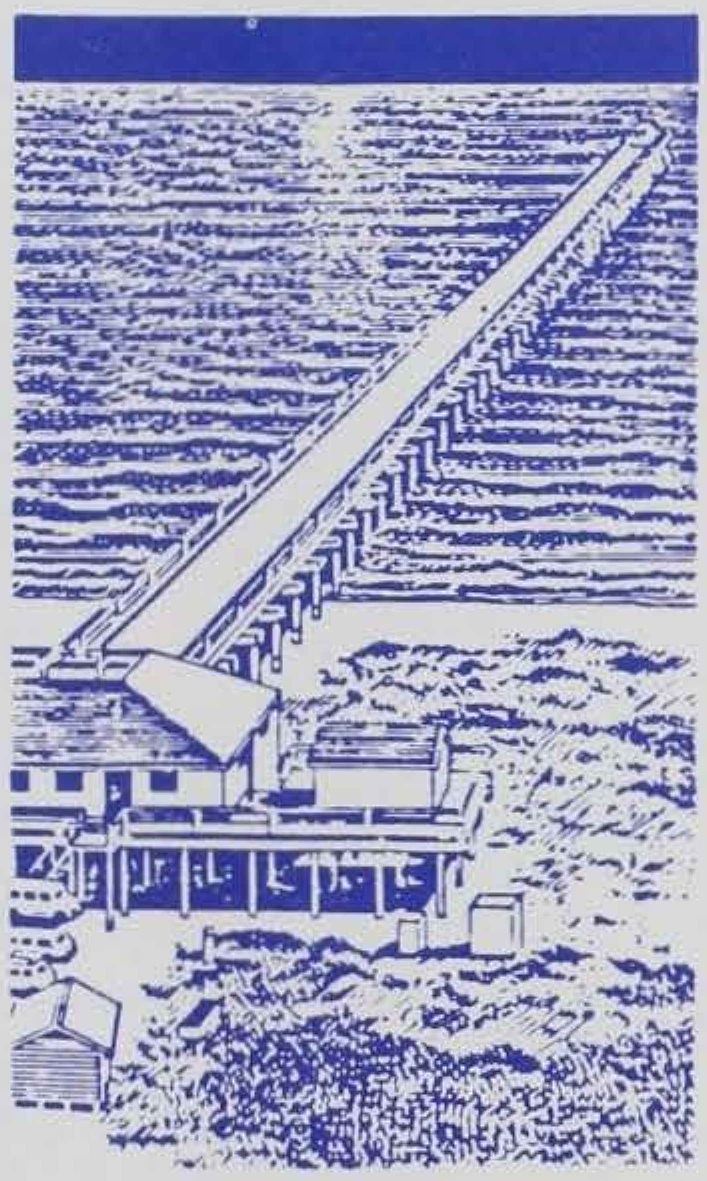
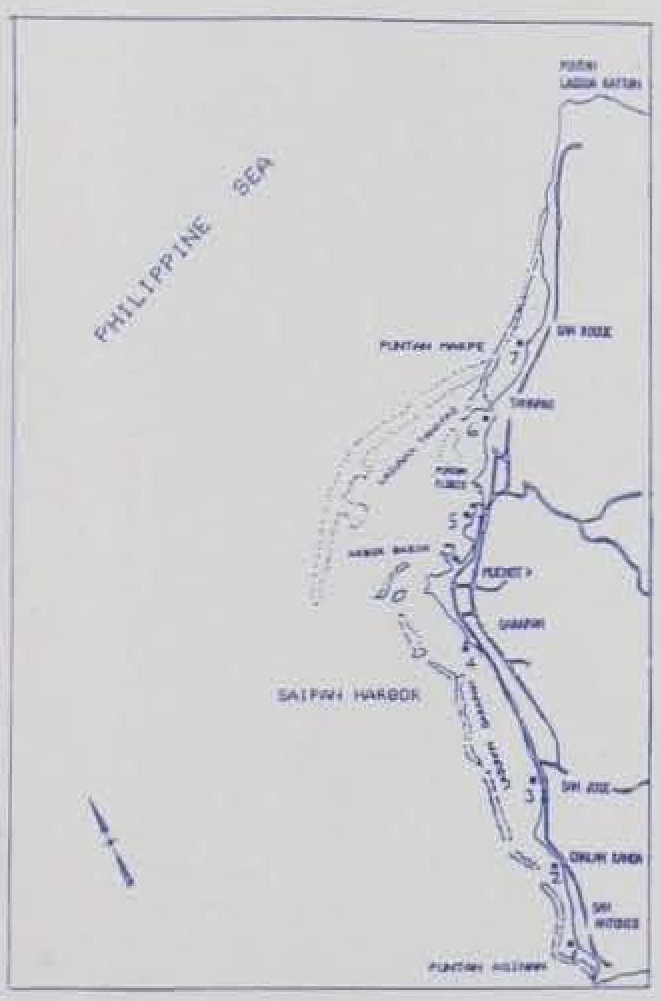




MISCELLANEOUS PAPER CERC-89-12

TYPHOON WATER SURFACE ANALYSIS FOR WEST COAST OF SAIPAN MARIANA ISLANDS

by

Lucia W. Chou

Coastai Engineering Research Center

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

September 1989

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for US Army Engineer Division, Pacific Ocean
Fort Shafter, Hawaii 96858-5440

Under Intra-Army Order No. E86880005

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): Miscellaneous Paper CERC-89-12	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: USAEWES, Coastal Engineering Research Center; 6b. OFFICE SYMBOL (If applicable): WESCR-P	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code): 3909 Halls Ferry Road, Vicksburg, MS 39180-6199	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: US Army Engineer Division, Pacific Ocean; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Intra-Army Order No. E86880005
8c. ADDRESS (City, State, and ZIP Code): Ft. Shafter, HI 96858-5440	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Typhoon Water Surface Analysis for the West Coast of Saipan, Mariana Islands

12. PERSONAL AUTHOR(S)
Chou, Lucia W.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final report	FROM Dec 1987 TO Jul 1988	September 1989	55

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Coastal flooding; Storm surge; Stage-frequency; Wave setup

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The Coastal Engineering Research Center of the US Army Engineer Waterways Experiment Station (WES) was requested by the US Army Engineer Division, Pacific Ocean (POD) to conduct a Typhoon Water Surface Analysis for the Flood Insurance Study of Saipan, Commonwealth of the Northern Mariana Islands. A comprehensive investigation to determine the frequency of occurrence of typhoon-induced flood elevations for the west coast of Saipan was performed. Since Saipan is located within the region subjected to typhoons similar to those considered in a previous stage-frequency analysis for Agana Bay, Guam, the synthetic typhoon ensemble used in that study was utilized in this investigation. The surge time-histories of the storms were computed using the WES Implicit Flooding Model (WIFM). Deepwater wave conditions associated with each storm were calculated using a wave hindcast model. Predicted still water levels (swl) were calculated by combining surge and astronomical tide time-histories, and the ponding water levels caused by deepwater wave

(Continued)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. ABSTRACT (Continued).

breaking on and over the reef. Wave setup for each storm was estimated using procedures presented in the Shore Protection Manual (SPM 1984). Stage-frequency relationships were established using the probability of occurrence of each storm event in the ensemble and the maximum swl generated by the storm.

