

**EVALUATION OF STORM TIDE IN
WAKULLA COUNTY, FLORIDA**

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Sponsored By

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I. INTRODUCTION

1.1 Background

The National Flood Insurance Act of 1968 and the Flood Disaster Protection Act of 1973 provide a national insurance program for property owners and businesses in the event of damage or destruction by floods. State and local communities are required, as a condition of federal financial assistance, to participate in this program. The law is administered by the Federal Emergency Management Agency (FEMA).

To implement the Flood Insurance Act, the FEMA must first determine the flood elevations associated with the 10, 50, 100 and 500 year return periods. A flood elevation study has been completed for Wakulla County as shown in Reference (1)* for the latest revised publication.

Under the request by the Wakulla Board of County Commissioners to the Florida Department of Natural Resources (DNR) for an independent storm tide study, the Florida Department of Natural Resources, in turn, entered into a contract with the Beaches and Shores Resource Center of the Florida State University's Institute of Science and Public Affairs to perform the study. The results of the study will be used by the county to determine whether an appeal of the FEMA flood elevations is to be made. This report presents the details of the methodology and the study results. It should be pointed out that the study is not a detailed flood insurance study, except to provide the county with the open coast combined total storm tide elevations of 10, 50, 100 and 500 years in the first phase of the study and inland flooding elevations by a two-dimensional model analysis in the second phase of the study.

*Numbers in parentheses indicate the references listed at the end of this report.

1.2 Location and General Description of the Study Area

Wakulla County is located in northwest Florida on the Apalachee Bay which is part of the Gulf of Mexico. It is bordered by coastal counties of Franklin to the west, Jefferson to the east and is about 15 miles south of Tallahassee in Leon County. Figure 1 shows the general location of the county.

Large land areas in Wakulla County are occupied by the St. Marks National Wildlife Refuge, the Apalachicola National Forest, the Leon-Wakulla Wildlife Management Area, and the Aucilla Wildlife Management Area. Major communities in the county are St. Marks, Sopchoppy, Crawfordville, Medart, Newport, Panacea, and Wakulla.

The coast of Wakulla County is a tidal marsh with an irregular shoreline and an almost total absence of sandy beaches. Ground elevations are generally low, ranging from sea level to ten feet (NGVD) near the coast and to over 50 ft. in the northwestern portions of the county. Principal rivers in the county are the St. Marks and the Ochlockonee. A more detailed description of the county can be obtained from References (1) and (2).

1.3 Scope of the Study

The objective of the study is twofold. The first phase of the study is to develop, verify and apply a procedure which will yield valid estimates of the combined total storm tides for various return periods in the vicinity of the Wakulla County shoreline. Throughout this report, "combined total storm tide" denotes the storm surge due to astronomical tide, wind stress and barometric pressure effects combined with the dynamic wave set-up, the latter occurring dominantly within the wave breaking zone. Available historical hurricane/storm statistics are combined with a set of numerical models to simulate the storm tides at the site of interest. Tide gage recordings during hurricanes of June

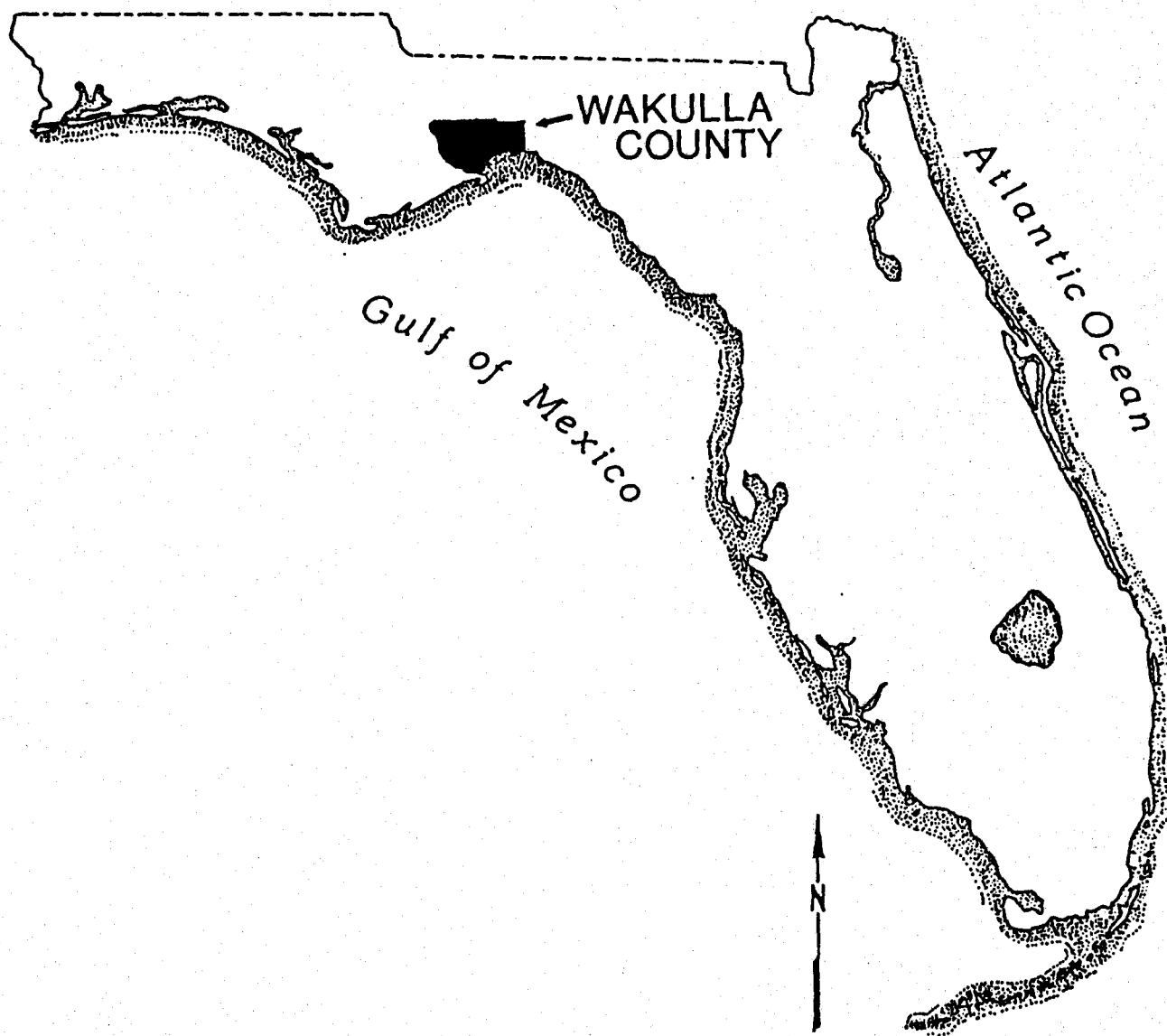


Figure 1 General Location of Study Area

1966, June 1972 and September 1975 are employed for model calibration. Friction characteristics for various types of vegetation, buildings and underwater areas are developed to represent the actual variation of friction in the model. A simple one-dimensional model is calibrated and used to reduce the cost of computations for a large number of runs simulating a 2,000-year duration of storm tides. The dynamic wave set-up is based on analytical studies and wave tank tests.

The results of the first phase of the study are established as if the maximum dynamic wave set-up and the maximum pressure and wind-stress induced surge occur in phase as would be the case in a narrow surf zone. These results are found to agree approximately with those determined by FEMA'S contractor.

The second phase of the study examines in more detail, the distribution of the inland flooding. In this analysis the storm surge extends over a wide vegetated zone thereby reducing substantially the wind stress contributions in this region. Additionally, in accordance with the physics, the wave set-up increases as the wave height and energy are reduced due to wave breaking. Crest elevations are then calculated using the FEMA methodology. This detailed examination of the superposition of wind stress and barometric pressure induced surge and wave set-up results in crest elevations somewhat different from those recommended by FEMA. In general, the crest elevations developed herein are somewhat lower along the coastline and higher inland.

II. HISTORICAL PROBABILITIES OF HURRICANE/STORM CHARACTERISTICS IN THE AREA OF INTEREST

2.1 Introduction and Data Source

For purposes of calculating the storm tides that occur during a long period, it is necessary to use realistic statistical representations of the important hurricane/storm parameters: p_0 (= central pressure), R (= radius to maximum winds), V_F (= forward speed), θ (= storm translation direction) and landfall or alongshore characteristics. The statistical parameters are based on historical hurricane/storm data as presented in References (3), (4) and (5). In brief, the empirical cumulative probability distributions are plotted for each of the parameters of interest and are then approximated by a series of straight line segments for computer application. With the exception of central pressure, p_0 , and radius to maximum winds, R , all of the parameters are considered to be independent. The following subsections describe the statistical characteristics of the individual parameters of interest.

2.2 Hurricane/Storm Frequency and Direction

The hurricanes/storms causing appreciable storm tides in the vicinity of the Wakulla County shoreline are classified as "landfalling", "alongshore" or "exiting" storms. Reasonably good data are available describing the characteristics of these storms, from 1886 to 1985. For purposes of this report, the data contained in References (3), (4), and (5) are merged for a 250 n.mi. segment of the coast centered at the mid-location of the Wakulla County coastline. The storm direction is defined here as the azimuth of storm translation direction at the time of landfall, or, if an alongshore storm, when in close proximity to the site.

The designation of a storm as "landfalling", "alongshore" or "exiting" is

somewhat arbitrary as storms travel over a continuous range of directions and there is not a particular direction relative to the shoreline for which the storm tide generating characteristics change markedly. Moreover, the one directional distribution (Figure 2) is applied for all three types of storms. It is important to note that the manner in which the track of a storm is characterized for the purposes of this study is different for landfalling, alongshore and exiting storms. For landfalling and exiting storms, the track is specified by a location of landfall (or exit) and track direction, whereas for the alongshore storms, the track is specified by an offshore distance and a track direction (see Section 2.5). Figure 3 presents a definition sketch of the three types of storms.

For purposes of this study, landfalling and exiting storms are considered to be of possible significance if they made landfall within a 250 n.mi. segment of the coast comprising the study area. This segment is centered about the midpoint of the Wakulla County shoreline. A rectangular grid 250 X 70 n.mi. with the landward side aligned with the general shoreline of Wakulla County and the gulf side extended 70 n.mi. into the ocean, as shown in Figure 4, is used to select historical storms which passed through the sides of this grid. Accordingly, there are 52 landfalling storms, 5 alongshore storms and no exiting storms of significance occurred in the historical data base. Figure 5 shows the sectors of propagation paths for the three types of storms and Tables AI and AII in Appendix A list all the storms used in this study.

Based on historical data, it is expected that within a 2,000 year period a total of 1,140 storms will occur within a distance of 250 n.mi. Of the 1,140 storms, 1,040 will be landfalling and 100 alongshore.

For purposes of computer use, the cumulative probability distribution of hurricane track direction is developed from Figure 2 and is presented in Figure 6.

WAKULLA COUNTY

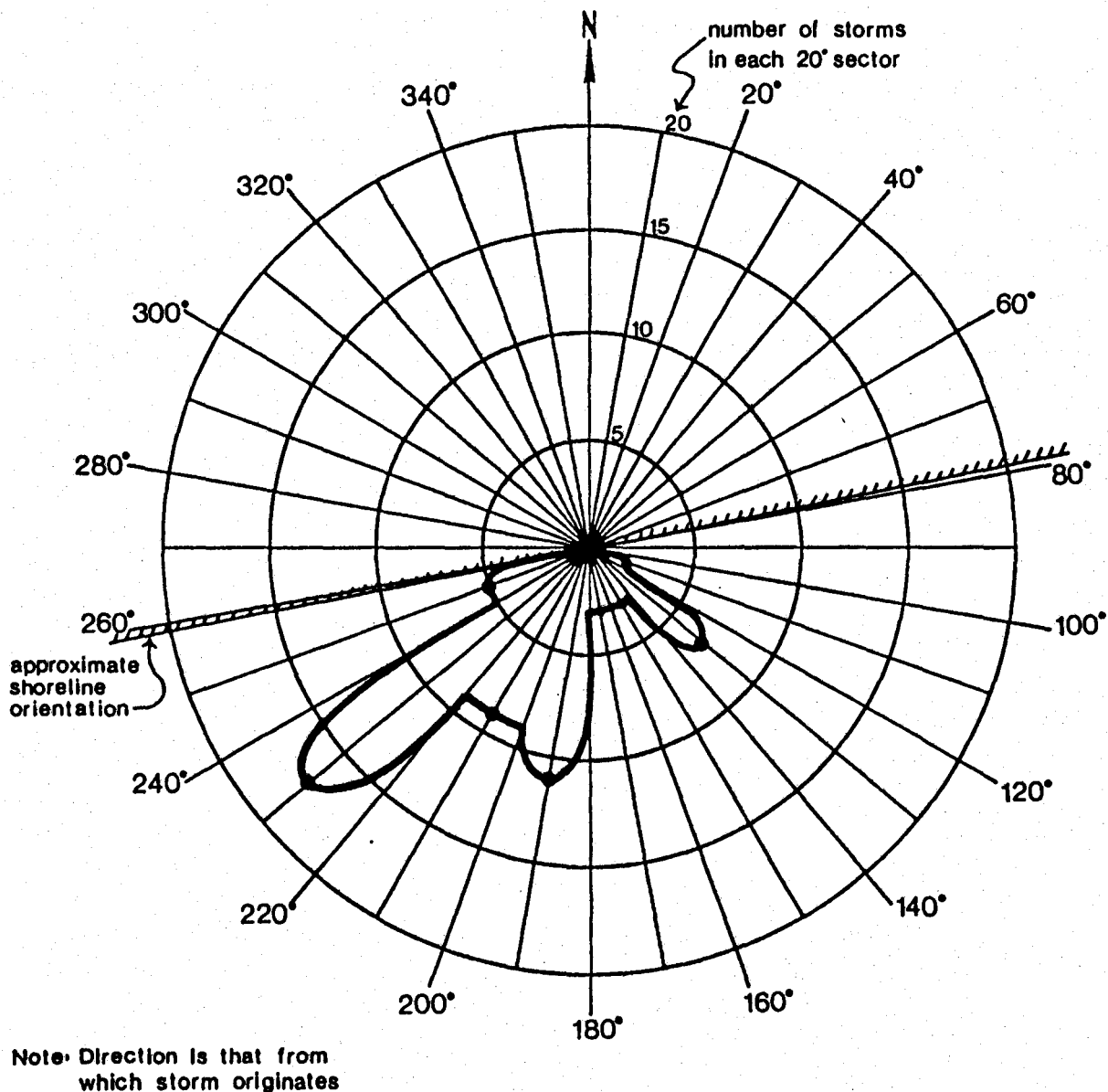


Figure 2 Directional Distribution of Historical Storms in a 250 n.mi. Segment of the Coast Centered at Mid-location of the Wakulla County Coastline

WAKULLA COUNTY

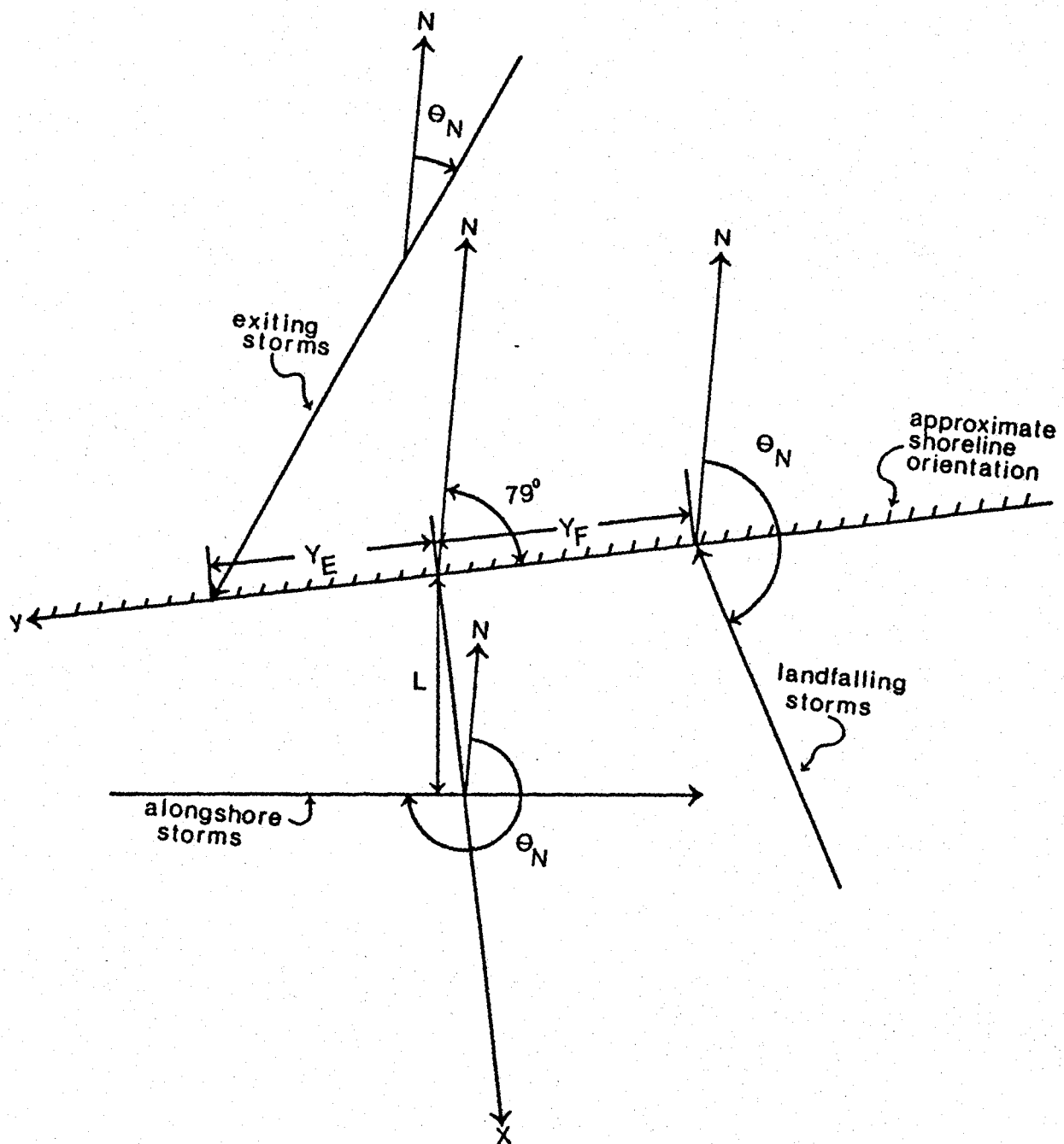


Figure 3 A Definition Sketch of Three Types of Storms

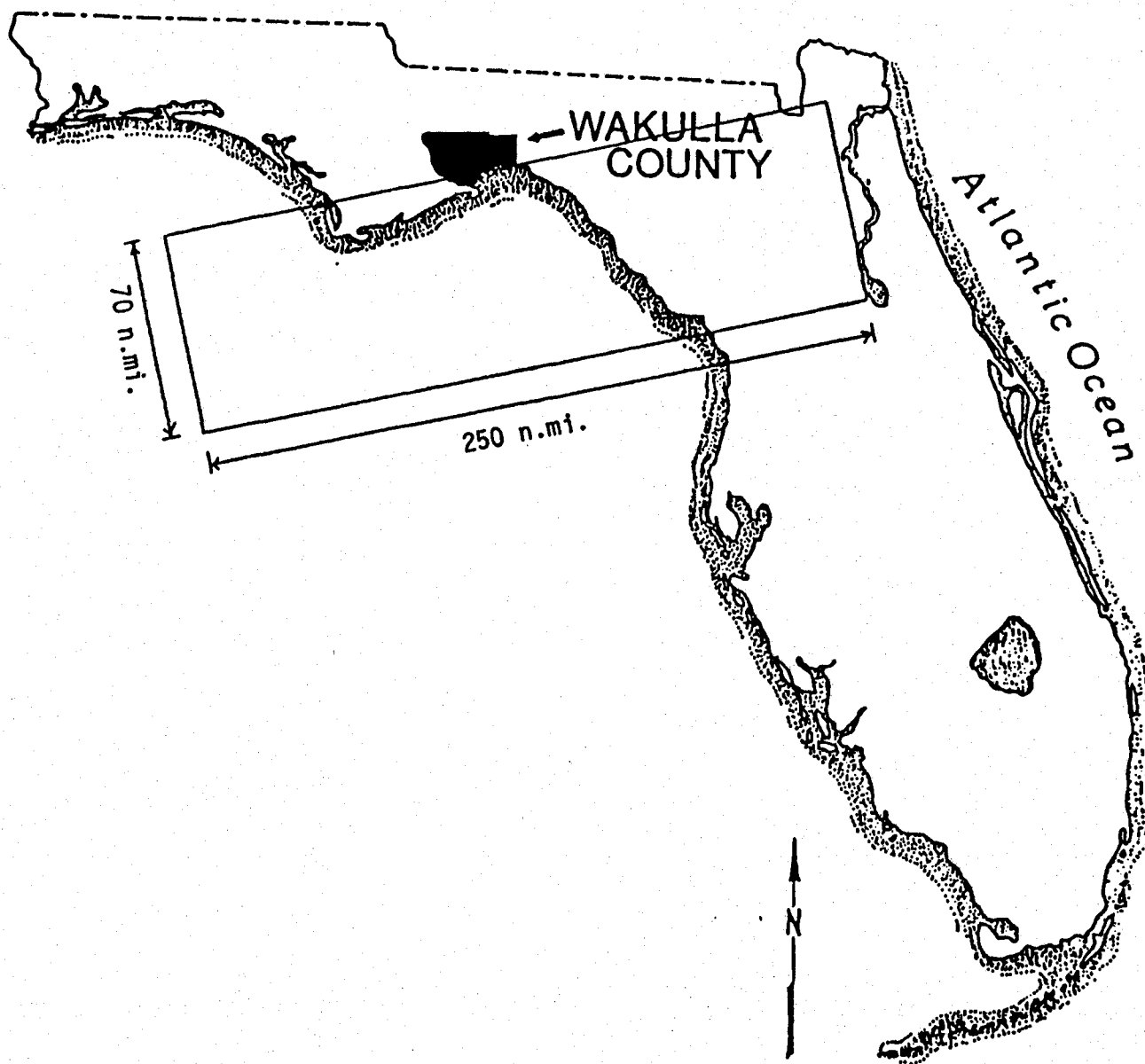


Figure 4 Rectangular Grid for Selection of Historical Storms

WAKULLA COUNTY

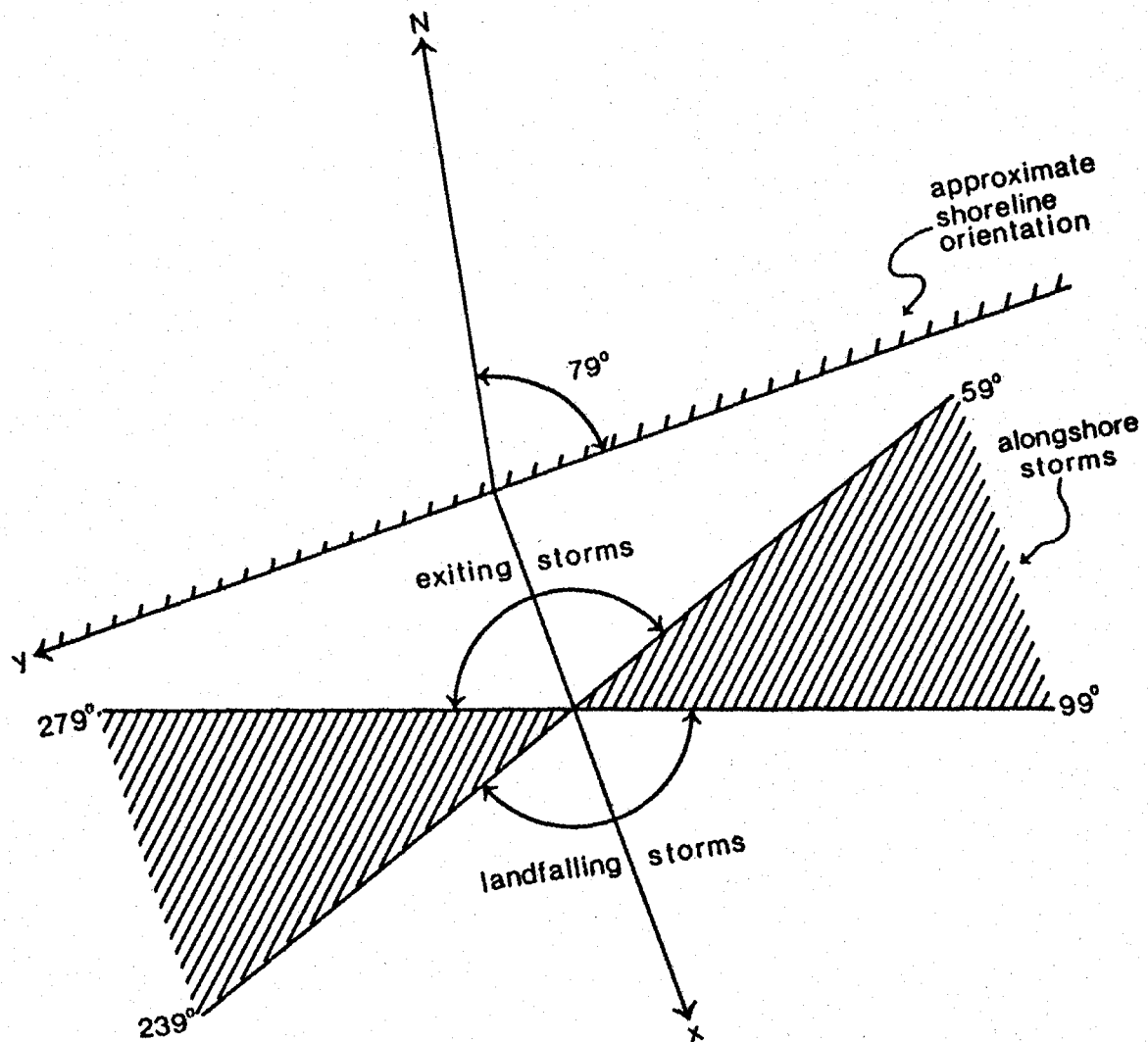


Figure 5 Designation of Landfalling, Alongshore, and Exiting Storms Depending on Track Directions Relative to Shoreline Orientation

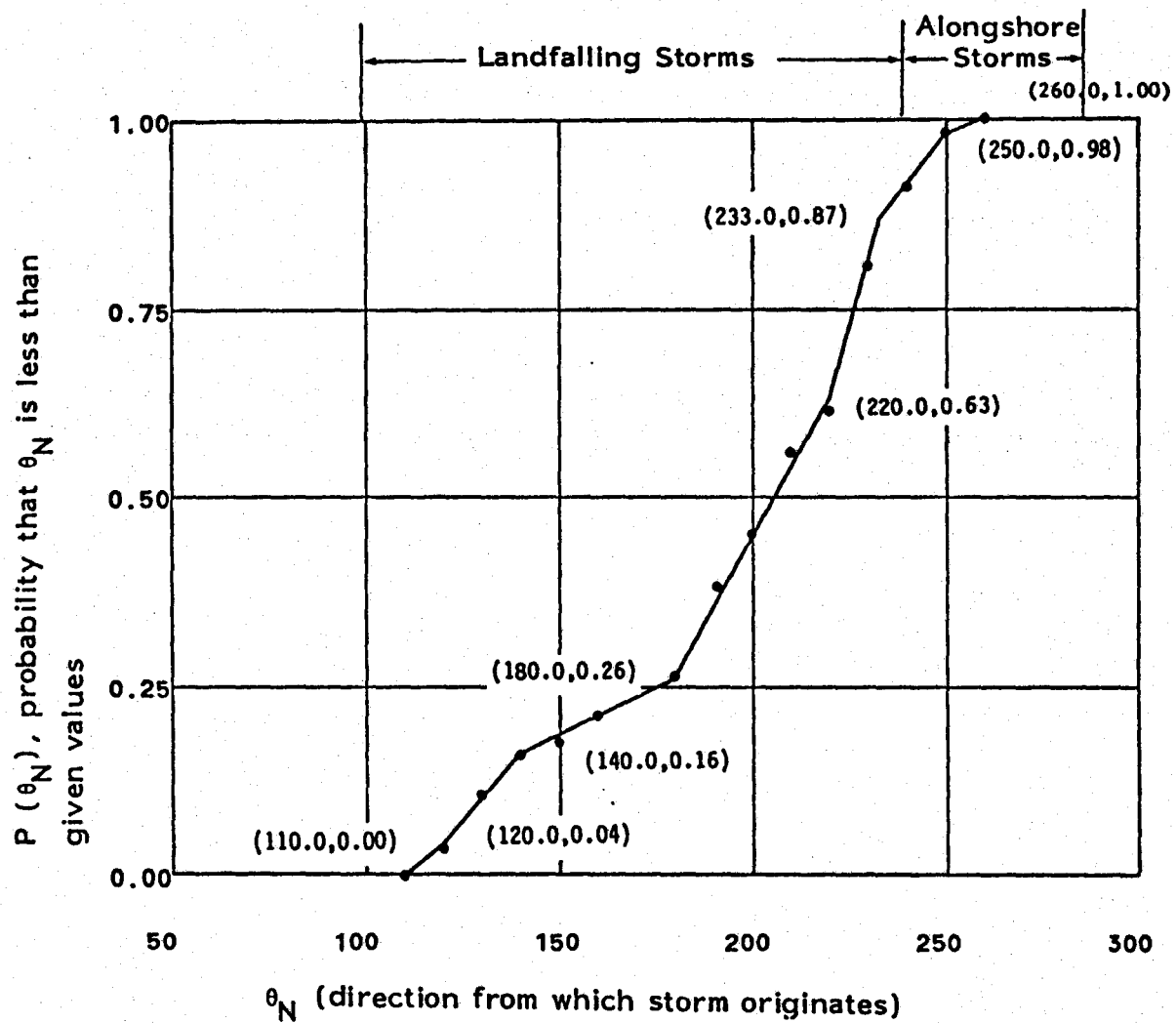


Figure 6 Cumulative Probability Distribution of Storm Track Direction

2.3 Radius to Maximum Winds and Central Pressure Deficit

Figure 7 presents the cumulative probability distribution of radius to maximum winds for landfalling and alongshore storms.

The cumulative probability distributions of central pressure deficit for landfalling and alongshore storms are presented in Figures 8 and 9, respectively.

Examination of historical storm data has demonstrated that the distributions for radius to maximum winds and central pressure deficit are not completely independent. The trend is such that the storms with the more extreme central pressure deficit tend to be smaller. Figure 10 presents the ranges for R and Δp for the 250 n.mi. coast comprising the area of interest. This limits of range on R and Δp is incorporated into the simulations to generate storms in accordance with the historical trend. For purposes of computer application, the joint cumulative probability distribution of R is modified to conform to the limited range shown on Figure 10 for any specific Δp selected within the range of -0.18 to -2.0 in. Hg.

2.4 Forward Speed

The cumulative probability distributions of the forward speed of translation for landfalling and alongshore storms are presented in Figures 11 and 12, respectively.

2.5 Track Position

For the landfalling storms, the track position is determined by the y coordinate, Y_F , representing the landfall point as defined in Figure 3. Figure 13 presents the cumulative probability distribution for the actual landfalling position, Y_F , for landfalling storms. Figure 14 presents the cumulative probability distribution of offshore distance of passage, L , for alongshore storms.

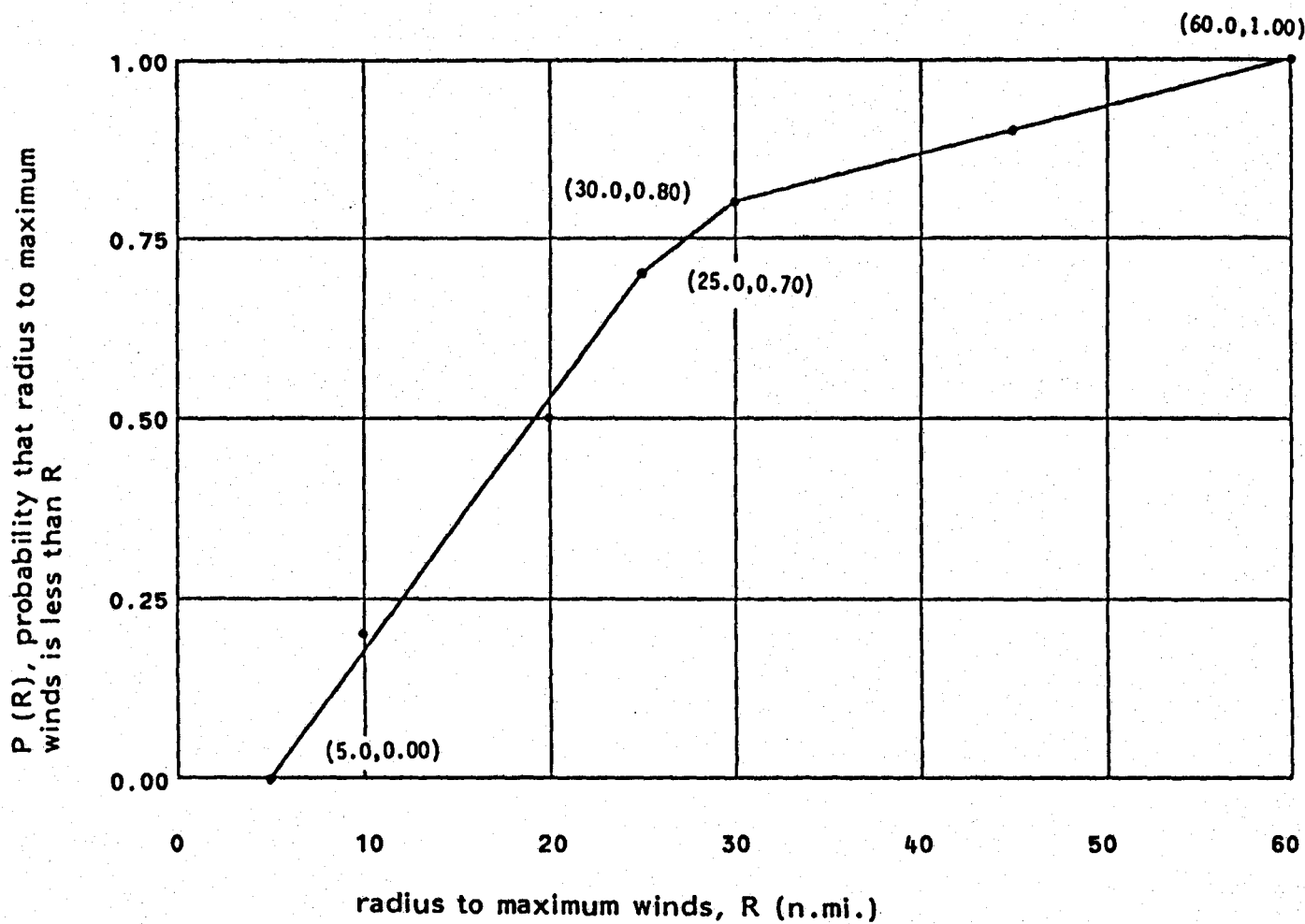


Figure 7 Cumulative Probability Distribution of Radius to Maximum Winds for Landfalling and Alongshore Storms

Landfalling Storms

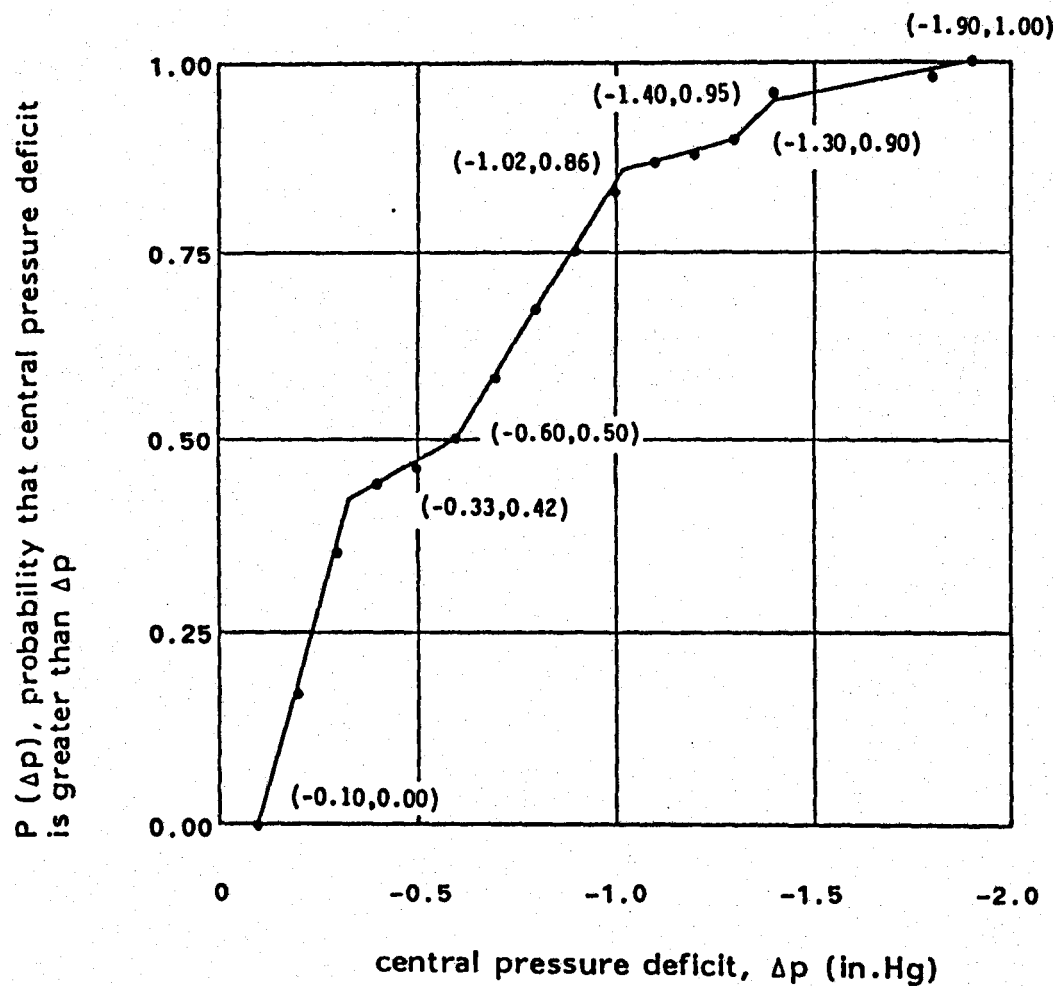


Figure 8 Cumulative Probability Distribution of Central Pressure Deficit, Δp , for Landfalling Storms

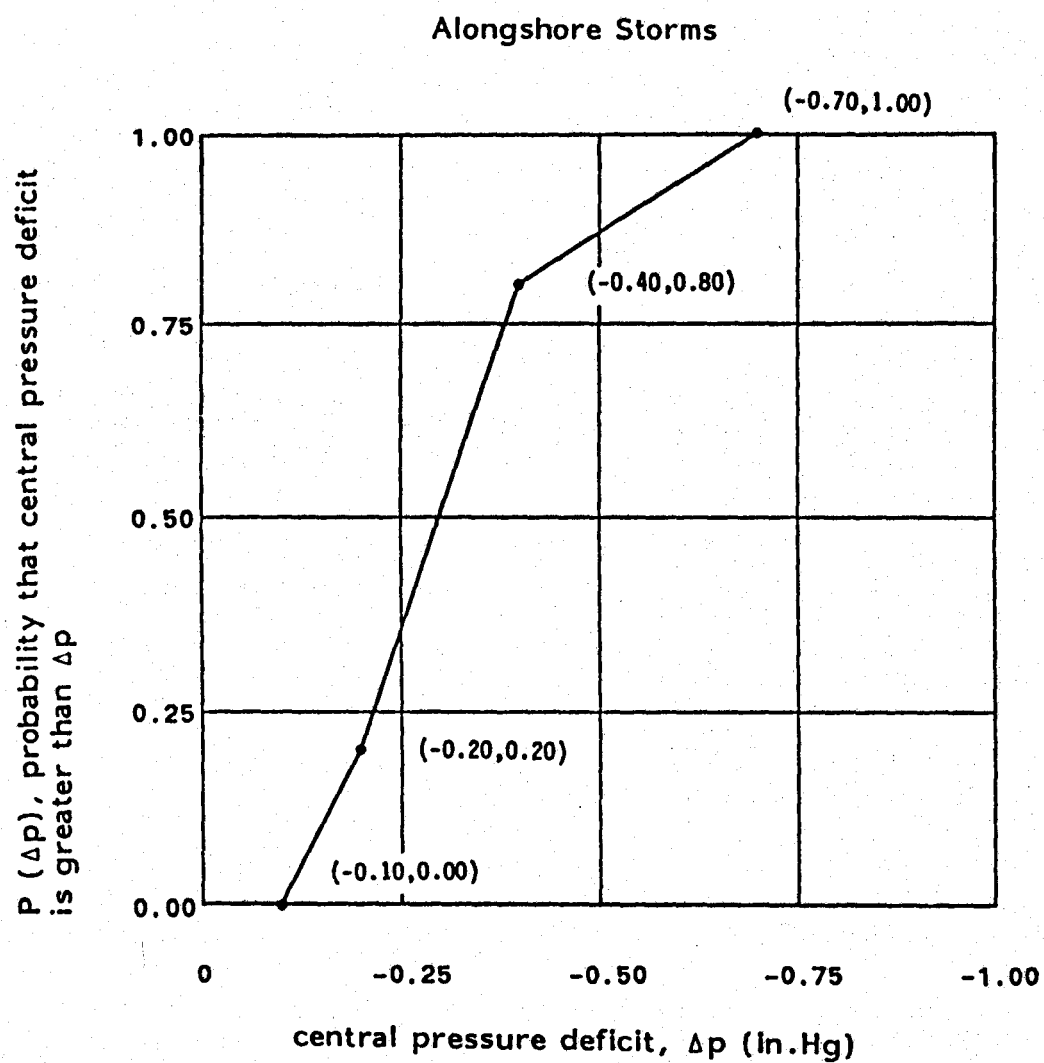


Figure 9 Cumulative Probability Distribution of Central Pressure Deficit, Δp , for Alongshore Storms

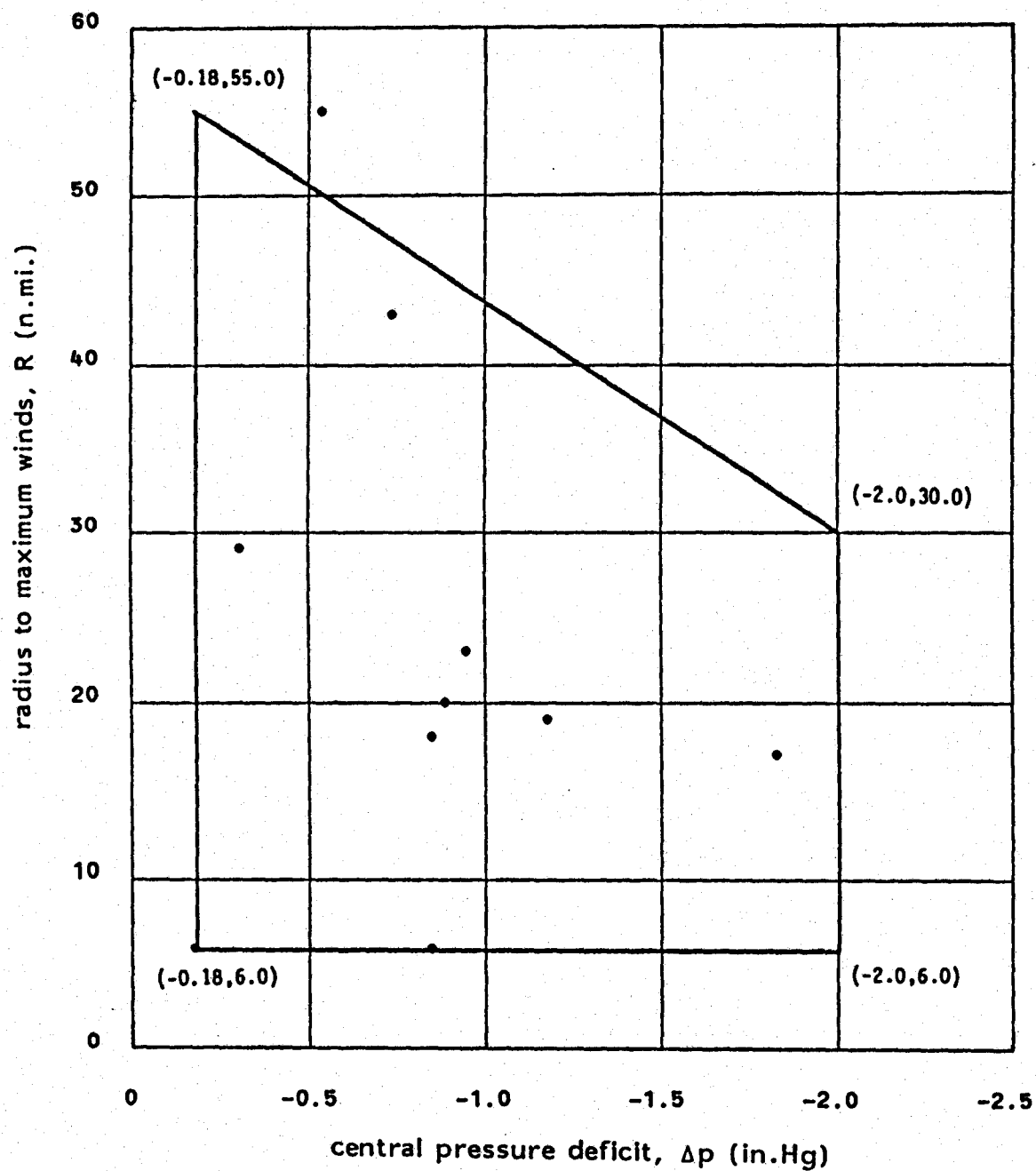


Figure 10 Historical Trend of Central Pressure Deficit, Δp , Radius to Maximum Winds, R

