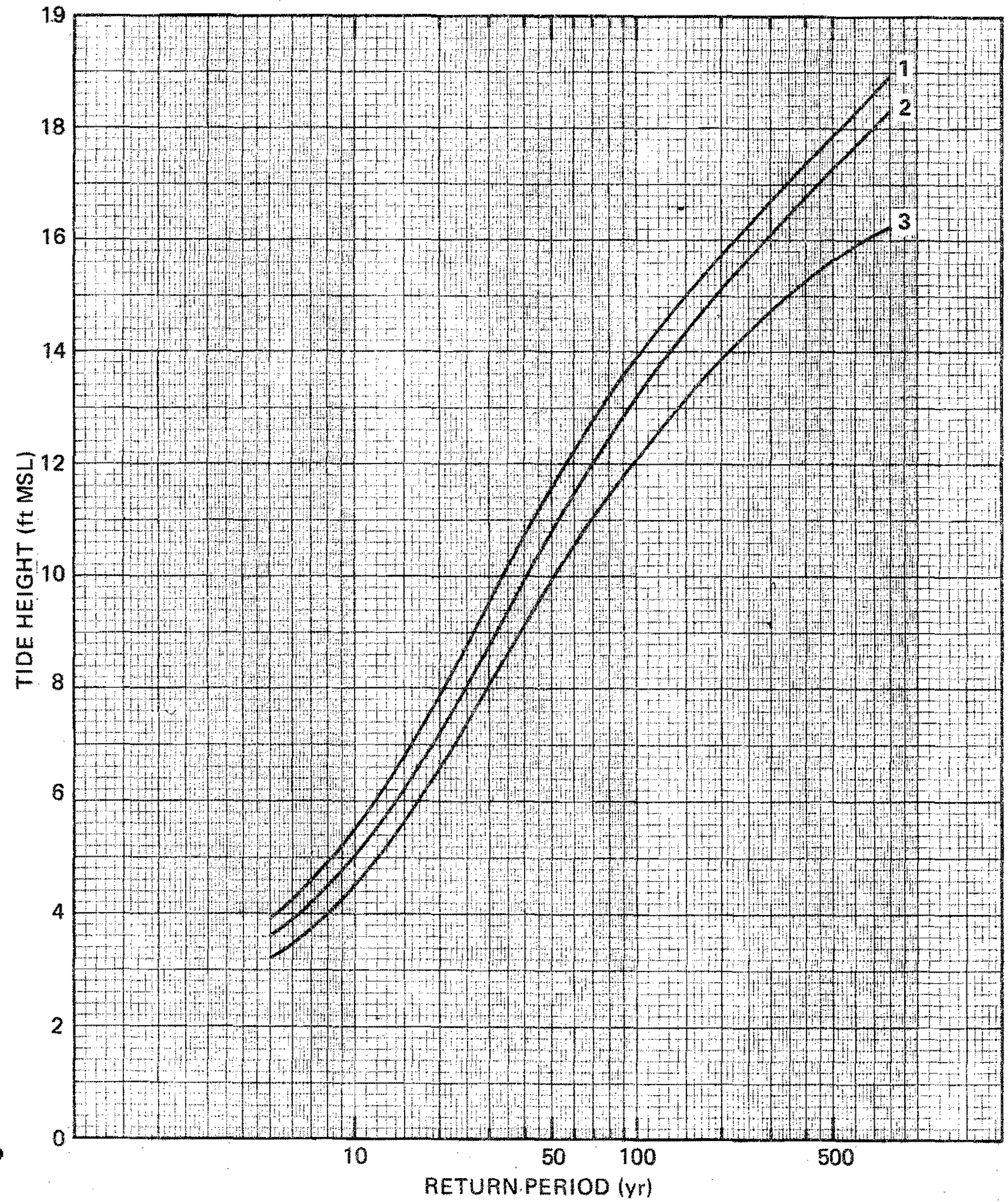

Figure 18.--Total tide frequency curves on the bay shore between Carrabelle and Cat Point, Franklin County, Fla. Datum is local MSL, 1949-51 epoch. See par. 3.6.1 for conversion to National Geodetic Vertical Datum of 1929. Points 1, 2, 3 identified in figure 4.