PREFACE

The study reported herein was authorized by Intra-Army Order No. E86880005 dated 3 December 1987 from the US Army Engineer Division, Pacific Ocean (POD), for the purpose of conducting a Typhoon Water Surface Analysis for the Flood Insurance Study of Saipan, Commonwealth of the Northern Mariana Islands.

This investigation was performed during the period December 1987 through July 1988 by personnel of the Coastal Processes Branch (CR-P), Research Division (CR), Coastal Engineering Research Center (CERC), of the US Army Engineer Waterways Experiment Station (WES). The study was conducted under the general supervision of Dr. James R. Houston, Chief, CERC; Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC; Mr. H. Lee Butler, Chief, CR; and Mr. Bruce A. Ebersole, Chief, CR-P. Ms. Lucia W. Chou, Mathematician, CR-P, performed the investigations described herein and prepared this report. Messrs. William Chang and Henry Nakashima were the POD Technical Monitors during the preparation and publication of this report.

COL Larry B. Fulton, EN, is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

CONTENTS

	Page
PREFACE	1
LIST OF TABLES	3
LIST OF FIGURES	3
CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT	4
PART I: INTRODUCTION	5
Description of the Study Area	5
Purpose of the Study	5
Overview of the Project Technique	8
Report Organization	10
PART II: STORM SELECTION AND ASSIGNMENT OF PROBABILITY	11
Joint Probability Method	11
Review of the Typhoon Analysis Study for Agana Bay, Guam	12
Adapting the Guam Typhoon Ensemble ar l Results to the Present Study	17
PART III: DEEP WATER WAVE SIMULATION	21
Wind Field Generation	21
Description of the Wave Model	23
PART IV: STORM SURGE SIMULATION	25
Storm Surge Model	25
Numerical Grid Generation	25
Model Calibration and Verification	28
Simulation of the Events Ensemble	28
Part V: ESTIMATION OF WAVE-INDUCED PONDING AND SETUP	35
Overview of the Ponding Level Technique	35
Estimation of Wave Setup	37
PART VI: COMBINING SURGE, TIDE, AND WAVE EFFECTS TIME HISTORIES	39
PART VII. STAGE-FREQUENCY CURVES	40
PART VIII: SUMMARY	49
REFERENCES	50

LIST OF TABLES

No.		Page
1	Joint Probability Method (JPM) Parameter Statistics, West Coast of Saipan	19
2	Range of Conditions Tested by Seelig (1983)	36
3	Ponding Water Level Coefficients	36
4	Return Periods for Total Water Level and Wave Setup West Coast of Saipan	48

LIST OF FIGURES

1	Location of the study area	6
2	Study area vicinity	7
3	Flow chart of the project technique	9
4	Probability distribution of central pressure deficit	14
5	Probability distribution of forward speed	15
6	Probability distribution of radius to maximum wind	16
7	Probability distribution of landfall point	18
8	Location of landfall points	20
9	Numerical grid for the storm surge model, WIFM	27
10	Wind field and isovels, design storm no. 29, hour 9	30
11	Wind field and isovels, design storm no. 29, hour 10	31
12	Wind field and isovels, design storm no. 29, hour 11	32
13	Surge elevations at gages 1-4	33
14	Surge elevations at gages 5-7	34
15	Stage-frequency curve for gage 1	41
16	Stage-frequency curve for gage 2	42
17	Stage-frequency curve for gage 3	43
18	Stage-frequency curve for gage 4	44
19	Stage-frequency curve for gage 5	45
20	Stage-frequency curve for gage 6	46
21	Stage-frequency curve for gage 7	47

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
knots (international)	0.5144444	metres per second
miles (US nautical)	1.852	kilometres
square miles	2.589998	square kilometres

TYPHOON WATER SURFACE ANALYSIS FOR THE WEST COAST OF SAIPAN, MARIANA ISLANDS

PART I: INTRODUCTION

Description of the Study Area

1. Saipan is the second largest island in the Mariana Islands, which are located in the western Pacific Ocean. It lies about 120 n.m.* northeast of Guam, 1600 n.m. east of Luzon Island in the Philippines, and about that same distance southeast of Tokyo (Figure 1). The island is approximately 14 miles in length. The widest point of the island is approximately 6.5 miles across and the narrowest point is about 1.5 mile wide. The total area of Saipan is approximately 48 square miles.

2. The fringe coral reef along the west coast of Saipan (Figure 2), from Puntan Makpe to the Puntan Aginan, divides the body of water into shallow onshore and deep water offshore segments. The shallow reef flat, varying in width from 500 to 12,000 ft, has water depths that range from 1 to 11 ft relative to the mean lower low water (MLLW) datum. The Arbor Basin is located almost in the middle of the reef flat at its widest point and divides the reef flat into two parts, Lagunan Tanapag to the north and Lagunan Garapan to the south. Water depths, seaward of the reef of Lagunan Tanapag, rapidly increase to over 2,400 ft approximately 12,500 ft offshore. Saipan Harbor, located on the southwest coast of Saipan, is immediately offshore of the reef of Lagunan Garapan. Depths in Saipan Harbor vary from 60 to 600 ft. It is one of the most flourishing harbors in the Mariana Island chain.

Purpose of the Study

3. The purpose of this study is to determine the frequency of flood levels along the west coast of Saipan that are caused by the combined effects of astronomical tide and typhoon-induced water level changes. Results of this study are stage-frequency relationships for the seven locations labeled 1 through 7 in Figure 2. Stage-frequency curves relate the elevations of flood waters to the average waiting time between floods of equal or greater severity. The ordinate of these curves is typically stage measure in feet