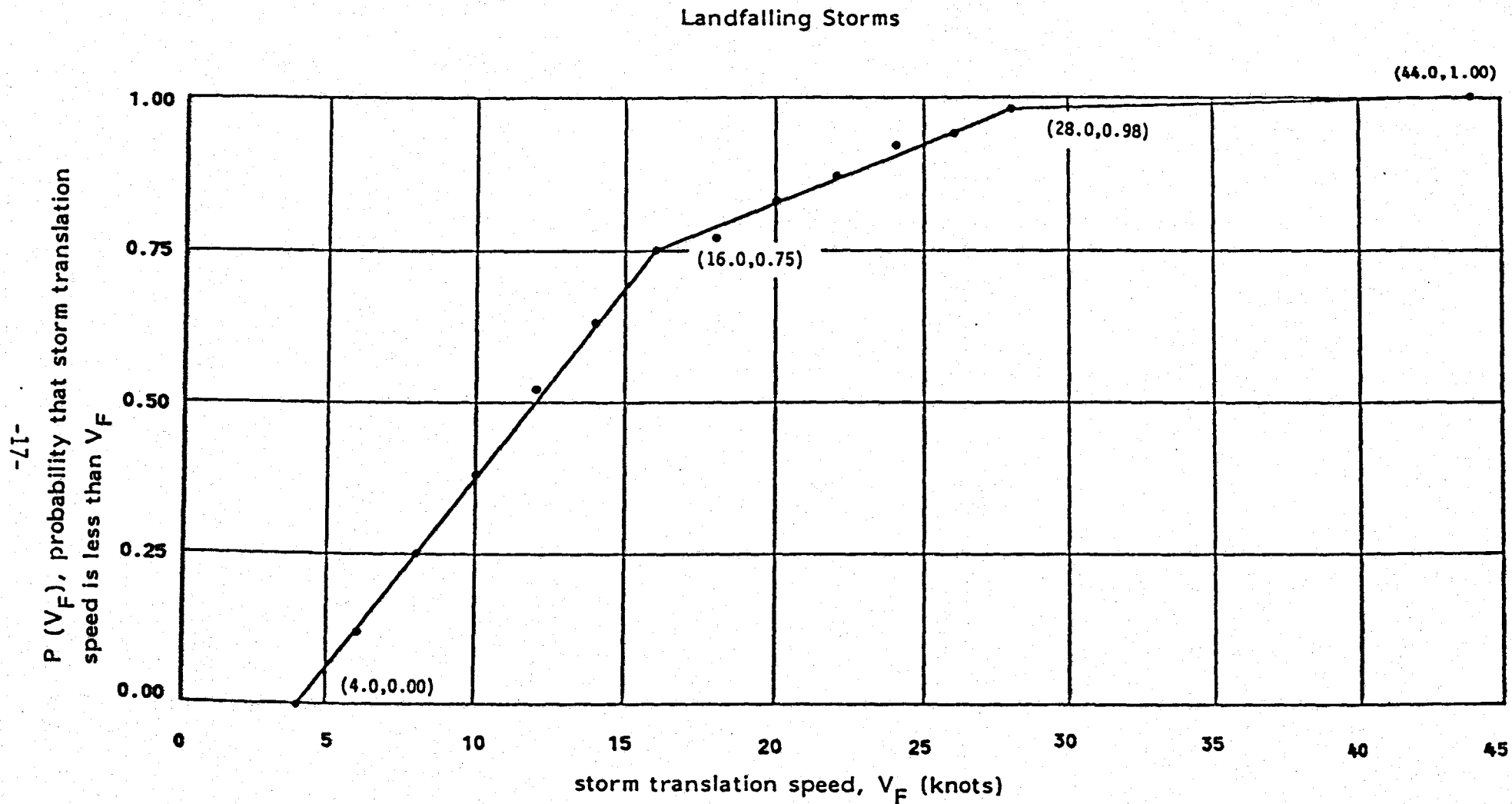


Figure 11 Cumulative Probability Distribution of Storm Translation Speed, V_F , for Landfalling Storms

Alongshore Storms

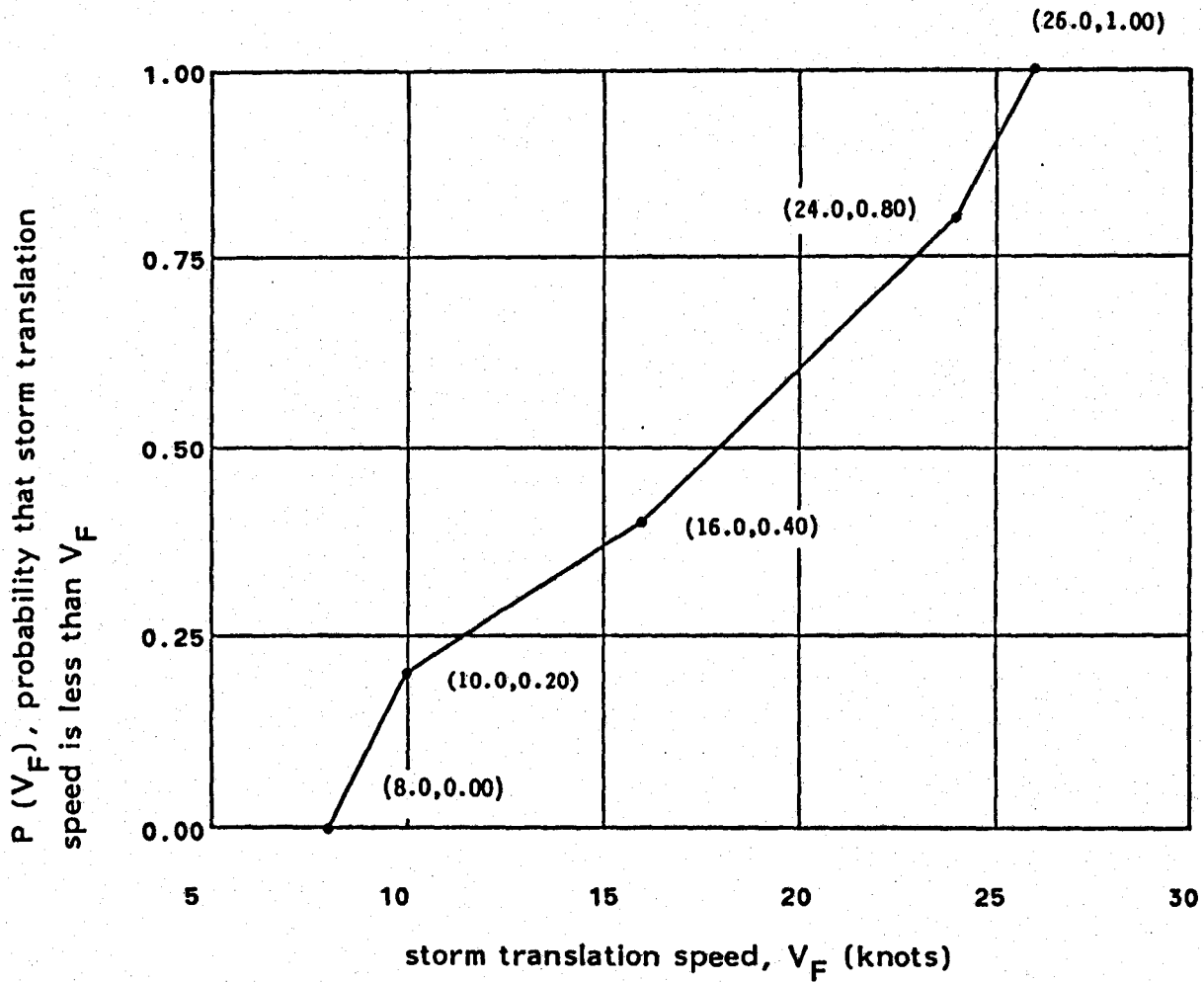


Figure 12 Cumulative Probability Distribution of Storm Translation Speed, V_F , for Alongshore Storms

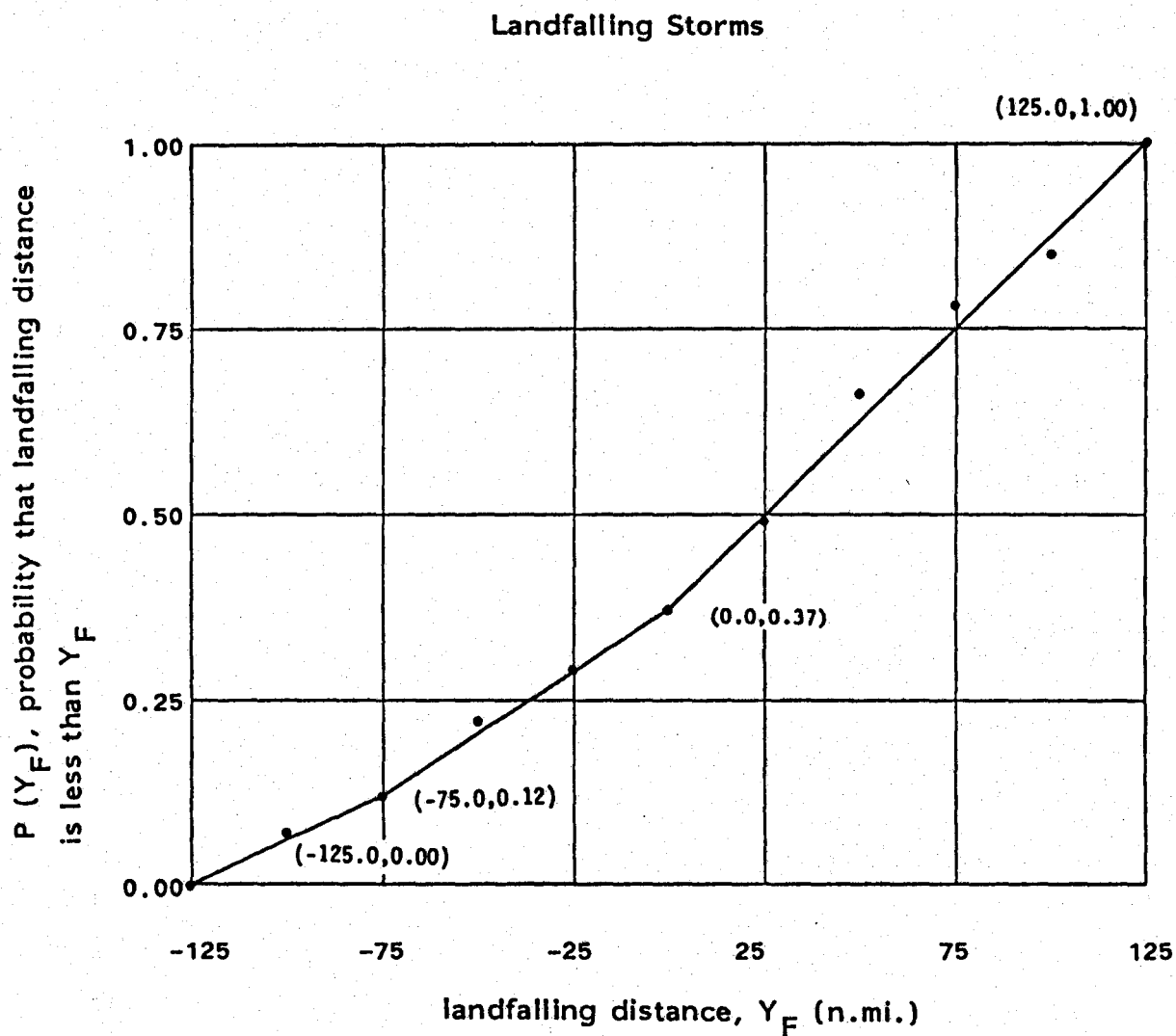


Figure 13 Cumulative Probability Distribution of Landfalling Distance, Y_F , for Landfalling Storms

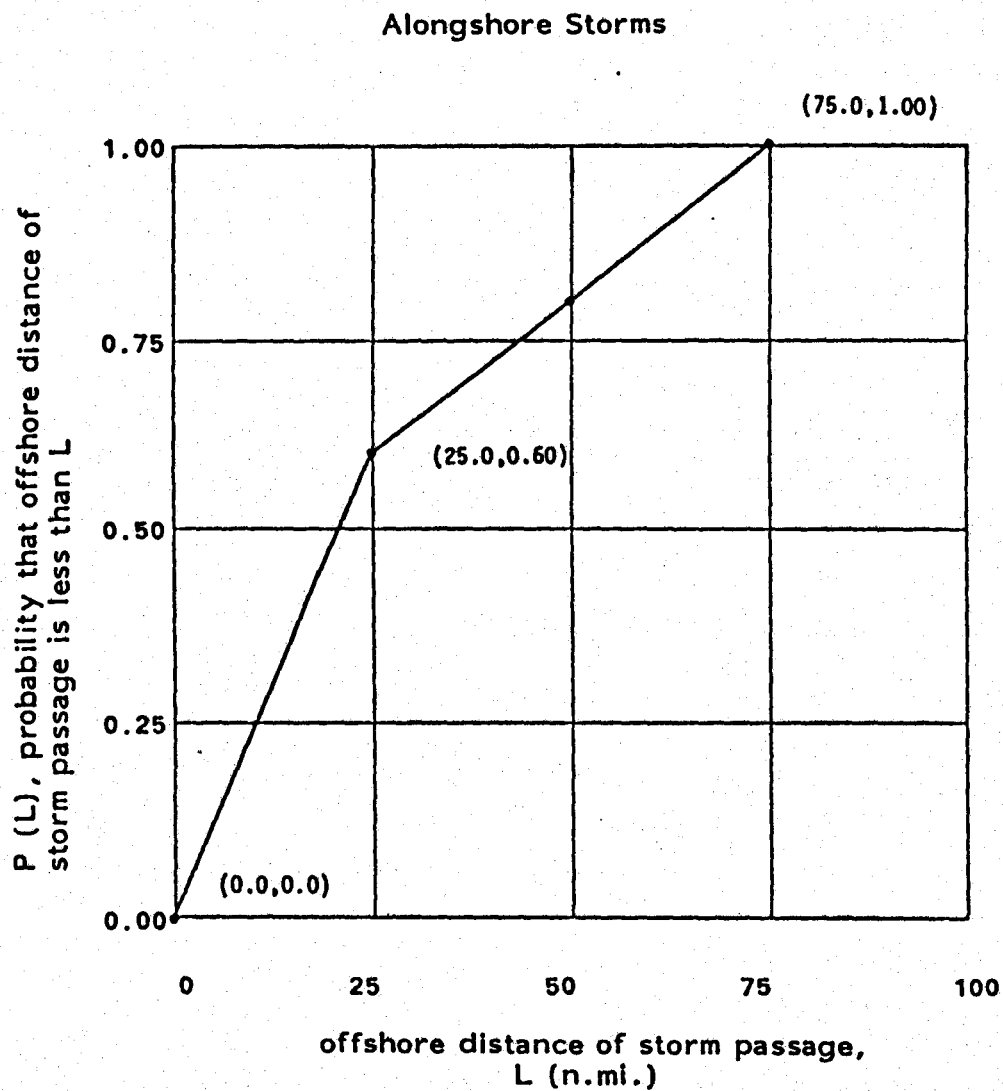


Figure 14 Cumulative Probability Distribution of Offshore Passage Distance, L , for Alongshore Storms

III. METHODOLOGY

3.1 Introduction

This section describes the overall methodology at a very general level to provide the reader with an understanding of the general procedures without addressing the details. The objective of this phase of the study is to develop, verify and apply procedures which will yield valid estimates of the combined total storm tides associated with various return periods at the site of interest.

The approach used here is to combine the available historical statistics of storms with a set of numerical models to simulate the storm tides at the site of interest. Figure 15 is a flow chart illustrating the overall procedure. The numerical models include two-dimensional representations by a variable grid system for the offshore and coastal areas which are of possible significance to the generation of storm tides at the site of interest. Prior to its application, the model is verified using tide gage recordings from hurricanes of June 1966, June 1972 and September 1975. The two-dimensional model is significantly more expensive to operate and, because the simulation phase (which generates the statistics of the combined total storm tides) requires the computations of more than eleven hundred storm events, a simpler, far less expensive one-dimensional model is developed and calibrated to yield reasonably good agreement with the predictions of the two-dimensional model. The following sections describe each of the elements in the overall calculation procedure.

3.2 Model Hurricane

The numerical models require, as input, some representation of the atmospheric pressures and winds which are responsible for the storm tide generation. For this purpose, a model hurricane is used that is characterized by the following five parameters:

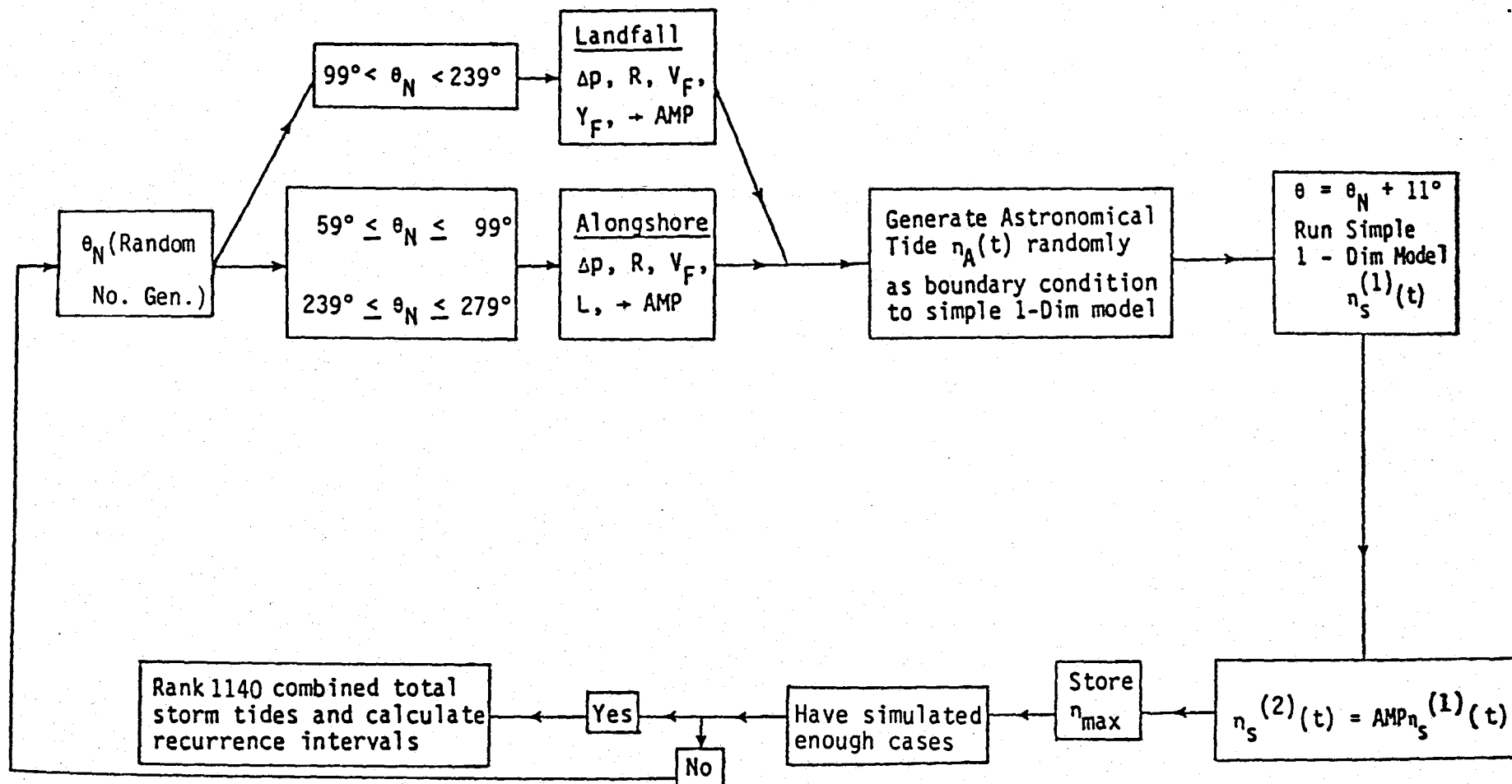


Figure 15 Flow Chart of Methodology

Δp = Central Pressure Deficit

R = Radius to Maximum Winds

V_F = Speed of Hurricane System Translation

θ = Hurricane Direction

Y_F = Landfall location or some other descriptor of hurricane track

The model hurricane is one proposed by Wilson (6) and is characterized by circular isobars. The associated wind field is determined from a solution of the governing equations of motion. The model hurricane is described in Appendix B.

3.3 Features of the Two-Dimensional Numerical Model

As noted previously, there is a variable grid two-dimensional model for the offshore and coastal areas that affects the generation of storm tide for Wakulla County. The grids of the model are arranged in such a way that

- 1) The finest grids cover the coastal areas of Wakulla County to yield detailed information for the study area. Fine grids are also used in locations where calibration of the model results against measured storm tides is to take place.
- 2) The coarsest grids cover the model boundary areas where detailed information is not needed.
- 3) A number of grids varying gradually in size are used for the transition from the coarsest to the finest grids and vice versa.

This arrangement of the varying grid system for the two-dimensional model gives good efficiency of computer time utilization.

The size of the finest grid is 1,000 ft. X 2,000 ft. and the coarsest 60,000 ft. X 60,000 ft. The two-dimensional model covers an area of 180.4 n.mi. X 262.9 n.mi. with the longer side aligned approximately with the general shoreline of Wakulla County. Figure 16 shows the grid system layout..

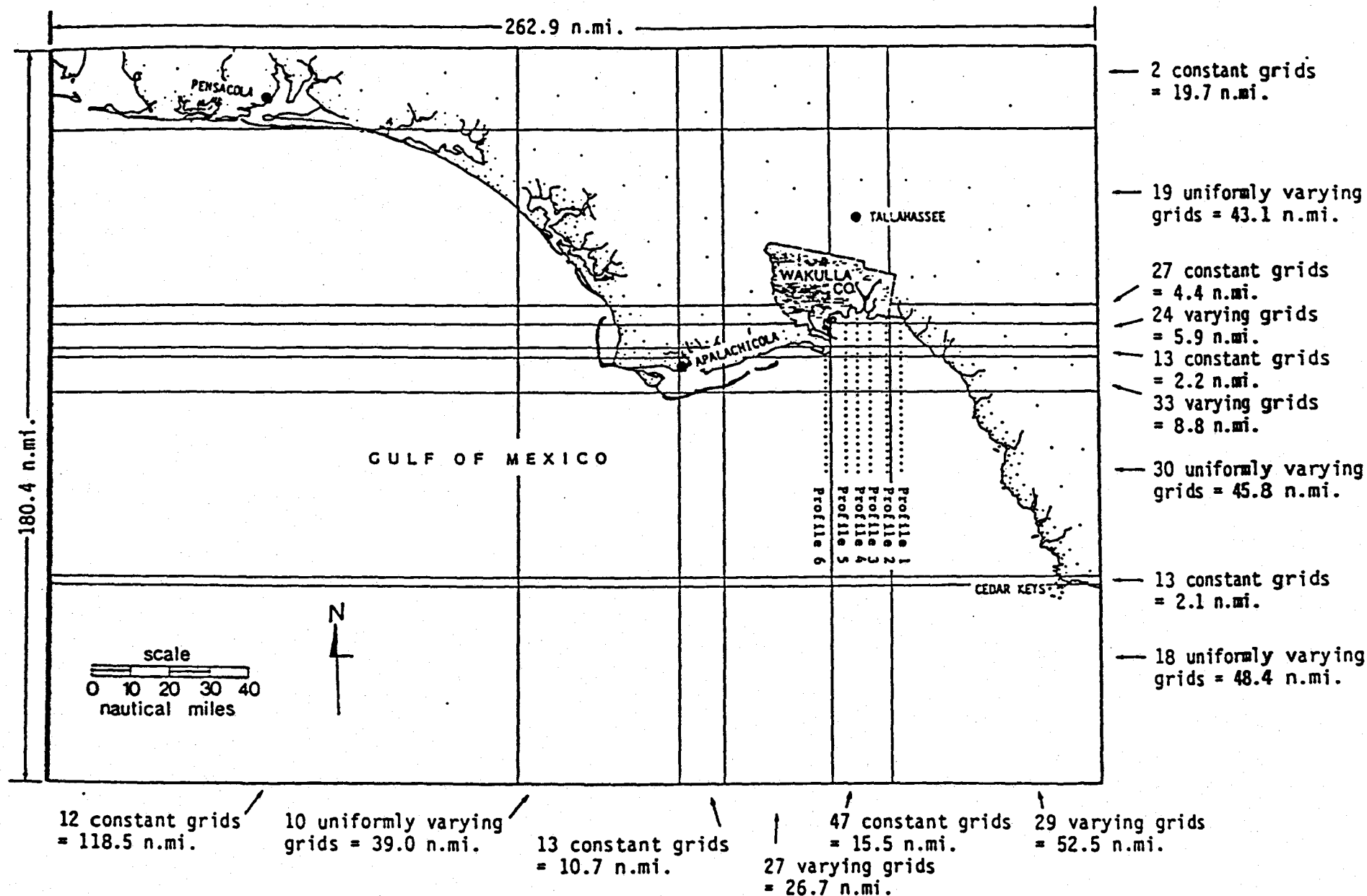


Figure 16 Grid System Layout for Wakulla County

The two-dimensional storm surge model is an implicit finite difference system in which the three governing differential equations are the two vertically averaged equations of momentum and the equation of continuity. The solution to the equations is carried out in a fractional time step procedure. The advantage of this fractional time step procedure is that it is time and space centered to the first order. The finite difference equations appropriate for implicit solution are solved by the "double sweep" method, which is described in detail in Chapter IV. The surface (wind) and bottom (friction) shear stresses, the barometric pressure, the Coriolis effect, the components of slope of the water surface and the boundary conditions are all incorporated into the solution processes.

Inlets and barrier islands which are too small to be resolved by the normal grid sizes are represented in the model by a special treatment. The boundary conditions specified on the two-dimensional model are that the water surface displacement on the boundaries where water is present are equal to the barometric head, due to atmospheric pressure variations. The normal discharge at these boundaries is that necessary to satisfy the volume requirement by the rising and falling water surface encompassed by the boundaries. Although this is an approximation, if the boundaries are sufficiently distant from the site of interest, any extraneous effects of this approximation should be small. The second type of boundary condition is the no-flow requirement which ensures that the flows are zero normal to grid lines where land elevations exist that are higher than the adjacent water elevations. At times when the elevation of a rising water surface exceeds the land elevation of an adjacent grid block, that block is flooded by a simple algorithm and vice versa for the "deflooding" from grid blocks at times that the falling water surface leaves a block exposed. The effects of vegetation on bottom and surface friction factors are accounted for in

an approximate manner.

3.4 Features of the One-Dimensional Numerical Model

As noted earlier, a simple one-dimensional numerical model was developed and calibrated to allow the statistics to be generated based on simulation (calculations) of many storms and associated storm tides.

The one-dimensional numerical model is described as follows. A transect line is established along a line which is approximately perpendicular to the bottom contours. The characteristics (Δp , R , θ , V_F and track) of the storms are defined and the storm is advanced along the track line. The water surface displacement (boundary condition) at the seaward end of the transect line is taken as the static response of the water surface to the barometric pressure deviation at that point. The locations of the six transect lines (profiles) for Wakulla County are shown in Figure 16. Figures 17a, 17b, 17c, 17d, 17e and 17f present the profiles of the six transect lines and their one-dimensional grid representations.

3.5 Flooding and Dynamic Wave Set-Up In Vegetated Areas

The two-dimensional model was modified to include the capability to reduce wind stresses in vegetated areas and to distribute the static and dynamic wave set-up over the active surf-zone, i.e. the region of active wave breaking due to decreasing water depth. Detailed vegetation type and size in the county's coastal areas were collected by a registered land surveyor for use in the analysis. Consistent with the findings and recommendations of the NRC Panel (7), in which it was shown that a relatively small density of over land vegetation protruding through the elevated water surface reduces the wind stress on the water to a very small value (3%), the wind stress in the flooded area was set to zero. In this

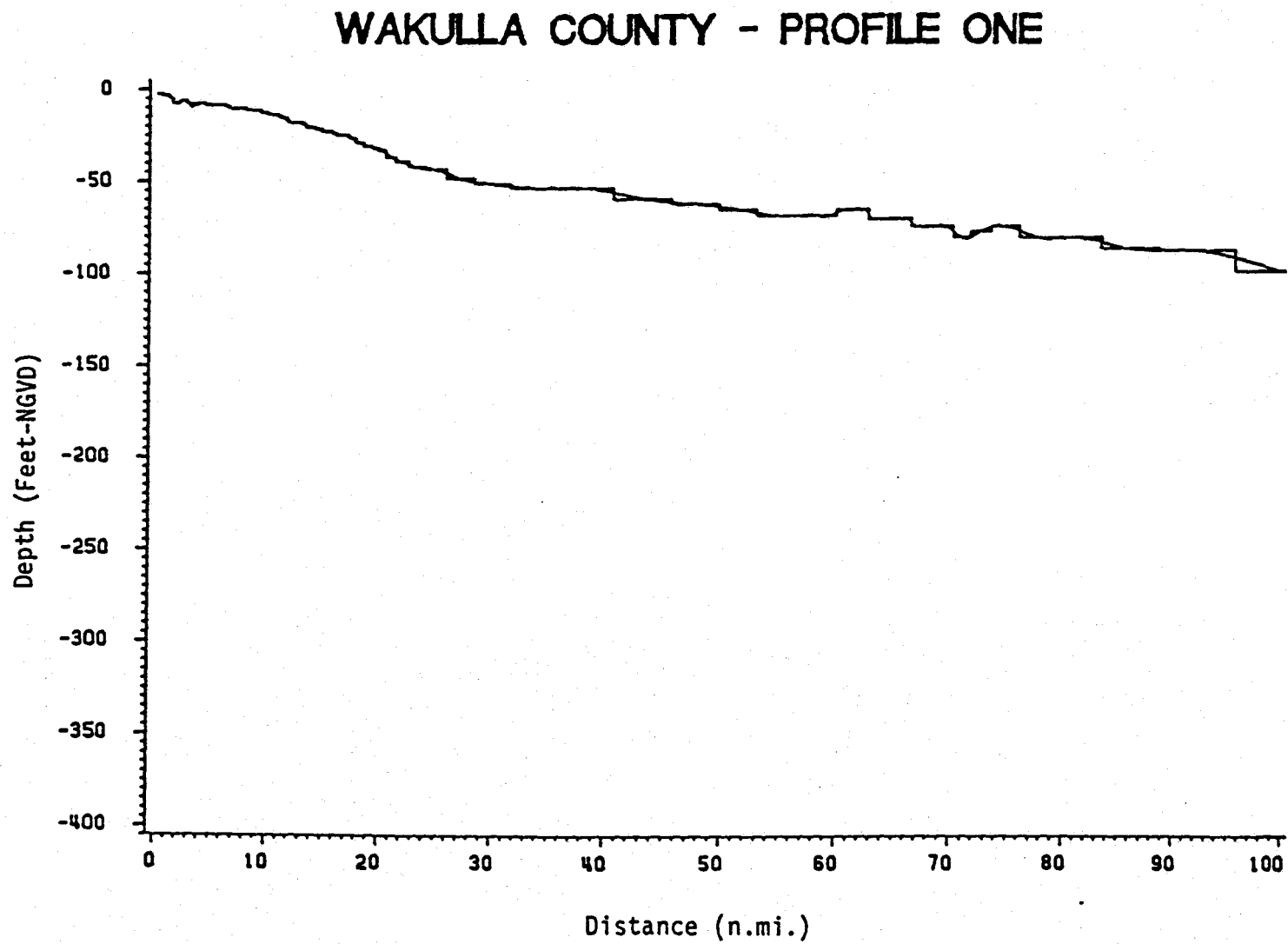


Figure 17a Profile of Transect Line One and its One-Dimensional Grid Representation

WAKULLA COUNTY - PROFILE TWO

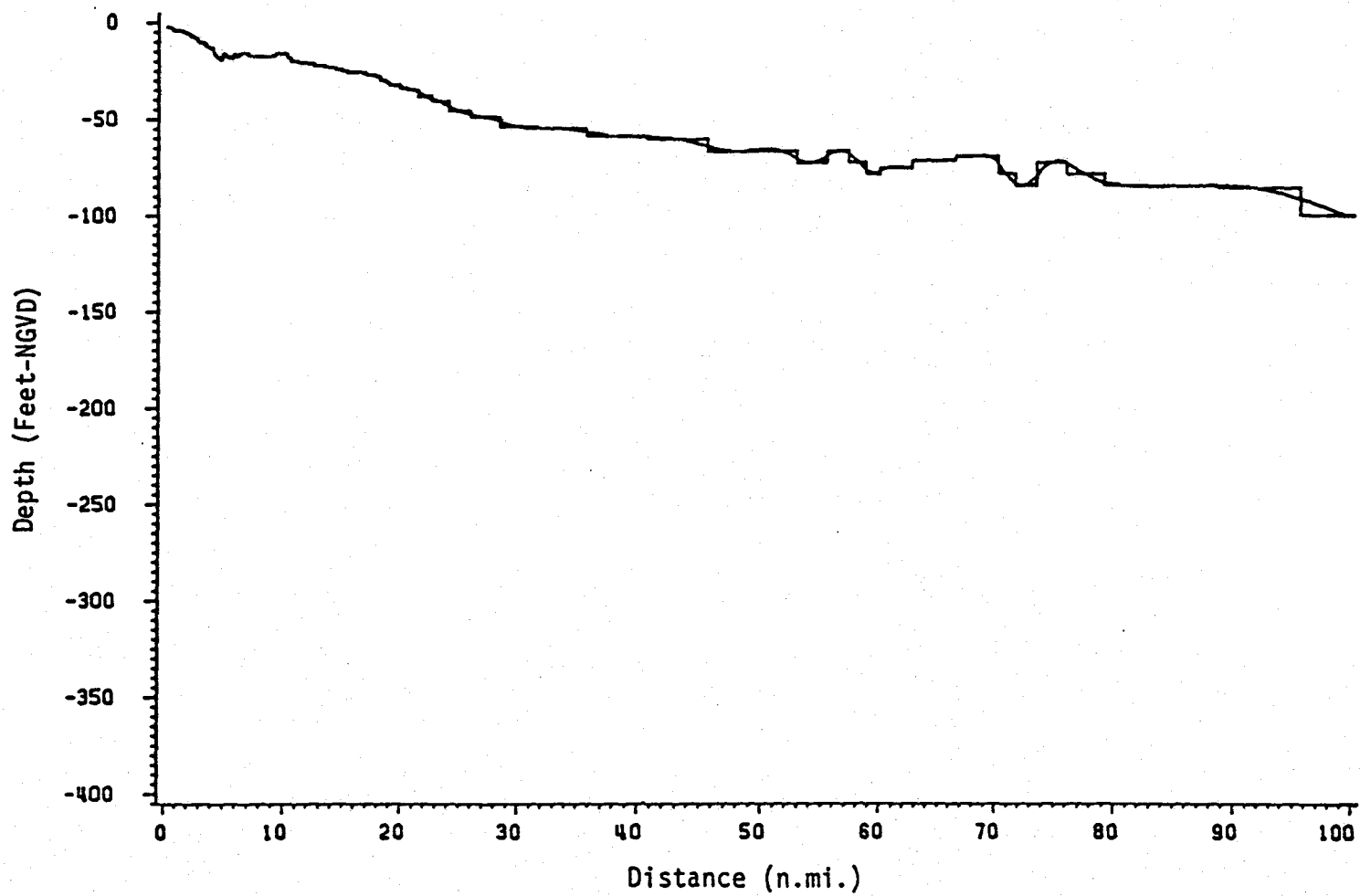


Figure 17b Profile of Transect Line Two and its One-Dimensional Grid Representation

WAKULLA COUNTY - PROFILE THREE

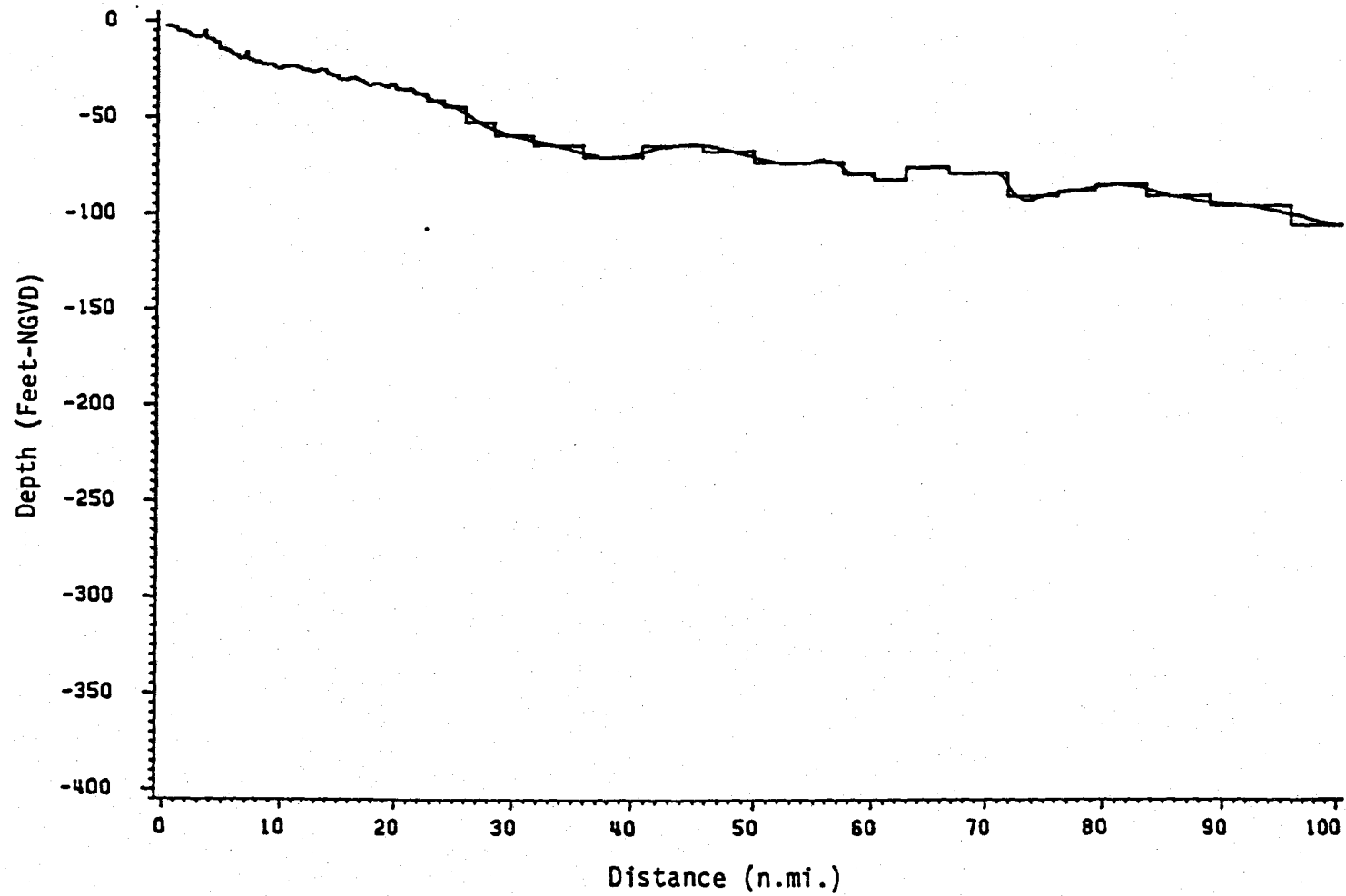


Figure 17c Profile of Transect Line Three and its One-Dimensional Grid Representation

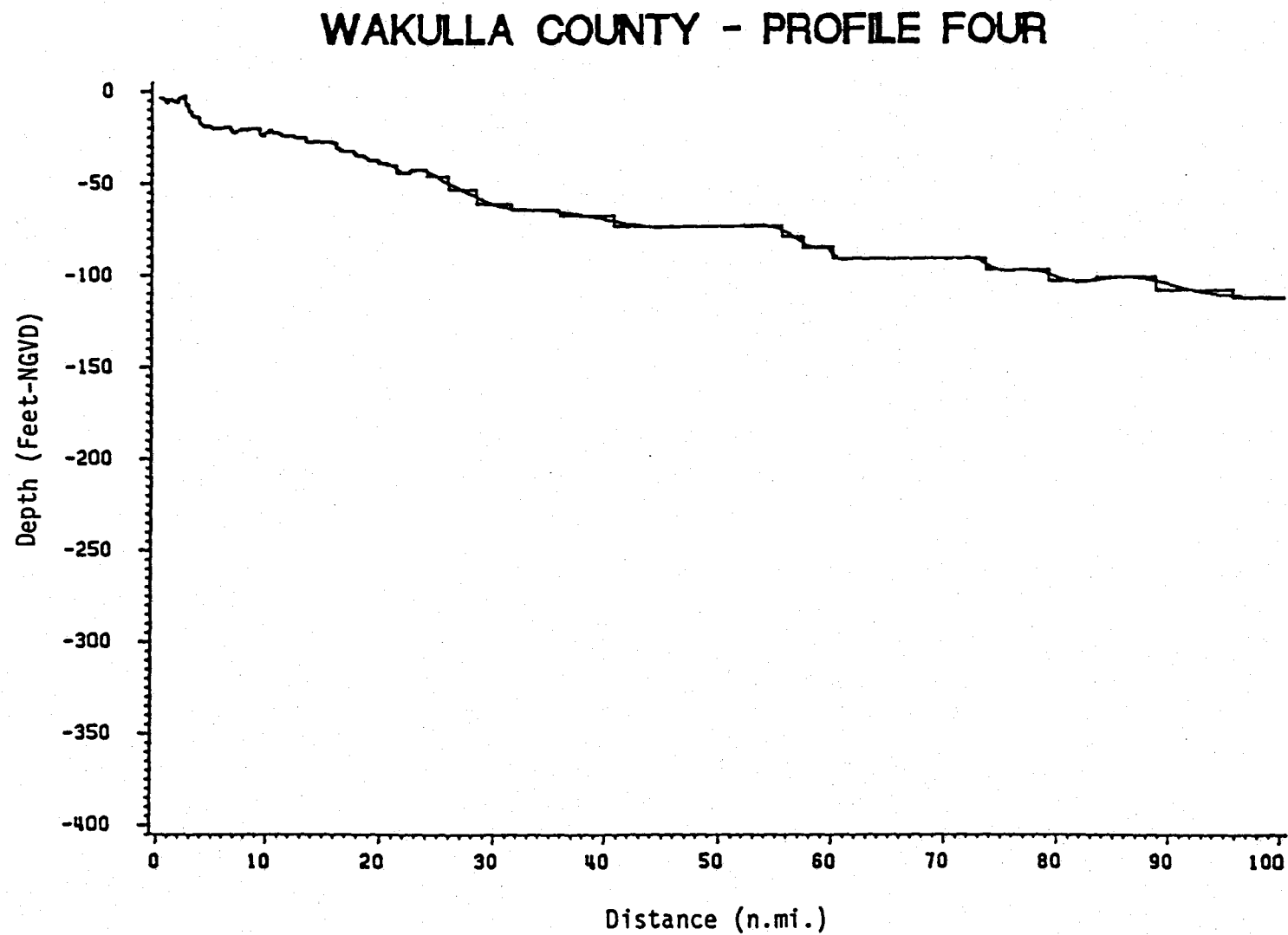


Figure 17d Profile of Transect Line Four and its One-Dimensional Grid Representation

WAKULLA COUNTY - PROFILE FIVE

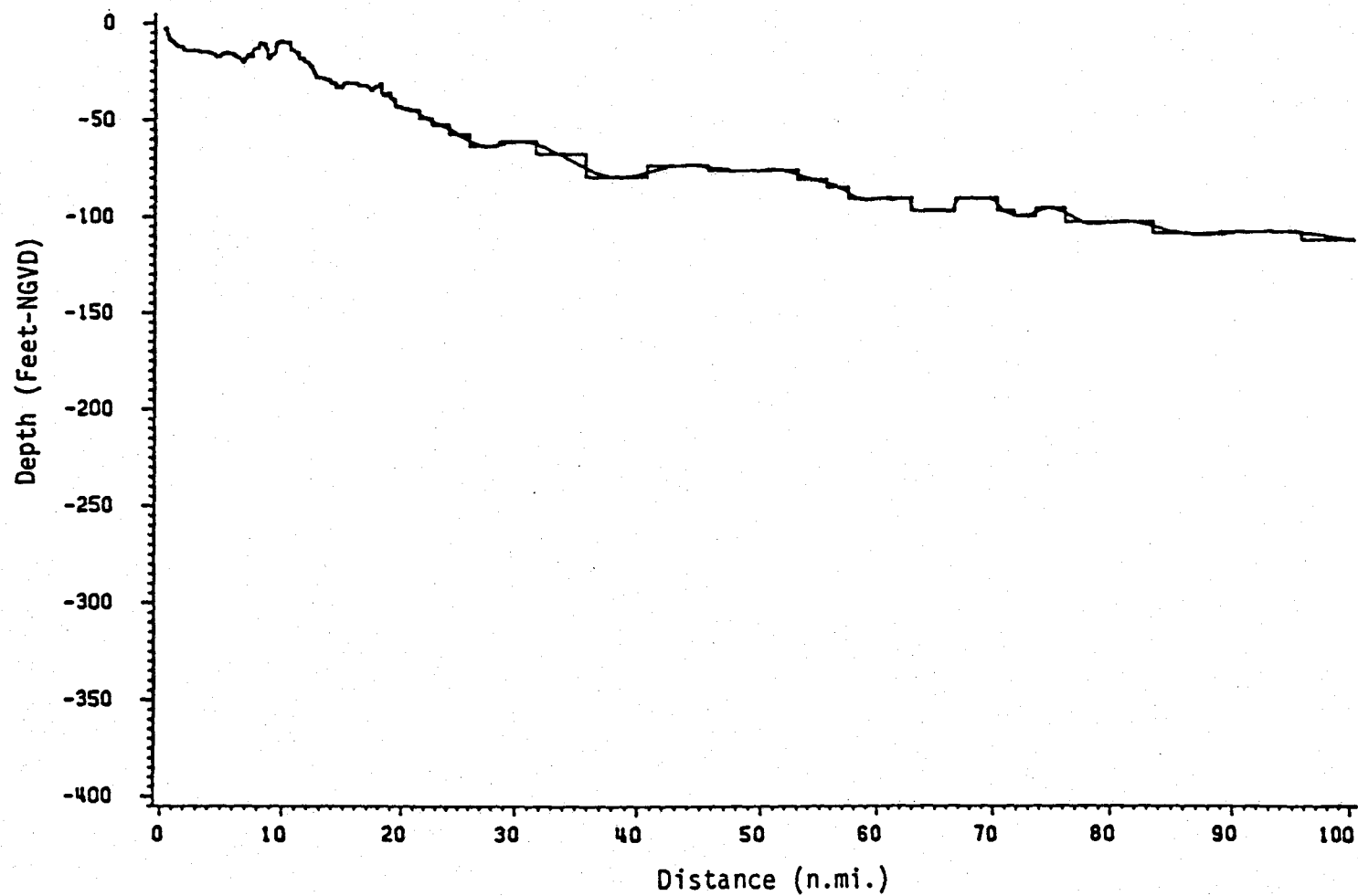


Figure 17e Profile of Transect Line Five and its One-Dimensional Grid Representation

WAKULLA COUNTY - PROFILE SIX

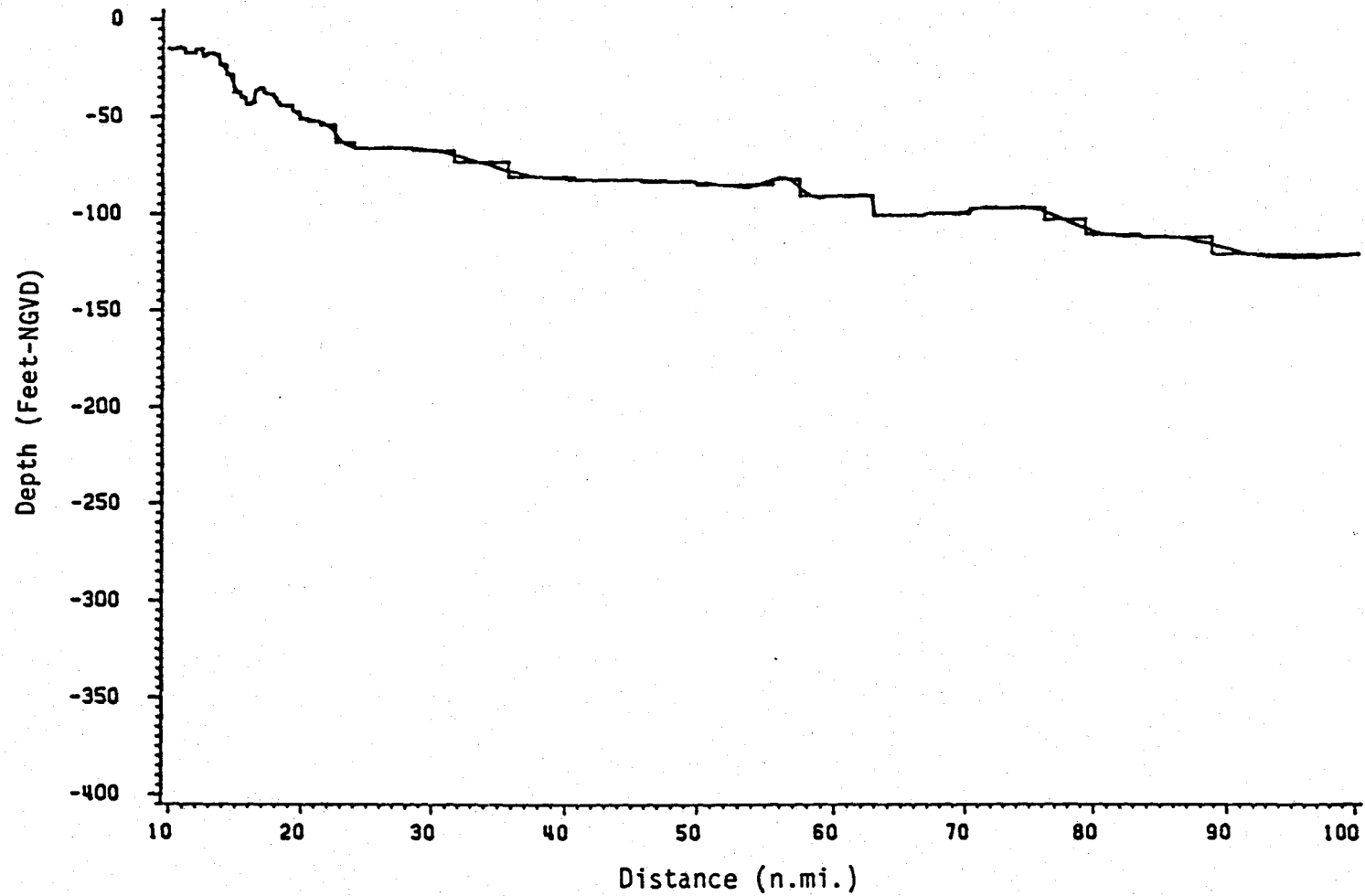


Figure 17f Profile of Transect Line Six and its One-Dimensional Grid Representation

region, the wind stress is applied to the vegetative elements rather than to the water surface. Thus the wind stress and barometric pressure induced storm surge propagates in this region as a "free" rather than as a "forced" wave. Additionally, within this zone, the dynamic wave set-up is distributed in accordance with wave breaking due to depth limitations.