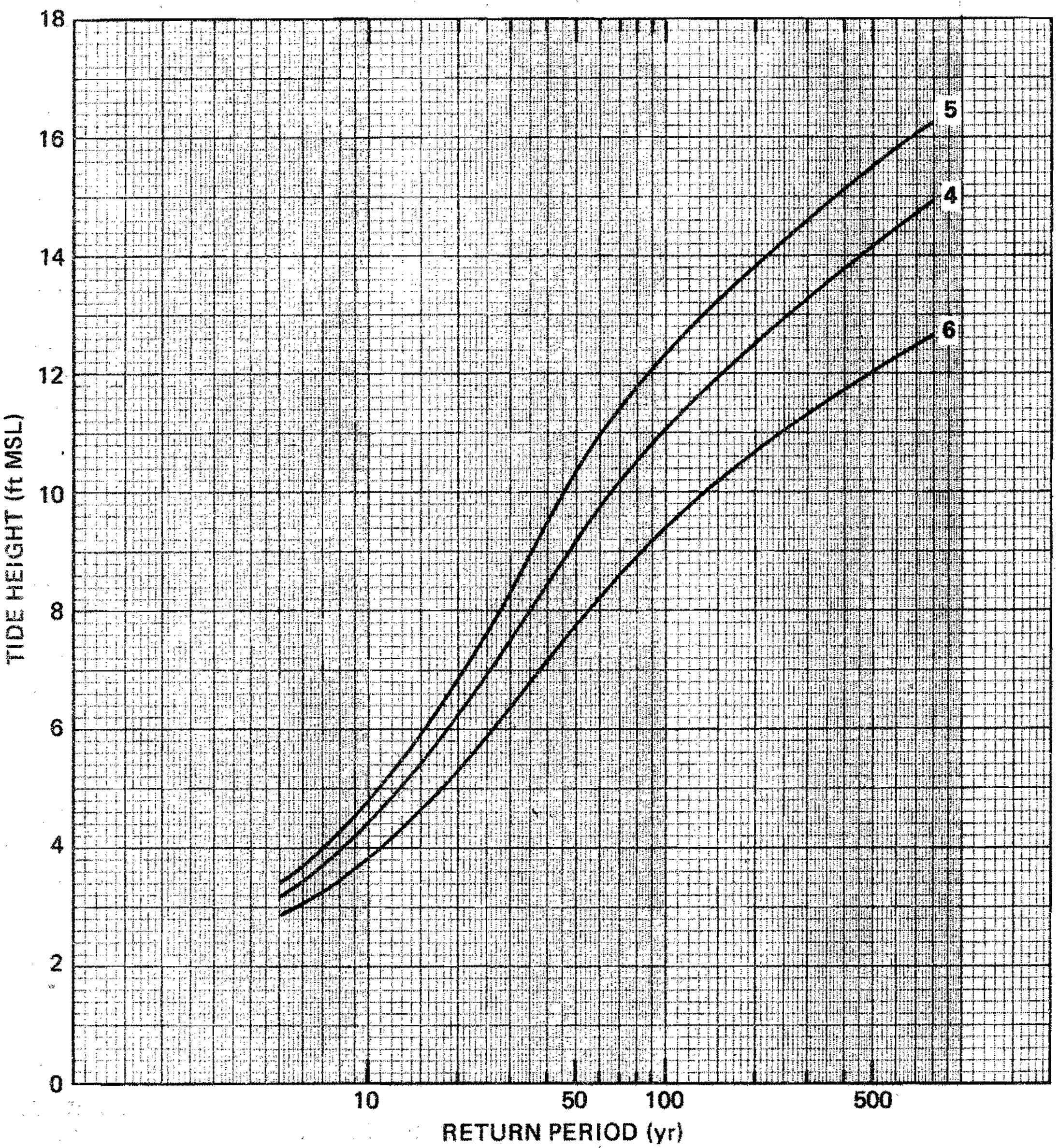

Figure 19.--Same as figure 18 but for locations inside Apalachicola Bay.

into account separately. In insurance rating on the open coast this is taken into account by the shore front "velocity zone," and also in bays where appropriate. The Galveston, Tex., District, Corps of Engineers, has studied wave action in bays for the Flood Insurance Program.