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

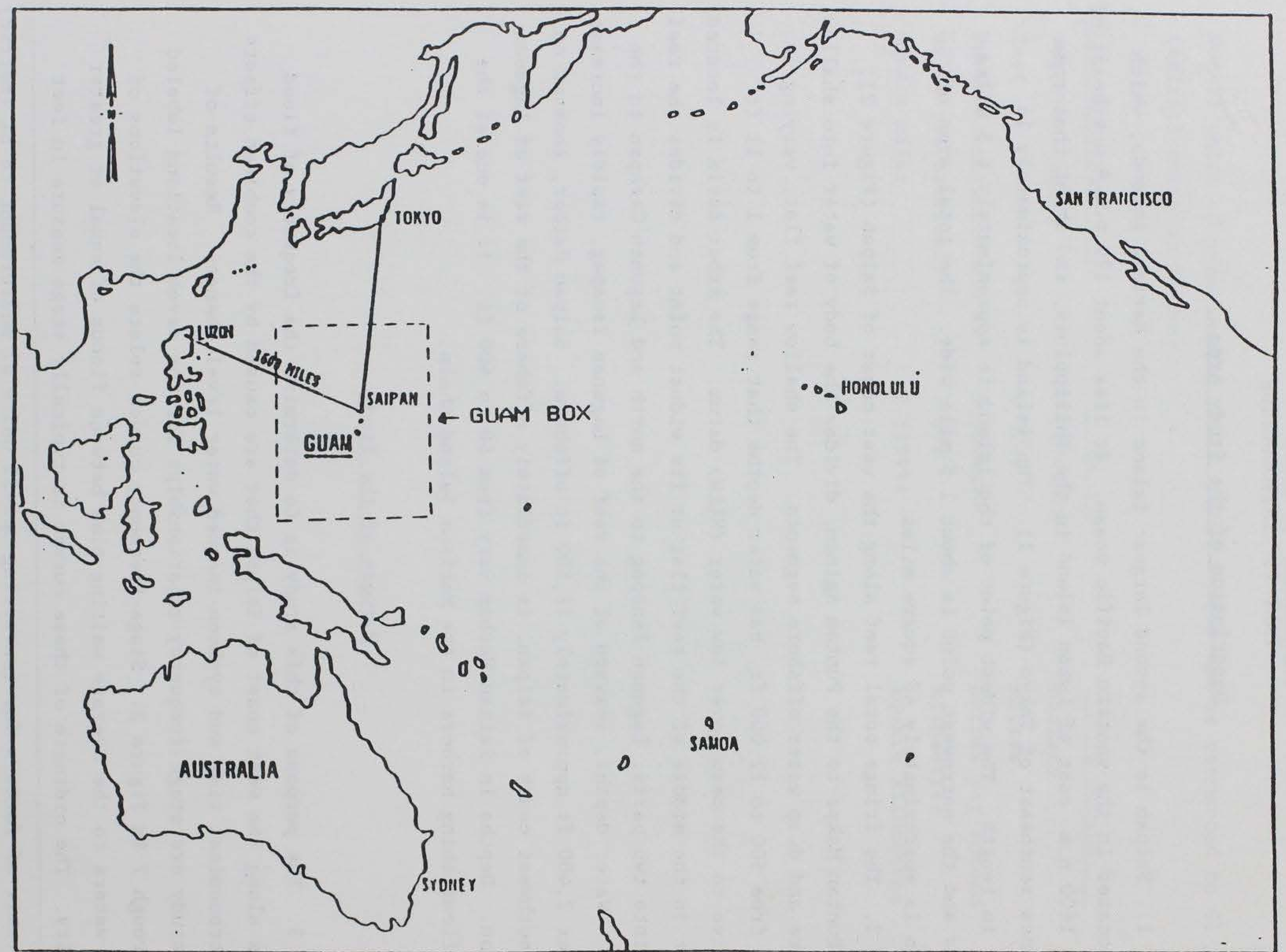


Figure 1. Location of the study area

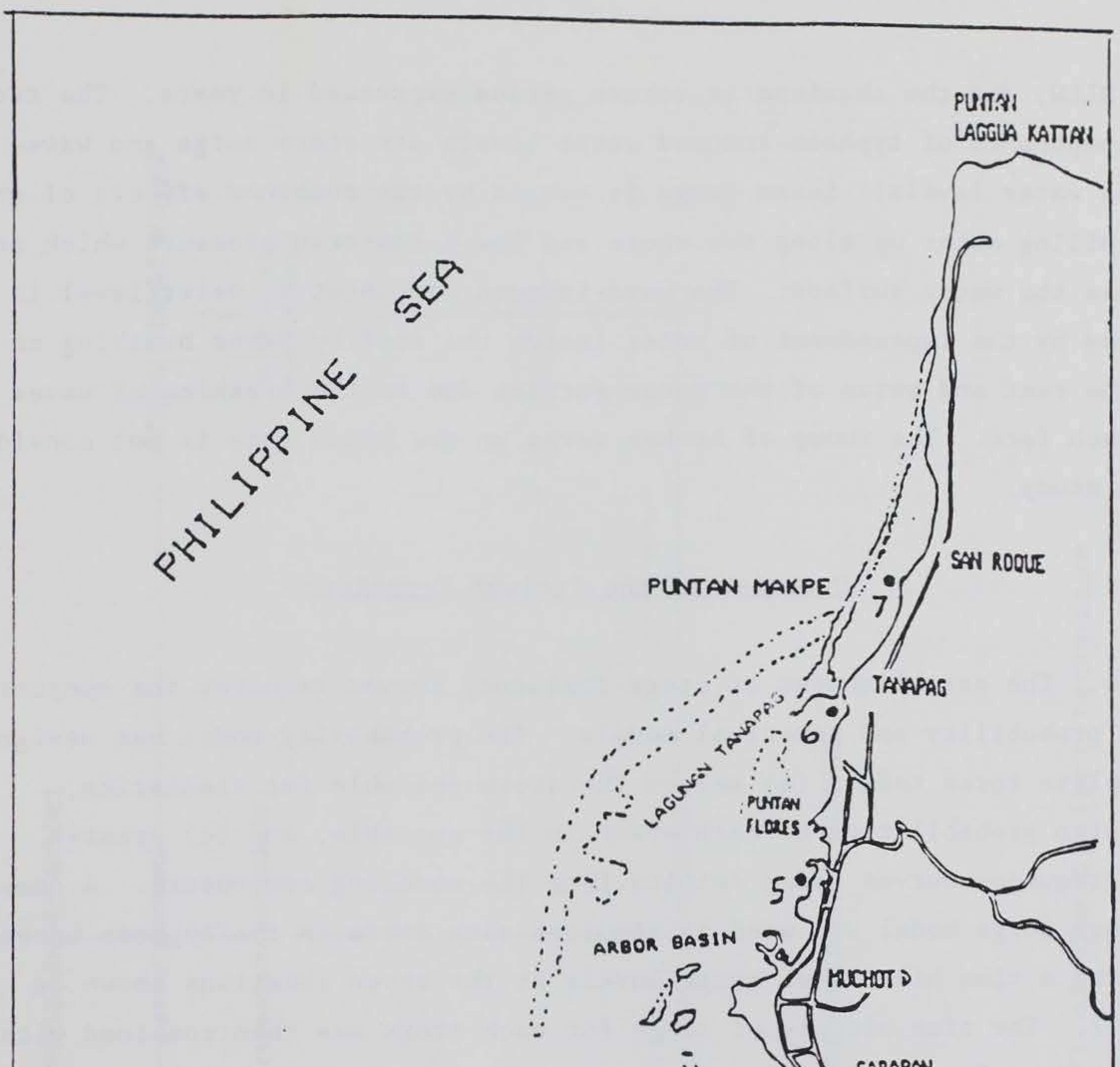


Figure 2. Study area vicinity

above MLLW, and the abscissa is return period expressed in years. The two main components of typhoon-induced water levels are storm surge and wave-induced water levels. Storm surge is caused by the combined effects of storm winds piling water up along the shore and low barometric pressure which acts to raise the water surface. The wave-induced component of water level is produced by the impoundment of water inside the reef by waves breaking on and over the reef and setup of the water surface due to the breaking of waves on the beach face. The runup of broken waves on the beach face is not considered in the study.