3.6 Application of Numerical Models

The numerical models are applied in the following different phases:

- 1) Verifications of the two-dimensional numerical model against tide gage recordings during the hurricanes of June 1966, June 1972 and September 1975.
- 2) Based on the characteristics of historical storms, the two-dimensional model is run for 22 cases of landfalling and alongshore storms with characteristics representative of the more probable and significant storms.
- 3) The one-dimensional model is run for the same 22 cases for each type of storm described in 2) above. The storm tides developed in 2) then serve as a basis for adjusting the output of the one-dimensional model during the simulation phase.

3.7 Simulation of a n-Year Sequence of Storm Tides

With the statistical characteristics of historical storms available and the simple one-dimensional model calibrated as described in the preceding section, the simulation shown in Figure 18 was carried out. The first phase of the simulation comprises the selection of the storm characteristics in accordance with the historical data. In each storm, this involves the following:

- 1) Quantify Δp , R , V_F , θ and storm track in accordance with the historical

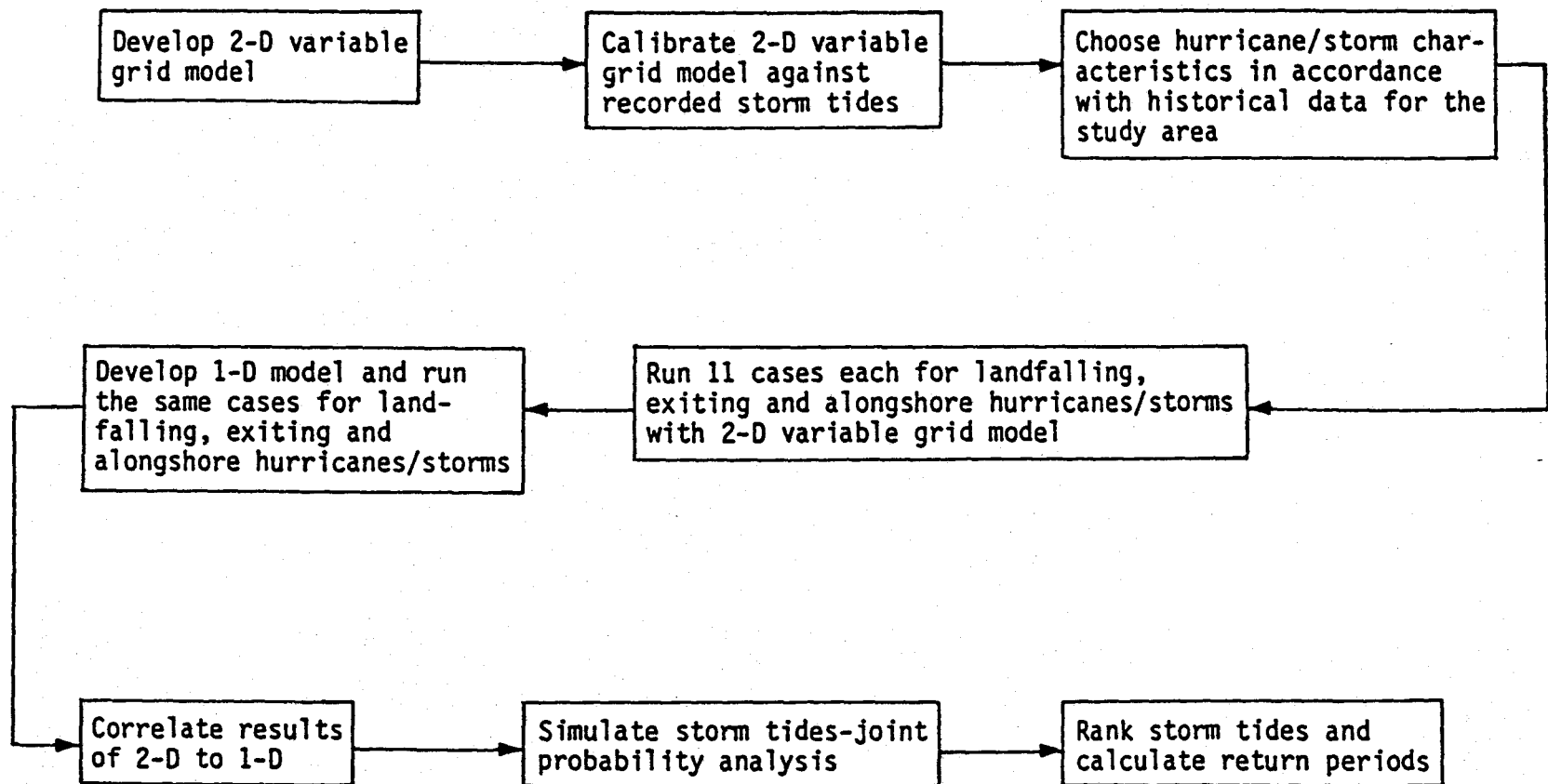


Figure 18 Flow Chart for Storm Tide Simulations (After Calibration to Determine AMP)

probabilities.

- 2) For these characteristics, a random astronomical tide from the storm season is generated as a boundary condition to the one-dimensional numerical model and the model is run to determine the storm tide at the site of interest. This storm tide with dynamic wave set-up is then adjusted in accordance with the factors obtained from the two-dimensional model calibration runs for the landward grid at each time step to yield the combined total storm tide.
- 3) Determine whether enough storms have been simulated for the n-year simulation.
- 4) After the required number of storms and associated storm tides have been simulated, the peak water levels for each storm are ranked and the return period, TR, is calculated, according to

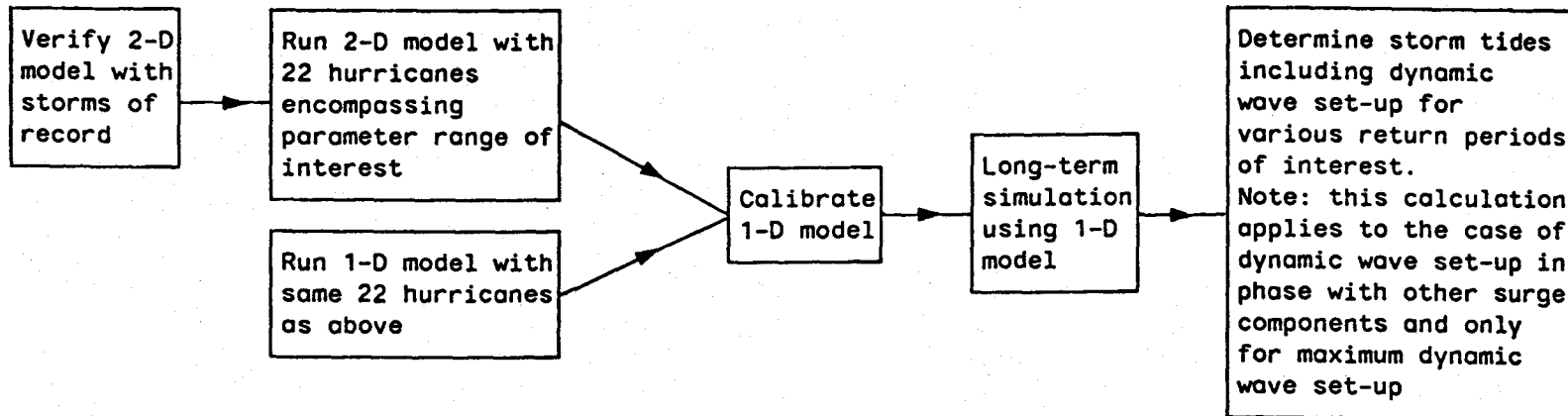
$$TR = 2000/M$$

where M is the rank of the combined total storm tide level. (For example, if the simulation was carried out for a 2,000 year period, the highest combined total tide level would have a return period of 2,000 years, the fourth highest water level would have a return period of 500 years, etc.) Finally, by presenting these results on semi-log paper, it is possible to interpolate the return periods of interest, i.e., TR = 10, 50, 100, 200 and 500 years, to yield the final results for the Phase I study.

3.8 Final Determination of Combined Total Storm Tide and Crest Elevation

Figure 19 presents the features of Phases I and II of this study.

Phase I*



*Note: Phase I is described more fully in Figure 18 of this report

Phase II

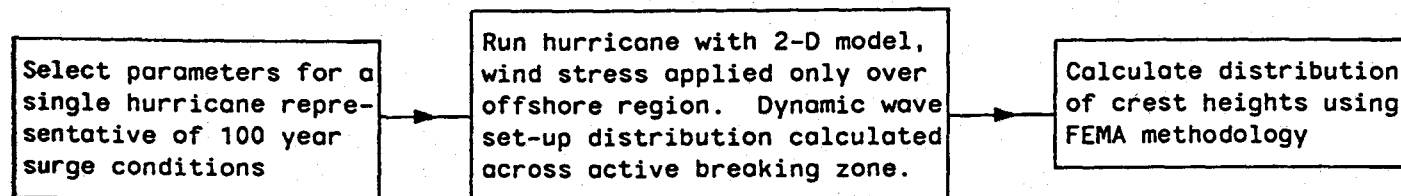


Figure 19 Flow Chart of Methodology for Phases I and II of Analysis

In Phase II, in order to establish the 100 year combined total storm tide and associated crest elevations overland, the results of the preceding section were used to identify the characteristics of a single hurricane which yielded maximum tides approximately the same as the 100 year values. For each alongshore position the resulting wind and barometric tide (hereafter termed "surge") were scaled to the appropriate 100 year value and routed inland using the two-dimensional model; however, in accordance with the NRC Panel and as discussed on page 26, the overland wind stresses were set to zero. As seen in Figure 20, the surge decreased slightly as it propagated landward. Additionally the distribution of wave set-up across the surf zone is calculated in accordance with the physics and depth-limited breaking. Finally the crest elevations are determined in accordance with FEMA methodology, with the exception that because of the fluctuating nature of the dynamic wave set-up component and the long overland distances due to the mild slopes, the dynamic component of the wave set-up was not included as a component to the total water depth governing the breaking wave height.

WAKULLA COUNTY, COLUMN 44

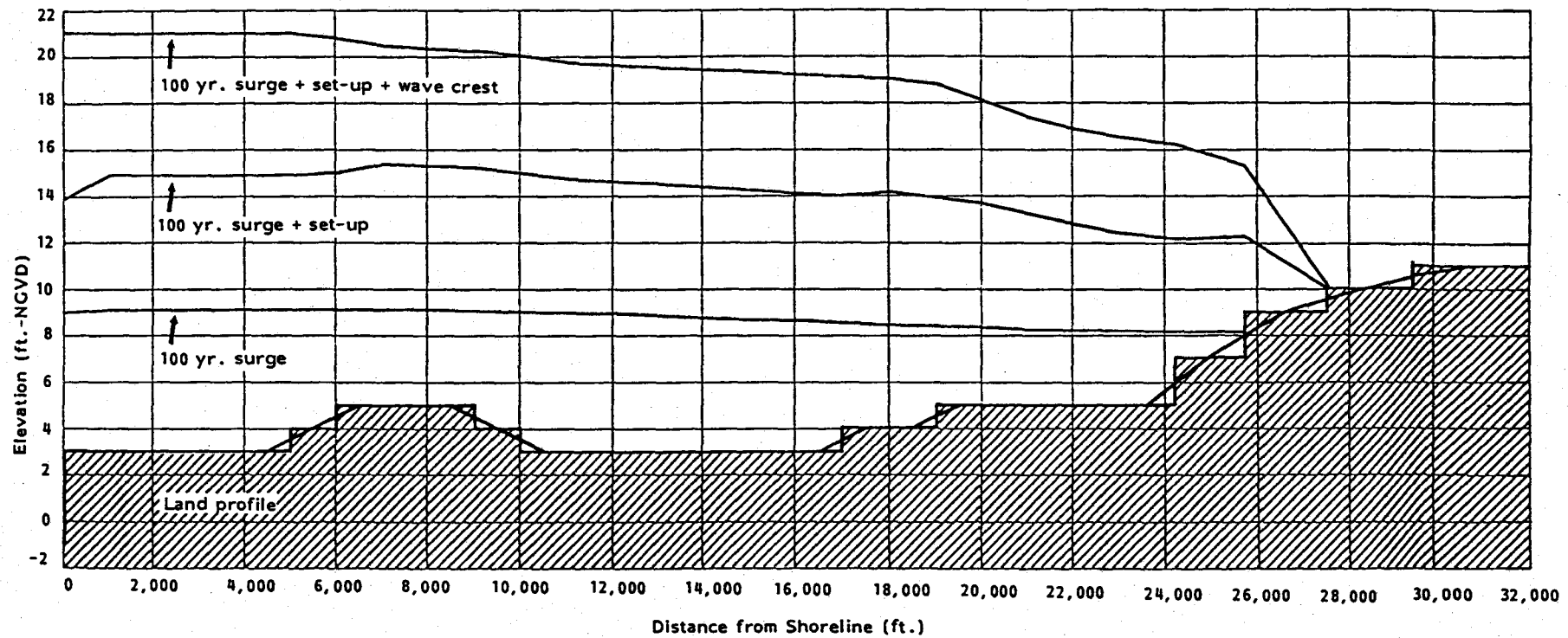


Figure 20 Surge, Wave Set-up and Flooding Elevations along Column 44 of Phase II Analysis

IV. NUMERICAL MODELS-DESCRIPTION AND CALIBRATION

As noted in the previous chapter the methodology included the development, calibration and application of a series of numerical models and statistical hurricane characteristics to the simulation of a long period (2,000 years) to establish storm water levels associated with various return periods of interest. Figure 15 presents a flow chart of the methodology. This chapter parallels that of Chapter III; however, much greater detail is presented. The following subsections review the various numerical models and calibration or calculation procedures.

4.1 Two-Dimensional Numerical Model

Variable-Grid Two-Dimensional Numerical Model - The grid associated with this numerical model relative to the shoreline is presented in Figure 16. The coarsest grid of the model is 9.87 n.mi. x 9.87 n.mi. and the finest is 0.16 n.mi. x 0.33 n.mi. and the purpose of the numerical model is to calculate the storm tides as the storm translates across the shelf.

Governing Differential Equations - The governing differential equations for the two-dimensional model are the two vertically averaged equations of momentum and the equation of continuity, given by:

$$\begin{array}{l} \text{Momentum} \\ \text{Equations} \end{array} \left\{ \begin{array}{l} \frac{\partial q_x}{\partial t} + \frac{q_x}{D} \frac{\partial q_x}{\partial x} + \frac{q_y}{D} \frac{\partial q_x}{\partial y} = -gD \frac{\partial \eta}{\partial x} - \frac{D}{\rho} \frac{\partial p}{\partial x} + \frac{\tau_{wx}}{\rho} - \frac{\tau_{bx}}{\rho} - \beta q_y \quad (1) \\ \frac{\partial q_y}{\partial t} + \frac{q_x}{D} \frac{\partial q_y}{\partial x} + \frac{q_y}{D} \frac{\partial q_y}{\partial y} = -gD \frac{\partial \eta}{\partial y} - \frac{D}{\rho} \frac{\partial p}{\partial y} + \frac{\tau_{wy}}{\rho} - \frac{\tau_{by}}{\rho} + \beta q_x \quad (2) \end{array} \right.$$

$$\begin{array}{l} \text{Continuity} \\ \text{Equation} \end{array} \quad \frac{\partial \eta}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \quad (3)$$

in which

$\begin{pmatrix} q_x \\ q_y \end{pmatrix}$ = volumetric transport components per unit width in the $\begin{pmatrix} x \\ y \end{pmatrix}$ directions
 t = time
 D = total water depth ($h+n$) including the still water depth, h and the storm surge, n
 n = storm surge above mean water level
 x = horizontal coordinate, directed offshore
 y = horizontal coordinate direction according to the left-hand coordinate system
 g = gravitational constant
 ρ = mass density of water
 p = barometric pressure

$\begin{pmatrix} \tau_{wx} \\ \tau_{wy} \end{pmatrix}$ = wind shear stress components in the $\begin{pmatrix} x \\ y \end{pmatrix}$ directions

$\begin{pmatrix} \tau_{bx} \\ \tau_{by} \end{pmatrix}$ = bottom shear stress components in the $\begin{pmatrix} x \\ y \end{pmatrix}$ directions

f = Darcy-Weisbach friction coefficient
 β = Coriolis parameter = $2\Omega \sin \psi$
 Ω = angular speed of earth rotation = 7.27×10^{-5} rad/sec
 ψ = latitude at site of interest

The surface and bottom shear stress components are related to the wind speed W and discharge components by:

$$\begin{pmatrix} \tau_{wx} \\ \tau_{wy} \end{pmatrix} = \rho K W \begin{pmatrix} W_x \\ W_y \end{pmatrix} \quad W = \sqrt{W_x^2 + W_y^2} \quad (4)$$

$$\begin{pmatrix} \tau_{bx} \\ \tau_{by} \end{pmatrix} = \frac{\rho f |q|}{8D^2} \begin{pmatrix} q_x \\ q_y \end{pmatrix} \quad |q| = \sqrt{q_x^2 + q_y^2} \quad (5)$$

in which K is an air-sea friction coefficient developed by Van Dorn (8); and depends on the wind speed as follows:

$$K = \begin{cases} 1.1 \times 10^{-6} & \text{for } W < W_{cr} \\ 1.1 \times 10^{-6} + 2.5 \times 10^{-6} \left(1 - \frac{W_{cr}}{W}\right)^2 & \text{for } W \geq W_{cr} \end{cases} \quad (6)$$

where $W_{cr} = 23.6$ ft/sec.

The quantity, f , is the Darcy-Weisbach bottom friction coefficient and varies with depth, bottom roughness and vegetation, if present. For purposes of this study, f was developed by Christensen and Walton (9) of the University of Florida and is presented in Figure 21.

Finite Difference Forms of Governing Differential Equations - The finite difference representations of Equations (1), (2) and (3) are expressed as

follows with the convective terms (i.e. $\frac{q_x}{D} \frac{\partial q_x}{\partial x}$, etc.) omitted in preparation

for an implicit type of solution. The solution to the equations will be carried out in a fractional time step procedure. This procedure is schematized in Figure 22. The advantage of this fractional time step procedure is that it is time and space centered to the first order.

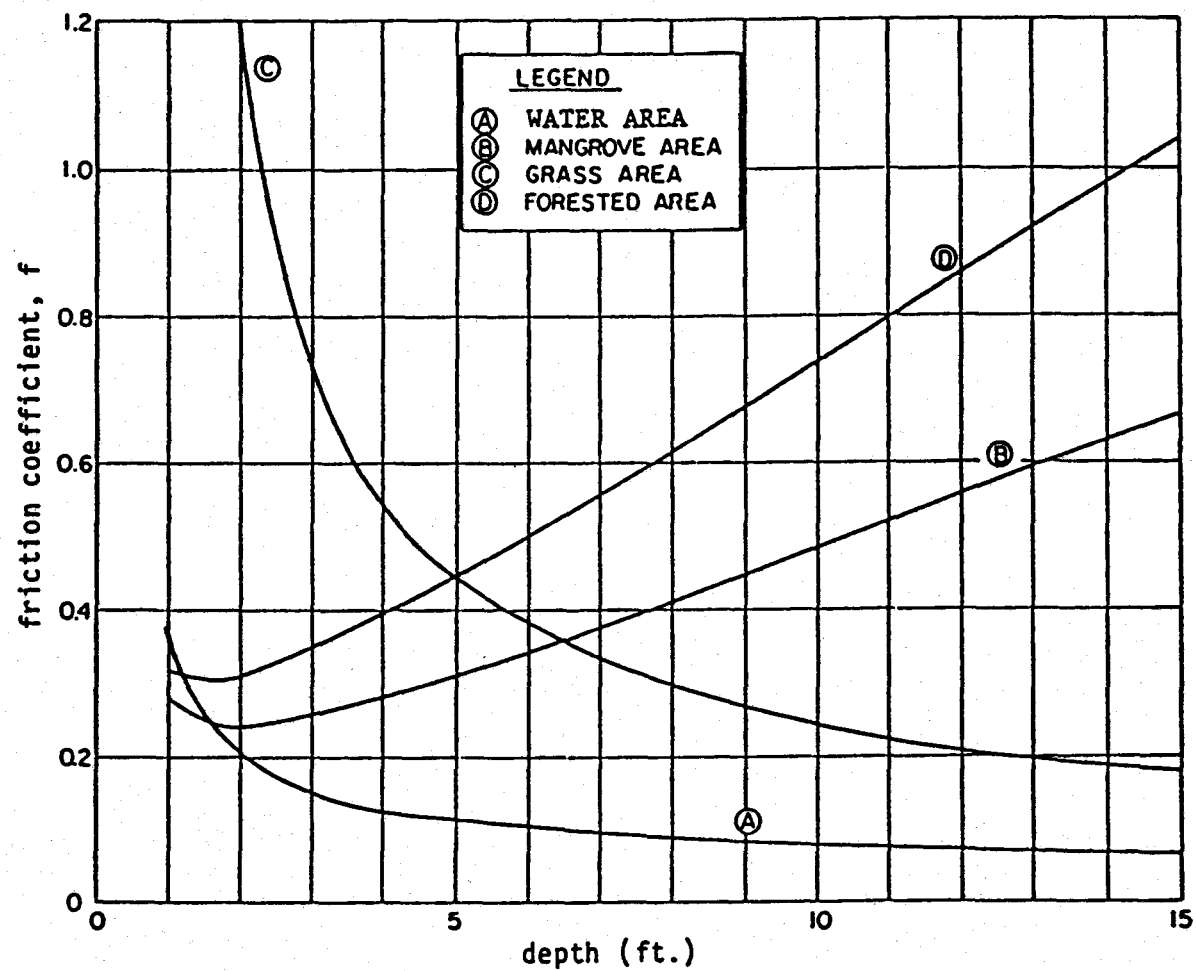
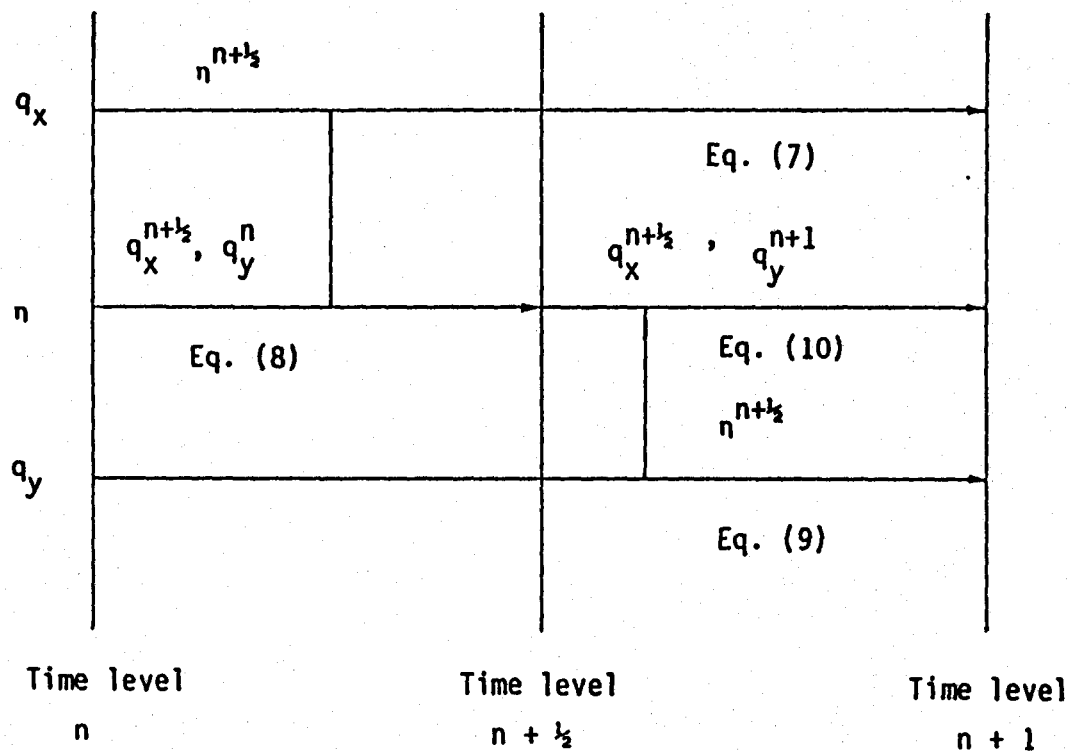


Figure 21 Bottom Friction Coefficients for Various Bottom Conditions



- Notes:
- (1) Vertical links denote equations which are solved simultaneously.
 - (2) Values adjacent to the horizontal bars indicate the time level of the different variables entering into the computations.

Figure 22 Schematic of Implicit Method of Solving Momentum and Continuity Equations

The finite difference equations for the first portion of the fractional time step that are appropriate for the implicit method of solution are:

$$A_i \eta_{i,j}^{n+\frac{1}{2}} + B_i q_{x_{i,j}}^{n+1} + C_i \eta_{i-1,j}^{n+\frac{1}{2}} = D_i \quad (7)$$

$$A_i^* q_{x_{i+1,j}}^{n+1} + B_i^* \eta_{i,j}^{n+\frac{1}{2}} + C_i^* q_{x_{i,j}}^{n+1} = D_i^* \quad (8)$$

where Eq. (7) represents the momentum equation in the x-direction and Eq. (8) represents the continuity equation; these two equations are to be solved simultaneously. The second set of simultaneous equations which is solved subsequent to the solution of the first set is:

$$A_j \eta_{i,j}^{n+\frac{1}{2}} + B_j q_{y_{i,j}}^{n+1} + C_j \eta_{i,j-1}^{n+\frac{1}{2}} = D_j \quad (9)$$

$$A_j^* q_{y_{i,j+1}}^{n+1} + B_j^* \eta_{i,j}^{n+\frac{1}{2}} + C_j^* q_{y_{i,j}}^{n+1} = D_j^* \quad (10)$$

Implicit Solution of the Finite Difference Equations - The solution for each time step progresses by first solving Eqs. (7) and (8) simultaneously for each j grid line sweeping over all values of i. This establishes the values of $\eta^{n+\frac{1}{2}}$ and q_x^{n+1} for the entire (i,j) field. The procedure is then repeated for Eqs. (9) and (10) in which this pair of equations is solved simultaneously for η^{n+1} and q_y^{n+1} for the entire (i,j) field. This latter pair of equations is expressed sequentially for each value of i, then solved for all values of j, for that particular i grid line. The expressions for the various coefficients are presented as follows.

$$A_i = g(\overline{h+\eta}) \frac{\Delta t}{\Delta x}$$

$$B_i = 1 + \frac{f|q_{i,j}^n| \Delta t}{8(\overline{h+\eta})^2}$$

$$C_i = -A_i$$

$$D_i = q_{x_{i,j}}^n + \Delta t \left[\frac{(\overline{h+n})}{\rho} \frac{\partial p}{\partial x} + \frac{\tau_{wx_{i,j}}}{\rho} - \beta(\overline{q_y})^n \right]$$

$$A_i^* = \frac{\Delta t}{4\Delta x}$$

$$B_i^* = 1.0$$

$$C_i^* = -\frac{\Delta t}{4\Delta x}$$

$$D_i^* = n_{i,j}^n - \frac{1}{4} \frac{\Delta t}{\Delta x} \left(q_{x_{i+1}}^n - q_{x_i}^n \right) - \frac{\Delta t}{2\Delta y} \left(q_{y_{i,j+1}}^n - q_{y_{i,j}}^n \right)$$

$$\overline{q_{y_{i,j}}}^n = \frac{1}{4} \left[q_{y_{i-1,j}}^n + q_{y_{i,j}}^n + q_{y_{i-1,j+1}}^n + q_{y_{i,j+1}}^n \right]$$

$$|q_{y_{i,j}}^n| = \sqrt{\left(q_{x_{i,j}}^n \right)^2 + \left(\overline{q_{y_{i,j}}}^n \right)^2}$$

$$A_j = \frac{g(\overline{h+n})}{2} \frac{\Delta t}{\Delta x}$$

$$B_j = 1 + \frac{f|q_{i,j}^n|\Delta t}{8(\overline{h+n})^2}$$

$$C_j = -A_j$$

$$D_j = q_{y_{i,j}}^n + \Delta t \left[-\frac{g(\overline{h+n})}{2\Delta x} \Delta t \left(n_{i,j}^n - n_{i,j-1}^n \right) - \frac{(\overline{h+n})}{\rho} \frac{\partial p}{\partial y} + \frac{\tau_{wy_{i,j}}}{\rho} + \beta(\overline{q_x})^n \right]$$

$$\overline{q_{x_{i,j}}}^n = \frac{1}{4} \left[q_{x_{i,j}}^n + q_{x_{i,j-1}}^n + q_{x_{i+1,j}}^n + q_{x_{i+1,j-1}}^n \right]$$

$$|q_{x_{i,j}}^n| = \sqrt{\left(\overline{q_{x_{i,j}}}^n \right)^2 + \left(q_{y_{i,j}}^n \right)^2}$$

$$A_j^* = \frac{\Delta t}{2\Delta y}$$

$$B_j^* = 1.0$$

$$C_j^* = -A_j^*$$

$$D_j^* = \eta_{i,j}^{n+\frac{1}{2}} - \frac{\Delta t}{4\Delta x} \left(q_{x_{i+1,j}}^n - q_{x_{i,j}}^n \right) - \frac{\Delta t}{4\Delta x} \left(q_{x_{i+1,j}}^{n+1} - q_{x_{i,j}}^{n+1} \right)$$

With the coefficients now specified, the method of solving the sets of simultaneous equations will be described. The method is termed the "double sweep" method in which the first sweep involves "conditioning" two sets of auxiliary coefficients (E_i, F_i, E_i^*, F_i^*). The second sweep determines the values of η and q and, in the process, incorporates the required boundary conditions. The procedure will be illustrated for Equations (7) and (8) and it is noted that the same exact procedure is applicable to solving Equations (9) and (10). The procedure commences by establishing two auxiliary equations with four variables (E_i, F_i, E_i^*, F_i^*) which are initially unknown,

$$\eta_{i,j}^{n+\frac{1}{2}} = E_i q_{x_{i,j}}^{n+1} + F_i \quad (11)$$

$$q_{x_{i+1,j}}^{n+1} = E_i^* \eta_{i,j}^{n+\frac{1}{2}} + F_i^* \quad (12)$$

Eqs. (11) and (12) are substituted in Eqs. (7) and (8) and the results simplified to yield

$$q_{x_{i,j}}^{n+1} = -\frac{C_i}{A_i E_i + B_i} \eta_{i-1,j}^{n+\frac{1}{2}} + \frac{D_i - A_i F_i}{A_i E_i + B_i} \quad (13)$$

$$\eta_{i,j}^{n+\frac{1}{2}} = -\frac{C_i^*}{A_i^* E_i^* + B_i^*} q_{x_{i,j}}^{n+1} + \frac{D_i^* - A_i^* F_i^*}{A_i^* E_i^* + B_i^*} \quad (14)$$

Comparison of Eqs. (13) and (14) establishes the values of the unknown coefficients (E, F, E^*, F^*) in terms of the known coefficients ($A, B, \dots, A^*, B^*, \dots$).

The expressions are

$$E_i = -\frac{C_i^*}{A_i^*E_i^* + B_i^*}, \quad F_i = \frac{D_i^* - A_i^*F_i^*}{A_i^*E_i^* + B_i^*} \quad (15)$$

$$E_{i-1}^* = -\frac{C_i}{A_iE_i + B_i}, \quad F_{i-1}^* = \frac{D_i - A_iF_i}{A_iE_i + B_i} \quad (16)$$

To illustrate the manner in which boundary condition information is incorporated into the procedure, suppose that water surface level, η , is specified at $i = \text{IMAX}$ and that q_x is specified as zero at $i = 2^6$. The first sweep commences by noting (from Eq. 11) that

$$E_{\text{IMAX}} = 0.0 \quad (17)$$

$$F_{\text{IMAX}} = \eta_{\text{IMAX},j}^{n+\frac{1}{2}}$$

With the values of E_{IMAX} and F_{IMAX} now known, $E_{\text{IMAX}-1}^*$ and $F_{\text{IMAX}-1}^*$ can be calculated from Eqs. (16), then values of $E_{\text{IMAX}-1}$ and $F_{\text{IMAX}-1}$ computed from Eqs. (15) and so on. E_1^* and F_1^* are set equal to

$$E_1^* = F_1^* = 0.0 \quad (18)$$

in accordance with the boundary condition and Eq. (12). This completes the first sweep and establishes all the coefficients over the grid line.

The second sweep simply consists of applying the methodology to the y-direction as described in detail for the x-direction. In summary, the "double" sweep" procedure as presented here progresses from large i to small i for the

§ It is noted that other combinations of boundary conditions at the two ends of the grid line could be accommodated. Also, internal boundary conditions of the type $q_{x_{i,j}}^{n+1} = 0$ are satisfied by the choice of coefficients: $E_{i-1}^* = F_{i-1}^* = 0$.

first sweep and then progresses back from small i to large i for the second sweep.

It can be shown that this procedure results in an exact solution of the tridiagonal set of simultaneous equations represented by Eqs. (7) and (8). As noted previously the same procedure is then applied to solve Eqs. (9) and (10) which completes establishing n , q_x and q_y at the $(n+1)^{\text{th}}$ time step.

4.2 Boundary Conditions

To complete formulation of the problem, conditions must be specified at the boundaries of the grid presented in Figure 16. On the "open" (water) boundaries, the water surface is specified to be that associated with the barometric pressure, i.e.

$$\eta_{B_{i,j}} = \left(\frac{p_{\infty} - p_{i,j}}{\rho g} \right) \quad (19)$$

in which p denotes the far field barometric pressure. In addition, on the open boundary grid cells, it is specified that only discharge components perpendicular to the boundaries occur and that these discharges on the exterior boundaries of the grid system are those required to satisfy the continuity equation (Eq. 8).

On the "closed" boundaries, i.e., at the shoreline where land elevations are higher than the adjacent water elevations, a no-flow boundary condition is specified perpendicular to that boundary. However, "flooding" and "deflooding" of grid blocks adjacent to the boundaries can occur. Flooding occurs when the water level is greater by a specified small amount than the ground elevation of an adjacent grid block. When this condition exists, the grid block is activated by a simple allocation of this excess elevation on the newly activated block and in subsequent time steps the grid block is incorporated into the normal calculation scheme. Deflooding occurs when the water level on a grid block drops below a specified level leaving a very small depth on that block. The block is "deactivated" and the excess water placed on the adjacent grid.

The solution is started from an initial condition of zero water surface displacement and zero discharge components. The storm system is translated along a specified path at a designated speed. At each time step, the storm ef-

fects (represented by the pressure and wind stress components) on each cell are calculated and the finite-difference equations (Eq. 7, 8, 9, and 10) employed. The results are updated values of η , q_x and q_y for each cell.

4.3 One-Dimensional Numerical Model

The one-dimensional numerical model is significantly less expensive and simpler to run and is used in the simulation phase, in order to generate the required data within budgetary constraints. The justification for using the one-dimensional model is that it can be adequately calibrated with the rather complete two-dimensional model.

The one-dimensional numerical model is a static model and therefore no effects of inertia are included. The finite difference forms of the governing one-dimensional differential equations are:

$$\eta_{i+1}^{n+1} = \eta_i^{n+1} + \frac{\Delta x}{g(\bar{h} + \eta)} \left[\frac{\tau_{wx_i}}{\rho} - \beta q_{y_i}^{n+1} \right] + \frac{p_i^{n+1} - p_{i+1}^{n+1}}{\rho g} \quad (20)$$

$$q_{y_i}^{n+1} = \frac{1}{BB} \left[q_{y_i}^n + \frac{\Delta t}{\rho} \tau_{wy_i} \right] \quad (21)$$

where $BB = 1.0 + \frac{f \cdot \Delta t |q_{y_i}^n|}{(\bar{h} + \eta)^2}$ and the remaining variables are as defined pre-

viously for the two-dimensional model.

The one-dimensional model is initiated from a condition of rest ($q_y = 0$) and zero water surface displacement ($\eta = 0$). The only boundary condition required is that at the seaward end ($i = 1$) of each transect where the "barometric tide" is imposed as

$$\eta_1 = \frac{p_\infty - p_1}{\rho g} \quad (22)$$

In applying the one-dimensional numerical model, a variable grid size (1,000 ft. to 60,000 ft.) is used as presented in Figures 17a, 17b, 17c, 17d, 17e and 17f.

4.4 Simulation

To summarize information presented earlier, this phase includes the simulation of the occurrence of 2,000 years of storms along a shoreline segment of 250 n.mi. The simulated storms include landfalling and alongshore storms with directional distributions according to Figure 6. In an average 2,000 year period, there would be a total of 1,140 storms.

Selection of Storm Parameters - Each of the five idealized storm parameters (Radius to Maximum Winds, R; Central Pressure, p_0 [or Central Pressure Deficit, Δp]; Track Direction, θ ; System Forward Speed, V_F ; and Track Position) is determined randomly in accordance with the associated cumulative probability distribution functions. The procedure is described below for the track direction, θ , and is similar for all other variables.

The approximate piece-wise linear cumulative probability distribution function for track direction, θ , is shown in Figure 6. The nature of this function is such that the more predominant directions are those where the function rises steeply. To randomly select a track direction in accordance with the distribution function, the computer first generates a random number between 0 and 1 corresponding to the cumulative probability. Suppose that this number is 0.445. Since this value corresponds to the linear segment between directions of 180° and

220°, the computer interpolates to find a track direction, θ , of 200°. We note that this is a landfalling storm. The other four parameters are determined similarly with a separate and independent random number being generated for each parameter and the appropriate cumulative probability distribution used.

Calculation of Storm Surge with the Effect of Astronomical Tide - A particular storm can be "phased" such that the maximum resulting storm surge is increased or decreased by astronomical tidal fluctuations. Considering the predicted astronomical tidal fluctuations at the western end of Dog Island from June 1 to November 30, 1984 to be representative of those occurring during the hurricane season and assuming the phasing of storm occurrence and astronomical tides to be independent, the combination of these tidal components was carried out in the following manner.

With the storm parameters established, a starting time for the storm is selected randomly between June 1 and November 30, 1984. The corresponding astronomical tide at the starting time is generated as the boundary condition in the one-dimensional model and varies with time thereafter according to the input astronomical tide data. The calculation of the storm surge history by the calibrated one-dimensional model is thus phased with the astronomical tide to yield the combined storm surge and astronomical tide water level history at the site of interest.

Dynamic Wave Set-Up - When waves break, a shoreward directed force in addition to the wind stress, is exerted on the water in the surf zone. This causes an additional rise in water level termed "wave set-up". This effect has been studied extensively in the laboratory [Saville (10), Bowen and Simmons (11)] and tide gage measurements during severe storms have confirmed its importance in na-

ture. Most of the information relative to wave set-up has been developed for "regular" waves, that is for a wave train in which each wave is the same as the preceding wave. Waves in nature, however, are not regular and tend to occur in groups. A recent analytic study by Lo (12) has shown that for natural wave trains there is a dynamic wave set-up that is approximately 50% larger than would be predicted by a static treatment. In order to evaluate this result, model studies were conducted in the University of Florida's large wave tank. It was found that the experimental and analytical results by Lo were in approximate agreement.

The maximum total wave set-up, $\eta'_{\max}$, across the surf zone can be shown to be approximately

$$\eta'_{\max} = 0.285 \left[1 - 2.82 \left(\frac{H_b}{gT^2} \right)^{\frac{1}{2}} \right] H_b \quad (23)$$

which includes the dynamic factor of 50% and in which T is the wave period and H_b is the breaking wave height based on the deep water significant wave height, H_0 , taken approximately as

$$H_b = 0.94 H_0 \quad (24)$$

The deep water significant wave height is determined from an extension of a method recommended for hurricane generated waves as summarized in the Shore Protection Manual (13),

$$(H_0)_{\max} = 16.5 e^{R(\Delta p/100)} \left(1 + \frac{0.208 V_F}{\sqrt{U_R}} \right) \quad (25)$$

where R = radius to maximum winds in nautical miles, Δp = central pressure deficit in inches of mercury, V_F = translation speed of storm in knots, and U_R =

maximum sustained wind speed in knots. For purposes here, the local effective deep water significant wave height is based on the local winds, W , at the surf zone area of interest and the maximum winds in the storm, $W_{\max}$, as

$$H_o = (H_o)_{\max} (W/W_{\max})^2 \quad (26)$$

Equations 23, 24, 25 and 26 provide the basis for determining the maximum total wave set-up within the surf zone. The computed value of $\eta'_{\max}$ was modified from Eq. (23) to account for the frictional effects of overland propagation. It is stressed that $\eta'_{\max}$ represents the maximum total wave set-up across the surf zone and that this value varies with time (because the wind speed varies with time). The value of $\eta'_{\max}$ was computed at each time step for the shoreward grid, and added to the corresponding surge value resulting from wind stress, barometric pressure and the effect of astronomical tide to yield the combined total storm tide history.

With the combined total storm tide history thus determined, it is a simple matter to search in the computer to obtain the maximum of the combined total storm tide at the site of interest.

The total wave set-up without frictional effects is

$$\eta' = 0.22 H_b - 0.243 h \quad (27)$$

in which h is the local water depth not including the effects of dynamic wave set-up. It can be shown that Eq. (27) is consisted with Eqs. (23) - (25) for the maximum total wave set-up, $\eta'_{\max}$, for the case of $h = 0$.

The maximum overland dynamic wave set-up was calculated step-wise as follows. Starting with the shore value given by Eq. (27), the frictional effects

(reducing the dynamic wave set-up) were calculated in accordance with

$$\eta''(x - \Delta x, y) = \eta''(x, y) \cdot B(x, y) + 0.081[h(x, y) - h(x - \Delta x, y)] \quad (28)$$

in which η'' represents the dynamic wave set-up component, h is the total water depth exclusive of the dynamic wave set-up and $B(x, y)$ accounts for the frictional damping over the grid block Δx . The variable x is directed gulfward. It can be shown that Eq. (28) is consistent with Eqs. (23) - (25) for the case of zero water depth $h = 0$ and no damping.

4.5 Computation of Return Periods

With a sufficient number (1,140) of maximum combined total storm tides simulated to represent a typical 2,000 year time interval, the tides associated with various return periods of interest are determined. The 1,140 maximum combined total storm tides were ranked in descending order with the largest occurring first. The return period, TR , of the ranked tides is then

$$TR = 2000/M \quad (29)$$

in which

TR = Return period in years between expected exceedances of
the associated maximum storm tide

M = Rank of maximum storm tide

As an example, for $M = 1,140$ (associated with the lowest water level) the return period would be:

$$TR_{1140} = 2000/1140 = 1.75 \text{ years}$$

which indicates that the smallest storm tide could be expected to be exceeded approximately once every 1.75 years. As a second example, the return period for $M = 4$ is

$$TR_4 = 2000/4 = 500 \text{ years}$$

The ranked maximum total storm tide and associated return periods can be plotted and the total storm tide associated with any return period determined.

Finally, it is noted that it is possible to run the simulation procedure any number of times to determine the stability (constancy) of any combined total storm tide associated with a given return period. It is expected that for a 2,000 year simulation, the storm tides associated with the longer ($TR > 500$ year) return periods would not be well-defined by one simulation and would exhibit variation from simulation to simulation. However, the storm tides associated with the lower return periods ($TR \leq 200$ years) should be well-defined by a 2,000 year simulation and hence are not expected to vary significantly for various simulations.

V. CALIBRATION RATIONALE AND RESULTS

5.1 Rationale

Ideally there are sufficient storm tide data (from tide gages) at a site of interest to allow calibration of the numerical model. If this is the case, then it would be possible to calibrate the one-dimensional numerical model with data from the site and it would not be necessary to utilize the two-dimensional model described earlier. Unfortunately, there are not sufficient tide measurements at the site, and it is therefore necessary to utilize the two-dimensional model as an intermediate representation.