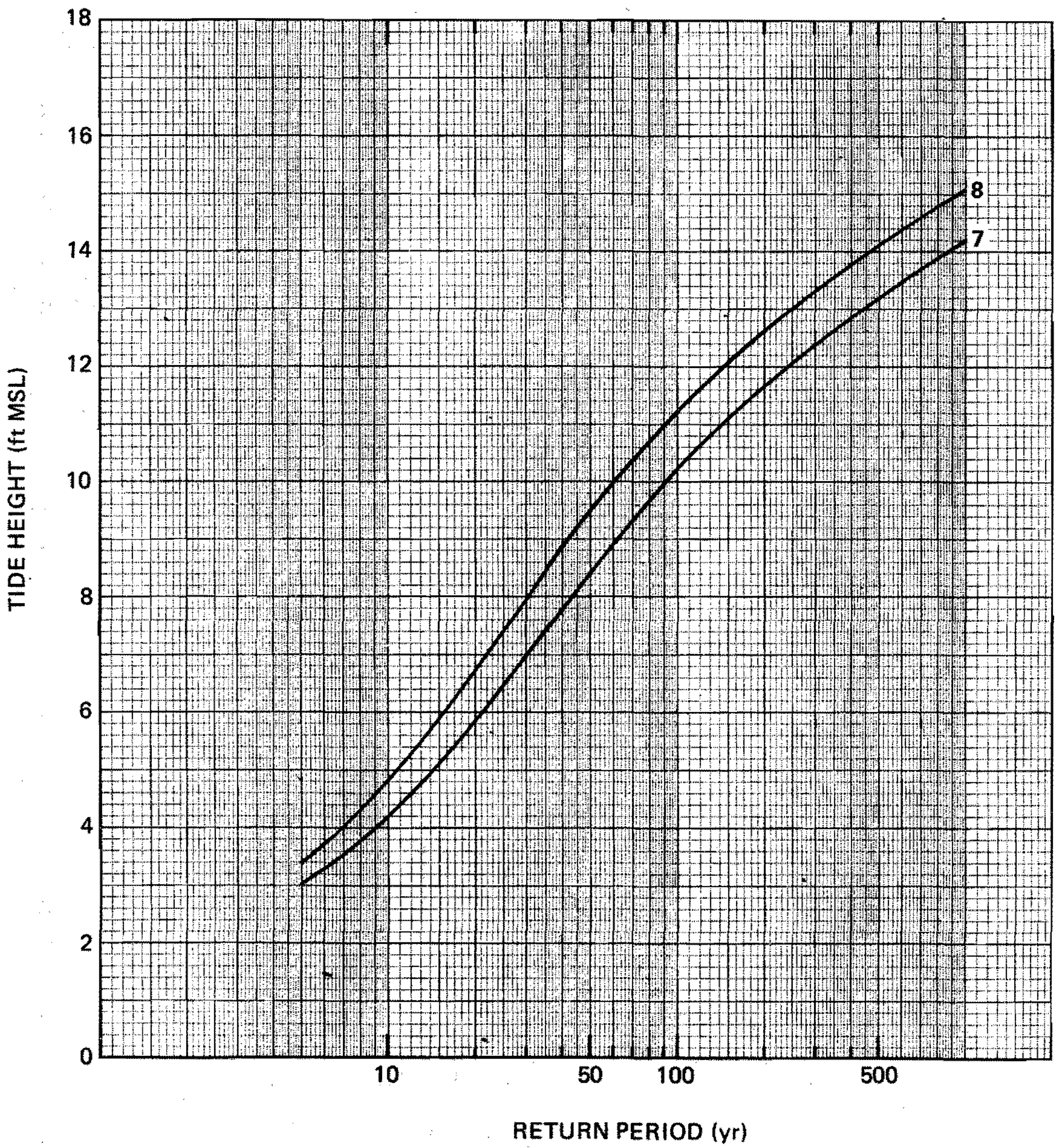

Figure 20.--Same as figure 18 but for locations inside East Bay.