Overview of the Project Technique

4. The establishment of stage-frequency curves requires the conjunctive use of probability and numerical models. The probability model was designed to complete three tasks; (a) select the storm ensemble for simulation, (b) assign probabilities to each event in the ensemble, and (c) create stage-frequency curves using results from the modeling components. A numerical storm surge model was used to simulate each storm in the typhoon ensemble, producing a time history of surge levels at the seven locations shown in Figure 2. The time history of surge for each storm was then combined with a large number of randomly chosen astronomical tide time histories to create a very large number of surge-plus-tide event time histories. A numerical wave prediction model used for a previous typhoon analysis of Agana Bay, Guam, (Mark in preparation) was used to simulate the wave conditions generated by each of the storms in the storm ensemble. The simulated deep water wave information was used with the reef ponding methodology (Seelig 1983) to calculate the impoundment of water due to waves breaking on the reef. The same wave information was also used as input to a procedure for estimating wave setup along the beach. Results of the separate modeling efforts were then combined to ascertain the maximum total water levels at each of the seven numerical gage locations. The stage-frequency curves were then generated from these maximum water levels. A flow chart depicting the project technique is presented in Figure 3.

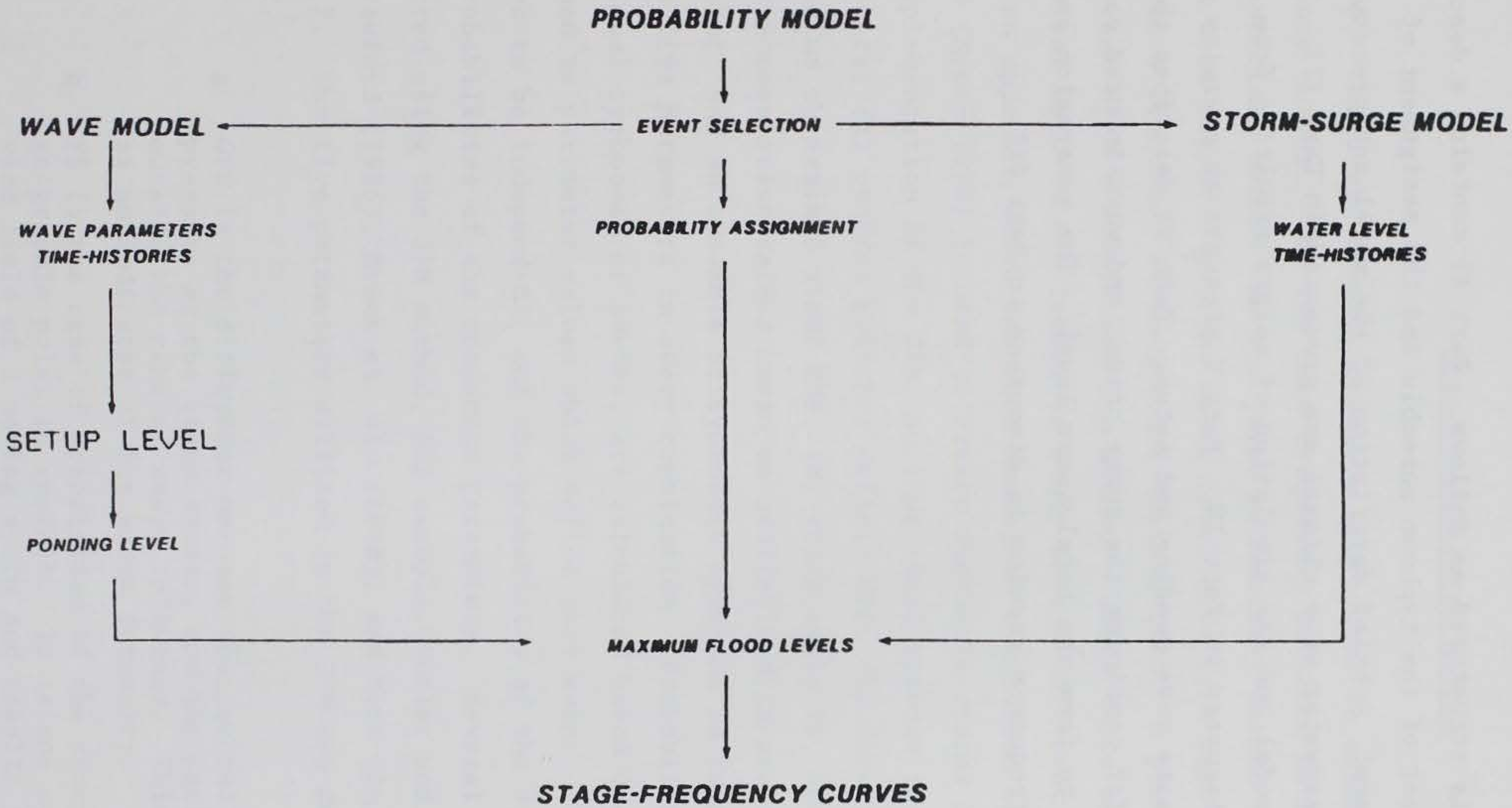


Figure 3. Flow chart of the project technique

Report Organization

5. This report is structured as follows. Part II contains a description of the establishment of the typhoon ensemble and the assignment of probability to each storm. A brief description of the model and procedures used to simulate the deepwater wave climate are presented in Part III. The numerical storm surge model and the simulation of surges resulting from the typhoon ensemble are discussed in Part IV. Part V presents an overview of the technique used to estimate wave ponding and setup. Part VI describes the convolution procedure for combining the surge, tide, and wave-induced components of water level to form the total water level. The generation and presentation of stage frequency results is discussed in Part VII.

PART II: STORM SELECTION AND ASSIGNMENT OF PROBABILITY

Joint Probability Method

6. There are several possible approaches in establishing stage-frequency curves. The two most frequently utilized methods are referred to as the historical method and the joint probability method (JPM). The historical method uses measured extreme water level data from past storm events to generate a frequency of occurrence distribution. A probability is assigned to each event by a standard ranking method. Where there exists a scarcity of historical data in the immediate study area a different approach is typically used, an approach which requires numerical simulation of the events. The JPM method (Myers 1970) is used to create synthetic storms to be simulated. In our implementation of the JPM, an individual typhoon is represented by five parameters; (a) central pressure deficit CPD, (b) forward speed FS, (c) radius to maximum winds RMW, (d) track angle TA, and (e) landfall point LP. Representative values based on available data are chosen for each parameter, and an ensemble of synthetic typhoons is formed by combining values of the five parameters in every combination. Probability assigned to individual typhoons, or events, are calculated based upon probabilities assigned to parameter values which define that event. The five parameters are assumed to be independent, and the probability of the event is the product of the probabilities of the component parameters. Several studies have been conducted using the JPM method, for example, Butler and Prater (1986), Hardy and Crawford (1986), Kraus et. al. (1988), and Mark (in preparation).

7. The five parameters utilized in the JPM are defined in the following manner.

- a. CPD is the difference between the central pressure, or the pressure at the storm center, and the peripheral pressure outside the zone of storm influence. This parameter serves as an indicator of the storm intensity.
- b. FS is the rate of translation of the storm center from one geographic point to another. It is one component of the wind field of a moving storm and results in higher winds on the right side of the storm and lower winds on the left. This asymmetry of the wind field is due to the additive effect of the forward speed to wind velocity on the right side of the storm and the negative effect of forward speed on the wind

at the left side of the storm. (This assumes the counterclockwise velocity circulation pattern of a tropical storm located in the northern hemisphere)

c. RMW is the radial distance from the storm center to the band of strongest winds within the storm. It is used as a measure of storm size and is an important factor in the generation of storm surge.

d. TA is the direction of storm translation and is measured in degrees clockwise from true north.

e. LP is a location along the coastline of interest through which the center of the storm passes.