The calibration procedure followed is, first, to validate/calibrate the two-dimensional numerical model using tide gage recordings for Hurricanes of 1966, 1972 and 1975. With this calibration as a basis for the two-dimensional model, it is then run for a series of storms with parameters encompassing representative ranges. These include 22 cases each for landfalling and alongshore storms to determine the peak storm tides at the site. These results are then utilized to calibrate the one-dimensional numerical model which is run for the same 22 cases for each of the two types of storms.

5.2 Results--Calibration of Two-Dimensional Numerical Model

The calibration is conducted by running the two-dimensional model for the hurricane characteristics presented in Table I and the results are then compared with the measurements (excluding predicted astronomical tide). The following paragraphs describe the calibration results with the three hurricanes.

1. Hurricane Alma of June 1966:

The measured and computed storm tides at Cedar Key are shown in Figure 23. The computed peak storm tide is 0.3 ft. below the measured peak storm tide level of 5.0 ft.

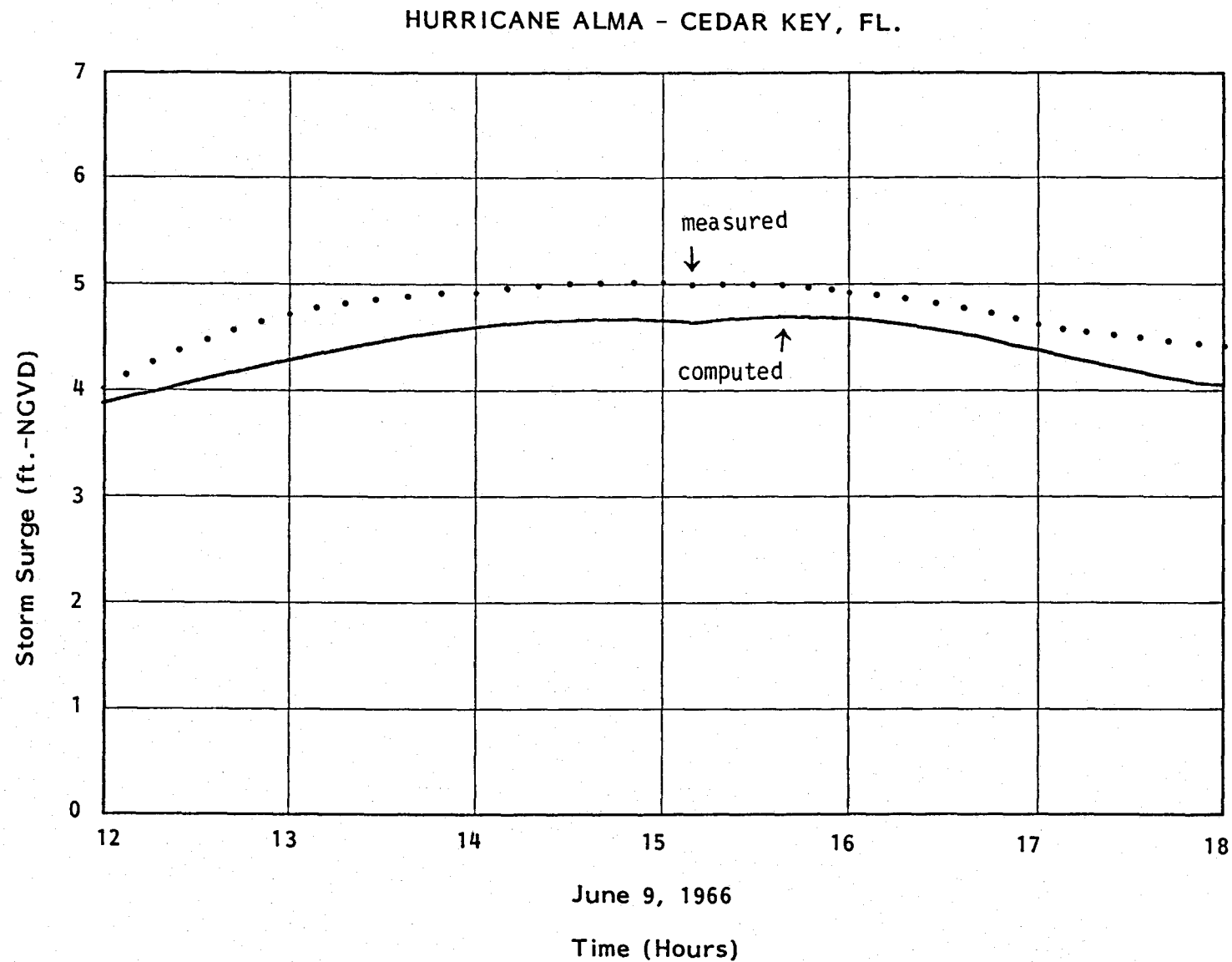


Figure 23 Comparison between Measured and Computed Storm Tides at Cedar Key, Florida for Hurricane Alma of June 1966

Table I
Input Parameters for Calibration Hurricanes

1. Hurricane Alma of June 1966

date	time (EST)	Δp (in. Hg)	V_F (knots)	R (n. mi.)	θ_N (degrees)
6/08	1900	-1.15	17.11	23.0	159.26
6/09	0100	-1.22	17.77	23.0	147.60
	0700	-1.27	9.16	23.0	169.11
	1300	-0.95	7.40	23.0	215.80
	1900	-1.07	11.82	23.0	233.67
6/10	0100	-0.46	11.82	23.0	233.67
	0700	-0.31	10.32	23.0	247.21

Starting Coordinates:

$$X_S = 274.32 \text{ n. mi.}$$

$$Y_S = 33.94 \text{ n. mi.}$$

Landfalling Coordinates:

$$X_F = 8.02 \text{ n. mi.}$$

$$Y_F = 12.13 \text{ n. mi.}$$

2. Hurricane Agnes of June 1972

date	time (EST)	Δp (in. Hg)	V_F (knots)	R (n. mi.)	θ_N (degrees)
6/18	1900	-0.92	12.0	20.0	180.0
6/19	0100	-1.04	13.0	20.0	180.0
	0700	-1.04	11.03	20.0	184.50
	1300	-0.89	9.64	20.0	201.04
	1900	-0.31	9.99	20.0	205.68
6/20	0100	-0.68	11.16	20.0	224.23
	0700	-0.14	11.13	20.0	231.03

Starting Coordinates:

$$X_S = 225.93 \text{ n. mi.}$$

$$Y_S = 120.62 \text{ n. mi.}$$

Landfalling Coordinates:

$$X_F = -4.17 \text{ n. mi.}$$

$$Y_F = 63.77 \text{ n. mi.}$$

3. Hurricane Eloise of September 1975

date	time (EST)	Δp (in. Hg)	V_F (knots)	R (n. mi.)	θ_N (degrees)
9/22	0100	-0.59	10.04	18.0	175.05
	0700	-0.80	7.05	18.0	187.05
	1300	-0.98	11.16	18.0	224.23
	1900	-1.33	15.13	18.0	223.35
9/23	0100	-1.63	19.97	18.0	205.68
	0700	-1.72	28.48	18.0	190.51
	1300	-0.92	27.78	18.0	205.85

Starting Coordinates:

$$X_S = 259.95 \text{ n. mi.}$$

$$Y_S = 322.93 \text{ n. mi.}$$

Landfalling Coordinates:

$$X_F = 36.77 \text{ n. mi.}$$

$$Y_F = 102.50 \text{ n. mi.}$$

2. Hurricane Agnes of June 1972:

The measured and computed storm tides at St. Marks Light House and Cedar Key are shown in Figures 24 and 25, respectively. The computed peak storm tide is 0.7 ft. higher than the measured peak storm tide level of 4.9 ft. at St. Marks Light House, and 2.6 ft. lower than the measured peak storm tide level of 4.6 ft. at Cedar Key. The tide gage at St. Marks Light House failed after 8:00 am on June 19, 1972. The indication is that that peak level of the hurricane tide was yet to come. The difference of +0.7 ft. is between the computed peak storm tide level and the last measured tide level.

3. Hurricane Eloise of September 1975:

The measured and computed storm tides are shown in Figures 26 and 27 for St. Marks Light House and Cedar Key, respectively. The computed peak storm tide is 0.6 ft. higher than the measured peak storm tide level of 5.7 ft. at St. Marks Light House, and 1.5 ft. lower than the measured peak storm tide level of 3.7 ft. at Cedar Key.

Except for the computed peak storm tide levels being 2.6 ft. and 1.5 ft. lower than the measured at Cedar Key for Hurricane Agnes and Eloise, respectively, the other three comparisons show that the computed peak storm tide range is from -0.3 ft. to a maximum of +0.7 ft. from the measured peak storm tide levels and that the range is close to the numerical model's accuracy of about ± 0.5 ft. Cedar Key is far from the study area. The much lower computed peak storm tides there than that measured for Hurricanes Agnes and Eloise should not outweigh the calibration results at St. Marks Light House located in the study area. Moreover, the remote location of Cedar Key from the tracks of Agnes and Eloise and the local conditions during the two hurricanes could all affect the computations and measurements of the storm tides there. Therefore, it appears

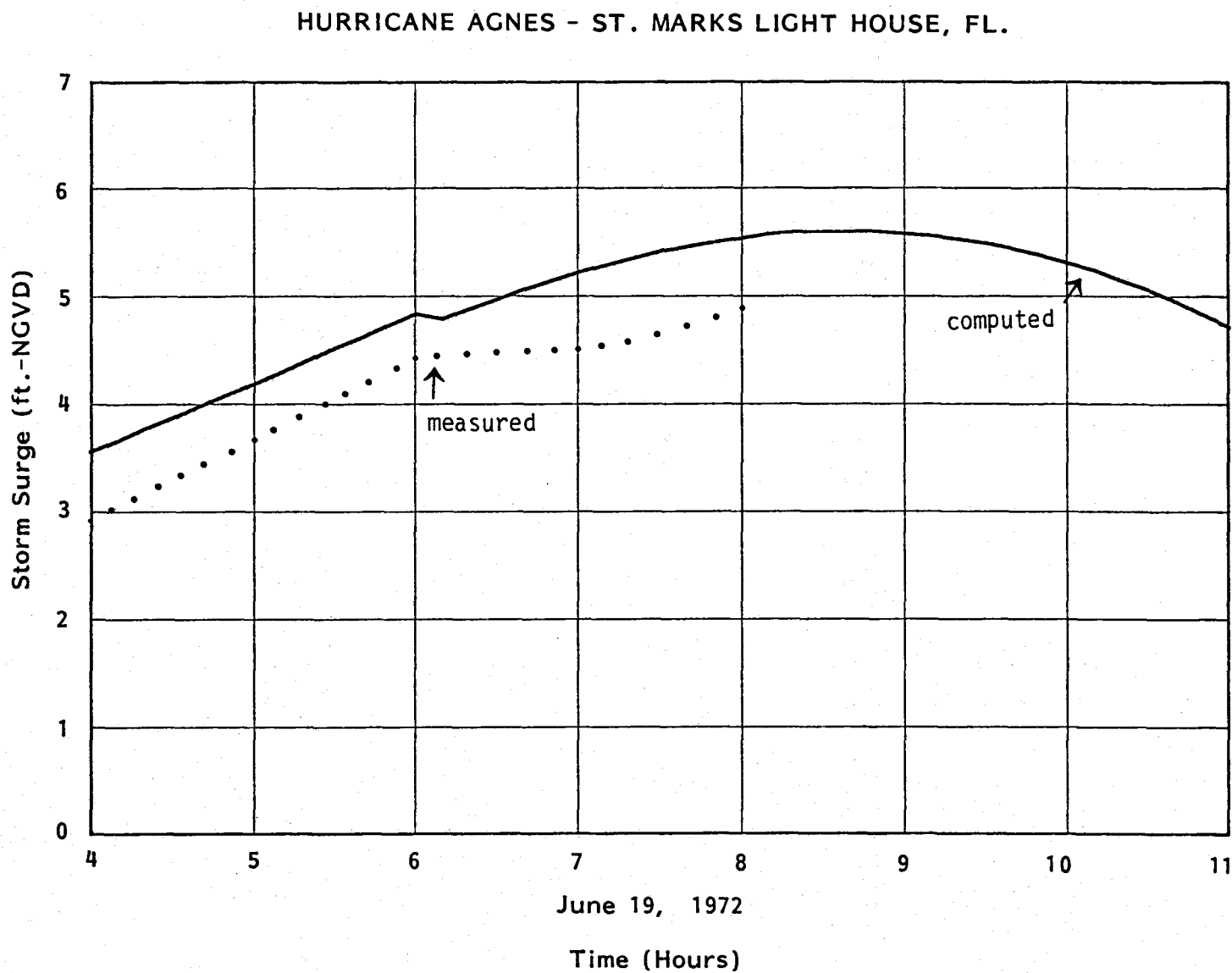


Figure 24 Comparison between Measured and Computed Storm Tides at St. Marks Light House, Florida for Hurricane Agnes of June 1972

HURRICANE AGNES - CEDAR KEY, FL.

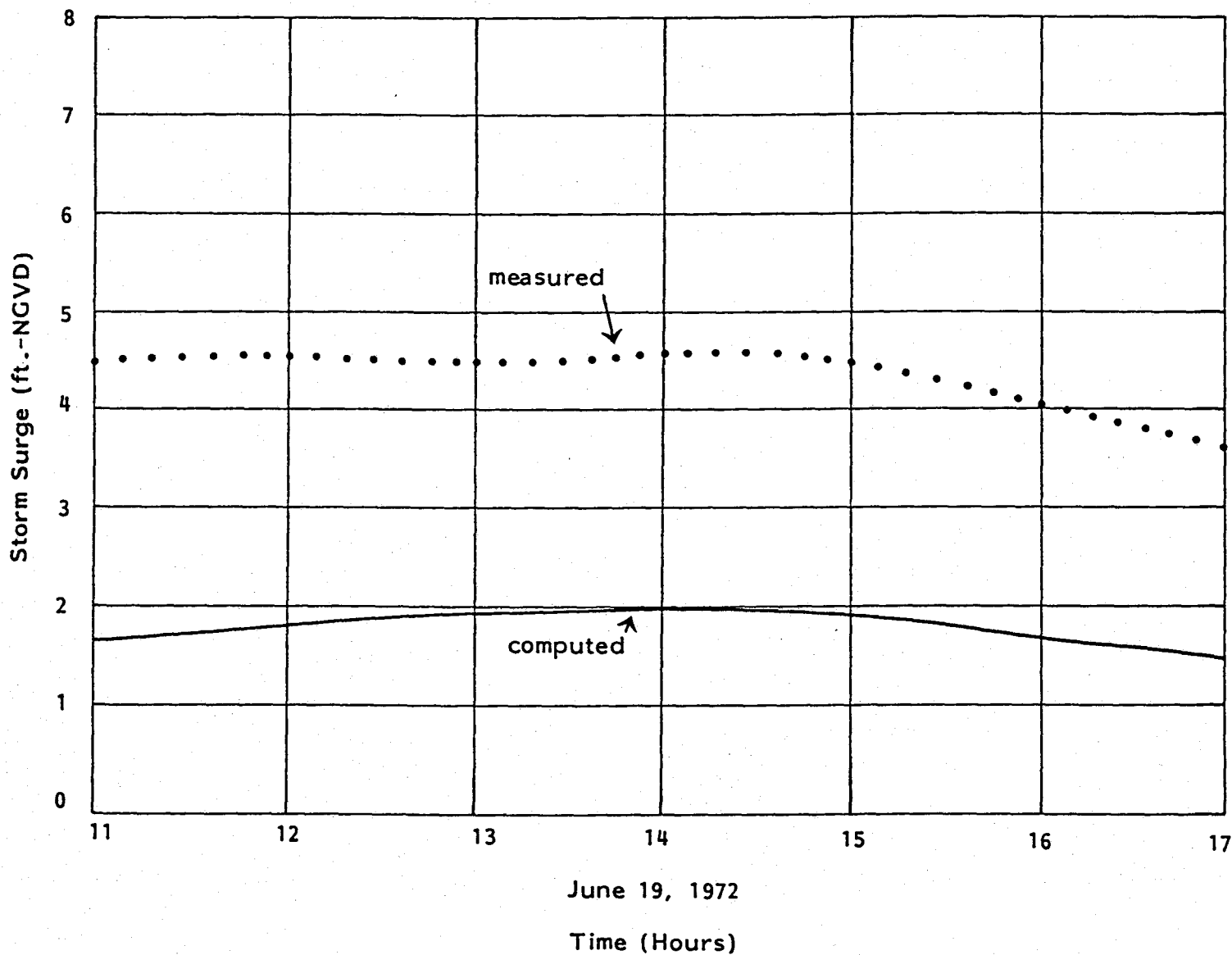


Figure 25 Comparison between Measured and Computed Storm Tides at Cedar Key, Florida for Hurricane Agnes of June 1972

HURRICANE ELOISE - ST. MARKS LIGHT HOUSE, FL.

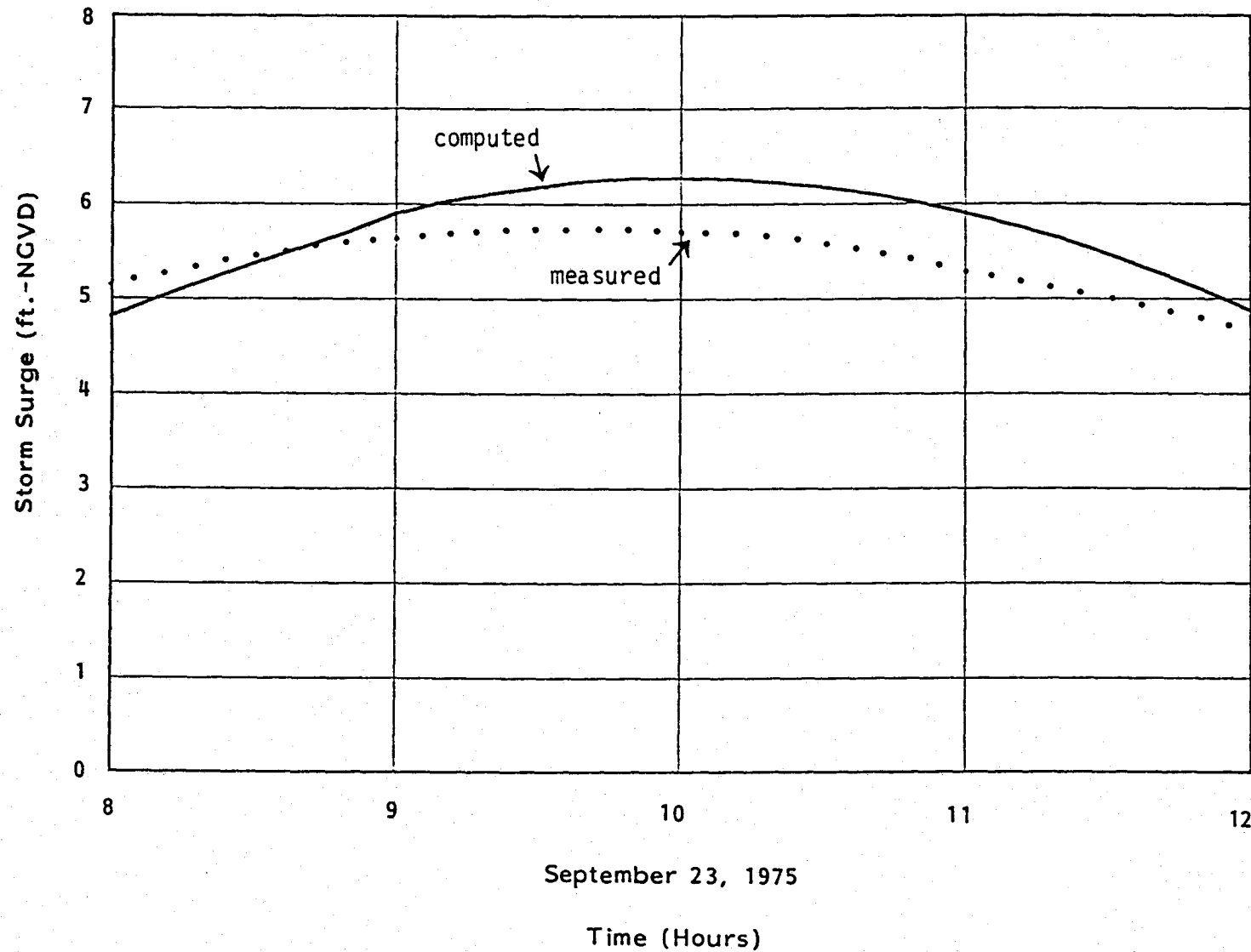


Figure 26 Comparison between Measured and Computed Storm Tides at St. Marks Light House, Florida for Hurricane Eloise of September 1975

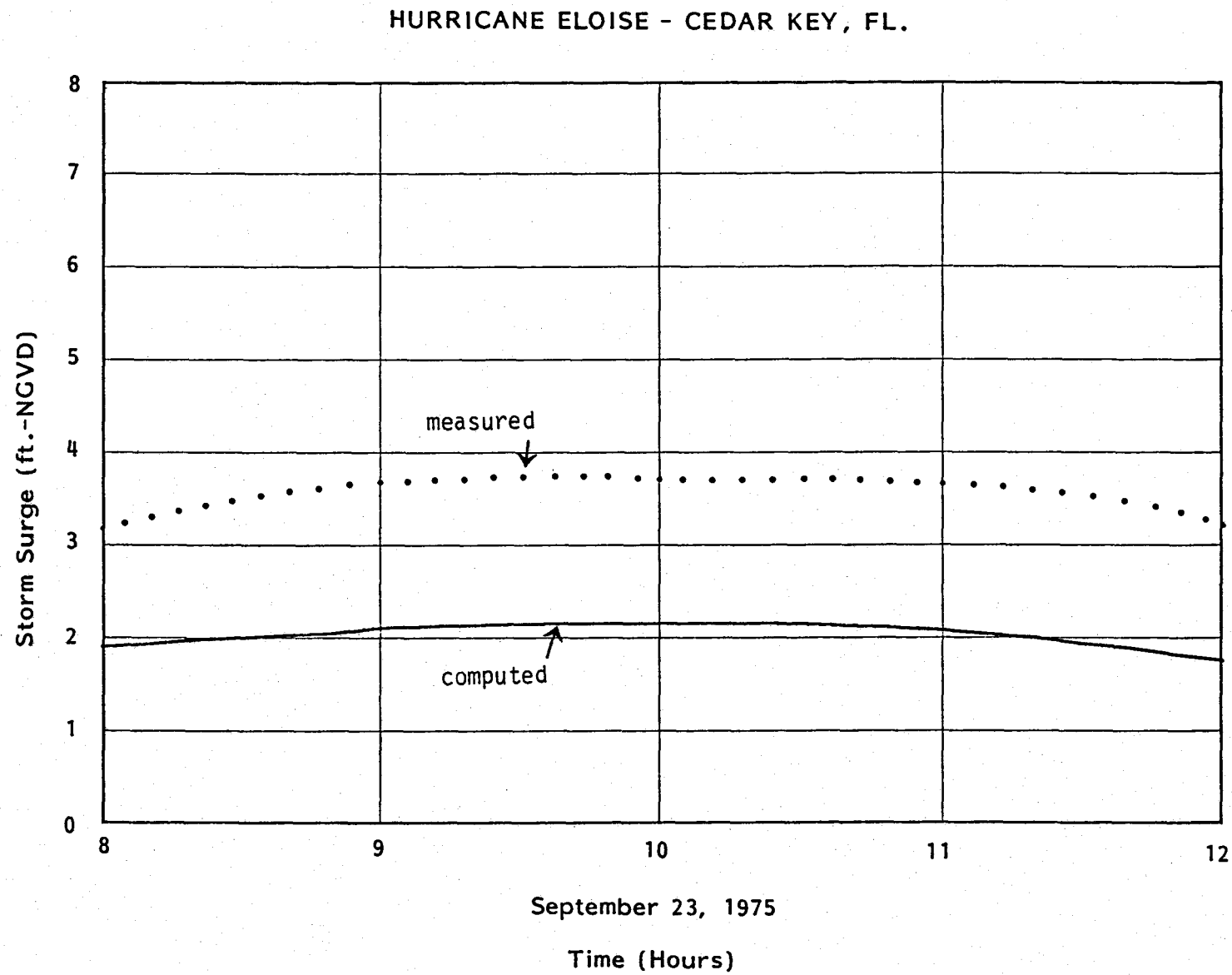


Figure 27 Comparison between Measured and Computed Storm Tides at Cedar Key, Florida for Hurricane Eloise of September 1975

that the two-dimensional model representing the actual hurricanes by parametric hurricanes yields reasonably good results. The calibration of the two-dimensional model is thus taken as 1.00, i.e. the calculated storm tides do not have to be adjusted.

5.3 Calibration of One-Dimensional Numerical Model

Twenty two cases for each of the two types of storms are run using the two-dimensional model to establish the peak surge at the site of interest. The characteristics of these storms and the peak storm surges at the site are presented in Tables IIa and IIb for landfalling storms and in Tables IIIa and IIIb for alongshore storms. In general, the peak storm surge were compared at the NGVD shoreline. It is evident from Tables II and III that landfalling storms result in much larger storm tides than do the alongshore storms.

A calibration relationship between the peak surges computed from the one-dimensional numerical model and those from the two-dimensional model is determined as follows. The peak surges computed from these two models are plotted in Figures 28a, 28b and 28c for landfalling storms for the transect lines 1 through 6. Correspondingly Figures 29a, 29b and 29c are for alongshore storms. The relationship between the two computed values are represented by the straight lines in the plots. In summary, the overall calibration procedure for the simulation is that presented in Figure 15. Twenty two cases for the landfalling and alongshore storms with parameters encompassing representative ranges of their cumulative probability distributions are chosen. Peak storm surges corresponding to six locations along the Wakulla County shoreline are calculated for the same 44 storms by both one-dimensional and two-dimensional numerical models. Then, for each of the six transect lines, the calculated peak surges are correlated to establish the relationship between the one-dimensional and two-dimensional

TABLE IIa

Parameters Defining 22 Landfalling Model Hurricanes
Used In Calibrating The One-Dimensional Model
With The Two-Dimensional Model

MODEL	Δp	R	V_F	θ_N	Landfalling Coordinates (n. mi.)		Starting Coordinates (n. mi.)	
STORM	(in.Hg)	(n. mi.)	(knots)	(degrees)	X_F	Y_F	X_S	Y_S
1	-1.1	22	11	200	-20	+30	74.29	86.65
2	-1.1	32	11	200	-20	+30	74.29	86.65
3	-1.1	12	11	200	-20	+30	74.29	86.65
4	-0.4	22	11	200	-20	+30	74.29	86.65
5	-1.8	22	11	200	-20	+30	74.29	86.65
6	-1.1	22	15	200	-20	+30	82.86	91.80
7	-1.1	22	7	200	-20	+30	70.00	84.08
8	-1.1	22	11	180	-20	+30	87.98	50.99
9	-1.1	22	11	220	-20	+30	49.23	115.49
10	-1.1	22	11	200	-20	-10	74.29	46.65
11	-1.1	22	11	200	-20	+70	74.29	126.65

CONTINUED

Parameters Defining 22 Landfalling Model Hurricanes
Used In Calibrating The One-Dimensional Model
With The Two-Dimensional Model

MODEL	Δp	R	V_F	θ_N	Landfalling Coordinates (n. mi.)		Starting Coordinates (n. mi.)	
STORM	(in.Hg)	(n. mi.)	(knots)	(degrees)	X_F	Y_F	X_S	Y_S
12	-1.2	40	20	200	-40	+30	131.43	133.01
13	-1.2	50	20	200	-40	+30	131.43	133.01
14	-1.2	30	20	200	-40	+30	131.43	133.01
15	-0.5	40	20	200	-40	+30	131.43	133.01
16	-1.9	40	20	200	-40	+30	131.43	133.01
17	-1.2	40	28	200	-40	+30	152.01	145.37
18	-1.2	40	12	200	-40	+30	114.29	122.71
19	-1.2	40	20	180	-40	+30	156.33	68.16
20	-1.2	40	20	200	-40	+30	85.86	185.43
21	-1.2	40	20	200	-40	-20	131.43	83.01
22	-1.2	40	20	200	-40	+80	131.43	183.01

TABLE IIb

Results of Calibration of Landfalling Model Hurricanes

Model Storm	$n_{\max}$ (ft. NGVD)											
	Profile 1		Profile 2		Profile 3		Profile 4		Profile 5		Profile 6	
	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D
1	9.41	11.35	9.00	11.52	9.40	11.63	10.13	11.98	9.99	11.98	8.13	10.49
2	11.97	14.06	11.39	14.20	11.69	14.22	12.31	14.46	11.94	14.28	9.86	12.53
3	5.85	7.39	5.62	7.53	6.03	7.65	6.69	7.97	6.64	7.99	5.32	6.98
4	5.44	6.34	5.43	6.50	5.77	6.68	6.27	7.02	6.29	7.06	5.64	6.41
5	13.08	15.87	12.40	16.03	12.85	16.06	13.76	16.50	13.63	16.39	10.76	14.40
6	10.18	11.42	9.74	11.61	10.16	11.73	10.93	11.98	10.78	11.97	8.81	11.12
7	8.65	9.64	8.26	9.83	8.65	10.03	9.35	10.46	9.19	10.57	7.45	9.18
8	9.88	11.32	9.48	11.60	9.94	11.80	10.71	12.18	10.66	12.36	9.05	11.07
9	9.29	10.84	8.81	10.87	9.13	10.85	9.76	11.15	9.44	10.89	7.29	9.03
10	11.71	10.22	9.62	8.98	7.90	7.56	5.98	5.33	3.57	4.85	2.20	4.06
11	5.47	6.76	5.19	6.87	5.44	6.96	5.94	7.19	5.73	7.15	4.61	6.10

CONTINUED

Results of Calibration of Landfalling Model Hurricanes

Model Storm	$\eta_{\max}$ (ft. NGVD)											
	Profile 1		Profile 2		Profile 3		Profile 4		Profile 5		Profile 6	
	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D
12	15.34	15.97	14.62	16.24	14.89	16.36	15.61	16.55	15.23	16.50	12.72	15.91
13	17.62	18.24	16.78	18.49	16.93	18.53	17.50	18.63	16.92	18.47	14.36	17.64
14	12.65	13.31	12.06	13.57	12.42	13.72	13.20	13.96	12.98	13.98	10.65	13.56
15	9.61	10.18	9.36	10.42	9.66	10.57	10.17	10.75	9.96	10.78	8.84	10.25
16	21.16	21.83	20.17	22.10	20.44	22.18	21.32	22.54	20.91	22.36	17.29	21.77
17	17.31	15.34	16.53	15.85	16.80	16.21	17.56	16.38	17.18	16.62	14.41	16.71
18	13.37	15.73	12.71	15.85	12.97	15.86	13.63	16.14	13.25	15.98	11.00	14.08
19	16.57	14.92	15.77	15.37	15.97	15.73	16.52	15.91	15.89	16.01	13.20	15.19
20	14.18	15.39	13.44	15.44	13.67	15.34	14.32	15.46	13.87	15.12	11.24	13.95
21	12.02	8.49	9.65	7.79	7.82	7.05	6.34	5.32	4.01	5.36	2.72	5.09
22	9.95	11.75	9.45	11.86	9.72	11.87	10.36	12.06	10.08	11.95	8.35	10.83

TABLE IIIa

Parameters Defining 22 Alongshore Model Hurricanes
Used In Calibrating The One-Dimensional Model
With The Two-Dimensional Model

MODEL	Δp	R	V_F	θ_N	Landfalling Coordinates (n. mi.)		Starting Coordinates (n. mi.)	
STORM	(in.Hg)	(n. mi.)	(knots)	(degrees)	X_L	Y_L	X_S	Y_S
1	-0.4	22	11	250	+35	-20	52.21	128.65
2	-0.6	32	11	250	+35	-20	52.21	128.65
3	-0.4	12	11	250	+35	-20	52.21	128.65
4	-0.2	22	11	250	+35	-20	52.21	128.65
5	-0.6	22	11	250	+35	-20	52.21	128.65
6	-0.4	22	15	250	+35	-20	53.77	138.52
7	-0.4	22	7	250	+35	-20	51.43	123.71
8	-0.4	22	11	260	+35	-20	33.08	129.98
9	-0.4	22	11	240	+35	-20	70.81	124.01
10	-0.6	22	11	250	+20	-20	37.21	128.65
11	-0.4	22	11	250	+50	-20	67.21	128.65

CONTINUED

Parameters Defining 22 Alongshore Model Hurricanes
Used In Calibrating The One-Dimensional Model
With The Two-Dimensional Model

MODEL	Δp	R	V_F	θ_N	Landfalling Coordinates (n. mi.)		Starting Coordinates (n. mi.)	
STORM	(in.Hg)	(n. mi.)	(knots)	(degrees)	X_L	Y_L	X_S	Y_S
12	-0.5	40	12	250	+35	-40	53.77	78.52
13	-0.5	50	12	250	+35	-40	53.77	78.52
14	-0.5	30	12	250	+35	-40	53.77	78.52
15	-0.3	40	12	250	+35	-40	53.77	78.52
16	-0.7	40	12	250	+35	-40	53.77	78.52
17	-0.5	40	16	250	+35	-40	55.02	86.42
18	-0.5	40	8	250	+35	-40	53.77	78.52
19	-0.5	40	12	260	+35	-40	32.91	79.98
20	-0.5	40	12	240	+35	-40	74.07	73.46
21	-0.5	40	12	250	+20	-40	38.77	78.52
22	-0.5	40	12	250	+50	-40	68.77	78.52

TABLE IIIb

Results of Calibration of Alongshore Model Hurricanes

Model Storm	$\eta_{\max}$ (ft. NGVD)											
	Profile 1		Profile 2		Profile 3		Profile 4		Profile 5		Profile 6	
	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D
1	1.55	1.84	1.38	1.90	1.31	1.90	1.36	1.74	1.25	1.81	1.46	2.10
2	2.20	2.51	1.99	2.59	1.92	2.59	1.98	2.40	1.83	2.48	2.07	2.79
3	0.79	1.02	0.69	1.05	0.64	1.04	0.68	0.94	0.61	0.98	0.77	1.20
4	0.93	1.08	0.87	1.08	0.83	1.06	0.83	0.97	0.79	0.99	1.05	1.30
5	2.20	2.57	1.91	2.75	1.81	2.78	1.93	2.56	1.71	2.72	1.82	2.93
6	1.44	1.65	1.28	1.70	1.22	1.67	1.28	1.54	1.17	1.59	1.38	1.81
7	1.64	1.85	1.46	1.93	1.40	1.94	1.45	1.81	1.32	1.88	1.53	2.14
8	1.60	1.84	1.48	1.92	1.45	1.95	1.53	1.83	1.45	1.92	1.72	2.28
9	1.54	1.88	1.30	1.92	1.19	1.87	1.22	1.67	1.06	1.72	1.22	1.93
10	3.28	3.23	2.95	3.34	2.82	3.29	2.79	3.02	2.59	3.11	3.13	3.71
11	0.89	1.08	0.81	1.13	0.77	1.14	0.81	1.04	0.75	1.09	0.86	1.23

CONTINUED

Results of Calibration of Alongshore Model Hurricanes

Model Storm	$\eta_{\max}$ (ft. NGVD)											
	Profile 1		Profile 2		Profile 3		Profile 4		Profile 5		Profile 6	
	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D	1-D	2-D
12	2.43	2.05	2.21	2.19	2.13	2.21	2.21	2.01	2.04	2.16	2.18	2.38
13	2.98	2.45	2.73	2.60	2.65	2.62	2.73	2.41	2.54	2.57	2.69	2.78
14	1.82	1.60	1.63	1.73	1.57	1.73	1.65	1.55	1.50	1.69	1.63	1.98
15	1.60	1.46	1.50	1.50	1.45	1.49	1.47	1.38	1.40	1.42	1.62	1.67
16	3.29	2.59	2.95	2.85	2.84	2.91	2.97	2.62	2.71	2.92	2.72	3.15
17	2.34	1.84	2.13	1.98	2.05	2.00	2.13	1.84	1.97	1.99	2.11	2.20
18	2.50	2.80	2.27	2.94	2.20	2.93	2.28	2.66	2.10	2.78	2.22	2.95
19	3.38	3.11	3.13	3.27	3.09	3.30	3.21	3.05	3.04	3.24	3.25	3.66
20	1.73	1.21	1.56	1.34	1.47	1.35	1.51	1.21	1.37	1.37	1.45	1.38
21	3.66	3.44	3.32	3.59	3.21	3.57	3.30	3.23	3.05	3.38	3.25	3.83
22	1.71	1.24	1.57	1.36	1.51	1.39	1.56	1.27	1.45	1.40	1.55	1.48

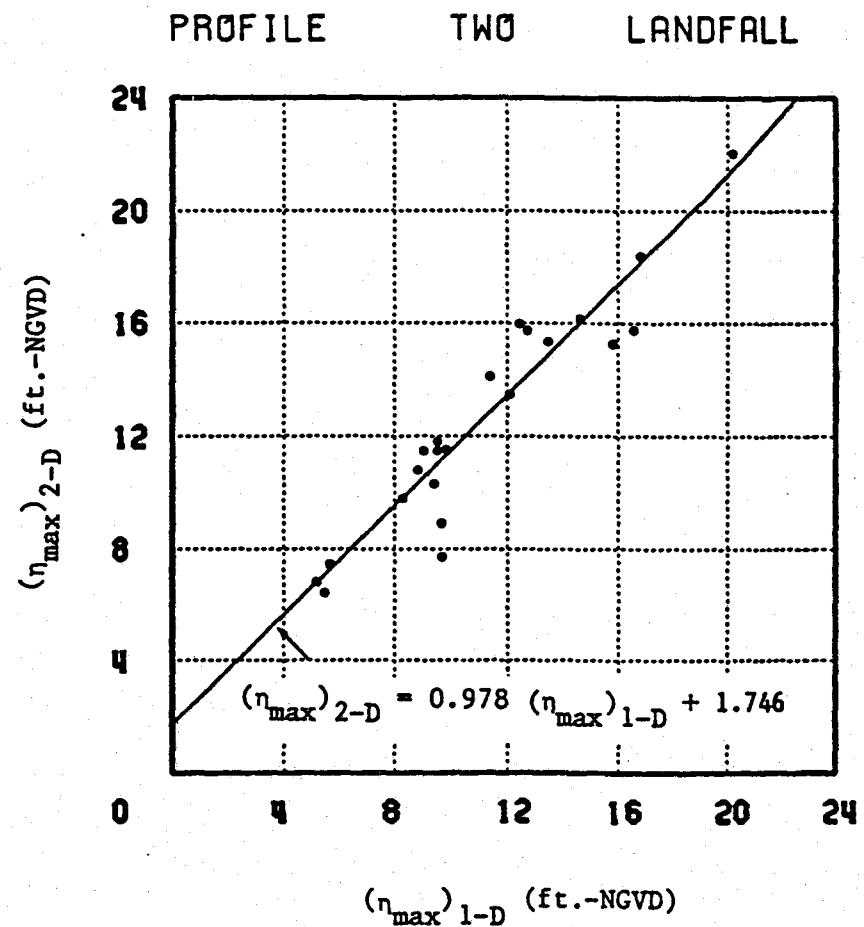
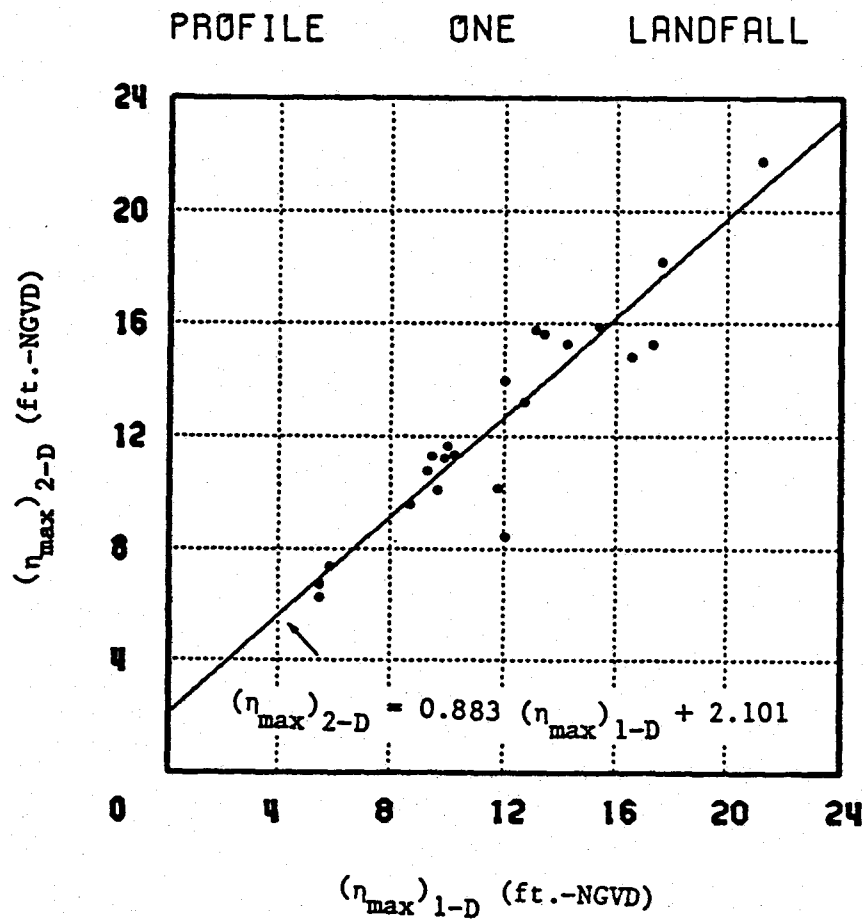


Figure 28a Calibration Relationship between the One-Dimensional and the Two-Dimensional Calculations of Peak Surges at Transect Lines One and Two of Wakulla County for Landfalling Storms

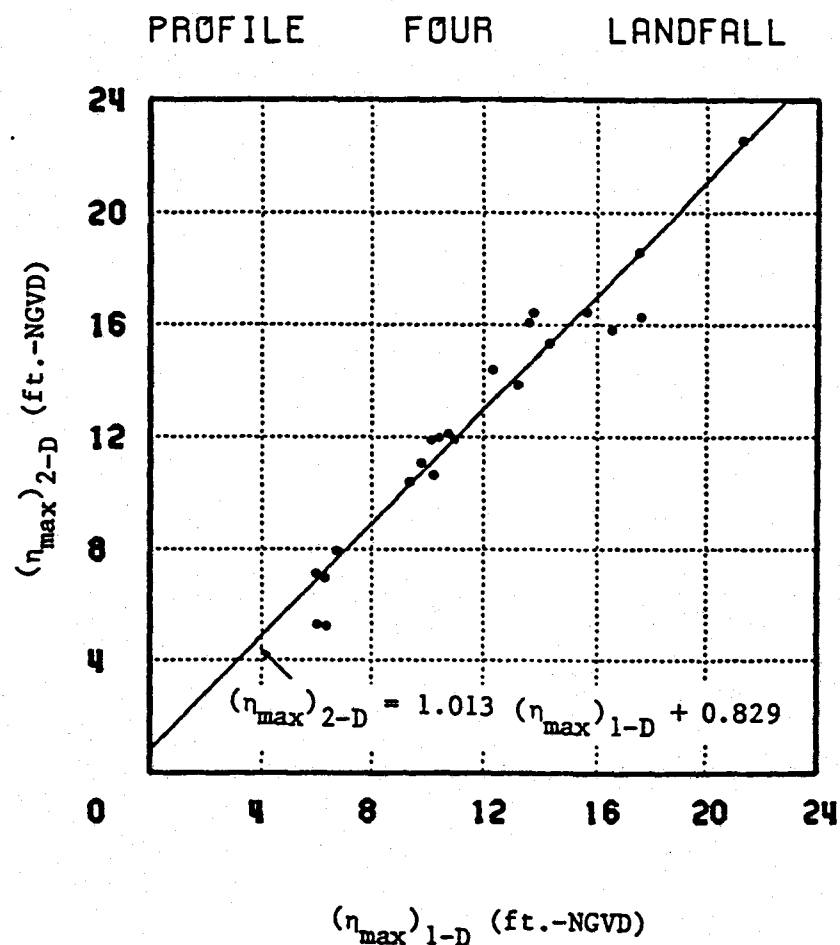
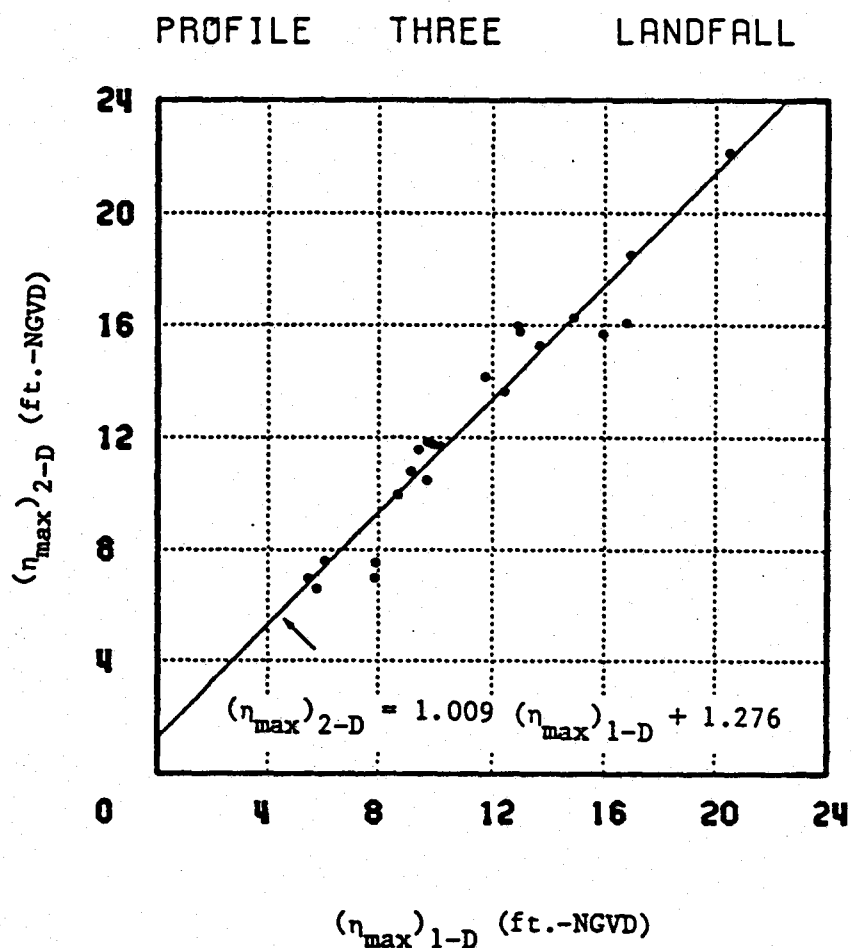


Figure 28b Calibration Relationship between the One-Dimensional and the Two-Dimensional Calculations of Peak Surges at Transect Lines Three and Four of Wakulla County for Landfalling Storms