3.7.2 Bay Tide Frequency Maps

Figures 21, 22, and 23 show the variation of the total tide heights for the 10-yr, 100-yr, and 500-yr return periods, respectively. The tide heights at the bay control points are scaled from figures 18, 19, and 20. In interpolating the curves between these values, consideration was given to the various responses of the bay to hurricanes discussed by Overland (1975). The denoted flood areas are approximate, based on topography on 7-1/2' quadrangles. The tide levels on the gulf side of barrier islands

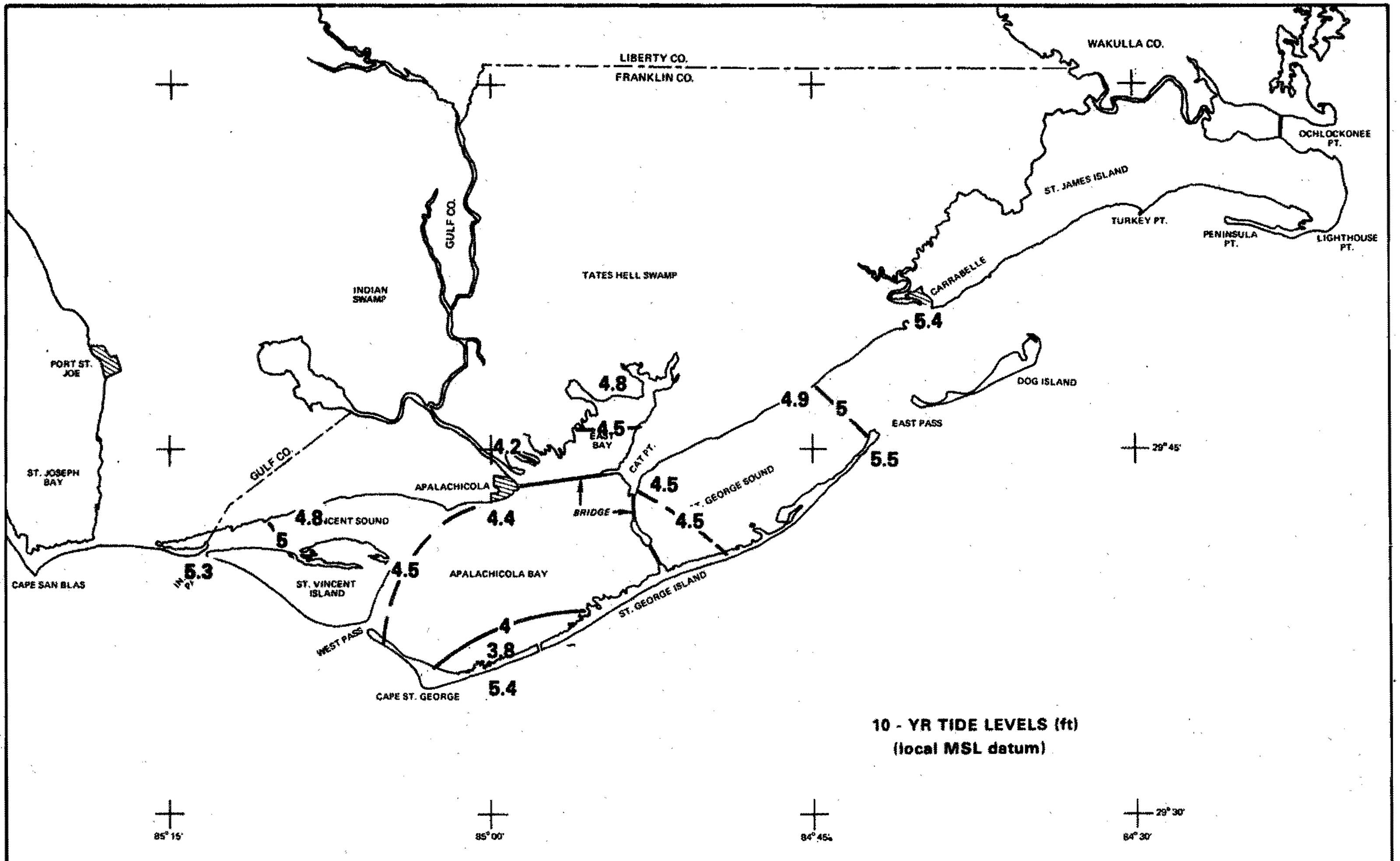

Figure 21.--Ten-yr tide level (ft). Datum is local MSL, 1941-59 epoch. See par. 3.6.1 for conversion to National Geodetic Vertical Datum of 1929.