8. Track angle, land fall point, and forward speed define the path of the storm and its position as a function of space and time.

Review of the Typhoon Analysis Study for Agana Bay, Guam

9. Saipan is geographically located within the "Guam Box" (Figure 1), 5° to 20° N latitude and 135° to 155° E longitude, a region where occurring storms are assumed to have similar characteristics. The same storms of the Guam typhoon ensemble were utilized for this investigation at Saipan. Due to the dependence of the present study on data from the previous typhoon analysis of Agana Bay, the following review is provided.

10. The JPM was employed to create the synthetic typhoon ensemble using the following steps:

a. Historical data for storms which occurred within the region of the Guam Box were gathered and values for each of the five parameters were specified.

b. Probability distributions were established for each parameter. Each distribution relates the value of the parameter to its probability of occurrence as determined from the historical data. The Weibull plotting position formula (Equation 1) was used to develop the probability distribution curves.

$$P = M / (N + 1) \qquad (1)$$

where P is the probability, M is the rank of the historical occurrence and N is the total number of historical values.

c. Discrete values of each parameter were selected to represent the range of parameter values possible in the study area.

d. Probability was assigned to the discrete values chosen for each parameter according to that portion of the probability distribution which the discrete parameter represents.

e. The parameters were assumed to be independent of each other. Therefore, the probability of the synthetic storm was computed as the product of the probabilities of the individual parameters.

f. The number of storms per year λ is determined from historical records. The probability of a particular synthetic storm P_s occurring during a year (Equation 2) is determined by multiplying λ times the product of the probabilities associated with each parameter value that defines the storm.

$$P_s = \lambda \underset{i=1}{\overset{5}{\Gamma}} P_i \qquad (2)$$

11. Data used in creation of the parameter probability distributions were obtained from the U.S. Naval Oceanography Command Center/Joint Typhoon Warning Center Annual Report (JTWC), 1959 - 1979 and Weir (1983) who summarizes this data for storms passing within 180 n.m. of Guam. These two sources provided data for all parameters except RMW which was obtained from National Oceanic and Atmospheric Administration (NOAA) Technical Report NWS 23 (1979).

12. Based on the information given by Weir (1983) and the JTWC annual report, six values of center pressure deficit (20, 40, 60, 80, 100, and 120 mb) and two values of forward speed (8 and 16 knots) were chosen. Figure 4 shows two probability distribution curves for CPD. One distribution is from the JTWC annual report, and the other is from Weir (1983). The probability distribution of FS is presented in Figure 5. Two values of radius to maximum winds (8 and 15 n.m.) were selected based upon information given by NOAA Technical Report NWS 23 (1979). Since it is known that there is a dependency of RMW on latitude, the higher the latitude the greater the RMW, the sensitivity of RMW to latitude was tested. Three probability distribution curves of RMW were obtained based on data from three regions; latitude less than 20 deg, latitude less than 25 deg, and all latitudes. The curve with latitude less than 20 deg was chosen for assigning the probability values. The probability distribution for RMW is shown in Figure 6. For