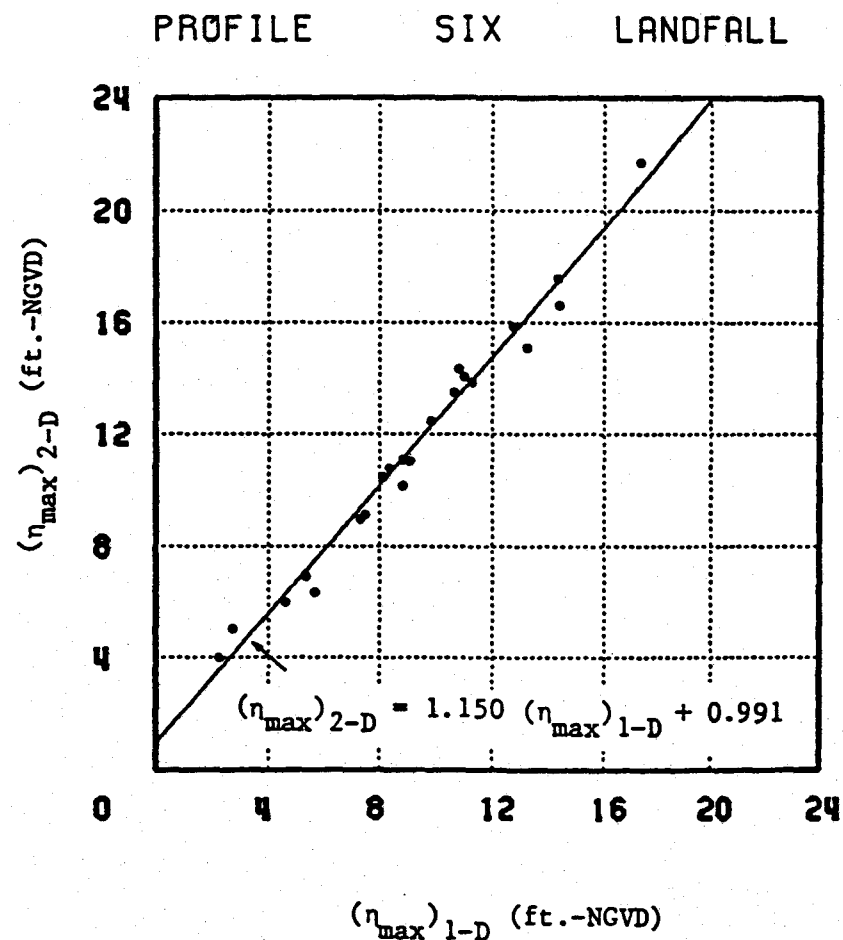
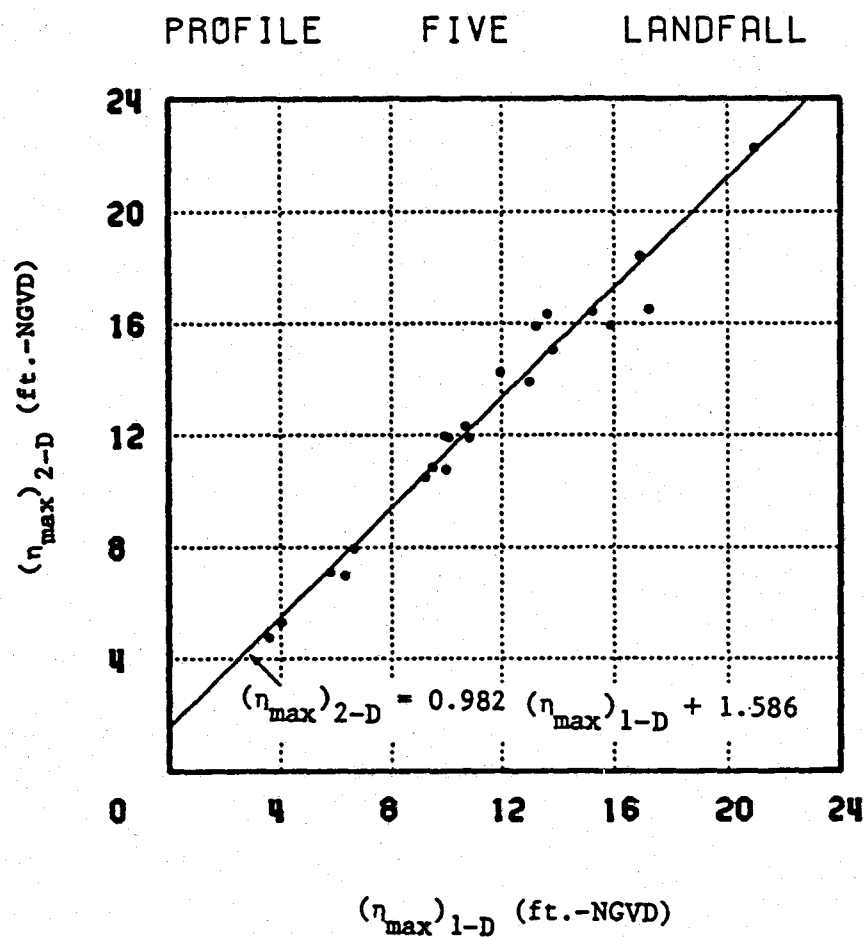


Figure 28c Calibration Relationship between the One-Dimensional and the Two-Dimensional Calculations of Peak Surges at Transect Lines Five and Six of Wakulla County for Landfalling Storms

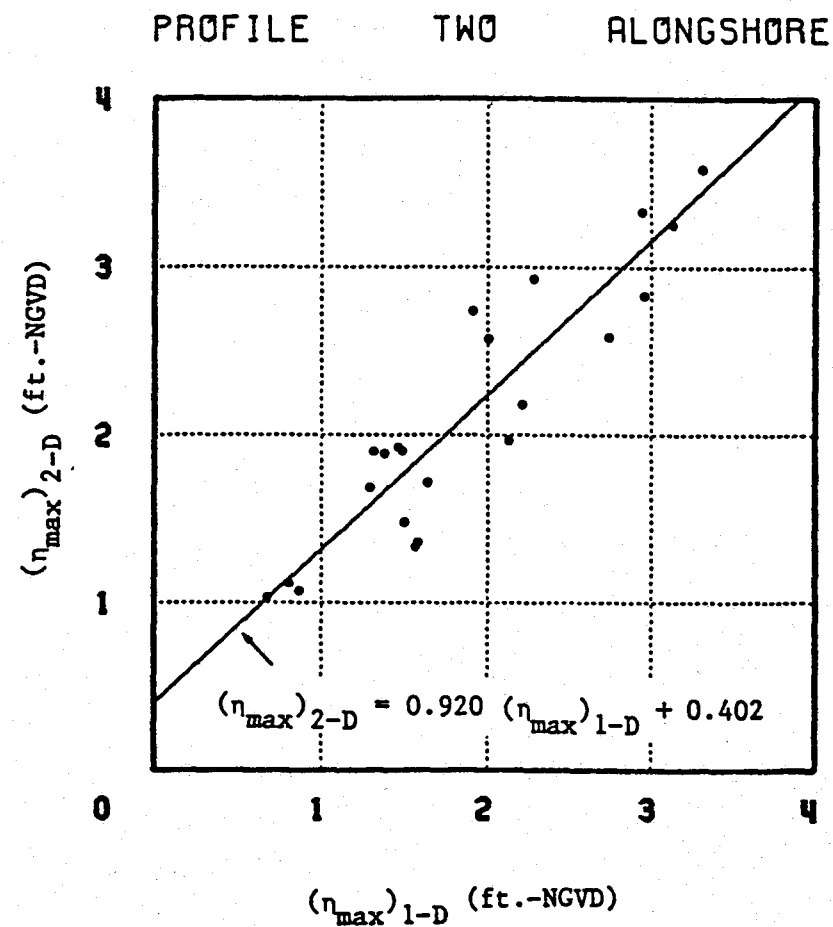
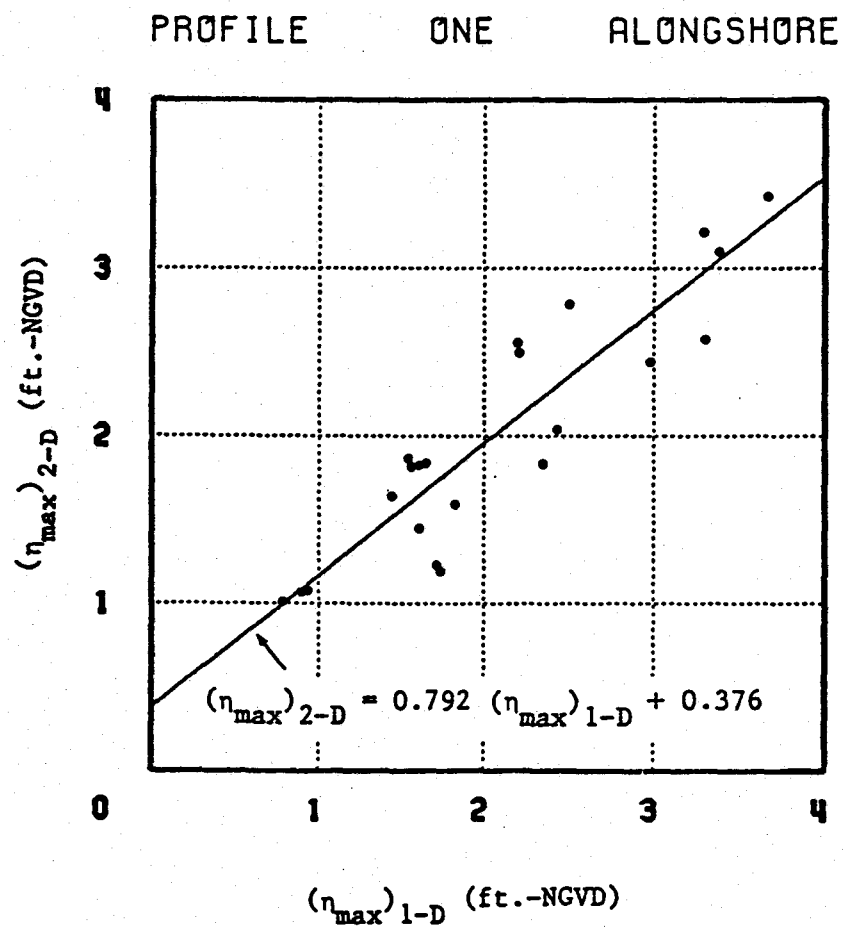


Figure 29a Calibration Relationship between the One-Dimensional and the Two-Dimensional Calculations of Peak Surges at Transect Lines One and Two of Wakulla County for Alongshore Storms

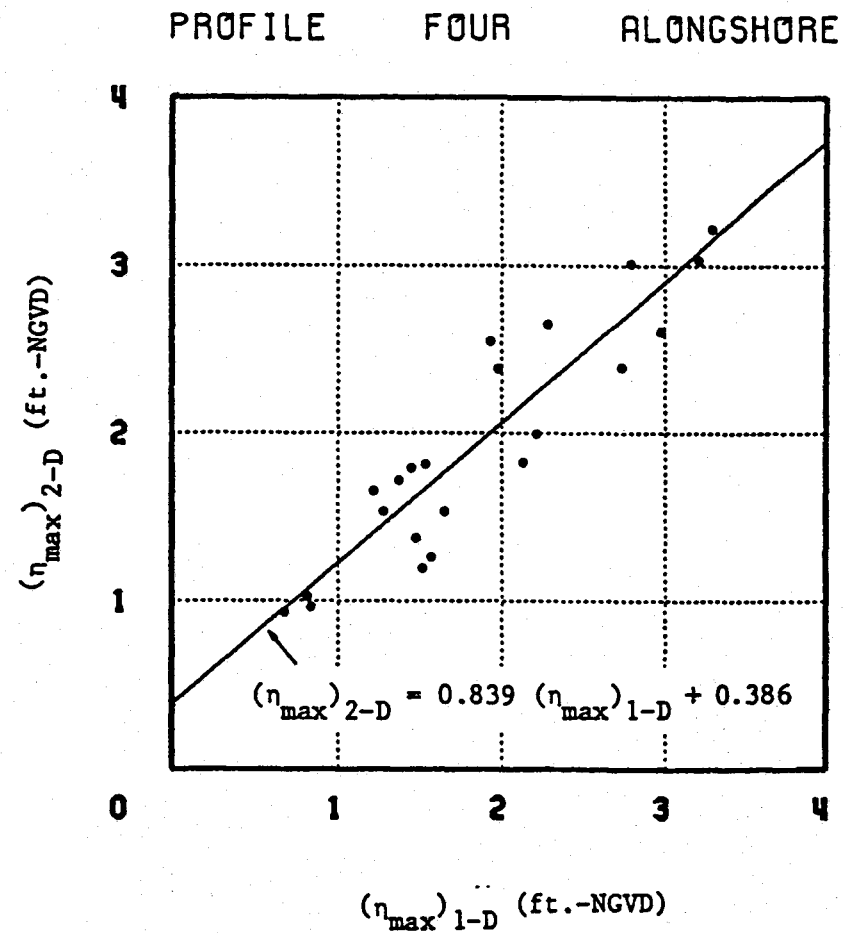
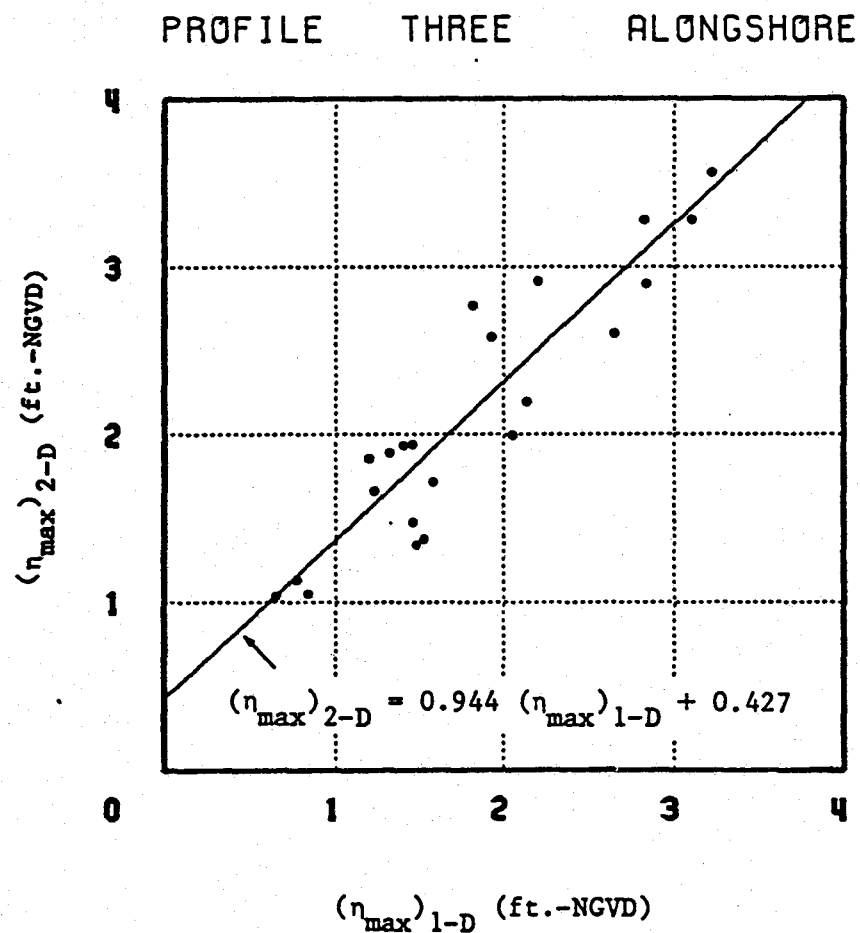


Figure 29b Calibration Relationship between the One-Dimensional and the Two-Dimensional Calculations of Peak Surges at Transect Lines Three and Four of Wakulla County for Alongshore Storms

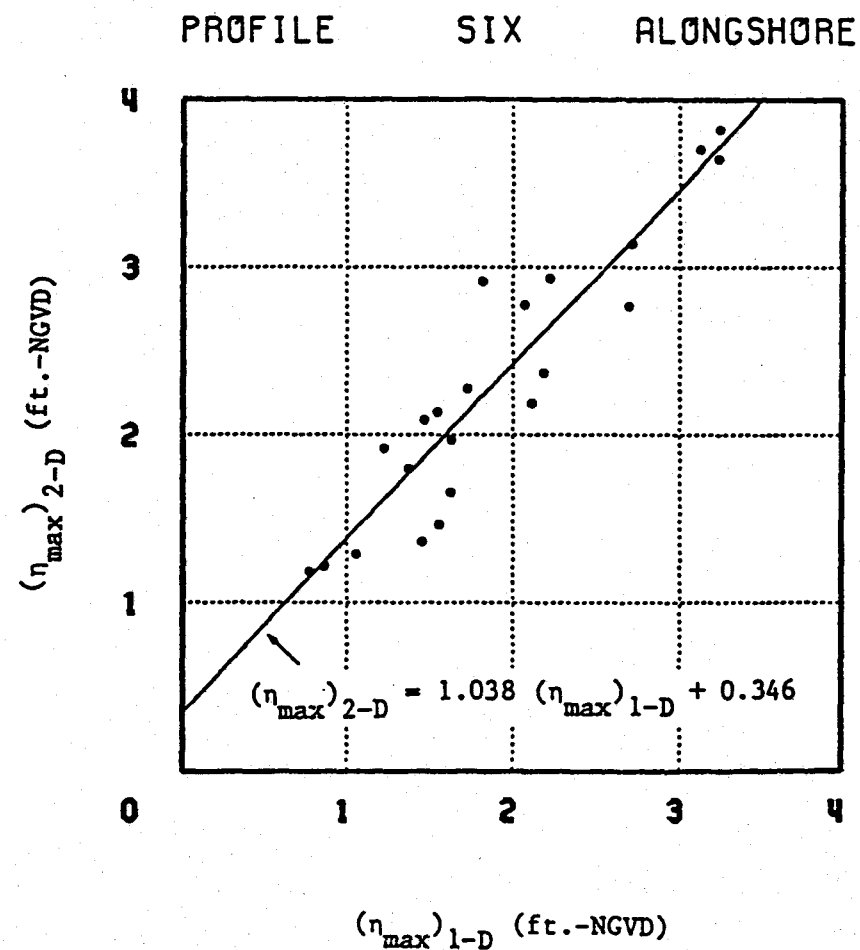
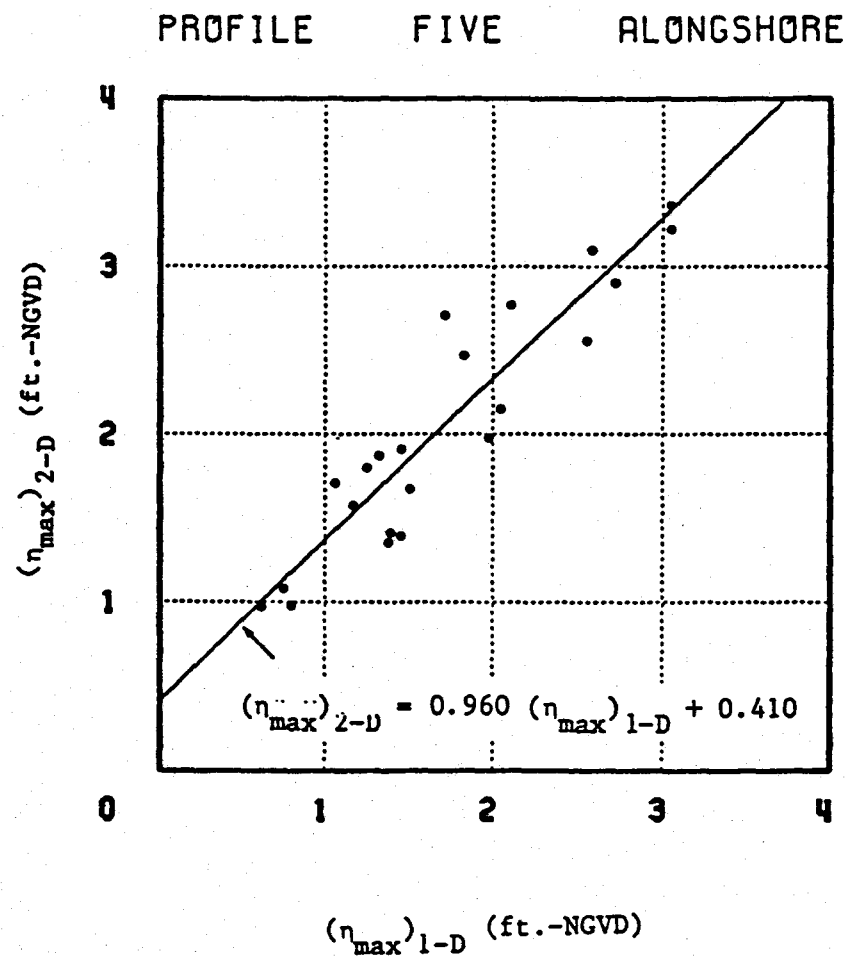


Figure 29c Calibration Relationship between the One-Dimensional and the Two-Dimensional Calculations of Peak Surges at Transect Lines Five and Six of Wakulla County for Alongshore Storms

results. This "calibrated" storm surge relationship for each of the six transect lines is then utilized in the simulation as described previously to establish a combined total storm tide. Finally the 1,140 peak values of the combined total storm tides are ranked to establish the storm tides associated with various return periods of interest.

VI. RESULTS OF LONG-TERM SIMULATIONS

Five 2,000-year simulations for each of the six transect lines are carried out employing the computer methods and storm statistics presented in the preceding sections. The combined total storm tides above NGVD and associated return periods computed from Equation 29 are plotted on semi-log paper in Figures 30a, 30b, 30c, 30d, 30e and 30f for the six transect line locations along the Wakulla County shoreline. Each data point on these figures represents the average value of five 2,000 year simulations and a curve drawn through the data points is adopted to represent the tide-frequency relationship for each of the six transect lines. Figure 31 presents all six combined total storm tide frequency curves depicted in Figures 30a, 30b, 30c, 30d, 30e and 30f.

Table IV below gives the combined total storm tide values and corresponding return periods for the six transect lines.

Table IV
Combined Total Storm Tide Values for Various Return Periods

Return Period, TR (years)	Combined Total Storm Tide Level* above NGVD (ft)					
	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6
500	17.9	18.3	18.1	17.8	17.3	17.3
200	16.7	17.0	16.6	16.1	16.1	15.9
100	15.2	15.5	15.3	15.3	15.1	14.7
50	13.9	14.2	13.9	13.5	13.3	13.1
20	11.5	11.7	11.4	11.0	11.0	10.9
10	9.5	9.5	9.3	8.9	9.2	9.0

*Includes contributions of: wind stress, barometric pressure, dynamic wave setup and astronomical tides.

WAKULLA COUNTY- Profile 1

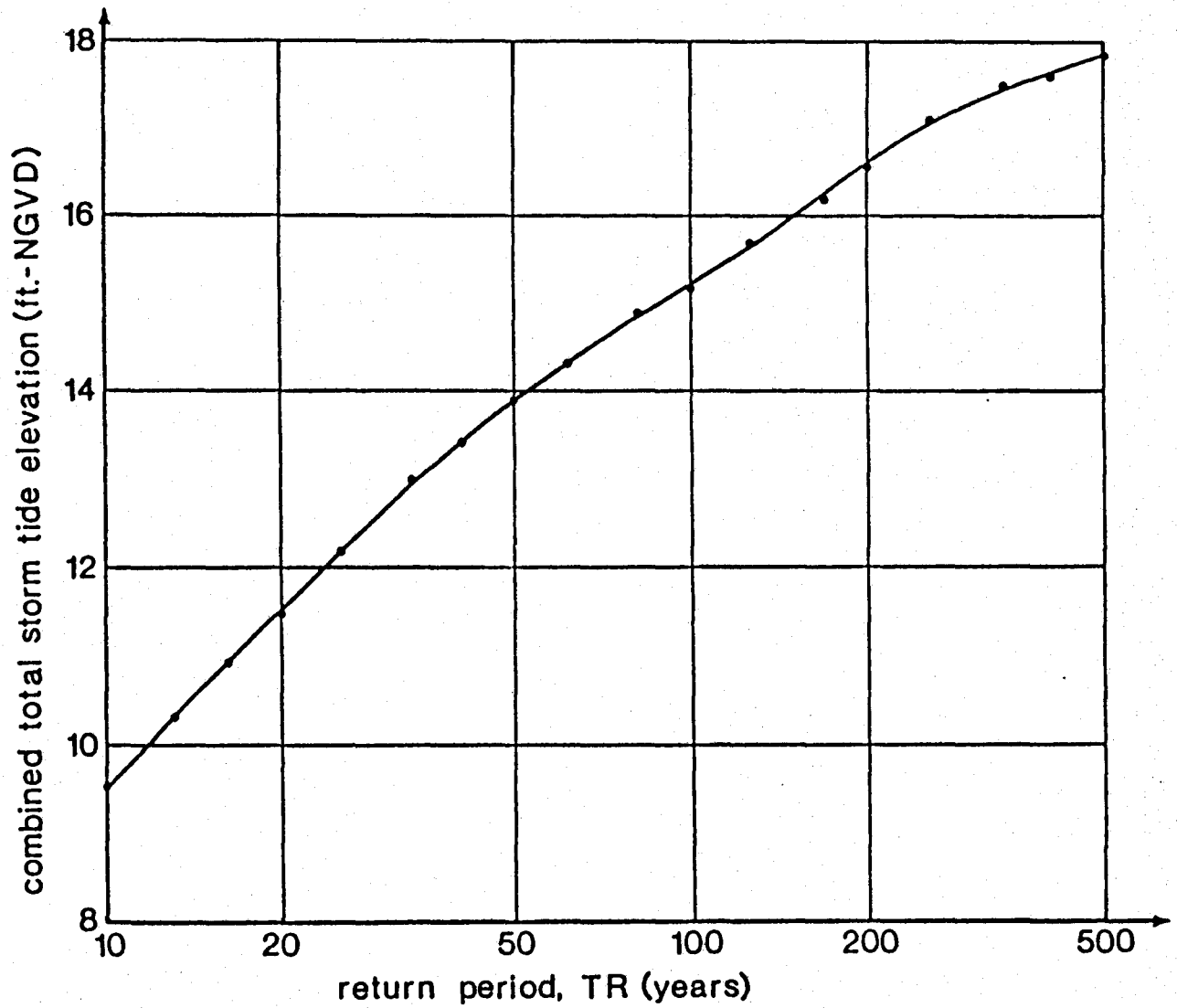


Figure 30a Average of Five 2,000-Year Simulations for Transect Line One of Wakulla County

WAKULLA COUNTY- Profile 2

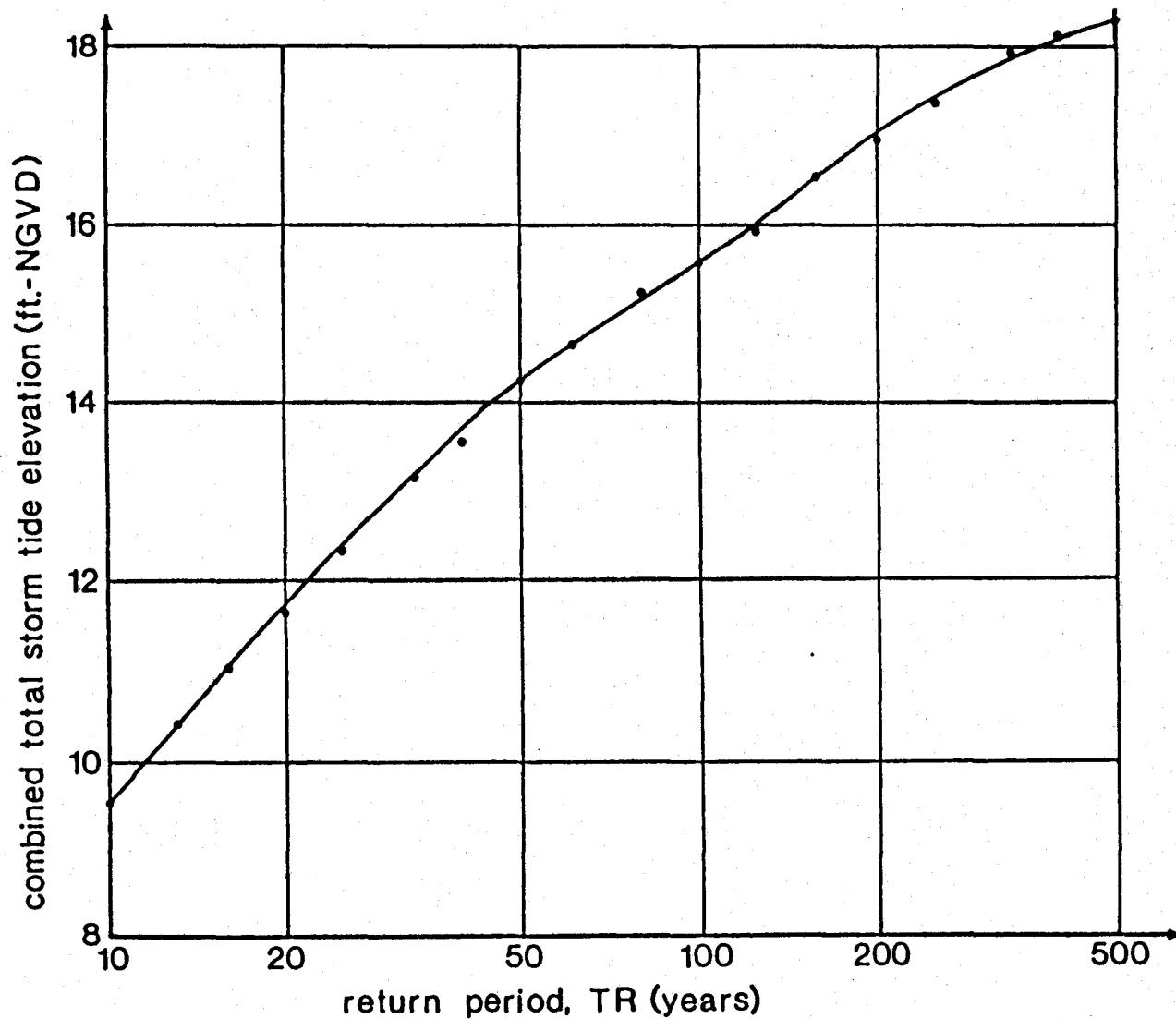


Figure 30b Average of Five 2,000-Year Simulations for Transect Line Two of Wakulla County

WAKULLA COUNTY- Profile 3

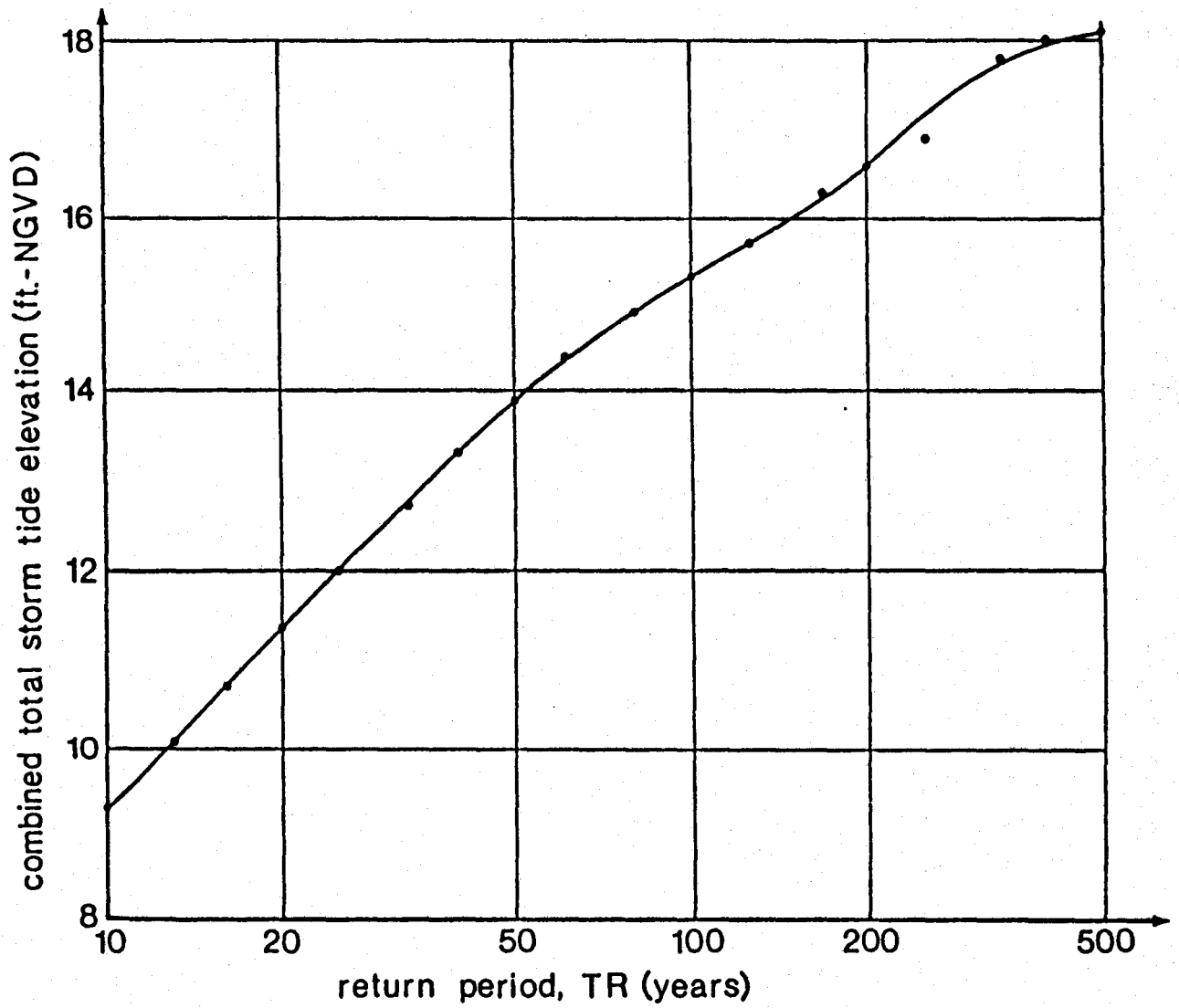


Figure 30c Average of Five 2,000-Year Simulations for Transect Line Three of Wakulla County

WAKULLA COUNTY- Profile 4

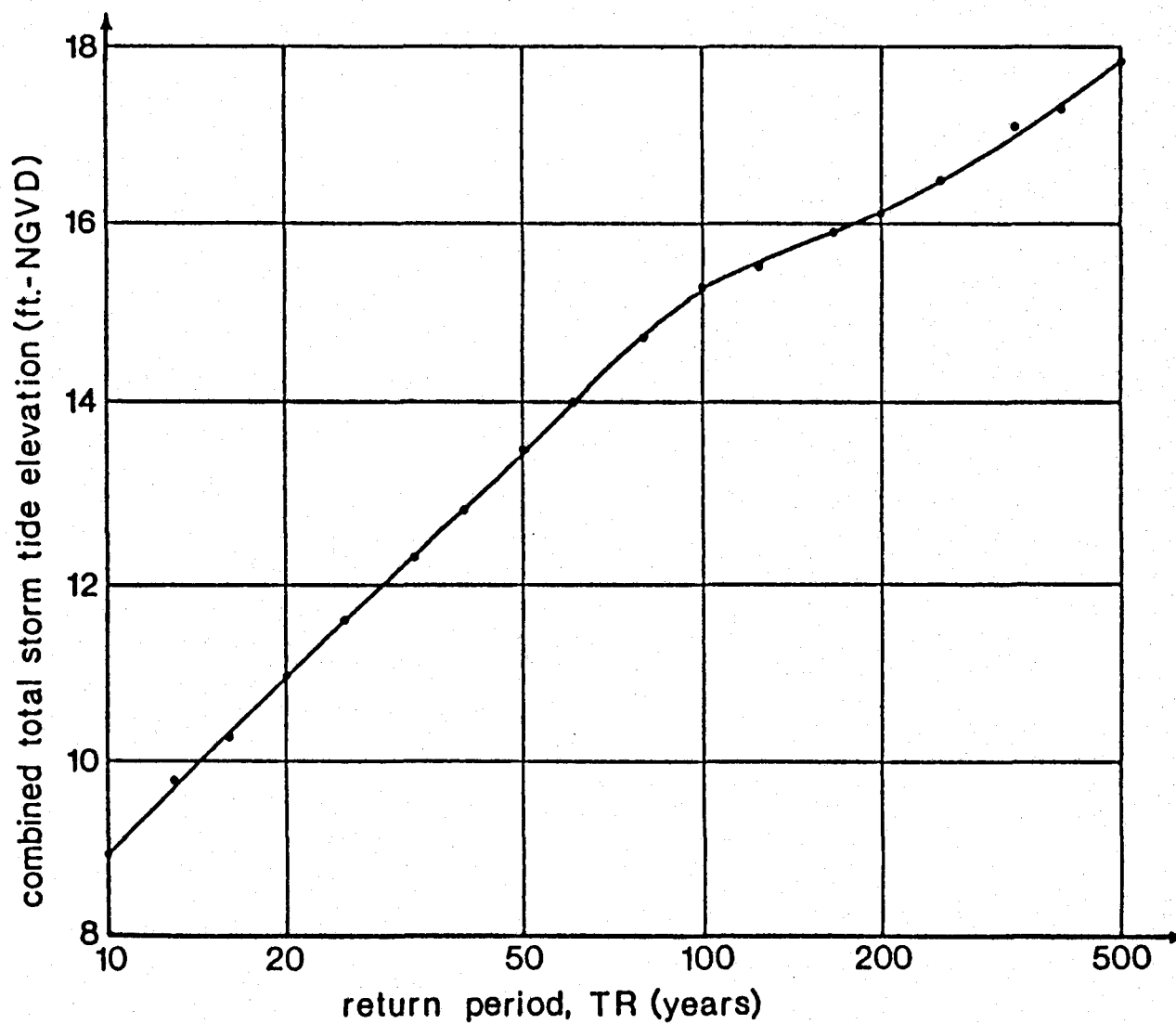


Figure 30d Average of Five 2,000-Year Simulations for Transect Line Four of Wakulla County

WAKULLA COUNTY- Profile 5

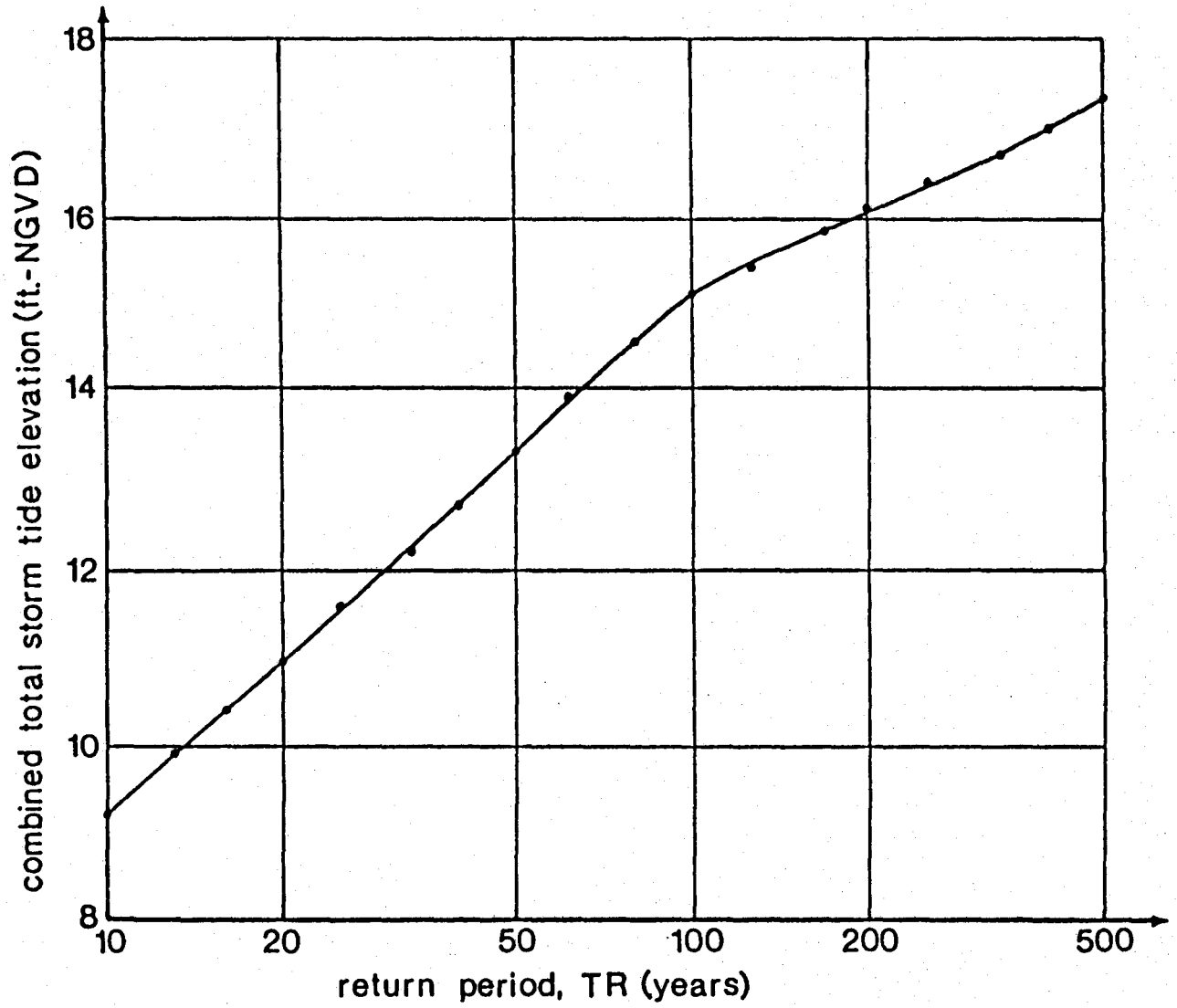


Figure 30e Average of Five 2,000-Year Simulations for Transect Line Five of Wakulla County

WAKULLA COUNTY- Profile 6

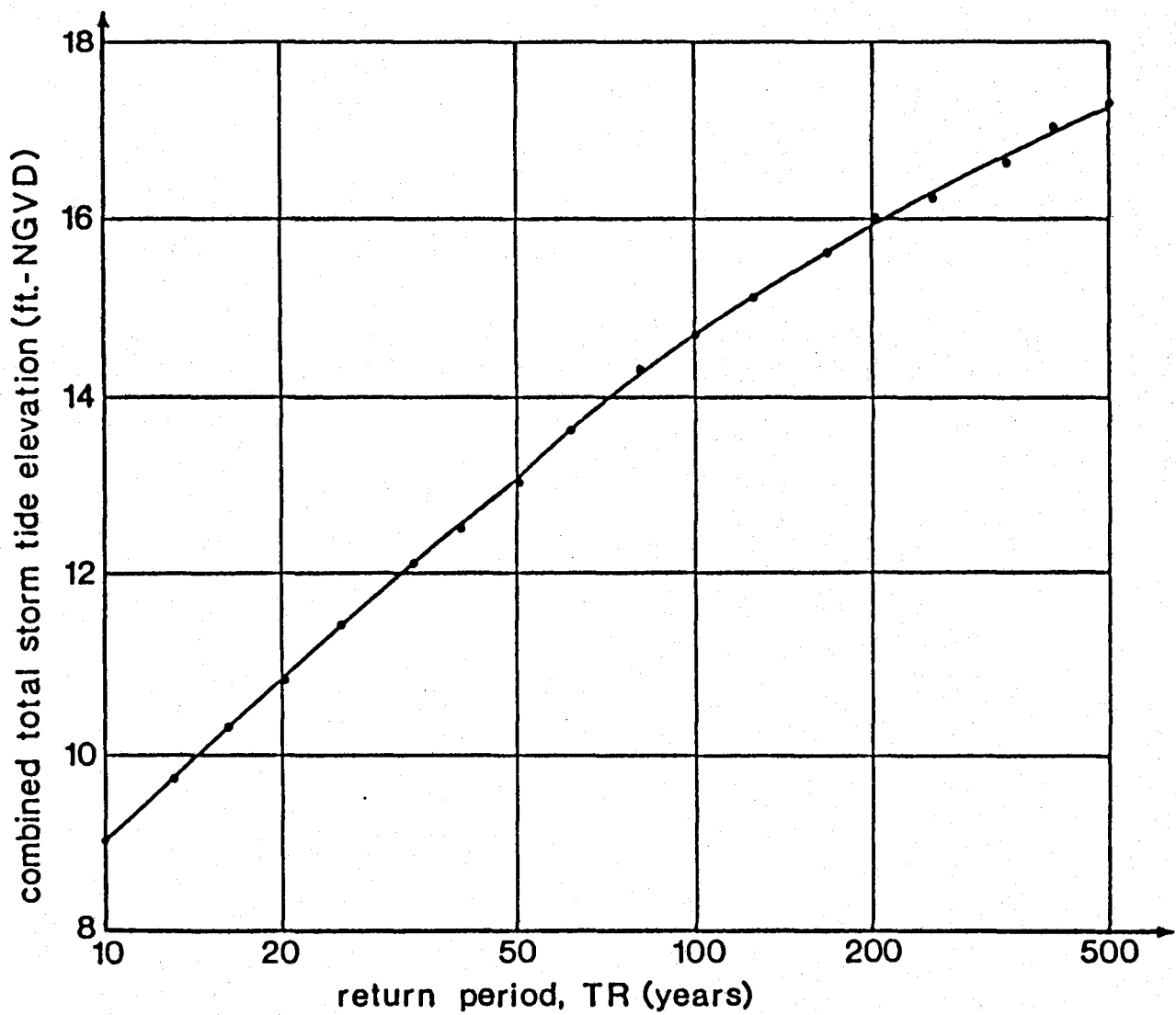


Figure 30f Average of Five 2,000-Year Simulations for Transect Line Six of Wakulla County

WAKULLA COUNTY - Profiles

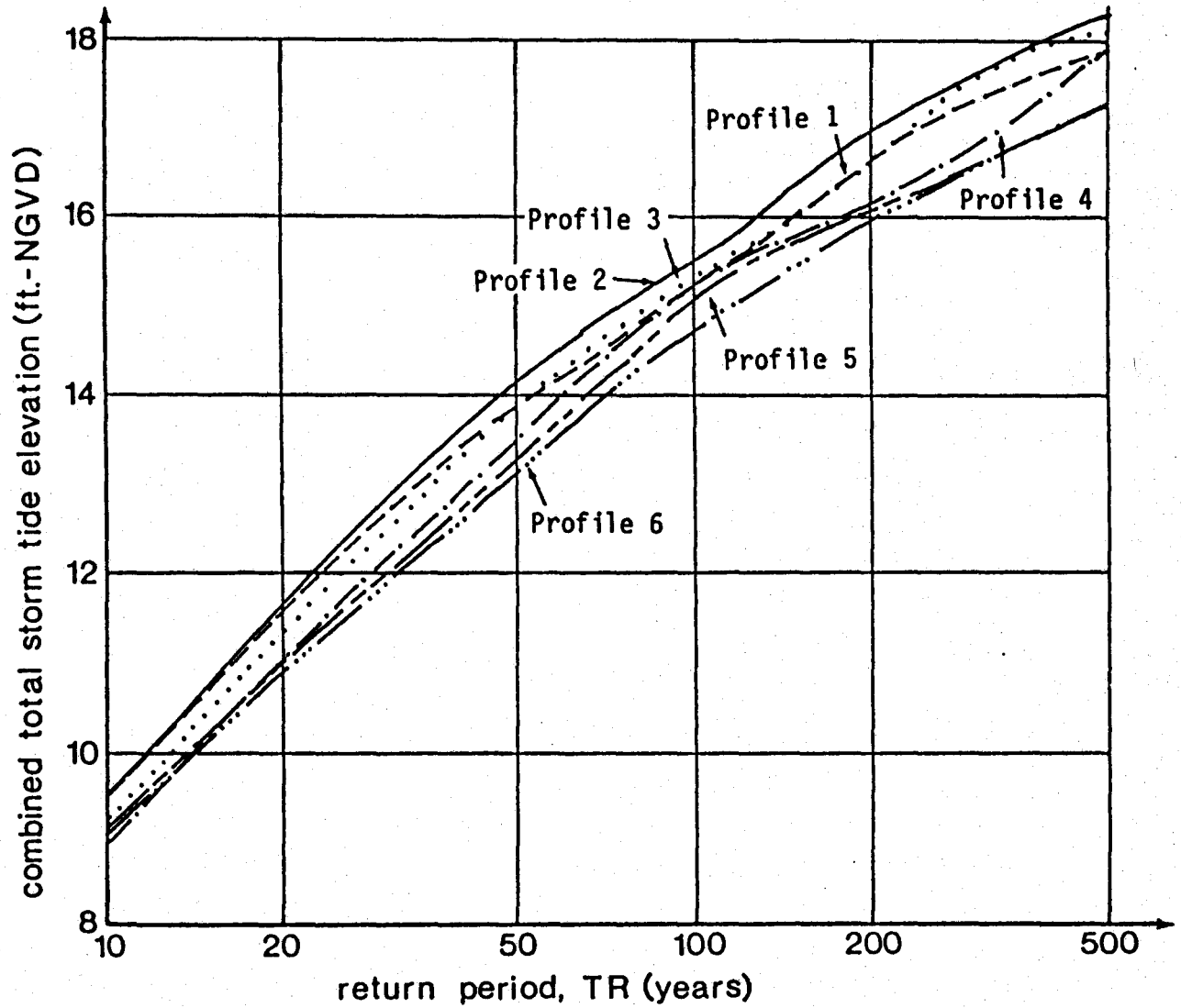


Figure 31 Combined Total Storm Tide Elevation Versus Return Period for Six Transect Lines of Wakulla County

VII. RESULTS OF FLOOD CREST ELEVATION CALCULATIONS

According to the methodology as presented in previous sections for the Phase II study, the results of the two-dimensional overland flooding crest elevations were compared with those of FEMA's. For convenience of comparison, eleven Community-Panels (shown on the FEMA's Flood Insurance Rate Map of June 1986 for Florida's Wakulla County unincorporated areas) were used to plot the calculated flooding crest elevations by the present study and those by FEMA. The differences in elevations are presented in Figures 32 to 42. By examining these figures, it is clear that the present study gives lower flooding crest elevations from 1 to 7 ft. near the shoreline and higher crest elevations farther inland. It should be noted again that the present study employed the two-dimensional model which uses the average elevations of a 1,000 ft. by 2,000 ft. area which may contribute to some of the elevation differences.