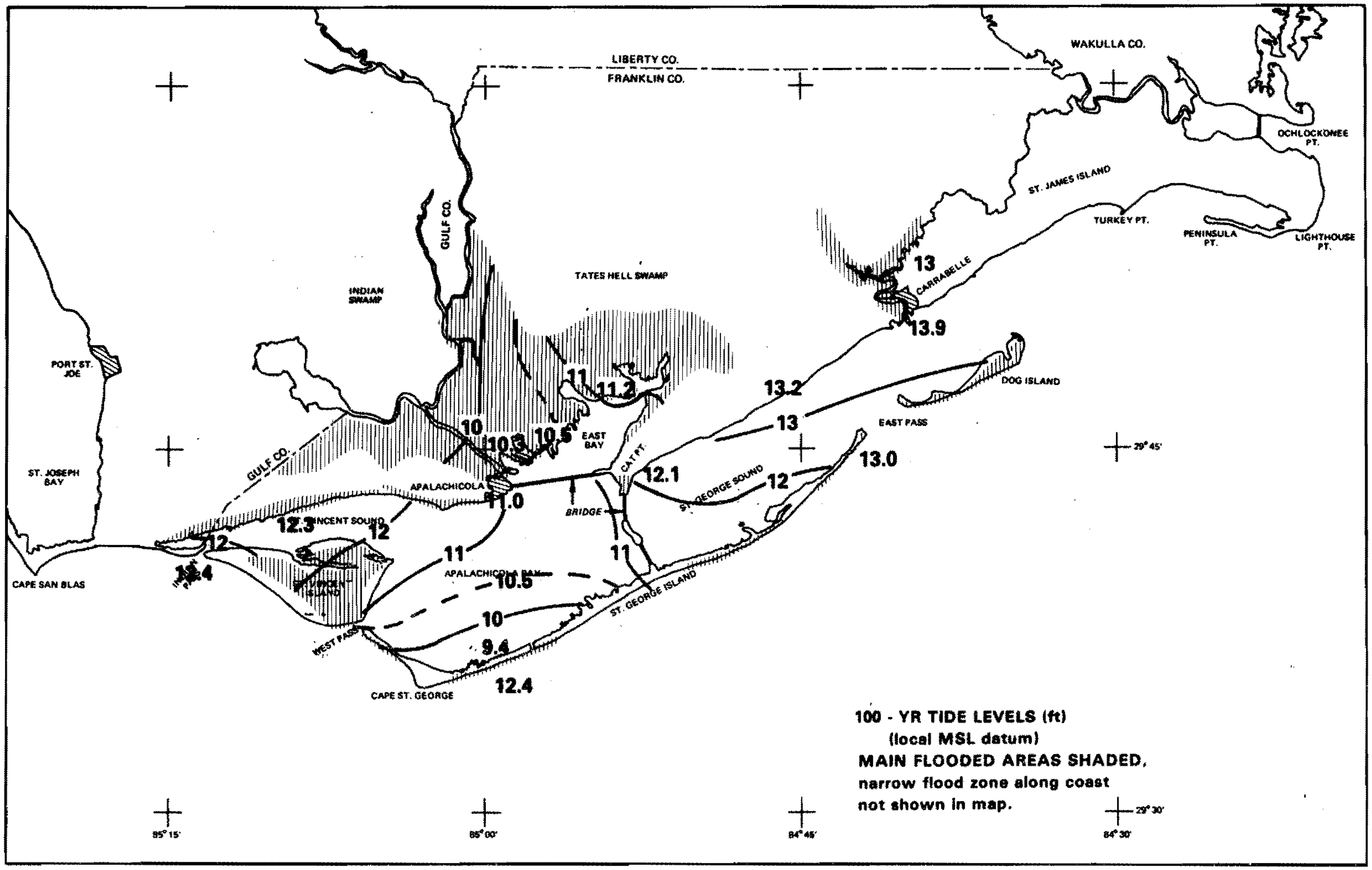

Figure 22.--Same as figure 21 but for the 100-yr return period.