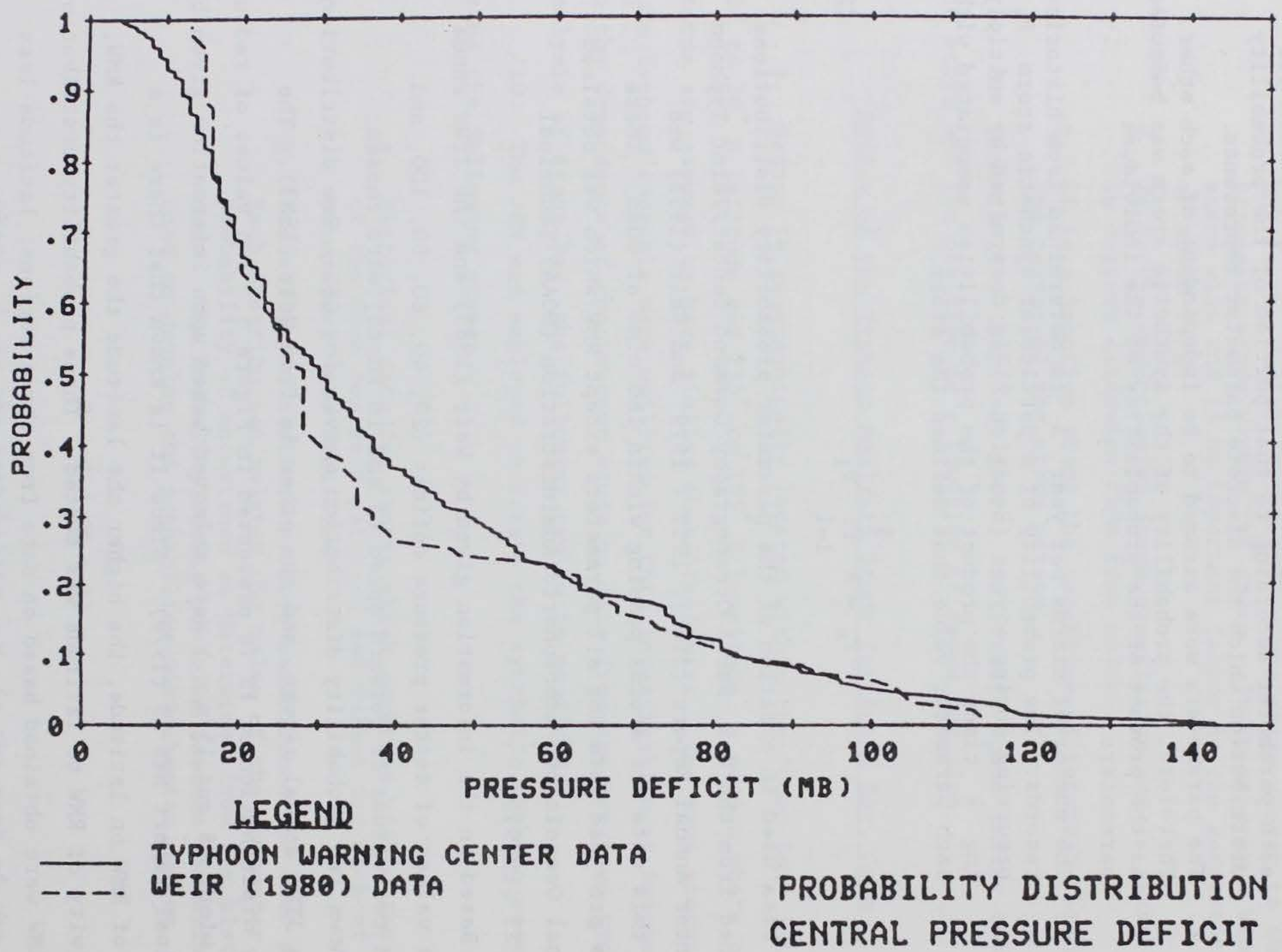


Figure 4. Probability distribution of pressure deficit

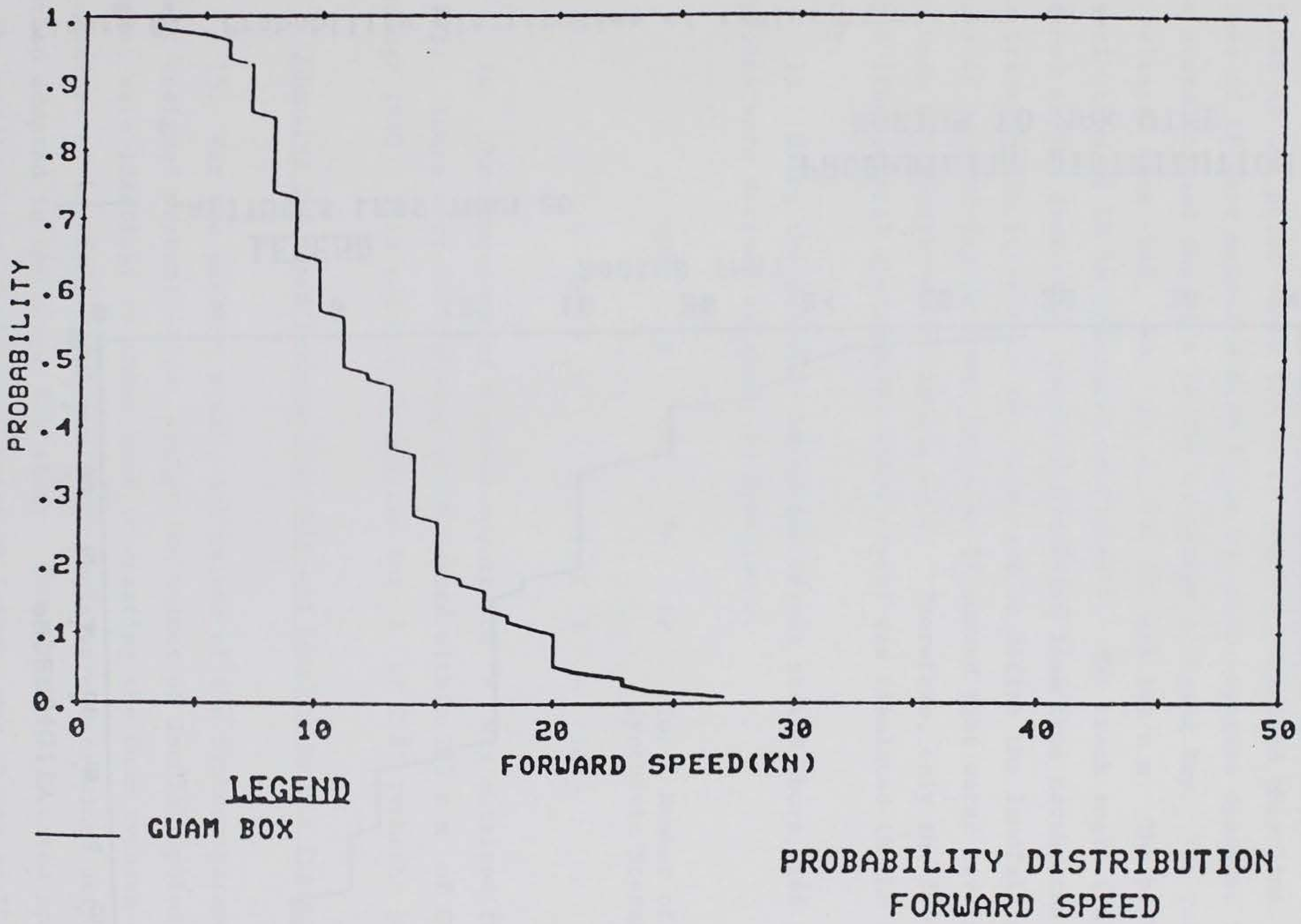


Figure 5. Probability distribution of forward speed

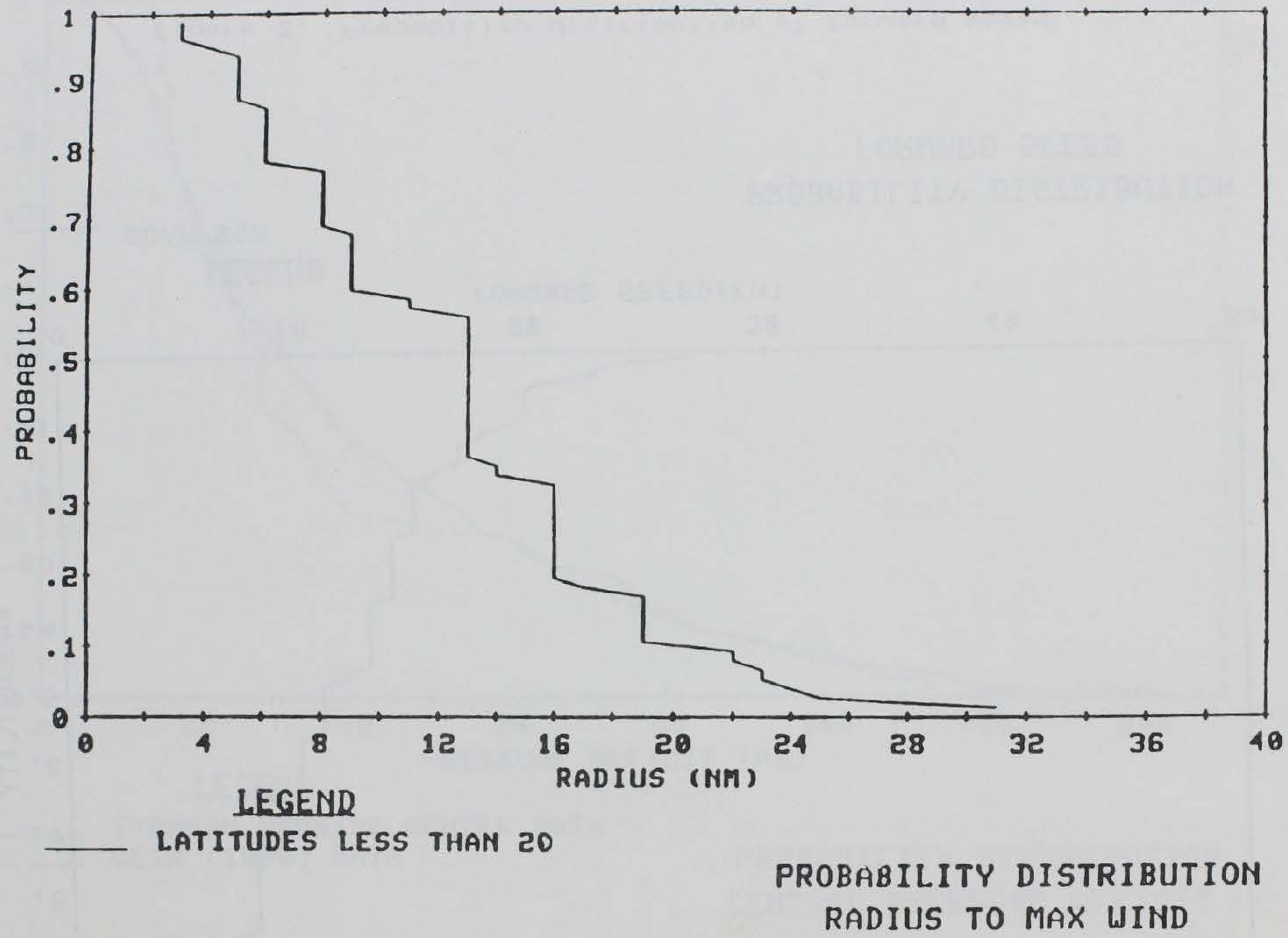


Figure 6. Probability distribution of radius to maximum wind

landfall point (LP), a line normal to the predominant direction of typhoon movement was drawn across the Guam Box through the Agana Bay. The LP was defined as the point where the storm track intersected this line. The values of LP were measured from Agana Bay with negative distance indicating the storm crossed the line to the southwest of Agana Bay. The values of LP selected were -140, -60, -25, 0, 25, 60, and 140 n.m. The probability distribution of LP is presented in Figure 7. The track angle (TA) was defined as the direction, measured clockwise from true north, that a typhoon was traveling as it crossed the line used to define the landfall point. Tests of sensitivity of water level to TA showed that water levels in Agana Bay were not sensitive to changes in TA. Therefore, only the 300 deg track angle (the general predominant storm track) was simulated in the Agana Bay study.

13. Using the discrete parameter values stated above, 168 synthetic typhoons were defined as shown in Equation 2.