For convenience to the readers, the overland flooding crest elevations resulting from the present study are shown in Figures 43 to 53 and that of FEMA's are shown in Figures 54 to 64. The overland flooding crest elevation lines in Figures 54 to 64 were copied from FEMA's Flood Insurance Rate Map of June 1986 by hand as close as humanly possible. Therefore, they approximately represent the flooding crest elevation lines of FEMA's.

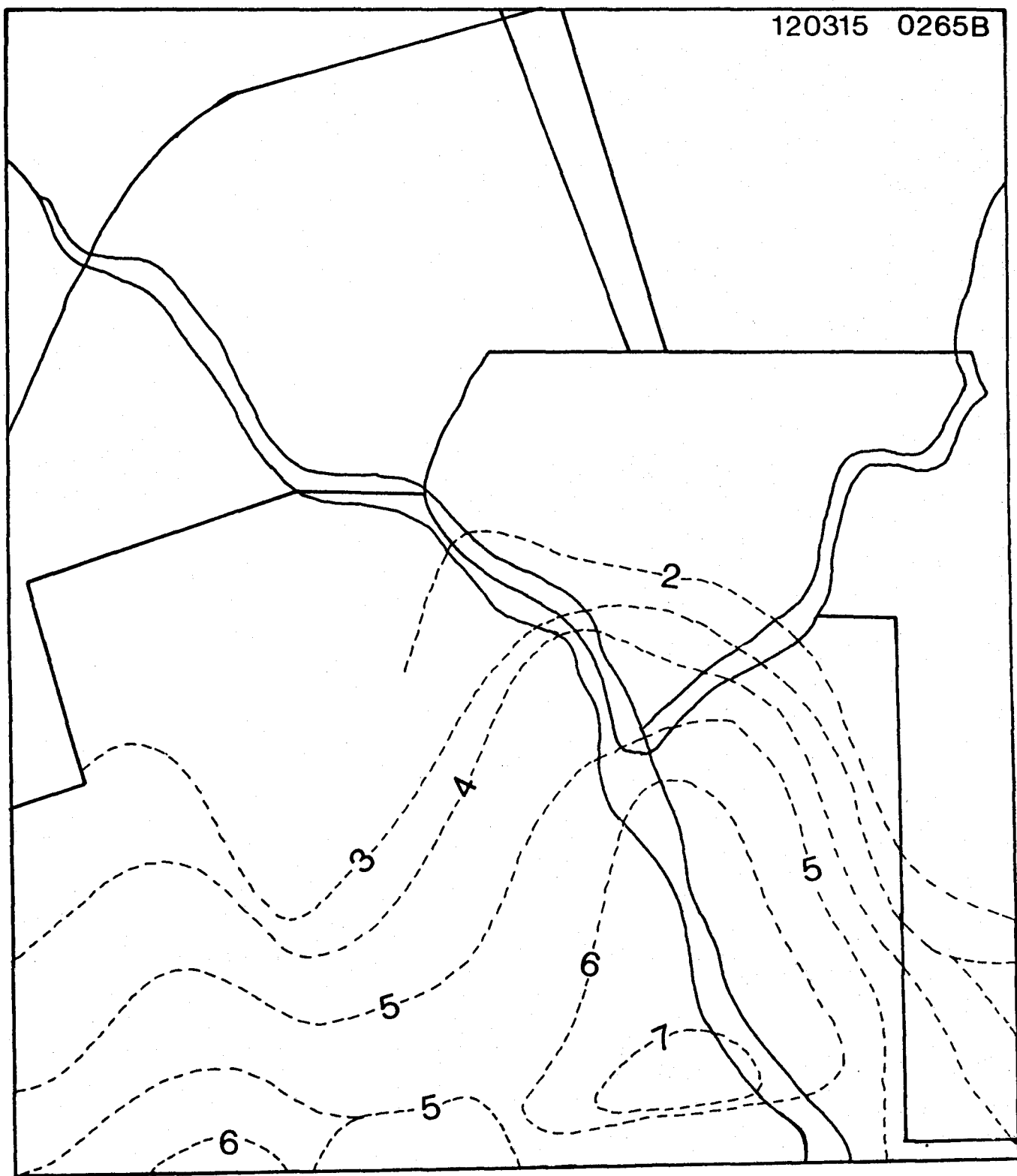


Figure 32 Difference in Flooding Crest Elevations of Community-
Panel 120315 0265B

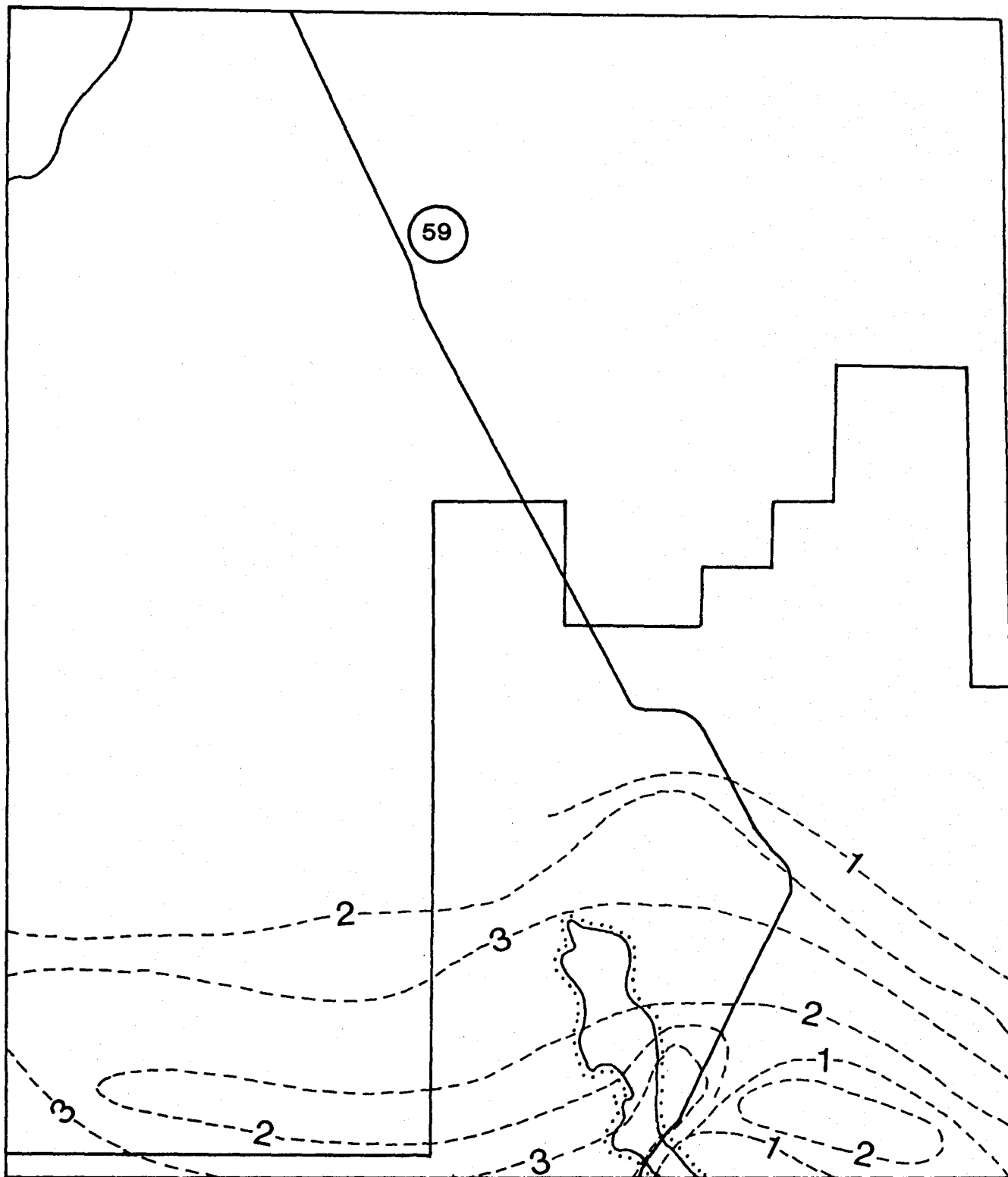


Figure 33 Difference in Flooding Crest Elevations of Community-
Panel 120315 0275B

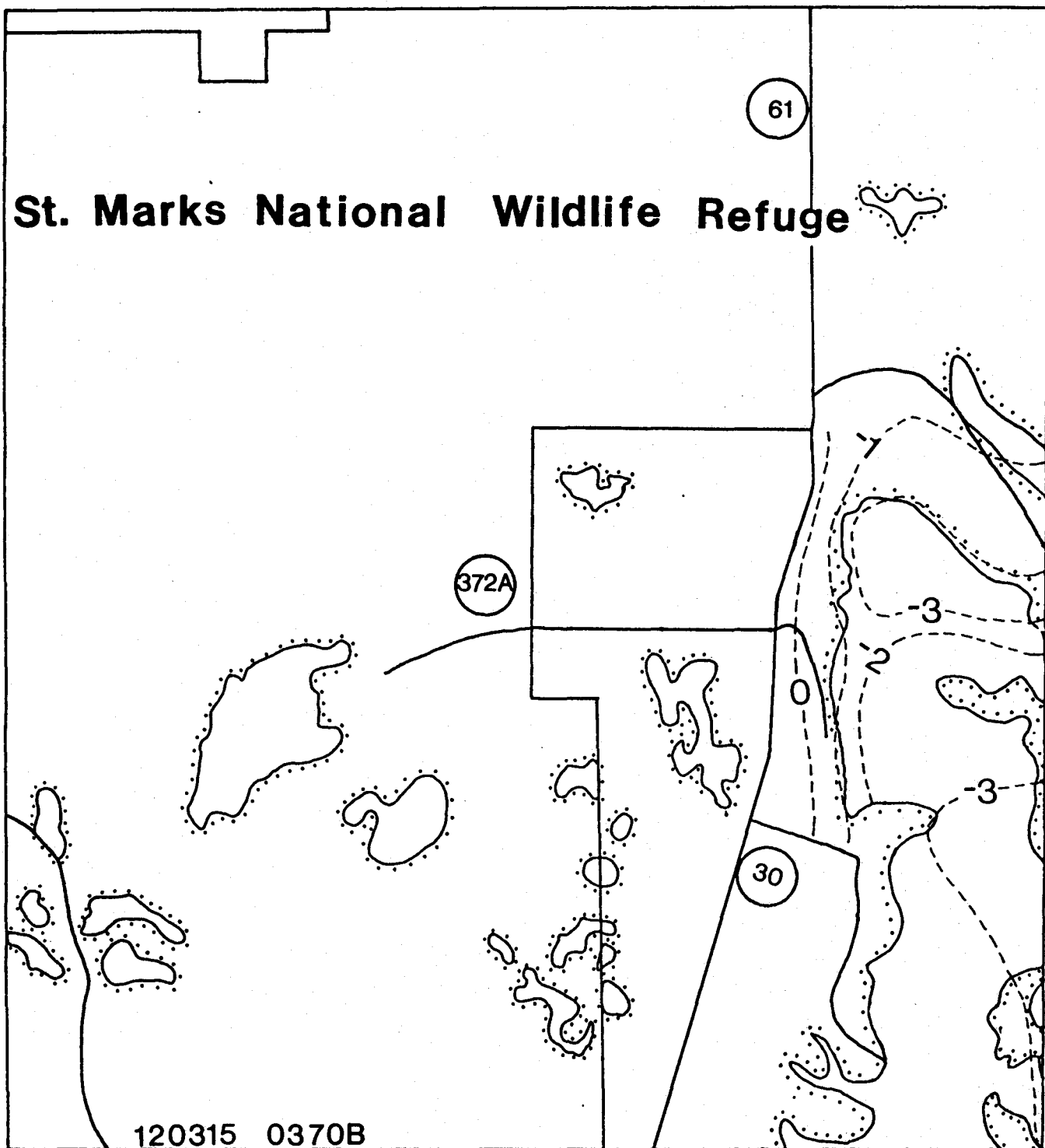


Figure 34 Difference in Flooding Crest Elevations of Community-
Panel 120315 0370B

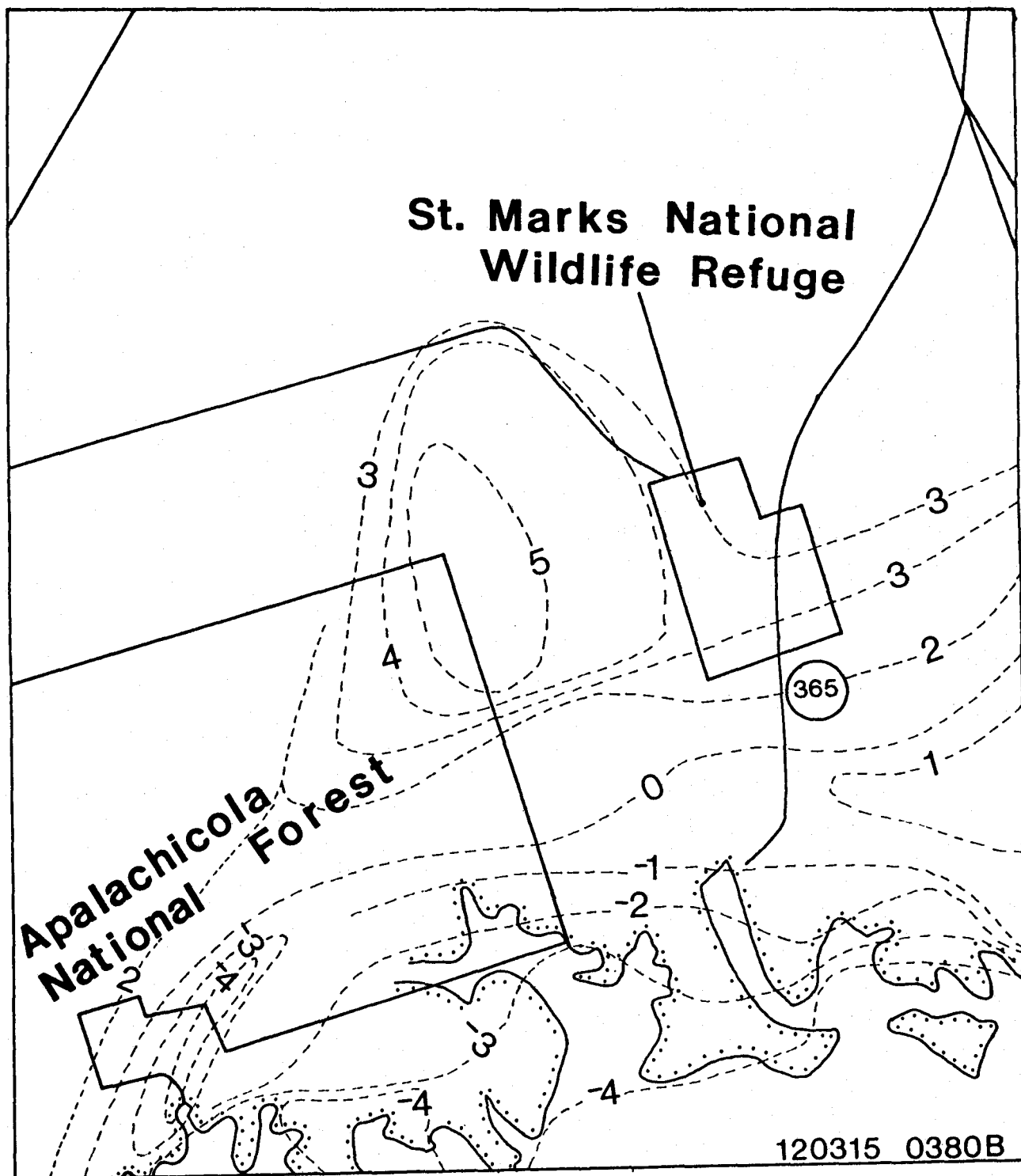


Figure 35 Difference in Flooding Crest Elevations of Community-
Panel 120315 0380B

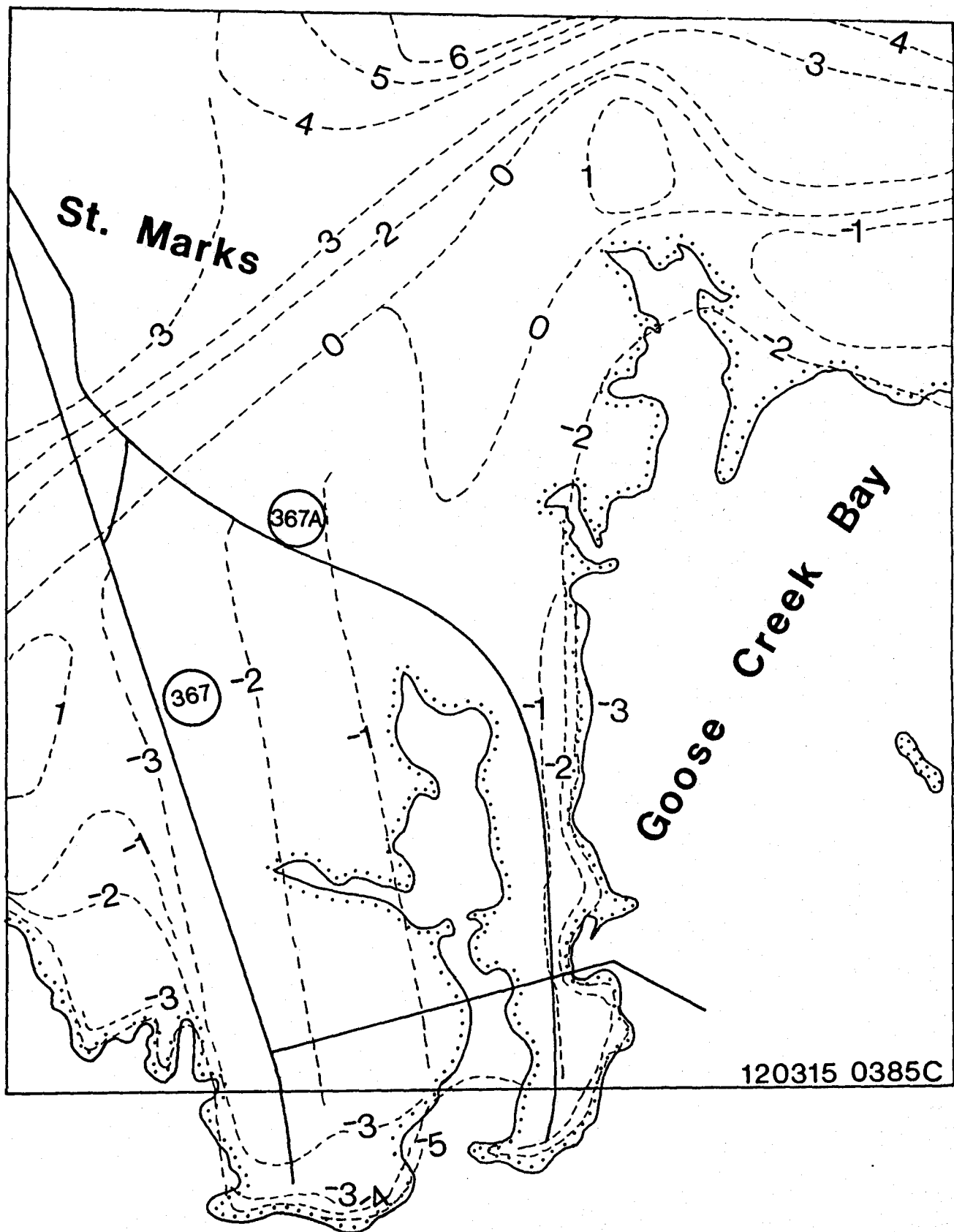


Figure 36 Difference in Flooding Crest Elevation of Community-
Panel 120315 0385C

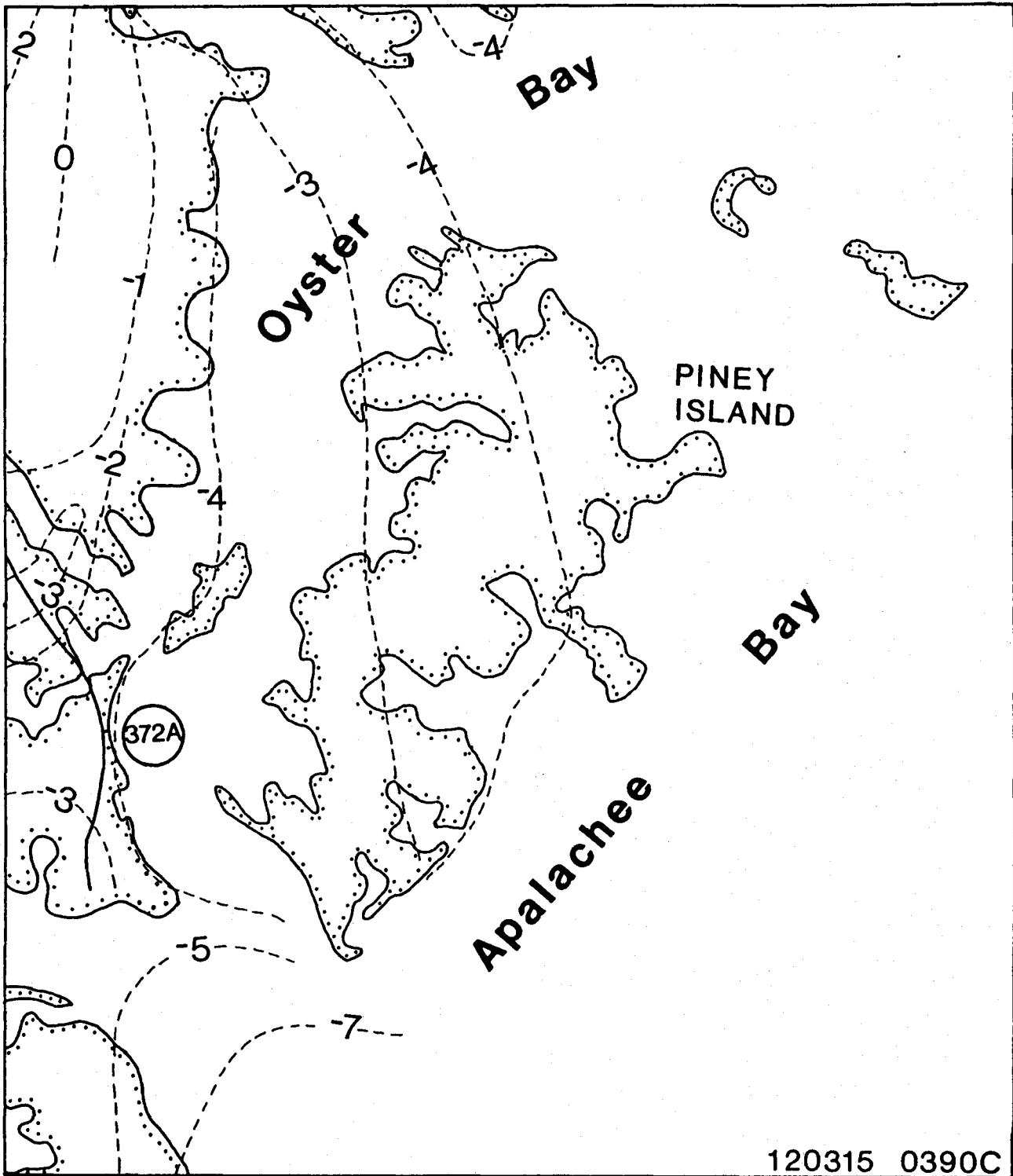


Figure 37 Difference in Flooding Crest Elevations of Community-
Panel 120315 0390C

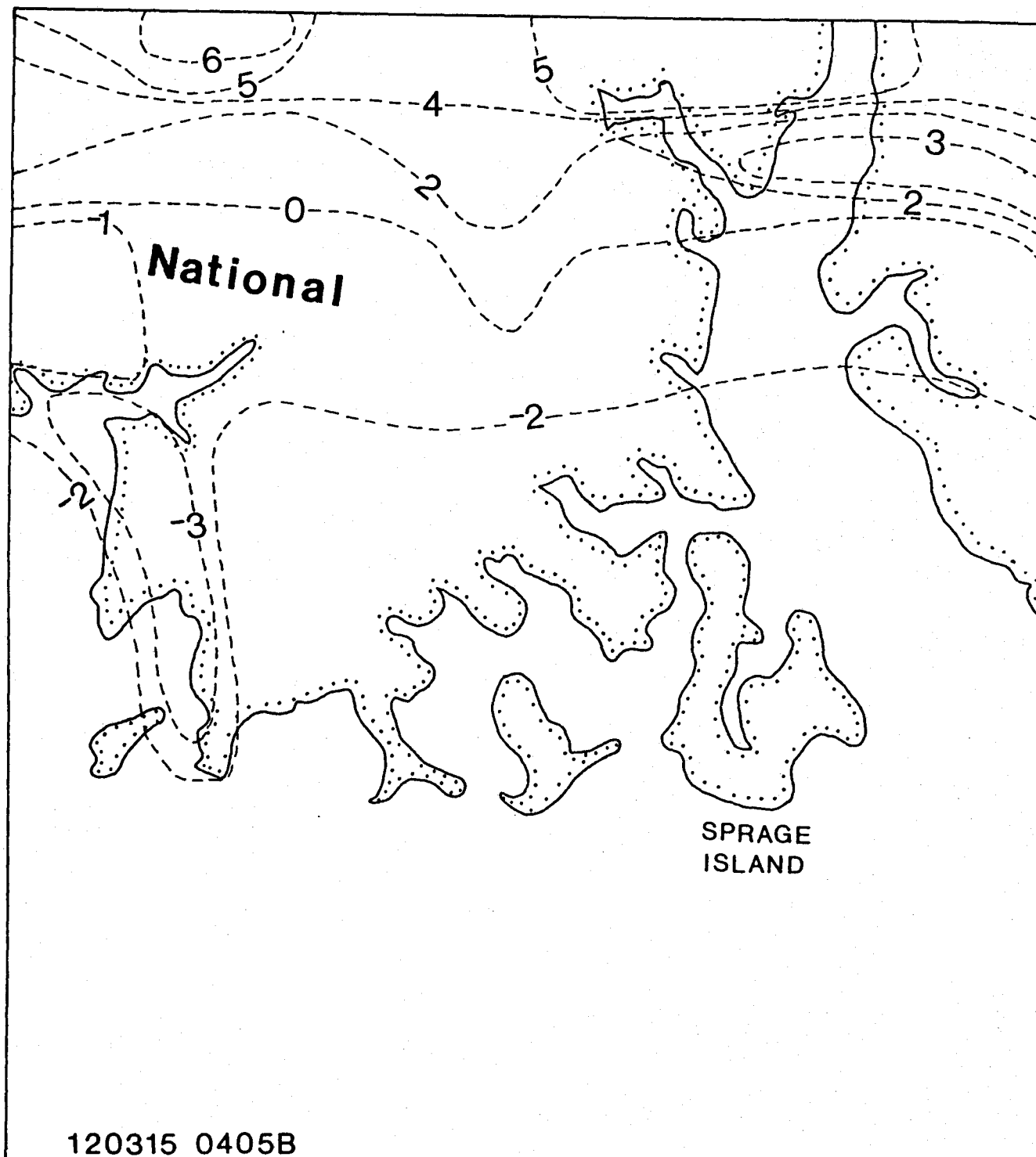


Figure 38 Difference in Flooding Crest Elevations of Community-
Panel 120315 0405B

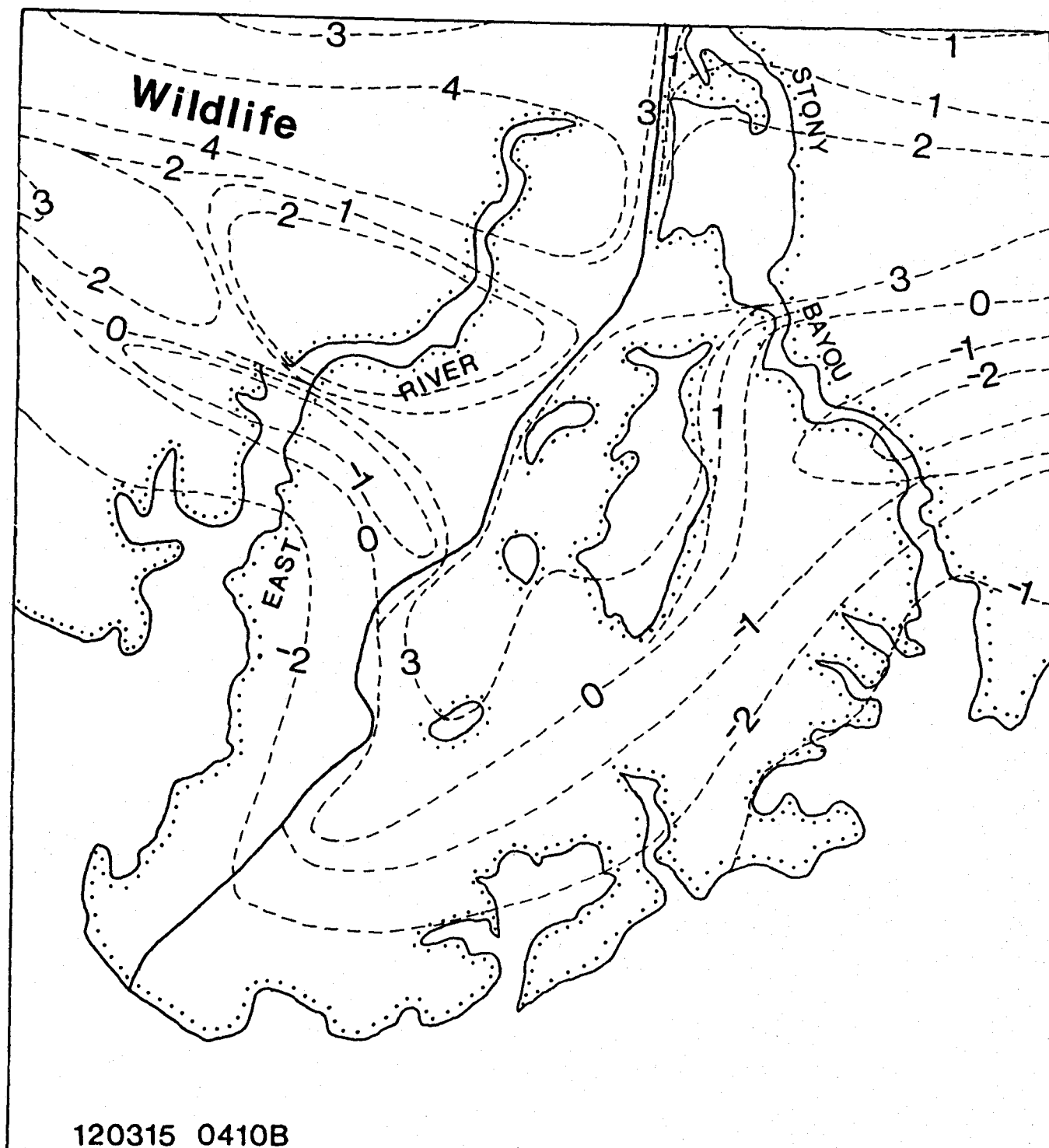


Figure 39 Difference in Flooding Crest Elevations of Community-
Panel 120315 0410B

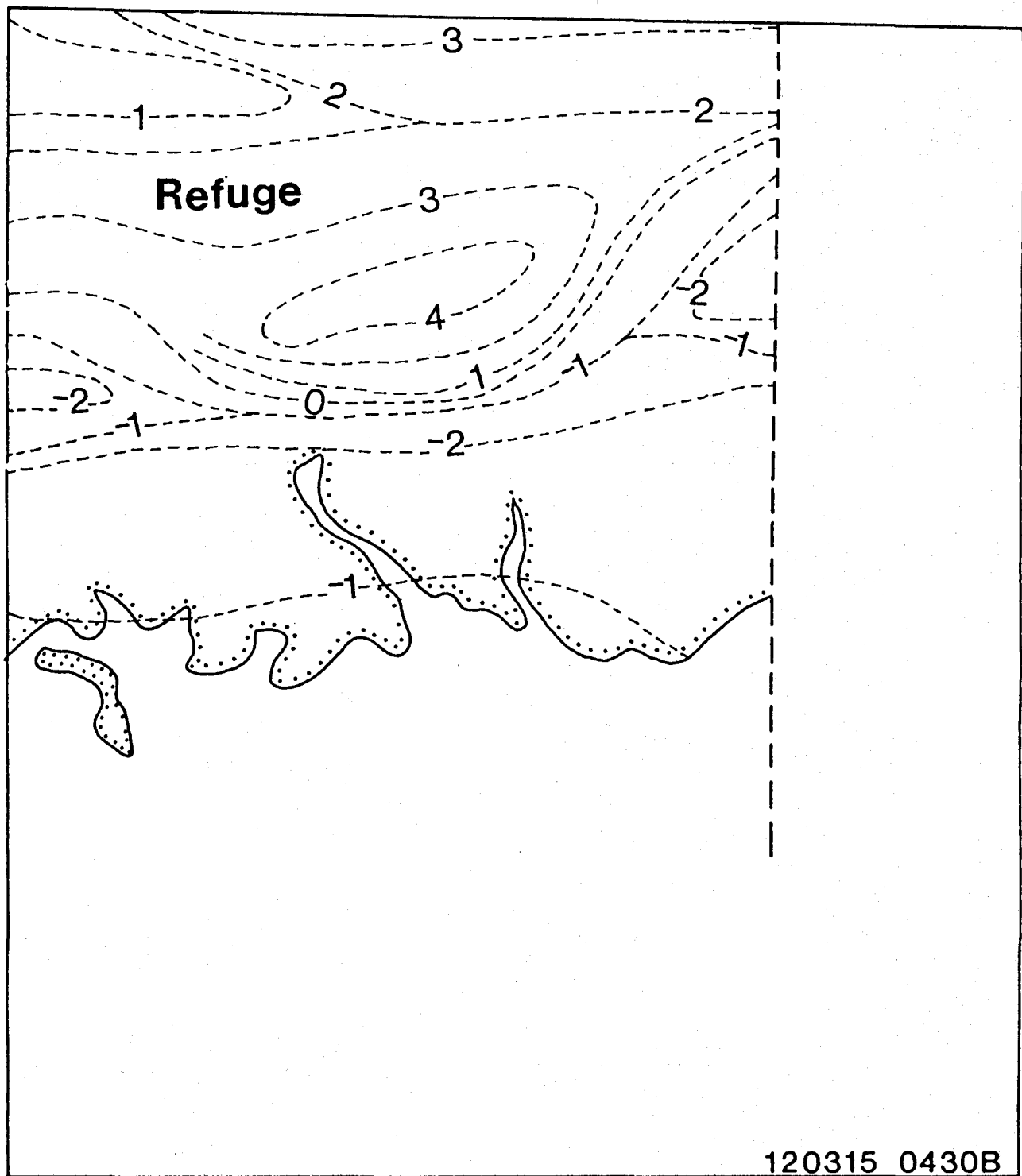


Figure 40 Difference in Flooding Crest Elevations of Community-
Panel 120315 0430B

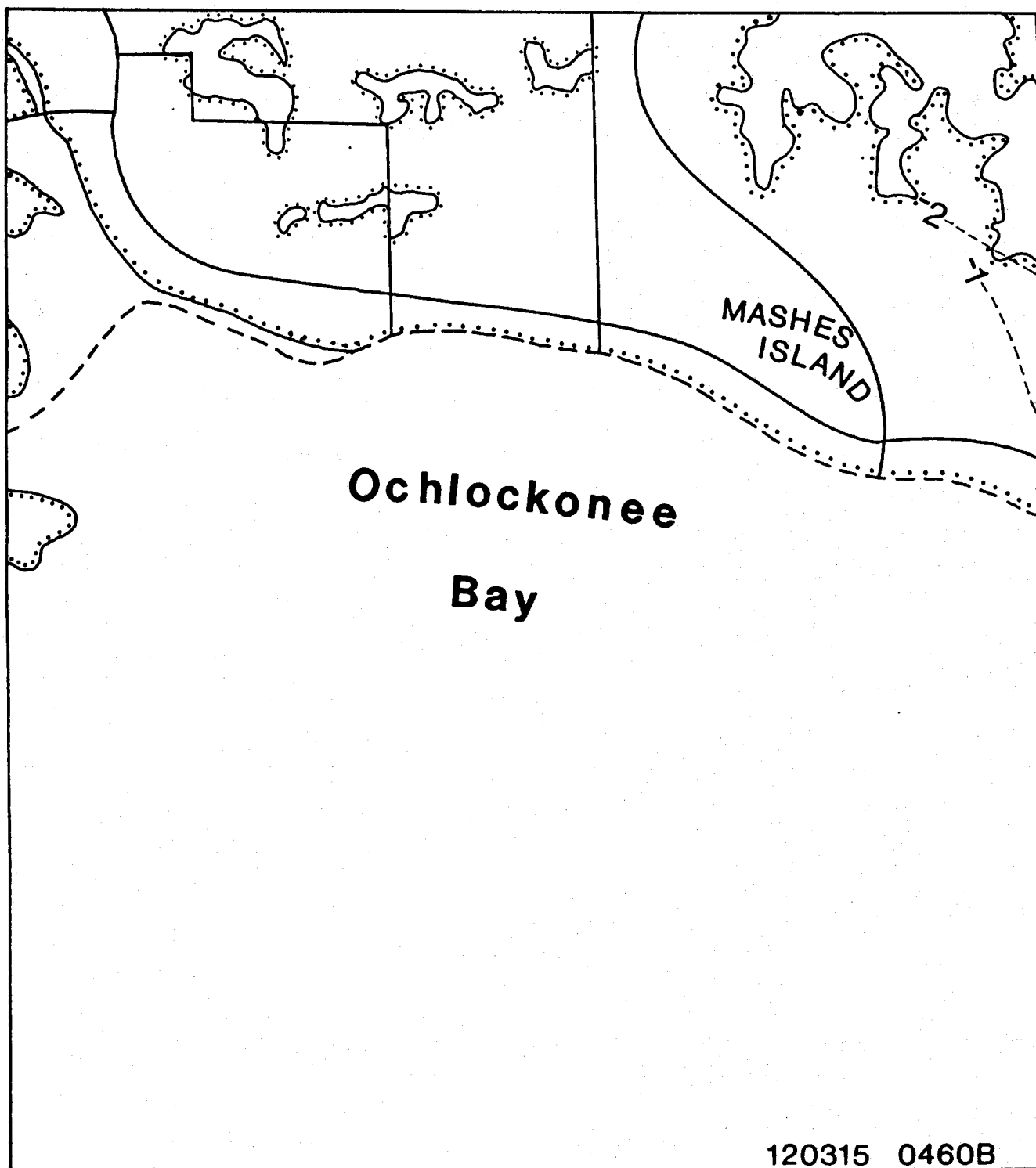


Figure 41 Difference in Flooding Crest Elevations of Community-
Panel 120315 0460B

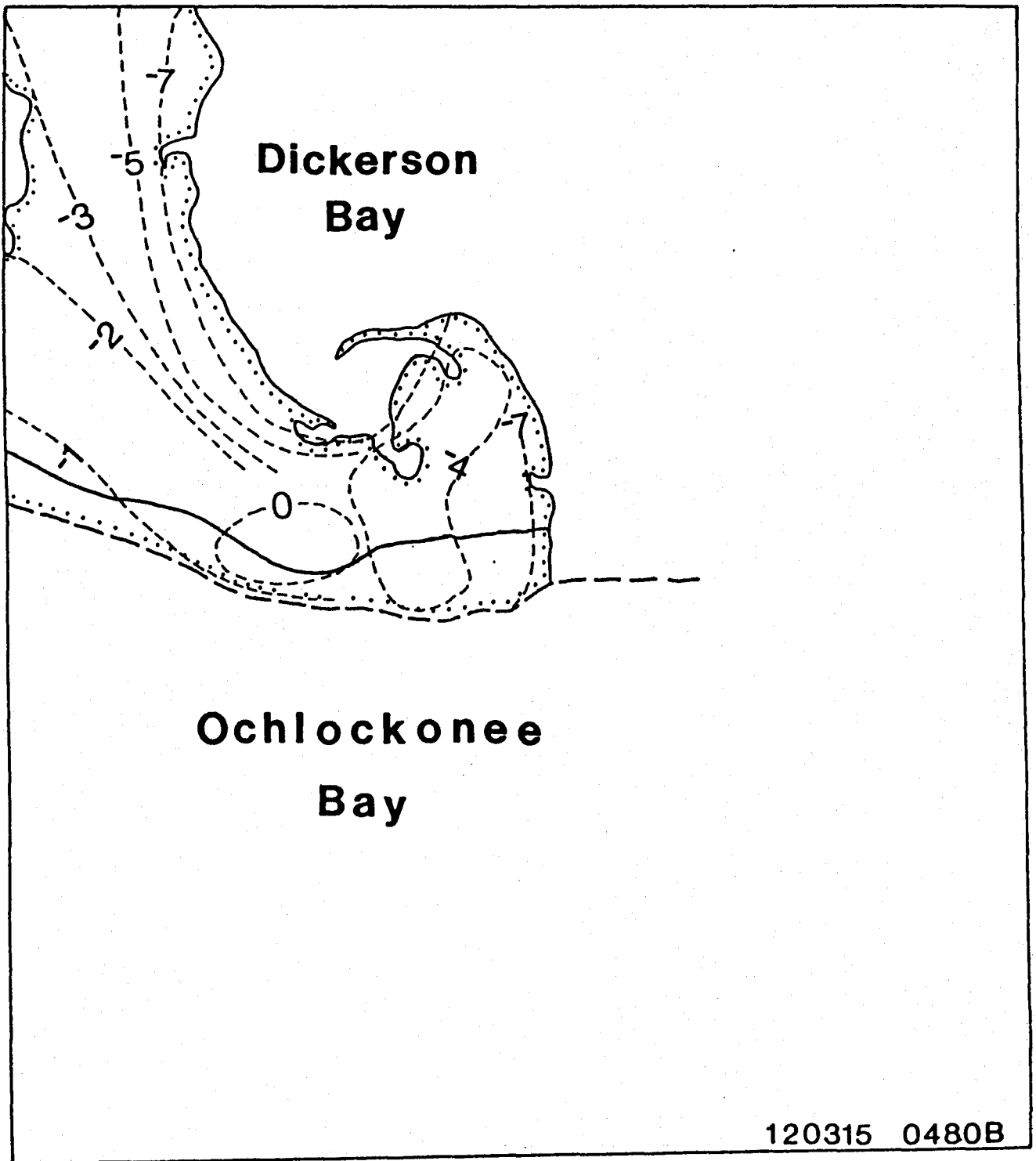


Figure 42 Difference in Flooding Crest Elevations of Community-
Panel 120315 0480B