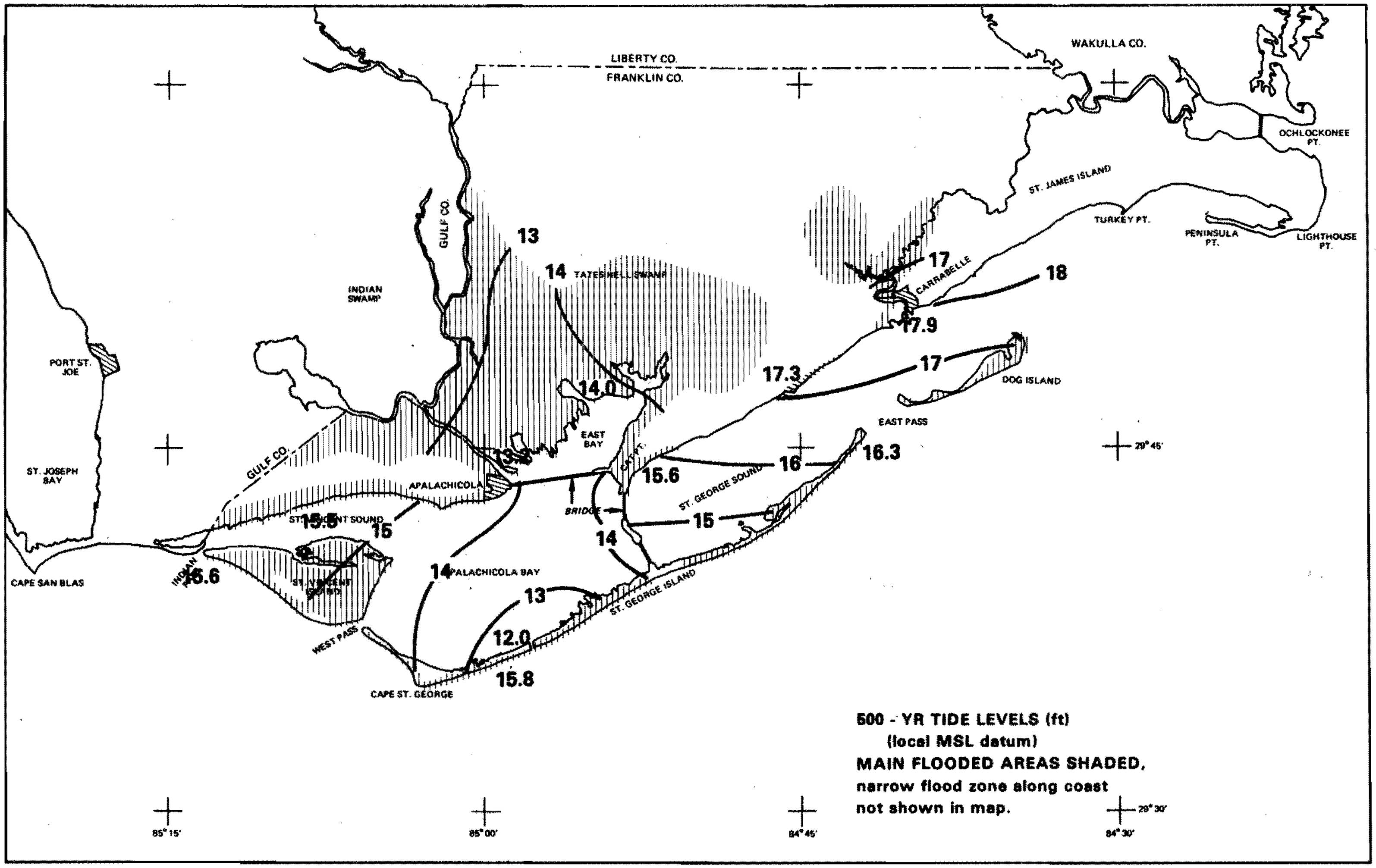

Figure 23.--Same as figure 21 but for the 500-yr return period.

are the open coast tide frequency estimates, from the regional study for the open coast (Ho and Tracey 1975). St. George Island is breached at only a few places by the 100-yr tide level, accounting for the 3-ft difference on the Gulf and Bay sides of the Island. At the 500-yr storm tide level, overtopping the Island is more severe, and the difference is lessened.