CPD		FS		RMW		TA		LP		Total Number of Synthetic Storms	
6	X	2	X	2	X	1	X	7	=	168	(3)

14. The frequency of typhoon occurrence λ was obtained from Weir (1983). There were 94 typhoons which passed within 180 n.m. of Guam from 1948 through 1980. This results in a value for λ of 2.85 typhoons per year.

Adapting the Guam Typhoon Ensemble and Results to the Present Study

15. For the present study, all values of the typhoon parameters and their assigned probabilities, except the values of landfall point and track angle, were identical to those used in creating the Guam typhoon ensemble. The values of landfall point and track angle were determined using the same method adopted in the Agana Bay study. Puntan Flores, located approximately at the middle point of the west coast of Saipan, was chosen as the central landfall point. The locations of all seven landfall points are presented in

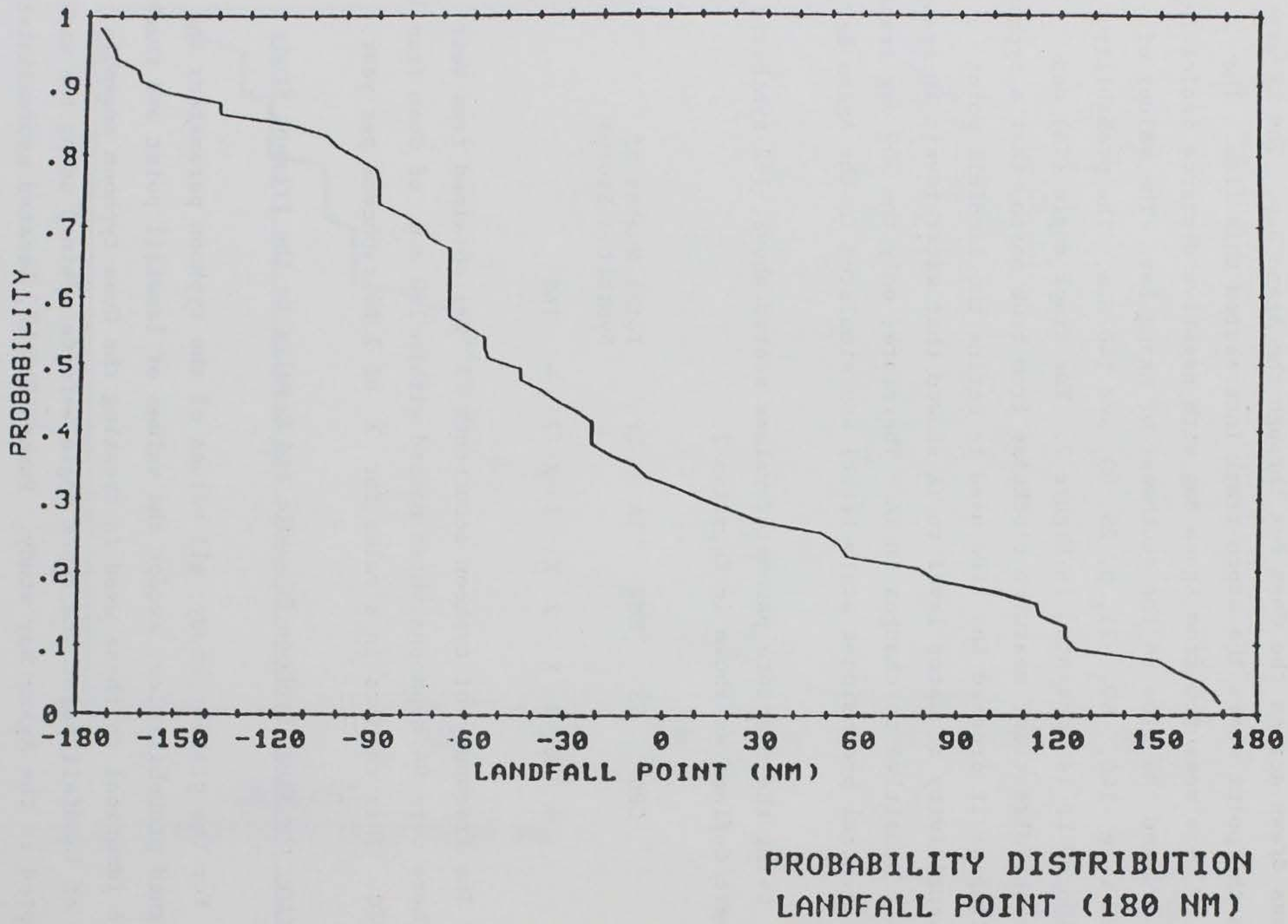


Figure 7. Probability distribution of landfall point

Figure 8. Based on the predominant storm path, the track angle was defined to be 120 deg relative to true north. The discrete values of the five parameters utilized in the JPM method and their probabilities of occurrence, as applied in this study, are presented in Table 1.