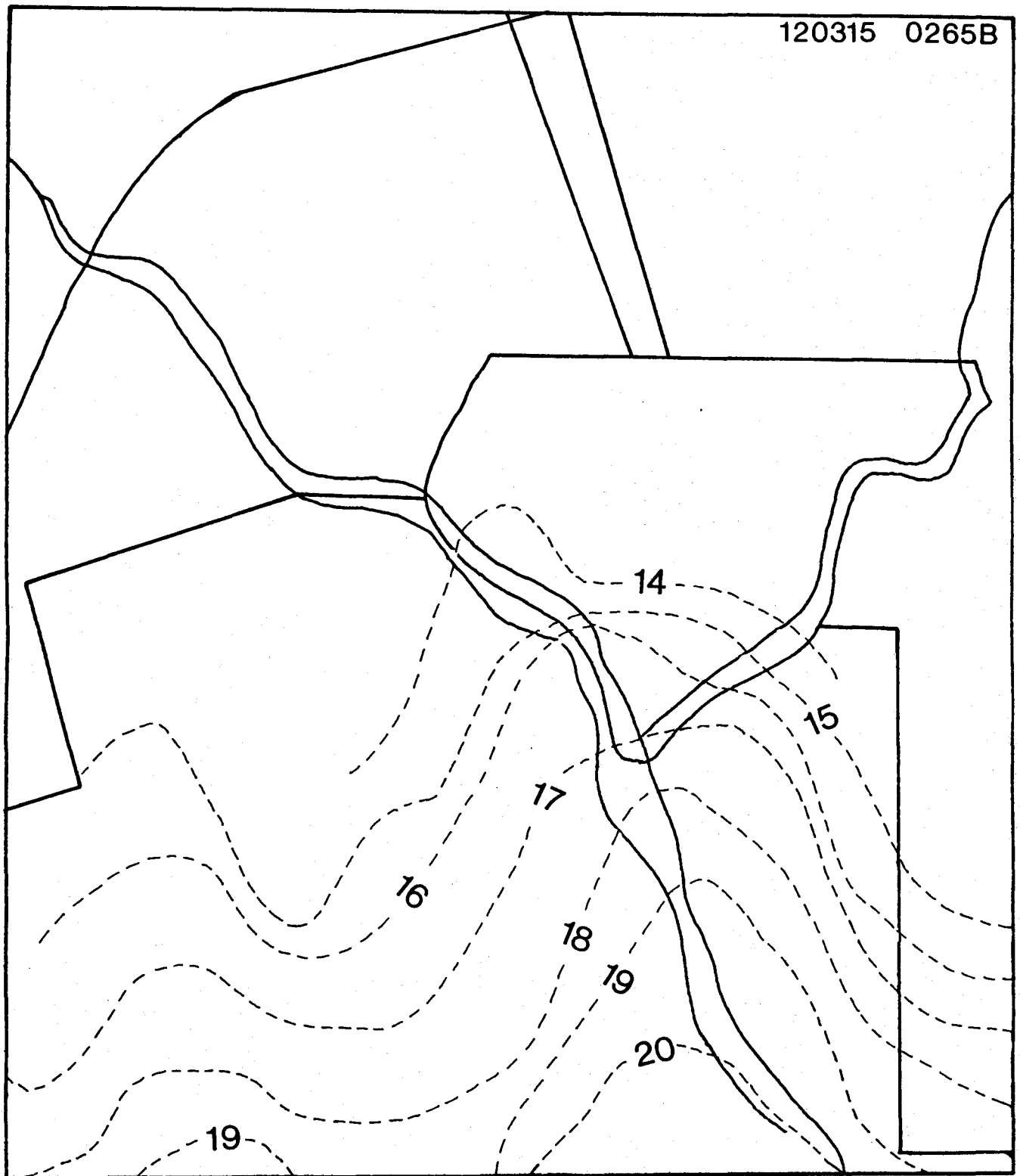


Figure 43 Flood Crest Elevation resulting from the present study for
Panel 120315 0265B

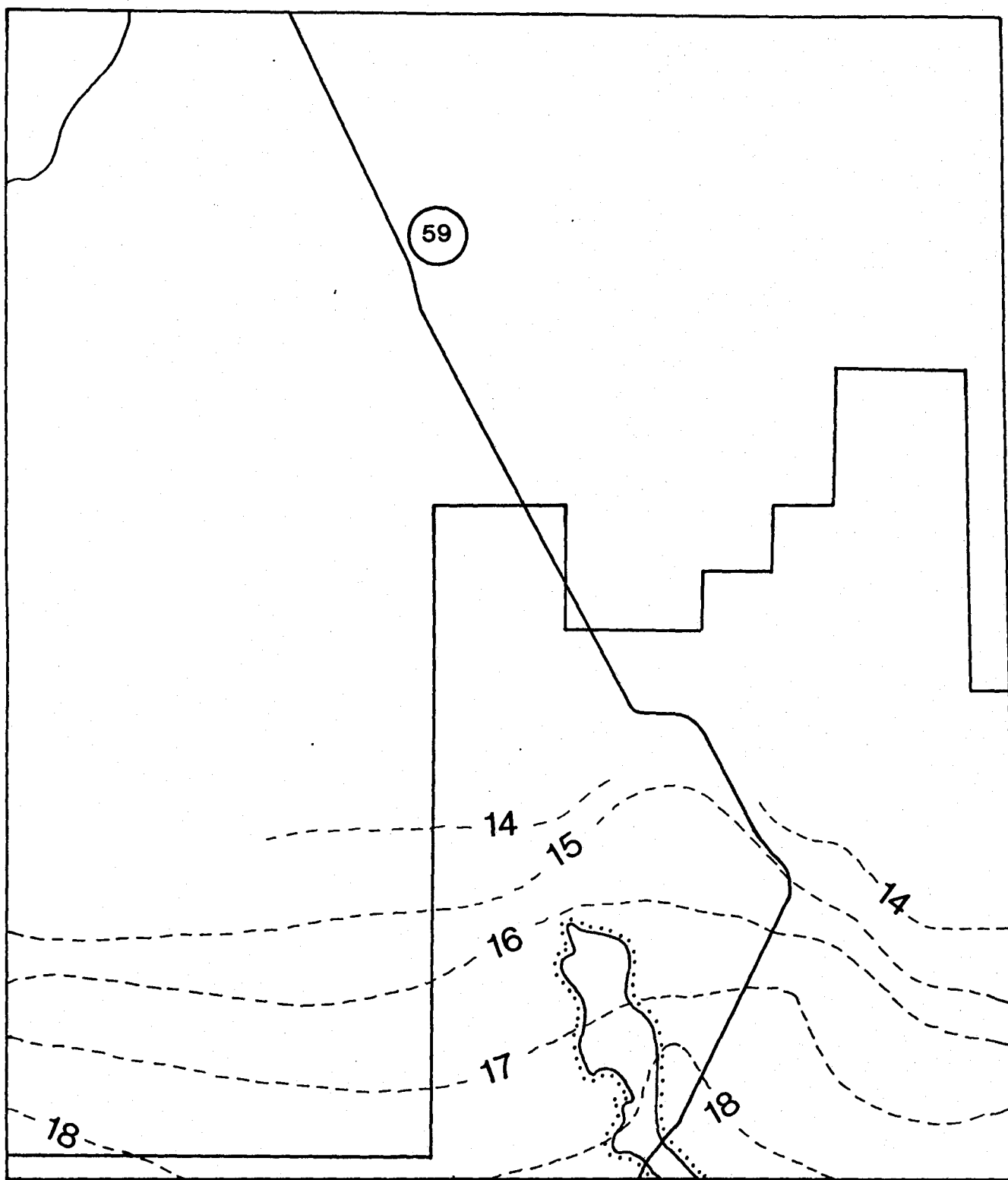


Figure 44 Flood Crest Elevation resulting from the present study for
Panel 120315 0275B

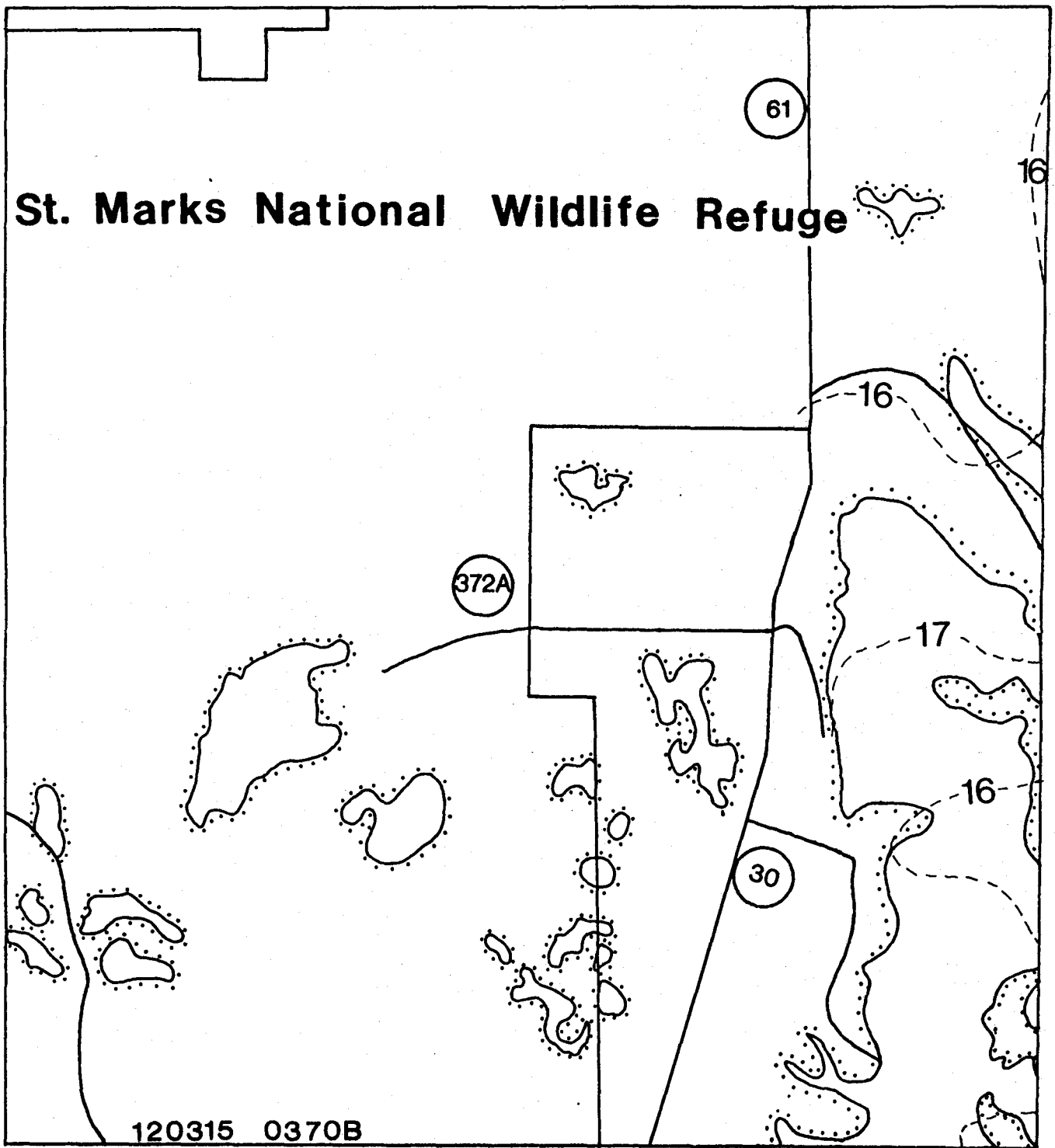


Figure 45 Flood Crest Elevation resulting from the present study for
Panel 120315 0370B

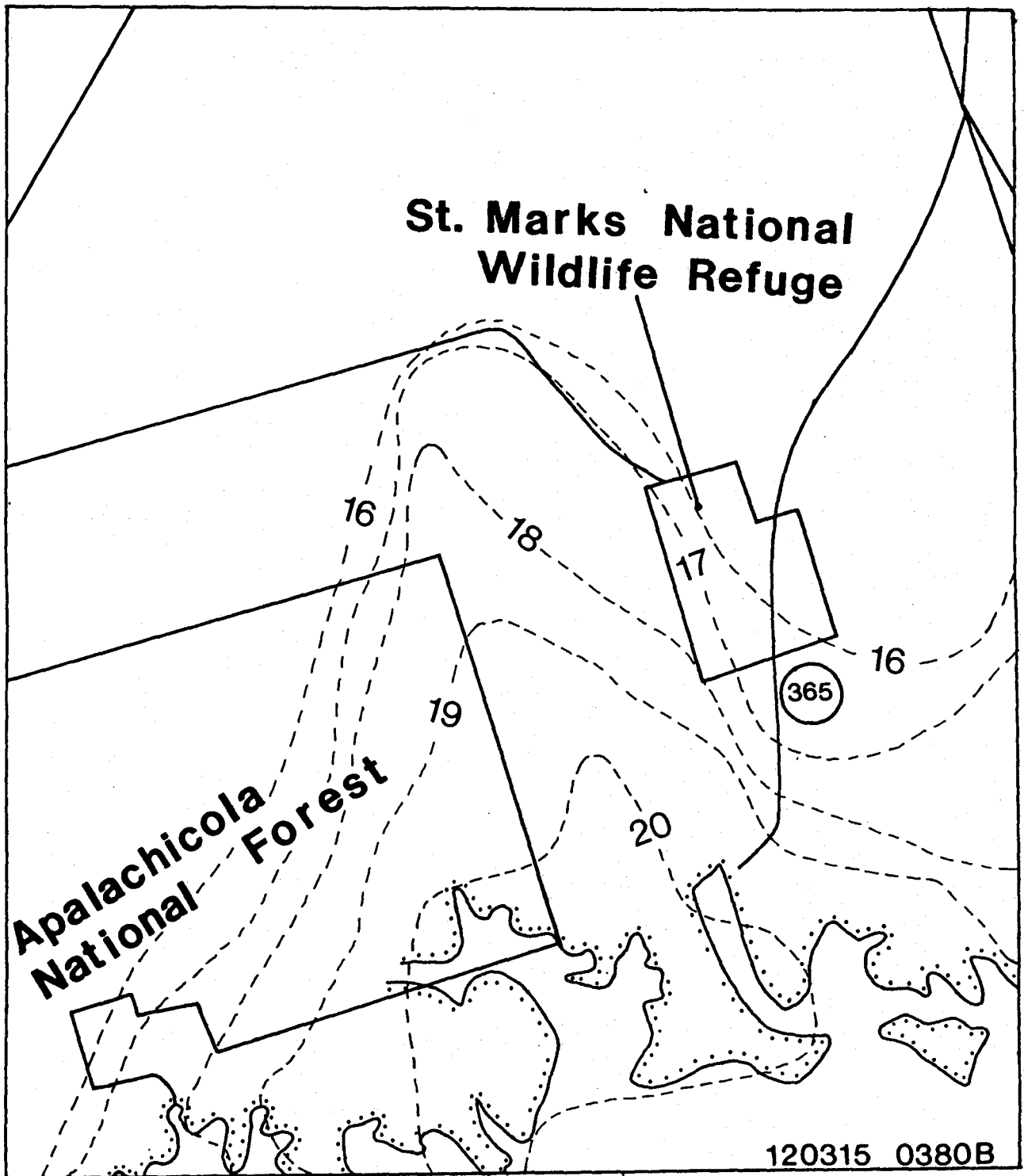


Figure 46 Flood Crest Elevation resulting from the present study for
Panel 120315 0380B

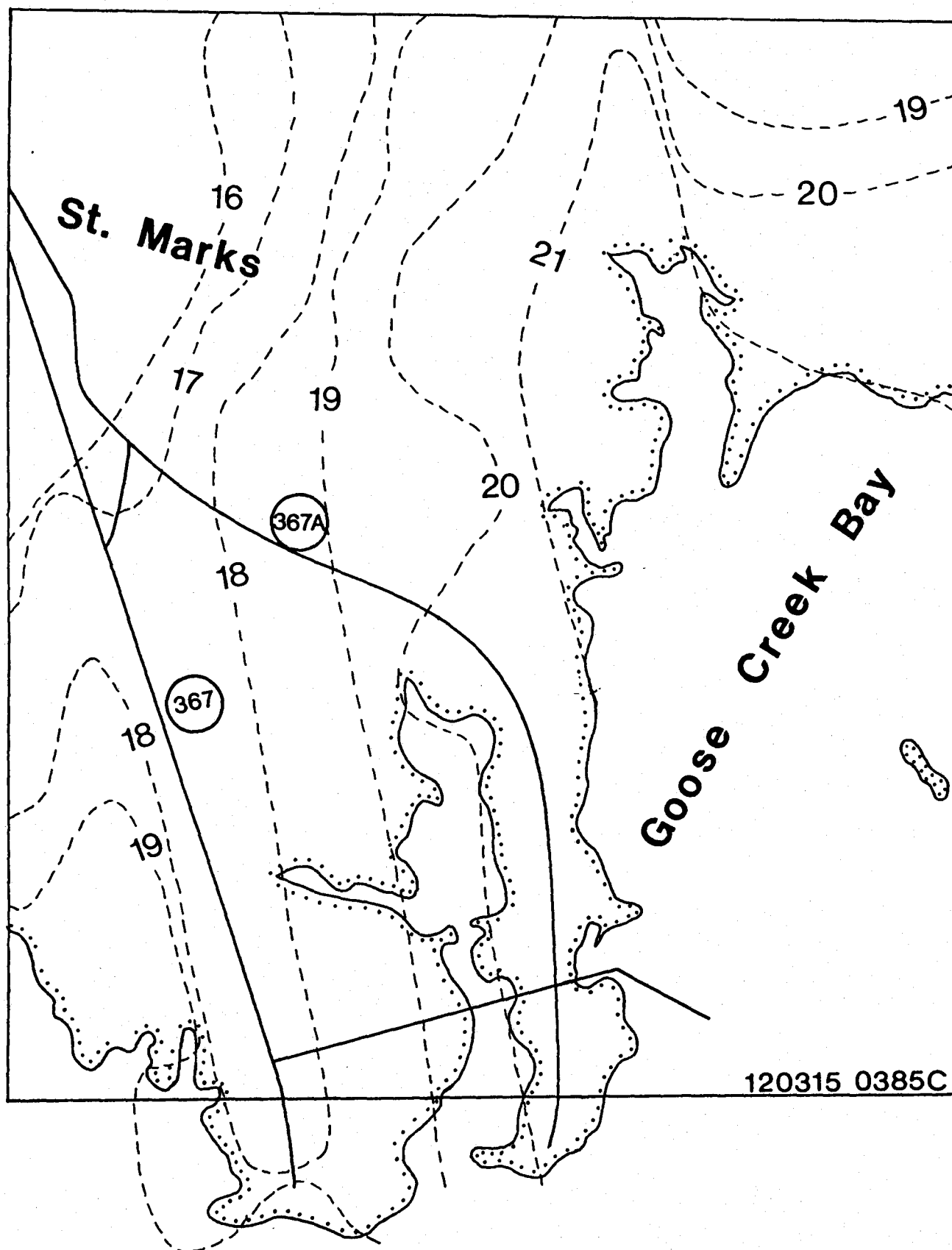


Figure 47 Flood Crest Elevation resulting from the present study for
Panel 120315 0385C

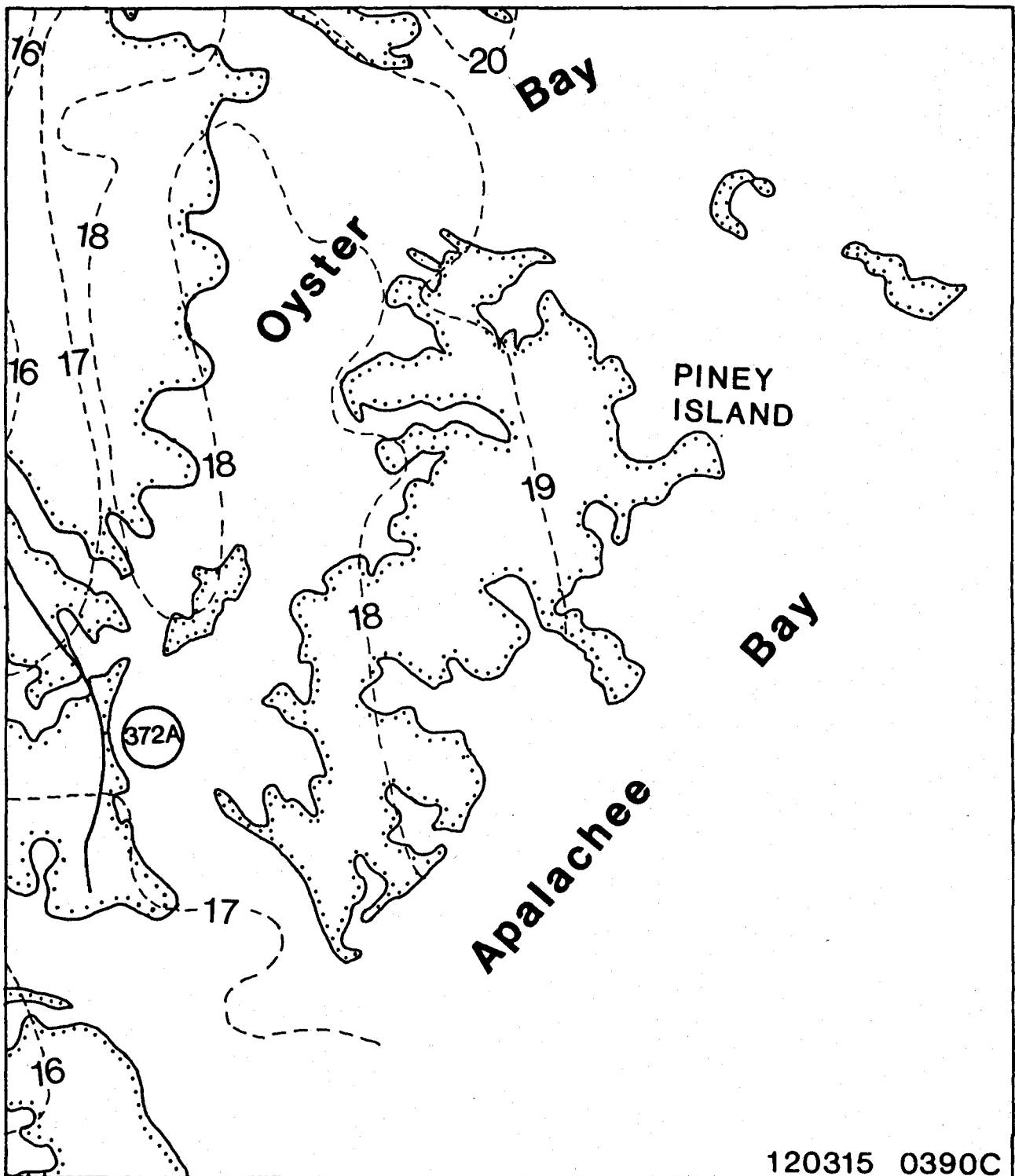


Figure 48 Flood Crest Elevation resulting from the present study for
Panel 120315 0390C

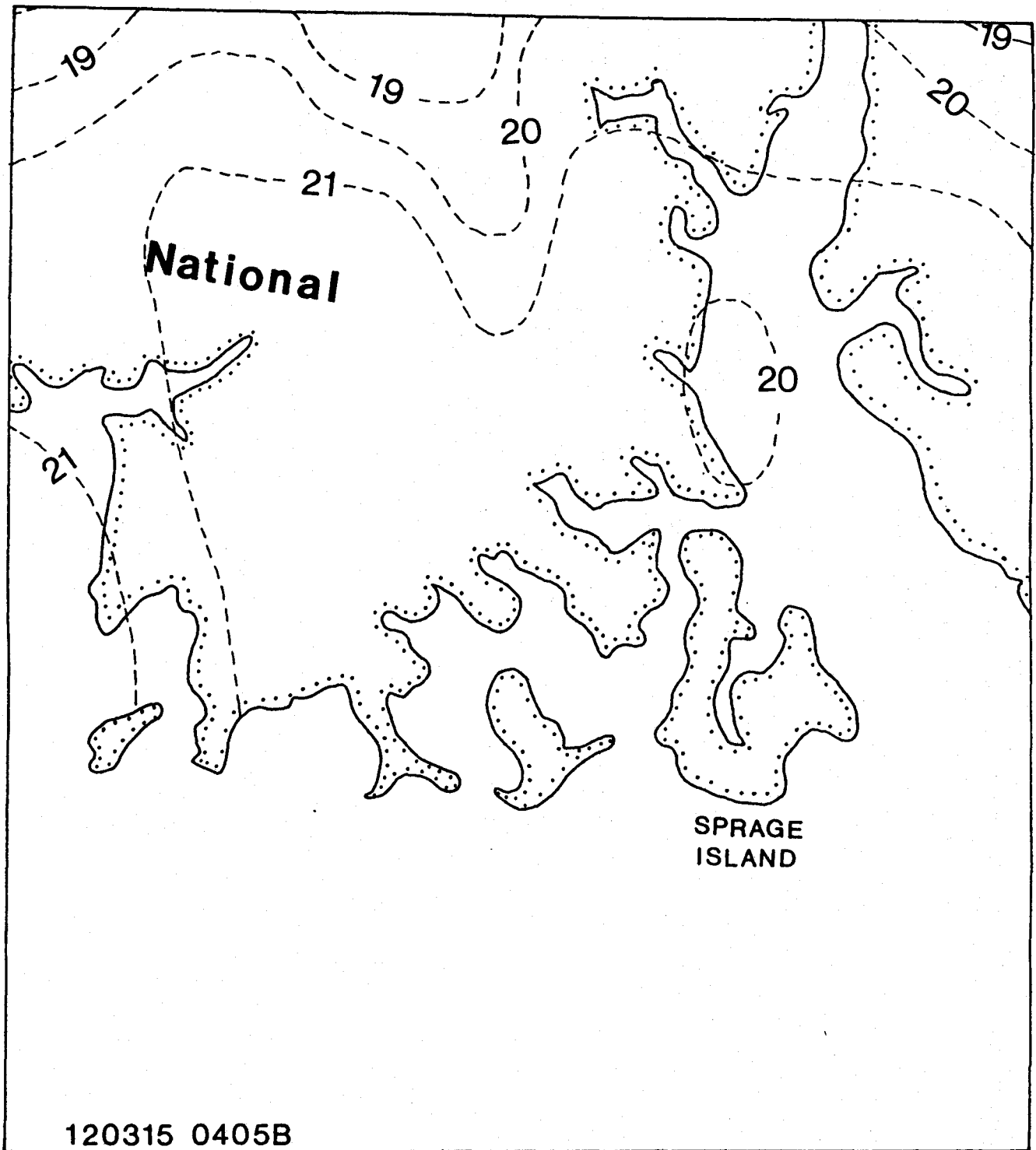


Figure 49 Flood Crest Elevation resulting from the present study for
Panel 120315 0405B

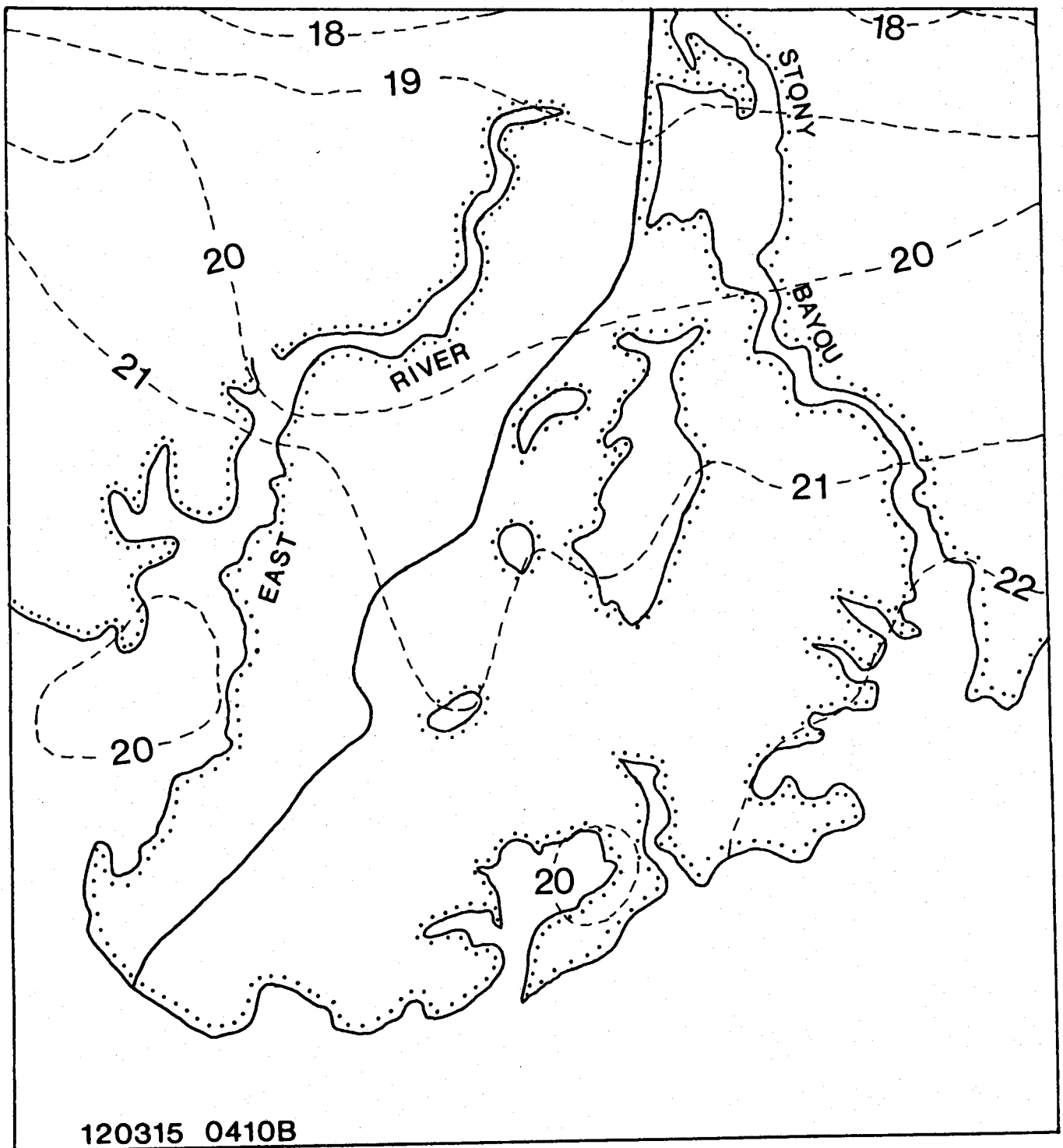


Figure 50 Flood Crest Elevation resulting from the present study for
Panel 120315 0410B

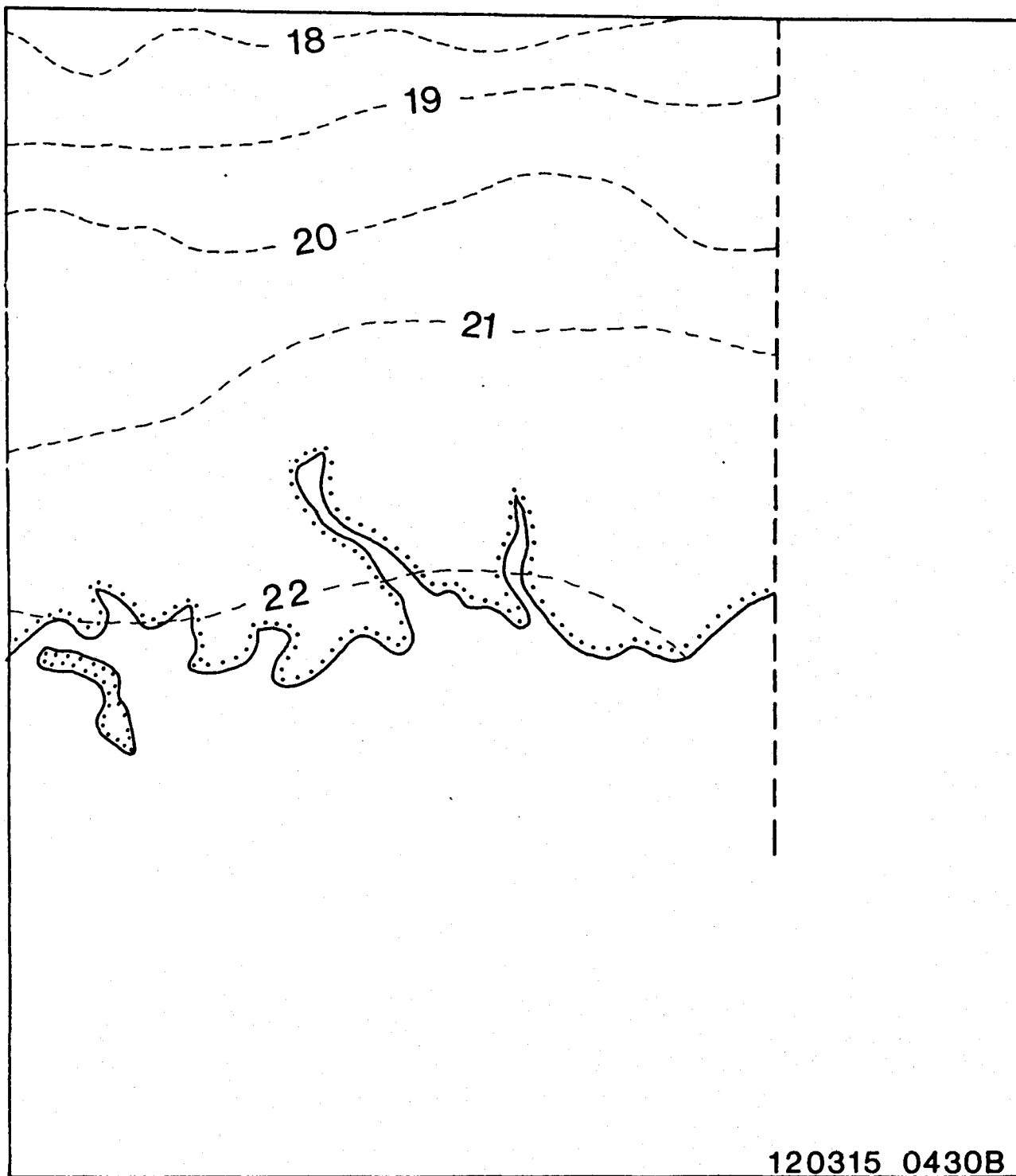


Figure 51 Flood Crest Elevation resulting from the present study for
Panel 120315 0430B

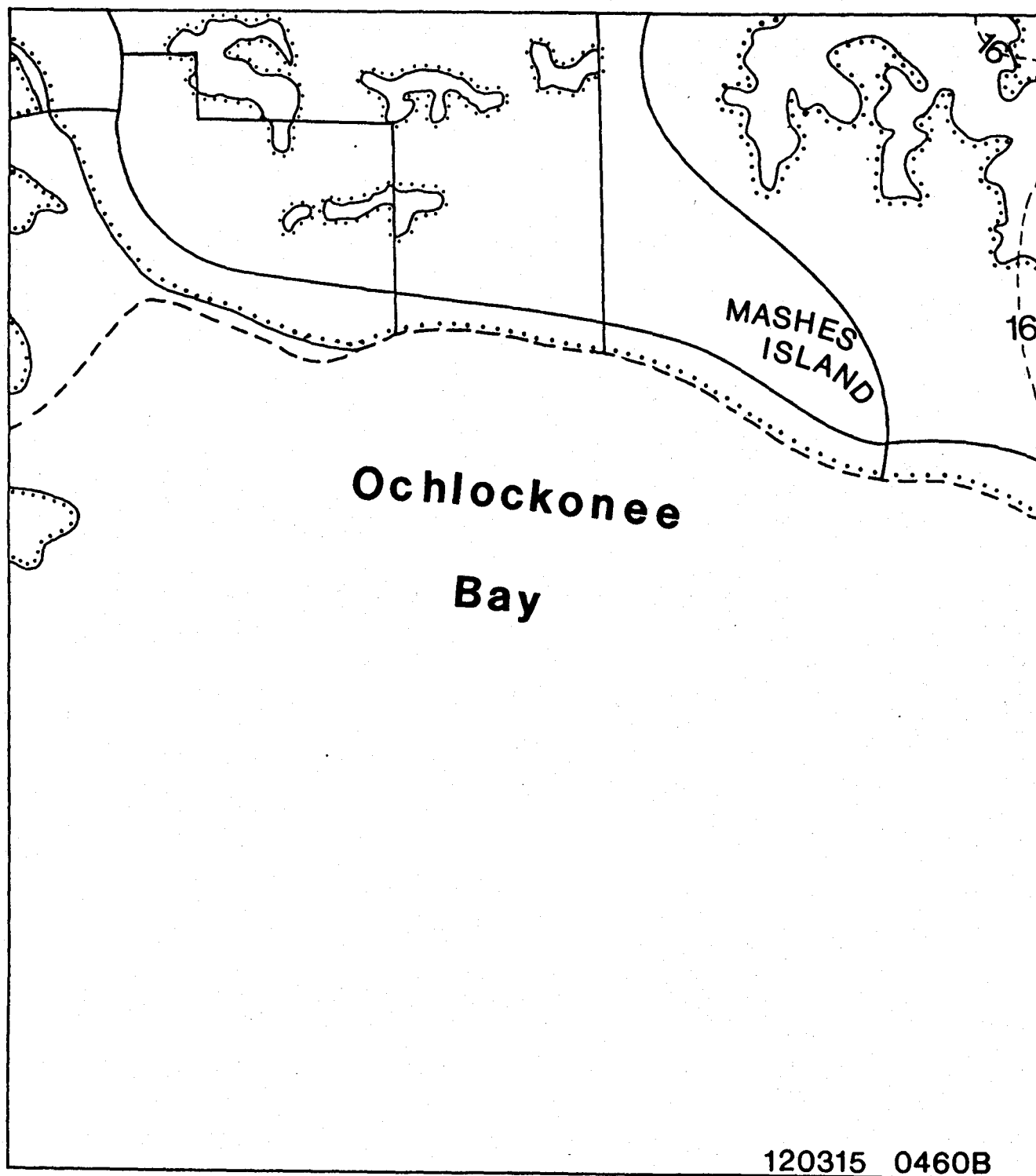


Figure 52 Flood Crest Elevation resulting from the present study for
Panel 120315 0460B

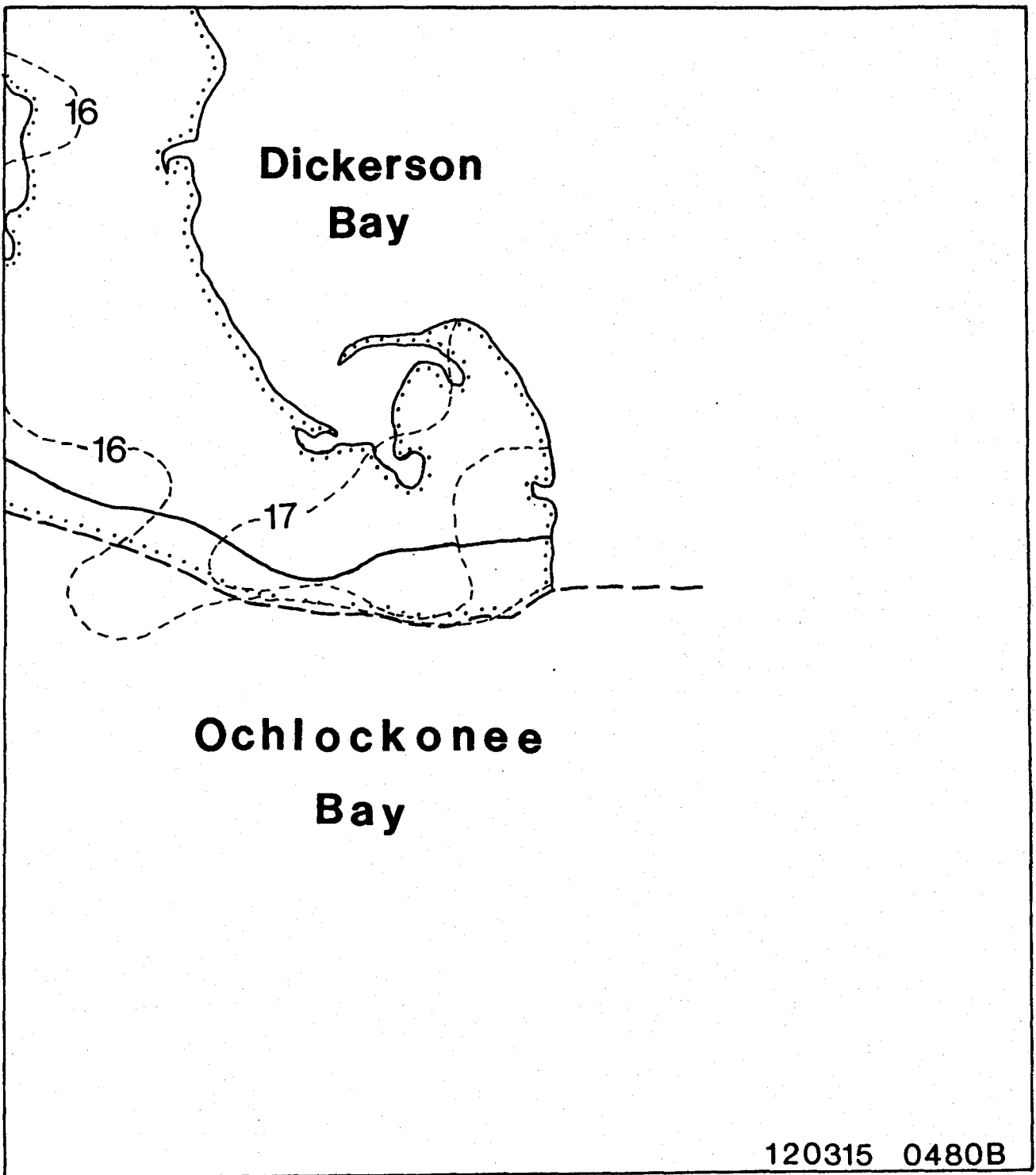


Figure 53 Flood Crest Elevation resulting from the present study for
Panel 120315 0480B

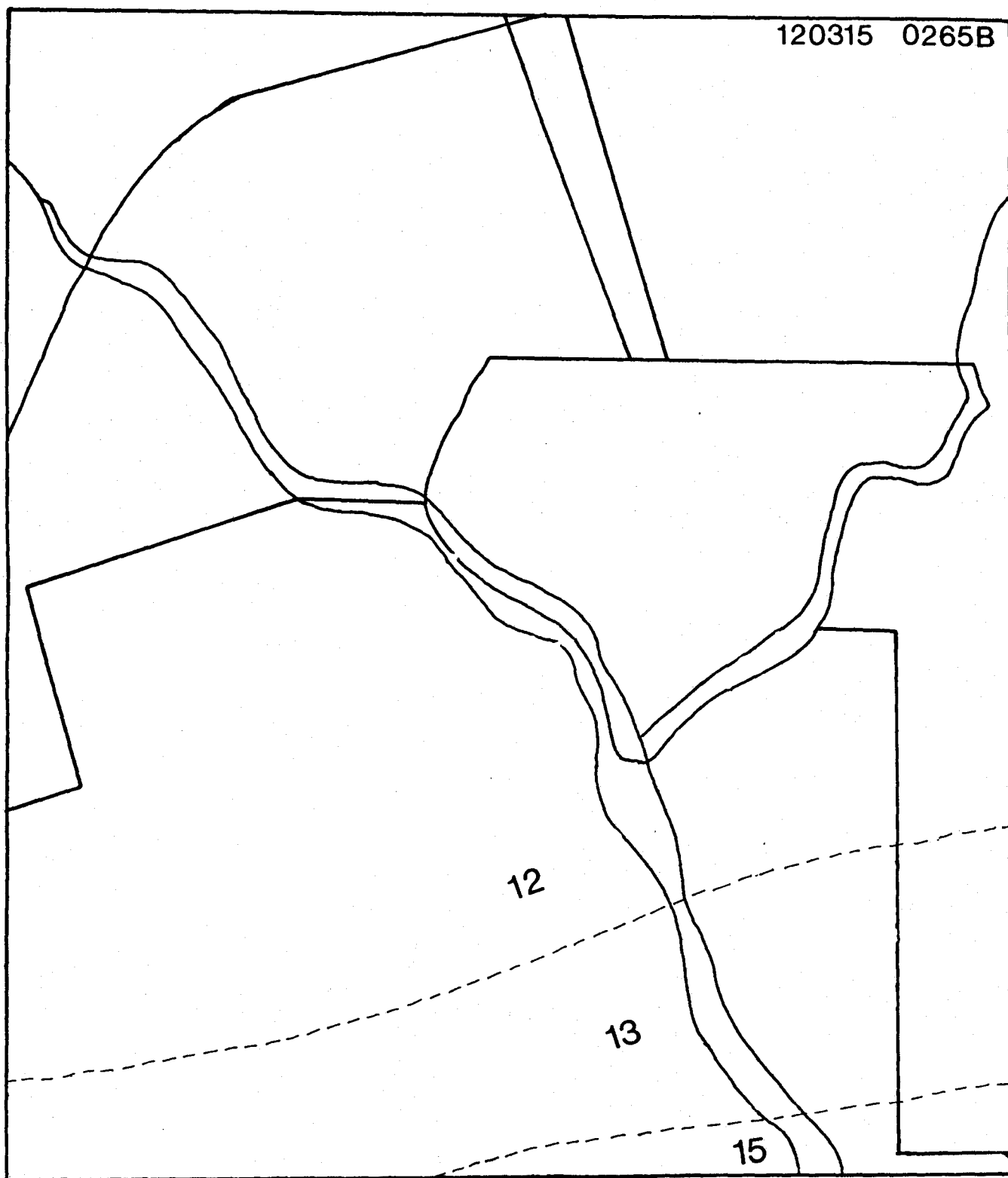


Figure 54 Approximated Flood Elevations determined by FEMA for
Panel 120315 0265B

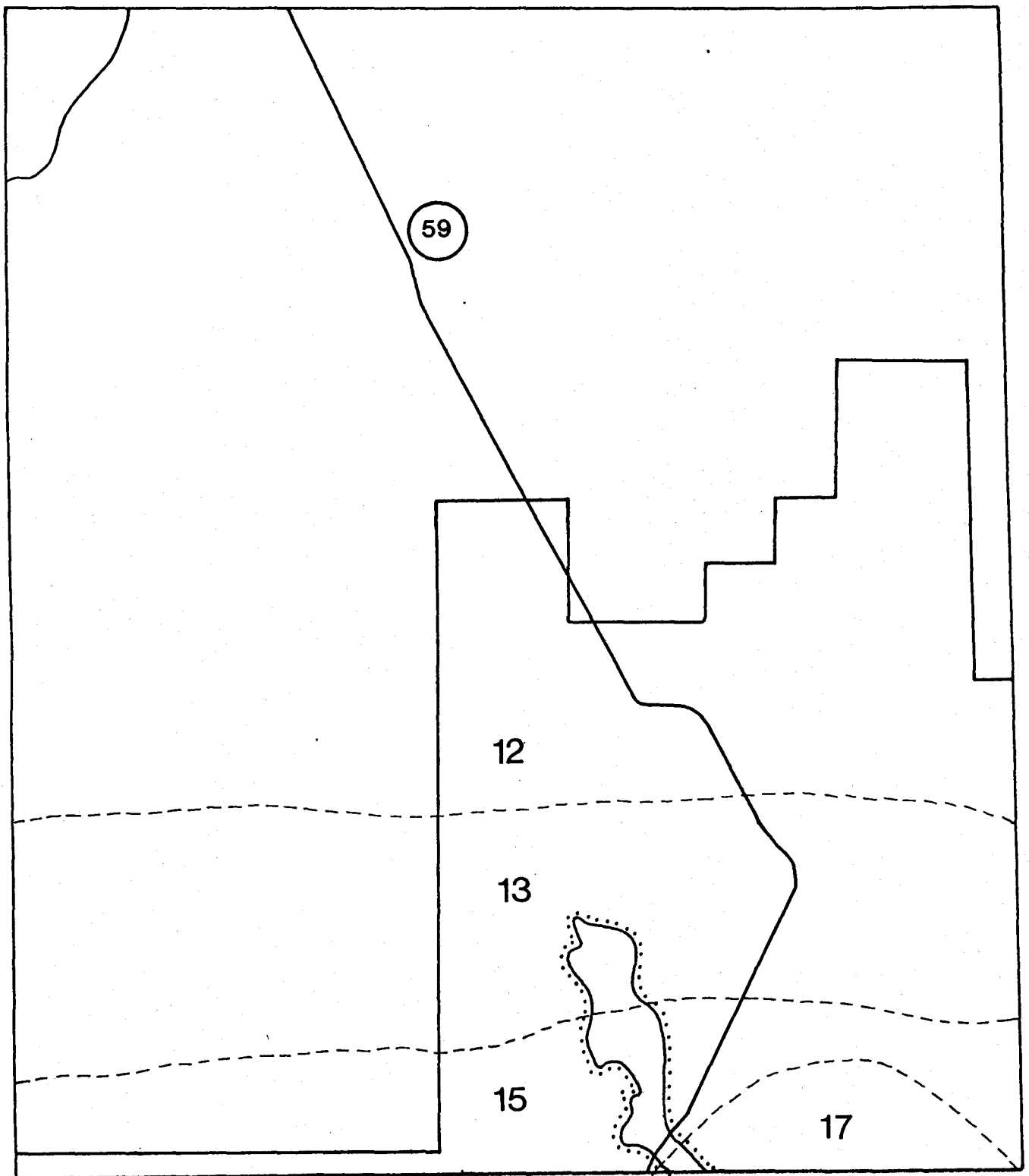


Figure 55 Approximated Flood Elevations determined by FEMA for
Panel 120315 0275B