4. DISASTER PLANNING

Hurricane Camille in 1969 struck the Bay St. Louis-Pass Christian-Gulfport-Biloxi portion of the Mississippi coast and according to high-water marks raised the tide as high as 24.6 ft above MSL. The central pressure at landfall was about 908 mb (Ho, Schwerdt, and Goodyear 1975). An even more intense but smaller hurricane crossed the Florida Keys on Labor Day 1935 with central pressure detected at 892 mb. In both of these hurricanes, there was a substantial loss of life. All of the Gulf of Mexico is exposed to a repeat of hurricane Camille, the most intense hurricane so far to strike the United States mainland during the period of record keeping. The National Weather Service recommends a repeat of this worst storm as a disaster planning objective without regard to the statistical frequency of such a storm at an individual point, for all of gulf coast. A frontal attack of a hurricane Camille on a critical path for Apalachicola Bay would flood all but the few highest points on Dog and St. George Islands, and would develop a general pattern of bay and inland flooding elevations similar to figure 23 with water levels generally above 20 ft MSL. The approaches to the single evacuation bridge for St. George Island would be flooded and impassable early in such a storm, as would the bridge between Apalachicola and Cat Point.

A hurricane Camille on a track slightly farther to the east would fill up Apalachee Bay and the upper end of St. George Sound to similar elevations with corresponding havoc.

The tide frequencies in this and all flood insurance reports pertaining to coastal areas are expressed in terms of probabilities at individual points, as they must be for insurance rating. The "100-yr" (equals 1 percent per year) storm tide level is the composite result of attack by moderate intensity hurricanes passing close by and by very severe hurricanes passing at greater distances away. Local disaster planning must include the possibility of a direct <u>nearby attack of a very severe hurricane</u> even though the formal calculated statistical likelihood of this is low.

This report is not intended as a complete guide to disaster planning, which should be based on studies made for that particular purpose.

5. SUMMARY AND RECOMMENDATIONS

5.1 Summary

The joint probability method of estimating storm tide frequencies applied to the open coast in earlier reports has been extended to a semi-enclosed bay. The previously developed hurricane climatology applies to this study, as do the previously developed open coast storm tide frequencies. It was necessary to develop a hydrodynamic model specifically for the bay, described in a separate report. The present report describes the techniques for applying this new model and the previously developed results to estimating tide frequencies within Apalachicola Bay and St. George Sound and adjacent flooded areas on the joint probability basis. The resulting tide frequencies are portrayed as frequency graphs at selected control points and as maps for selected frequency levels. The effects of storm intensity, forward speed, and landfall points were determined by calculations with the hydrodynamic model. The effect of variation of storm approach direction and storm size (as indicated by R) was assumed proportional to effects on the open coast. The frequencies of the various hurricane parameters, including landfall point, were carried through to the final storm tide frequency in the same manner as on the open coast. Inspection of the tide frequency maps gives insight into the relative roles of the open coast surge and local wind setup on bay water levels.

5.2 Recommendations

To our knowledge this is the first published report on the joint probability approach to estimating hurricane tide frequencies within a bay by use of a hydrodynamic model together with hurricane climatology. This experience leads us to the following recommendations with respect to bay tide frequency evaluations for the Flood Insurance Program:

1. Derive tide frequencies for the Flood Insurance Program in all principal bays and estuaries subject to hurricanes, from evaluations with a hydrodynamic model developed or adapted for the purpose (as in this study).

2. Apply the hydrodynamic model to direct joint probability assessment of tide levels in the bay (as in this study) in preference to routing single preselected 100-yr, etc., ocean tide levels inland under assumed representative conditions. By the latter method the influence of hydraulic and meteorological modifying factors on frequency is obliterated.

3. To the extent feasible, determine the effect of variation of each principal meteorological parameter, as well as combinations, by direct model calculations. A large fraction of the total project cost is in the original development and adaptation. The present project was planned to minimize computer costs, and substitute methods were used for estimating the variation of storm surges with hurricane R and with approach direction. In retrospect, a larger number of direct model computations would have been justified.

4. Include variation of astronomical tide as a dynamic variable in the model calculations where the tides are of moderate or greater range (not needed in this study because of the small tide range on the gulf coast).

5. Reduce hurricane winds over the bay for weakening of the storm over land and for overland trajectory of the wind, where appropriate. (Not needed in this study)

6. Consider possible influence of bay water level on the ocean water level boundary values, especially at wide, deep entrances. (Techniques were not developed in this study.)

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