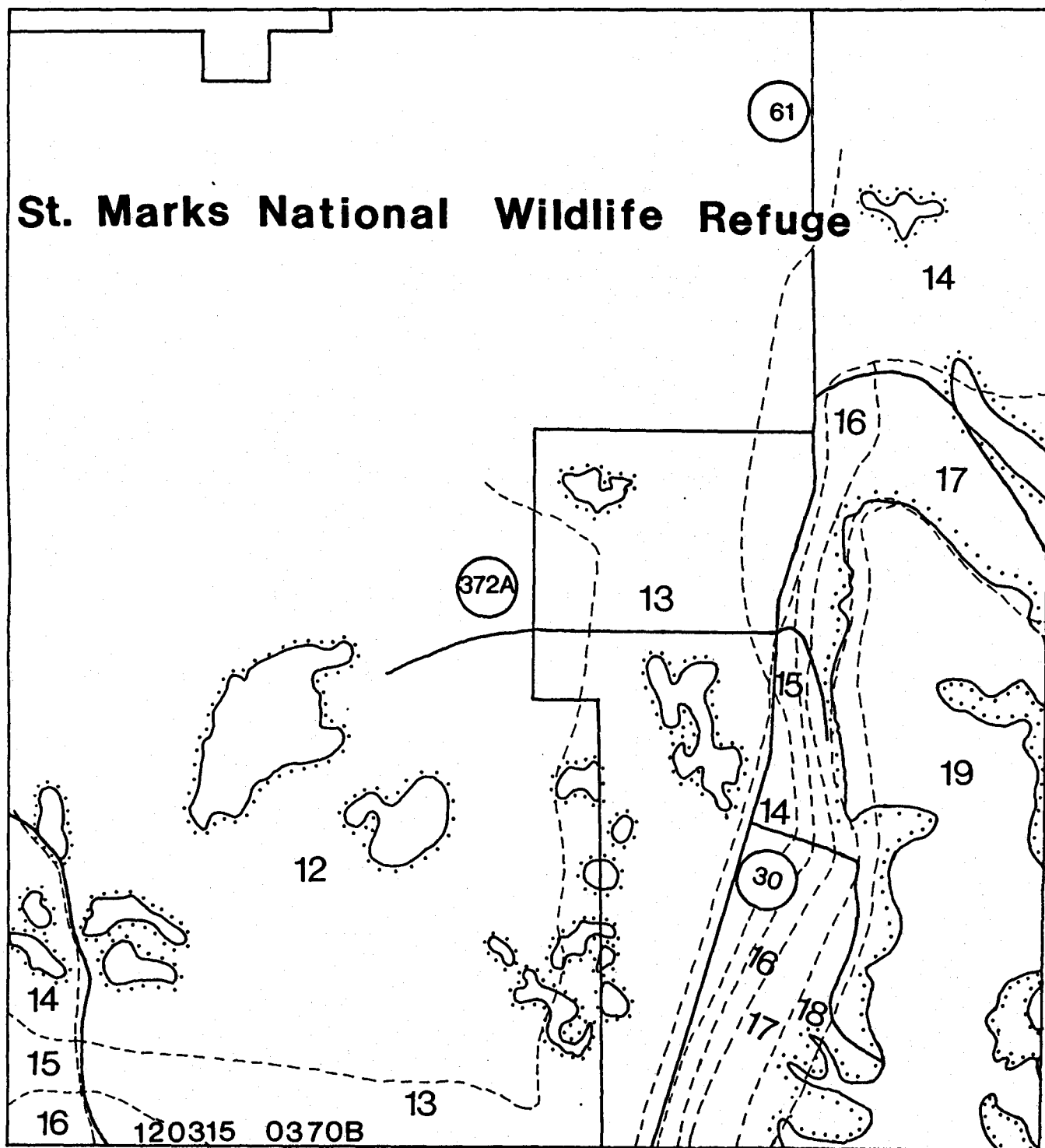


Figure 56 Approximated Flood Elevations determined by FEMA for
Panel 120315 0370B

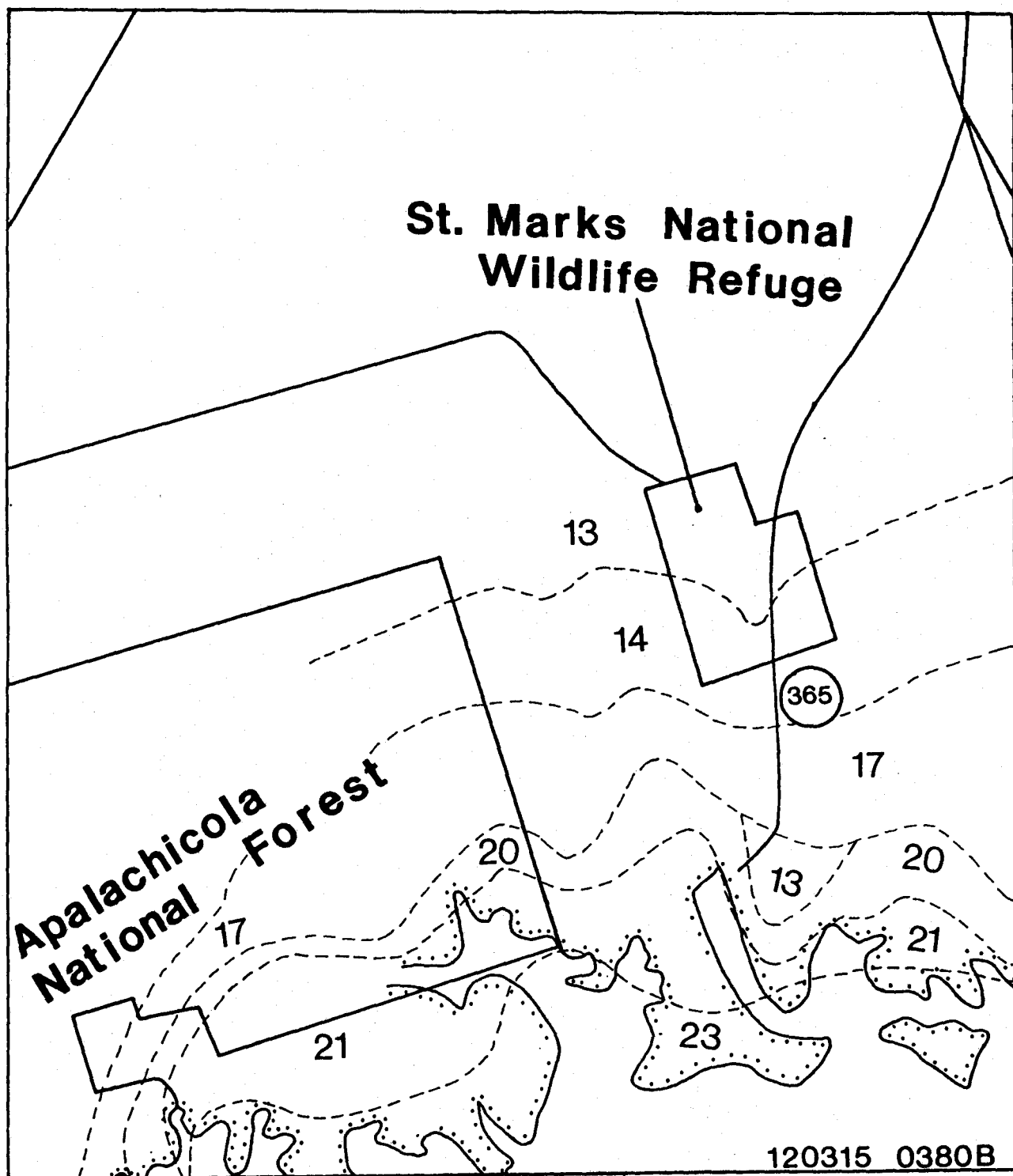


Figure 57 Approximated Flood Elevations determined by FEMA for
Panel 120315 0380B

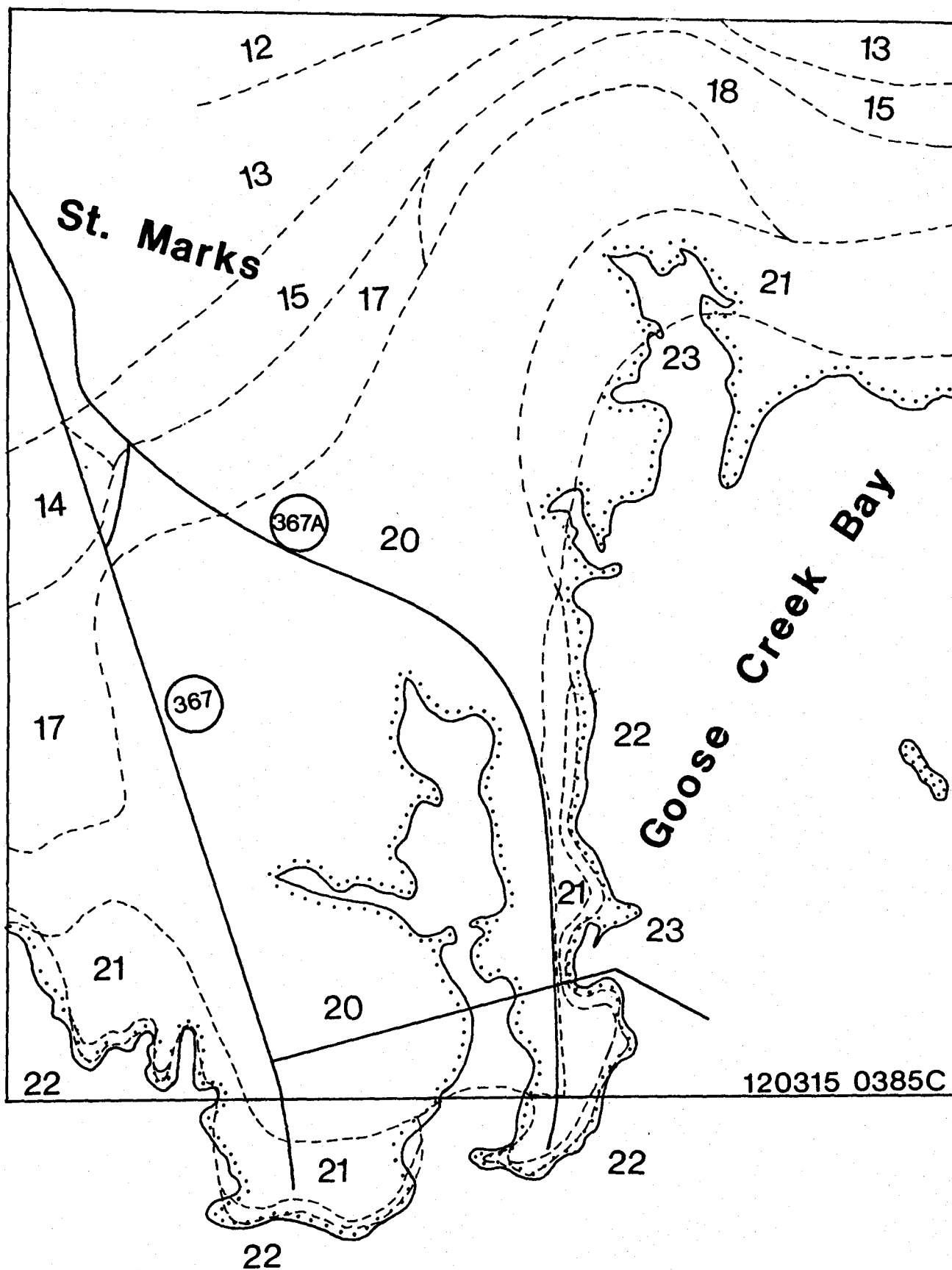


Figure 58 Approximated Flood Elevations determined by FEMA for
Panel 120315 0385C

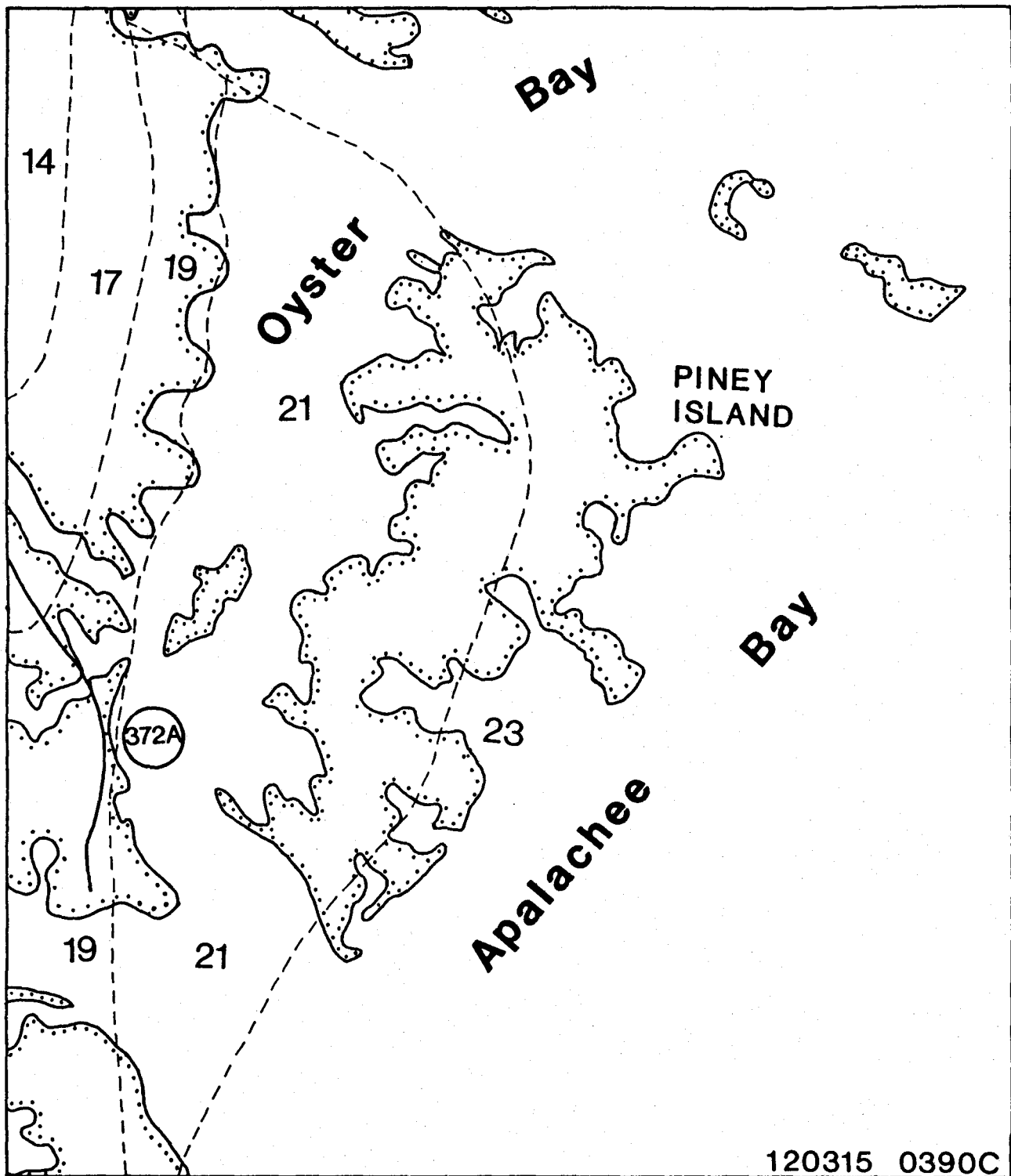


Figure 59 Approximated Flood Elevations determined by FEMA for
Panel 120315 0390C

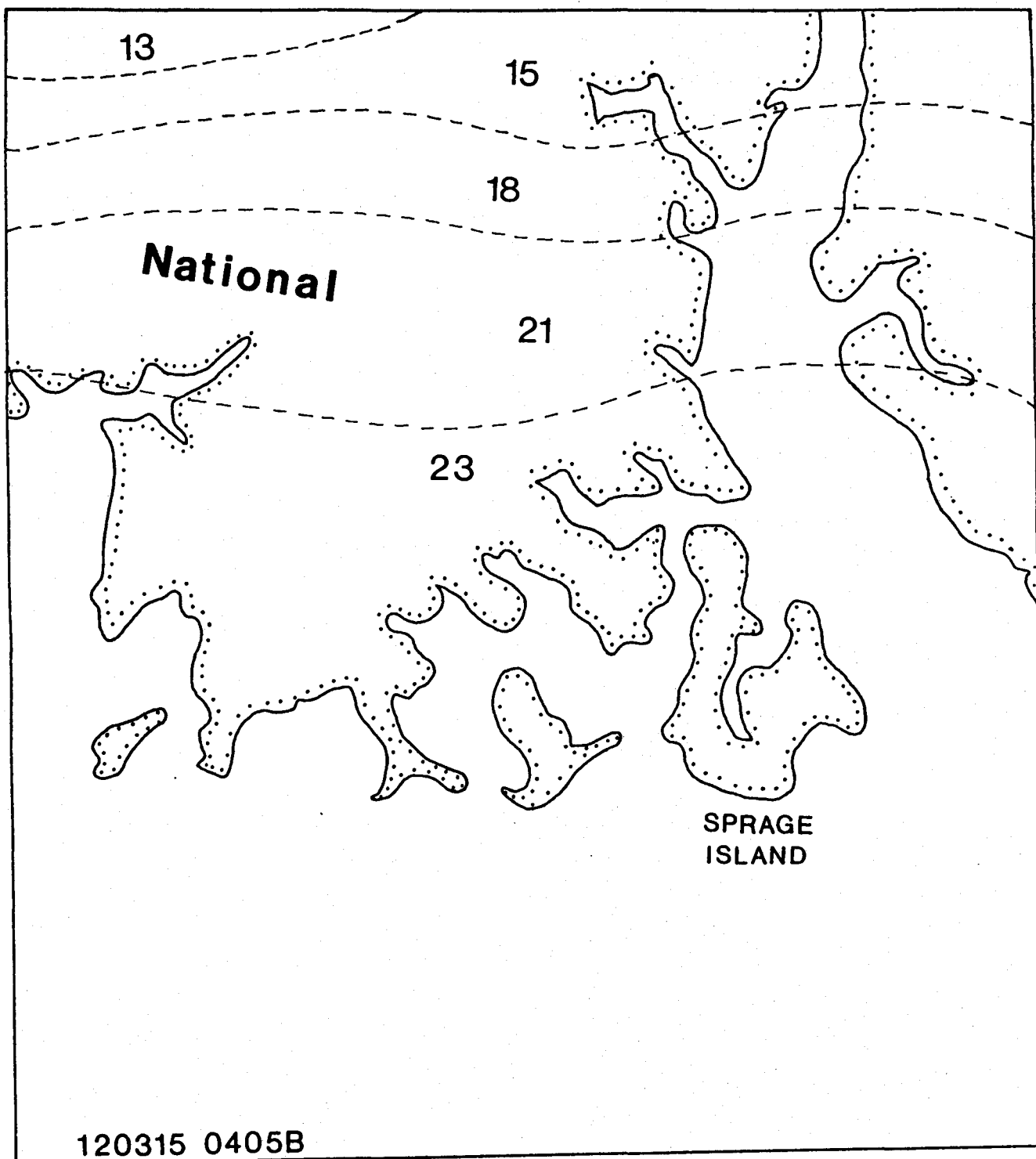


Figure 60 Approximated Flood Elevations determined by FEMA for
Panel 120315 0405B

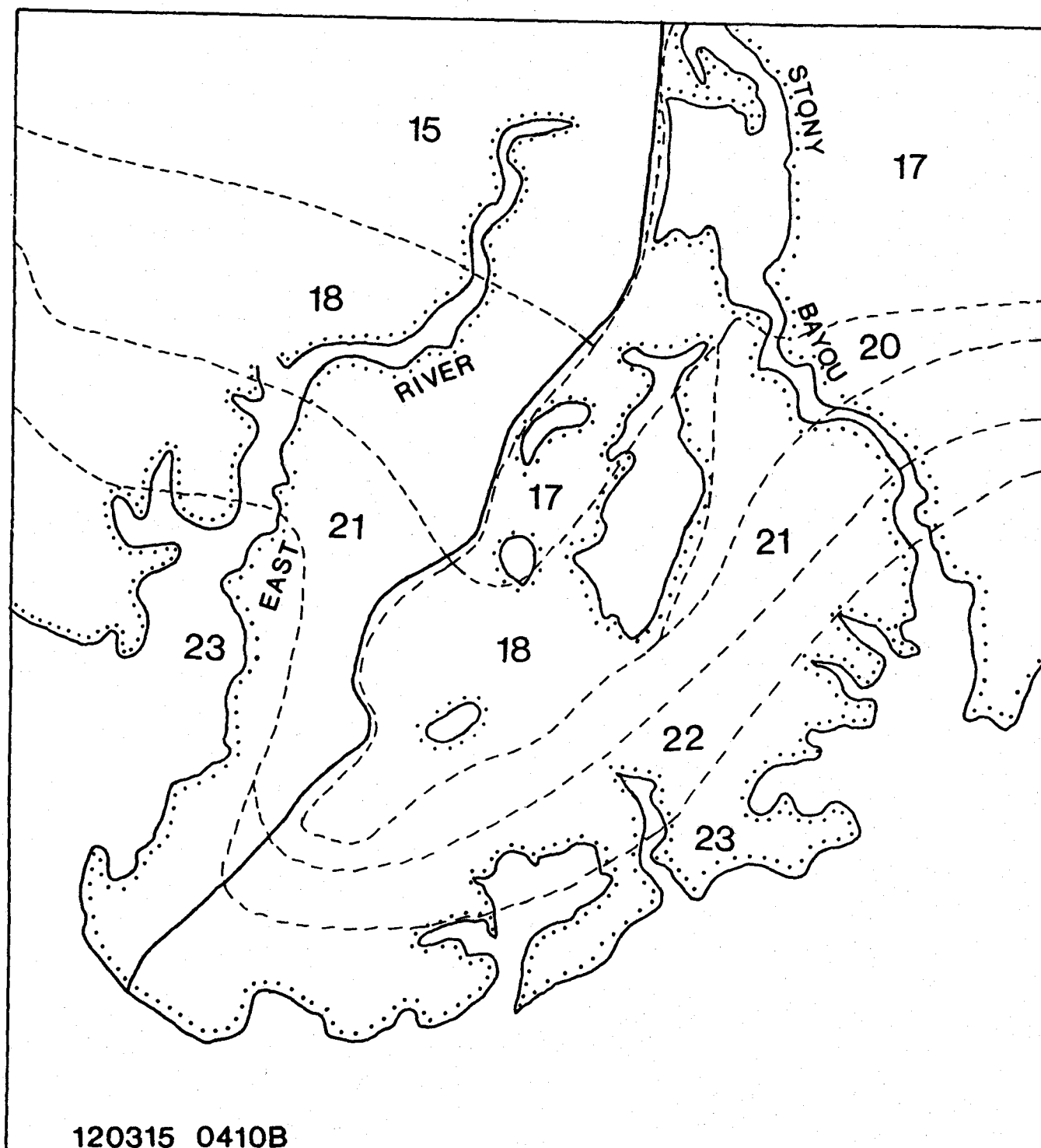


Figure 61 Approximated Flood Elevations determined by FEMA for
Panel 120315 0410B

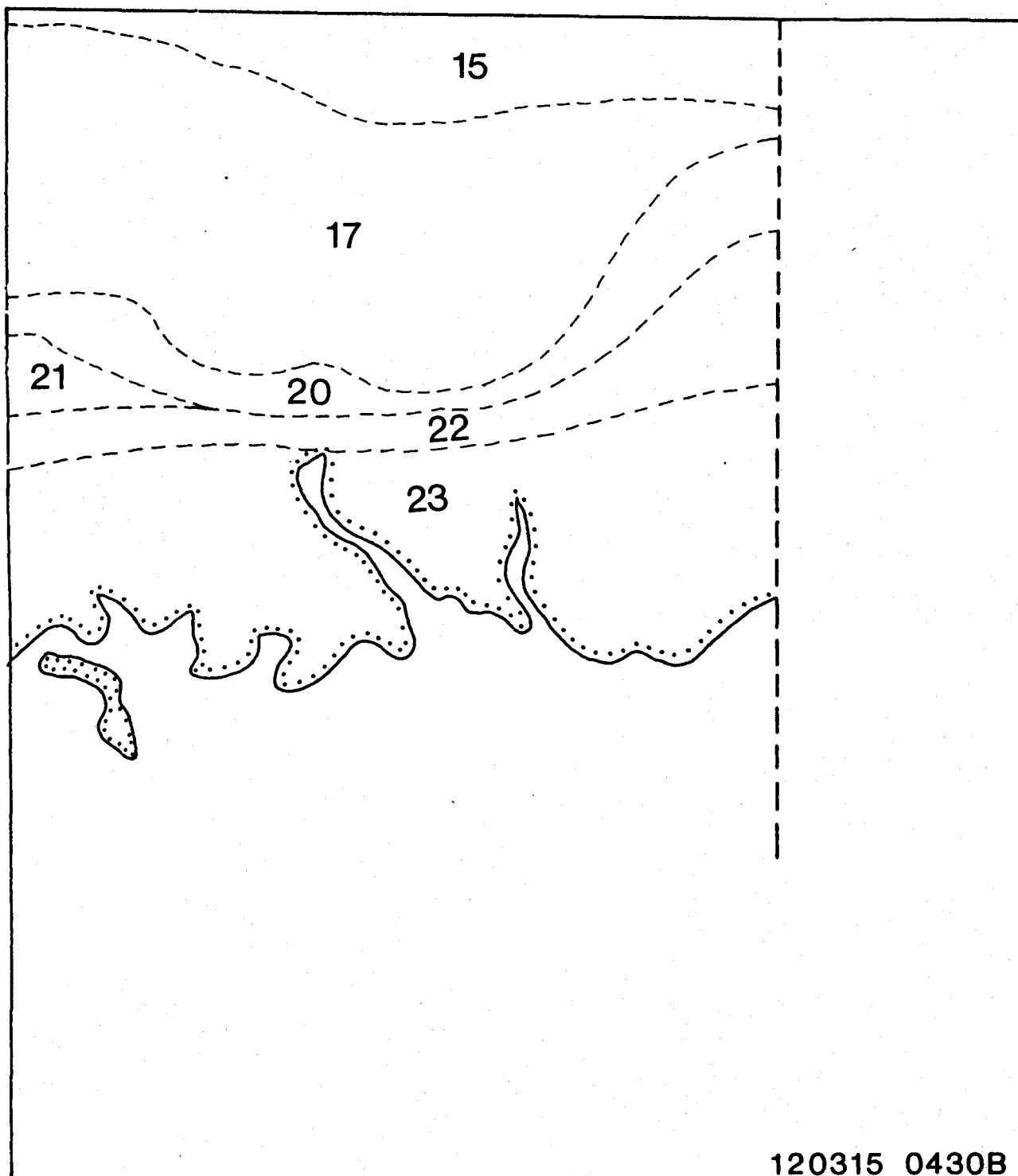


Figure 62 Approximated Flood Elevations determined by FEMA for
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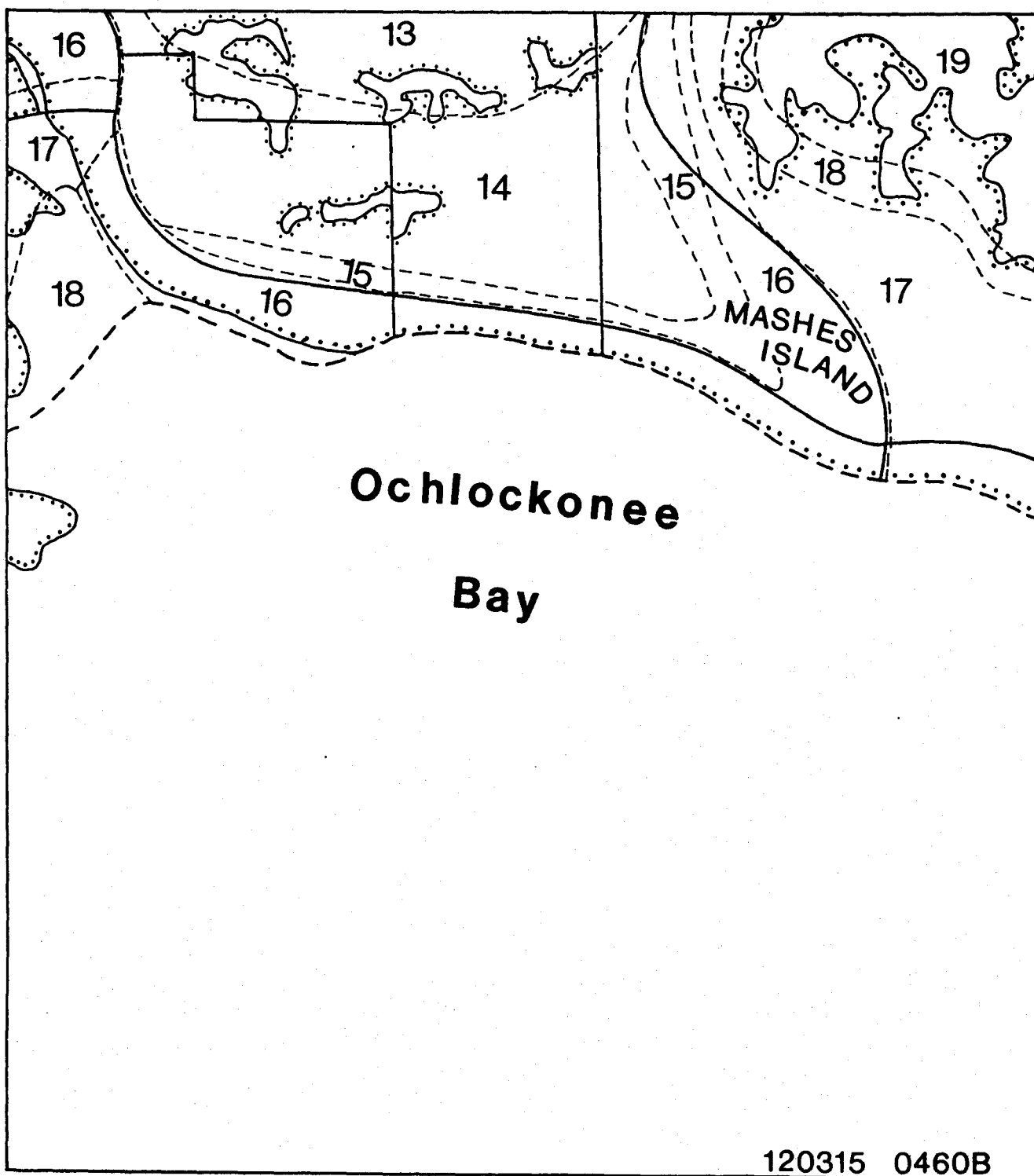


Figure 63 Approximated Flood Elevations determined by FEMA for
Panel 120315 0460B

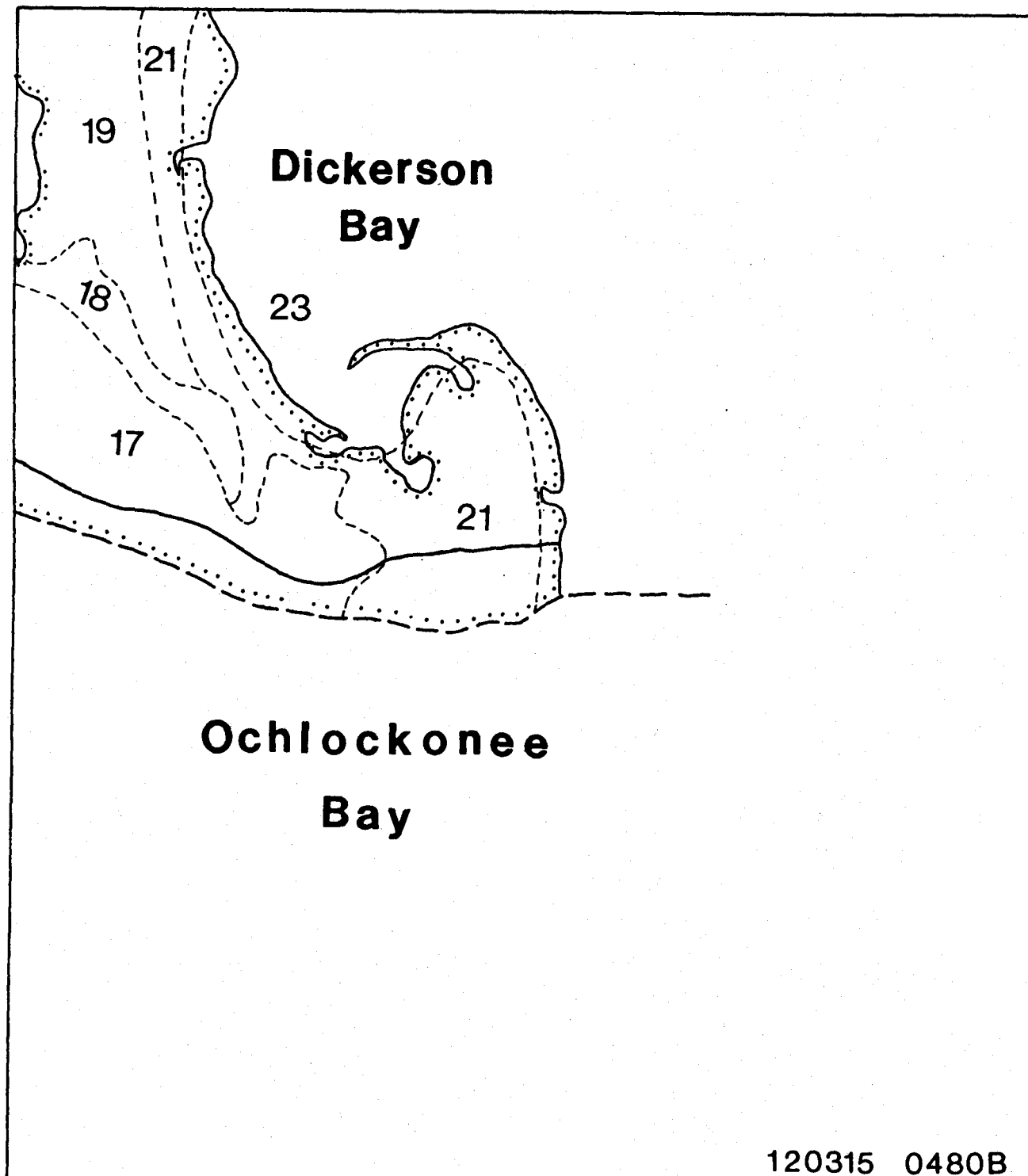


Figure 64 Approximated Flood Elevations determined by FEMA for
Panel 120315 0480B

REFERENCES

1. U. S. Army Corps of Engineers, "National Shoreline Study - Regional Inventory Report," South Atlantic Division, Atlanta, Georgia, August 1971.
2. Federal Emergency Management Agency, "Flood Insurance Study-Wakulla County, Florida-Unincorporated Areas," June 17, 1986.
3. U. S. Department of Commerce, National Oceanic and Atmospheric Administration, "A Tropical Cyclone Data Tape for the North Atlantic Basin, 1886-1977: Contents, Limitations and Uses," NOAA Technical Memorandum NWS HC 6, June 1978.
4. U. S. Department of Commerce, National Oceanic and Atmospheric Administration, "Meteorological Criteria for Standard Project Hurricane and Probable Maximum Hurricane Windfields, Gulf and East Coasts of the United States," NOAA Technical Report NWS 23, September 1979.
5. U. S. Department of Commerce, National Oceanic and Atmospheric Administration, "Tropical Cyclones of the North Atlantic Ocean, 1871-1980," June 1978, Revised July 1981.
6. "Wilson, B. L., "Hurricane Wave Statistics for the Gulf of Mexico," U. S. Army Corps of Engineers, Beach Erosion Board, Technical Memorandum 98, 1956.
7. Committee on Coastal Flooding From Hurricanes, National Research Council, "Evaluation of The FEMA Model for Estimating Potential Coastal Flooding From Hurricanes and Its Application to Lee County, Florida," National Academy Press, Washington, D. C. 1983.
8. Van Dorn, W., "Wind Stress on an Artificial Pond," Journal of Marine Research, Volume 12, No. 3, 1953.
9. Christensen, B. A. and Walton, R., "Friction Factors in Flooding Due to Hurricanes," Proceedings, National Symposium on Urban Stormwater Management in Coastal Area, Blacksburg, Virginia, June 19-20, 1980.
10. Saville, T., "Experimental Determination of Wave Set-Up," Proceedings, Second Technical Conference on Hurricanes, pp. 242-252, 1961.
11. Bowen, A. J., Inman, D. L. and Simmons, V. P., "Wave 'Set-Down and Set-Up'," Journal of Geophysical Research, Volume 73, No. 8, pp. 2569-2577, 1968.
12. Lo, J. M., "Surf Beat: Numerical and Theoretical Analysis," Ph.D. Dissertation, Department of Civil Engineering, University of Delaware, June 1981.
13. U. S. Army Corps of Engineers, "Shore Protection Manual, Volumes I, II and III," U. S. Government Printing Office, 1977.

APPENDIX A

TABLE AI

WAKULLA COUNTY

Landfalling Storms ($99^\circ < \theta_N < 239^\circ$)

#	Date	θ_N (degrees)	Y_F (n.mi.)	V_F (knots)	Δp (in Hg)	R (n.mi.)	Remarks
1	06/18/1886	203.4	26.8	15.3	-1.09*		
2	06/27/1886	220.9	35.0	26.5	-1.09*		
3	07/14/1886	233.7		11.8	-0.85*		
4	09/06/1888	205.3		12.2	-0.18*		
5	10/08/1888	226.1	-124.2	21.6	-0.97*		
6	06/15/1889	225.6		15.7	-0.24*		
7	06/12/1893	225.8	-52.8	22.9	-0.74*		
8	10/01/1894	220.9	33.6	10.6	-1.36*		
9	07/04/1896	180.0	100.2	8.0	-0.97*		
10	09/22/1896	202.2	-74.8	18.4	-1.22*		
11	08/03/1898	127.6	45.6	13.1	-0.64*		
12	07/31/1899	203.4	11.7	4.4	-0.64*		
13	10/02/1899	225.5		24.3	-0.24*		
14	10/08/1900	231.5	-125.0	17.7	-0.18*		
15	09/21/1901	196.1	3.4	12.5	-0.24*		
16	06/10/1902	200.4	-10.3	7.5	-0.24*		
17	09/19/1903	156.6	67.2	8.7	-0.74*	43.0	
18	06/08/1906	180.0	74.1	9.0	-0.31*		
19	09/27/1907	232.4	-118.0	22.9	-0.31*		
20	06/26/1909	125.8	19.2	8.5	-0.18*		
21	08/09/1911	133.9		7.2	-0.74*		
22	08/31/1915	180.0	63.1	15.0	-0.97*		
23	09/13/1924	227.3	115.9	5.9	-0.64*		
24	09/27/1924	219.5	-57.6	27.2	-0.38*		

*Calculated from W_{max}

Continue Table AI

WAKULLA COUNTY

Landfalling Storms ($99^\circ < \theta_N < 239^\circ$)

#	Date	θ_N (degrees)	Y_F (n.mi.)	V_F (knots)	Δp (in Hg)	R (n.mi.)	Remarks
25	09/11/1926	130.9	122.1	4.6	-1.83*	17.0	
26	08/07/1928	154.3	30.2	10.0	-0.31*		
27	09/22/1929	189.8	57.3	5.1	-0.54*	55.0	
28	08/26/1932	130.1		12.4	-0.74*		
29	08/12/1933	185.5	-15.1	9.0	-0.24*		
30	09/05/1933	170.2	-41.2	5.1	-0.31*	29.0	
31	08/29/1935	194.6	-48.7	10.3	-0.85*	6.0	
32	07/27/1936	144.2	100.2	7.4	-1.18	19.0	
33	08/24/1937	115.7	-6.2	11.5	-0.18*		
34	10/23/1938	232.4	-114.7	42.6	-0.24*		
35	08/07/1939	120.2	54.2	8.0	-0.74*		
36	10/03/1941	175.5	25.0	11.0	-0.85*	18.0	
37	10/15/1941	229.1		4.6	-0.24*		
38	06/20/1945	220.9		13.2	-0.64*		
39	09/07/1947	129.5		7.9	-0.24*		
40	09/20/1947	196.1	-98.1	18.7	-1.30		
41	10/18/1950 (Love)	173.0	-60.4	7.1	-0.18*	6.0	
42	05/25/1953 (Alice)	180.0	84.4	6.0	-0.24*		
43	06/08/1957	227.3	0.0	23.6	-0.18*		
44	07/28/1960 (Brenda)	215.8	-94.7	14.8	-0.18*		
45	06/02/1964	235.3		15.8	-0.14*		
46	06/04/1966 (Alma)	215.8	4.8	7.4	-0.95	23.0	

*Calculated from W_{max}

Continue Table AI

WAKULLA COUNTY

Landfalling Storms ($99^\circ < \theta_N < 239^\circ$)

#	Date	θ_N (degrees)	Y_F (n.mi.)	V_F (knots)	Δp (in Hg)	R (n.mi.)	Remarks
47	09/29/1969	180.0	121.4	15.0	-0.50		
48	07/19/1970 (Becky)	190.9	47.0	18.3	-0.12		
49	06/14/1972 (Agnes)	201.0	68.3	9.6	-0.89	20.0	
50	05/21/1976	235.3	-48.0	21.1	-0.45		
51	08/28/1985 (Elena)	117.7		10.8	-1.75		
52	11/15/1985 (Kate)	220.9	66.2	13.2	-1.36		

*Calculated from W_{max}

TABLE AII

WAKULLA COUNTY

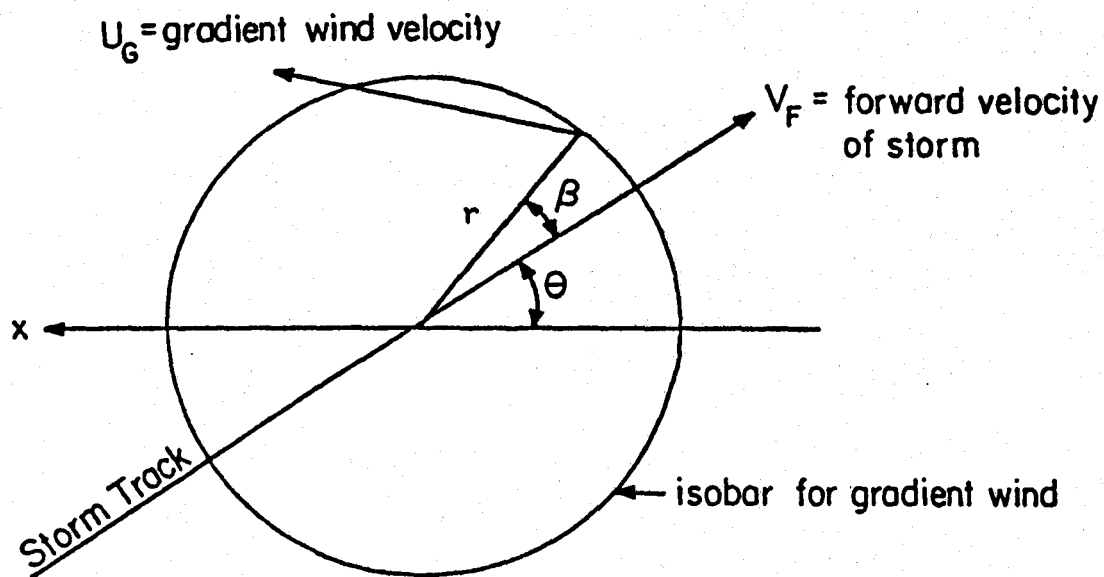
Alongshore Storms ($59^\circ \leq \theta_N \leq 99^\circ$)
 ($239^\circ \leq \theta_N \leq 279^\circ$)

#	Date	θ_N (degrees)	Y_F (n.mi.)	V_F (knots)	Δp (in Hg)	R (n.mi.)	Remarks
1	06/24/1907	249.7	12.3	23.1	-0.38*		
2	09/25/1920	241.0	66.5	24.7	-0.64*		
3	09/09/1932	243.3	32.9	22.3	-0.31*		
4	09/16/1937	242.8	23.3	8.8	-0.18*		
5	09/14/1953	254.8	20.6	15.2	-0.38*		

*Calculated from $W_{\max}$

APPENDIX B

The idealized hurricane model moving at a constant speed V_F at an angle, θ' , with respect to the x-axis of the grid system is shown below. The gradient



wind speed, U_G (wind speed at 30 ft. above water surface), is calculated by

$$U_G = U_c (\sqrt{\gamma^2 + 1} - \gamma) \cdot (0.83)$$

where

$$\gamma = \frac{1}{2} \left(\frac{V'}{U_c} + \frac{U_c}{U_g} \right)$$

and

$$U_c = \sqrt{\frac{\Delta p}{\rho_a} \frac{R}{r} e^{-R/r}}$$

$$U_g = \frac{\frac{\Delta p}{\rho_a} \frac{R}{r^2} e^{-R/r}}{2\omega(\sin \phi)}$$

$2\omega (\sin \phi) =$ coriolis effect

$\omega =$ earth rotation

$\phi =$ latitude

$R =$ radius to maximum winds

$V' = V_F \sin \beta$

$\beta =$ angle between observer and hurricane direction

$V_F =$ constant translational speed of hurricane

$\rho_a =$ mass density of air

$r =$ distance from hurricane center to observer

$U_g =$ geostrophic velocity component

$U_c =$ cyclostrophic velocity component.

The factor of 0.83 was applied to the calculation of U_g to take into account friction effects at 30 feet above the water surface.