Table 1

Joint Probability Method (JPM)

Parameter Statistics for West Coast of Saipan

Central Pressure Deficit (CPD)

Pressure (mb)	20	40	60	80	100	120
Probability	0.51	0.22	0.10	0.085	0.05	0.035

Forward Speed (FS)

Velocity (knots)	8	16
Probability	0.52	0.48

Radius to Maximum Winds (RMW)

Radius (n.m.)	8	15
Probability	0.48	0.52

Track Angle (TA)

Track Angle (deg)	120
Probability	1.0

Landfall Point (LP)

LP (n.m.)	-120	-60	-25	0	25	60	120
Probability	0.285	0.235	0.115	0.07	0.05	0.09	0.155

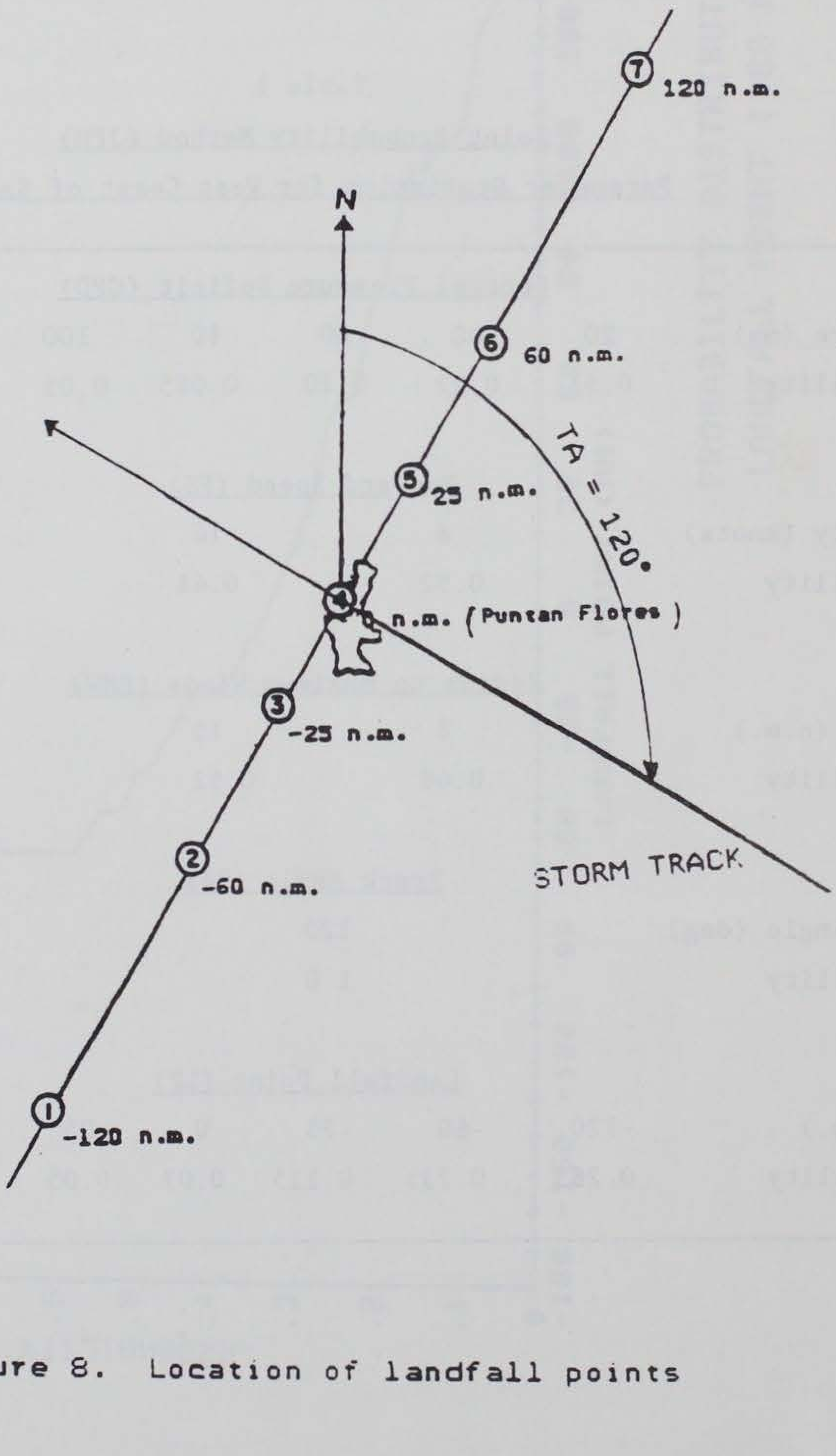


Figure 8. Location of landfall points

PART III: DEEP WATER WAVE SIMULATION

Wind Field Generation

16. Wind speeds and directions are the primary input to the wave model. These input data, along with atmospheric pressure deficits, were calculated on an uniformly spaced grid encompassing the study area using a tropical storm wind-field model developed by Reid et. al. (1977) for the U.S. Army Engineer District, Galveston, Texas. The model is an implementation of the Standard Project Hurricane (SPH) criteria as documented in the NWS Memorandum HUR 7 - 120 (1972) and updated in a NOAA Technical Report NWS 23 (1979).

17. The following are input pa~ameters to the SPH computer code: (a) coordinates (X_h, Y_h) of the storm's low pressure center (eye) relative to the origin of the computational grid; or alternatively, specification of the starting coordinates (X_o, Y_o), track heading, and forward speed from which (X_h, Y_h) are calculated internally in the model, (b) measured values (can be constant) of radial distance from the storm's eye to the band of maximum winds RMW, (c) the azimuth angle θ of this maximum wind band relative to the storm heading, (set equal to 120 deg based on limited data in Weir (1983)), (d) forward speed of the storm FS, (e) values of the difference between central and peripheral pressure CPD, and (f) the maximum wind speed W_m, (usually a 10-minute average at a 10-meter elevation). If W_m is unknown, it is calculated using CPD and an empirically derived expression that relates W_m to CPD.

18. This study uses CPD as the principal indicator of storm intensity, and leaves the maximum wind speed unspecified. The value of W_m was computed using the formulas given in NWS 23. First, the maximum overwater gradient wind was computed from

$$V_{gx} = k(CPD)^{1/2} - 0.5\,(f)(RMW) \tag{4}$$

where k is a parameter dependent on the mean latitude of the study area and f is the coriolis parameter at the mean latitude. The mean latitude of the Saipan area is approximately 15^{o} 14' N. Therefore, values of $k = 67.5$ and

$f = 2.308 \times 10^{-5}$ were used. The maximum wind speed in the moving storm is then estimated from

$$W_m = 0.9\ V_{gx} + 1.5\ FS^{0.63} \tag{5}$$

19. If (X_p, Y_p) are the coordinates of an arbitrary point in the computational grid, relative coordinates may be defined as $X = X_p - X_h$ and $Y = Y_p - Y_h$ or equivalently by radial distance r and azimuth angle ϕ. Thus

$$r = [\ X^2 + Y^2\ ]^{1/2} \tag{6}$$

and

$$\phi = \mathrm{Tan}^{-1}\ Y/X \tag{7}$$

The atmospheric pressure anomaly as a function of radial distance is given in terms of r, RMW, central and peripheral pressures as:

$$\Delta P = \frac{(P_\infty - P_o)}{\rho_w\ g} \exp(-RMW/r) \tag{8}$$

where ρ_w is the density of water defined so that ΔP has units of length (i.e., equivalent head) and P_∞ and P_o are peripheral and central pressures, respectively.

20. The azimuthal variation of maximum wind speed about the center of the storm is described by:

$$W_m' = W_m - 1/2\ FS[1 - \cos(\phi - \theta)] \tag{9}$$

where ϕ is defined by Equation 7, and θ is the azimuth angle of the maximum wind band center relative to the grid system. This function has a maximum at the azimuth of the peak wind center. Finally the components (U_w, V_w) of the wind velocity vector at any arbitrary point are determined from the following expression:

$$U_w = - W_m' \ FR \ Sin(\phi + \theta)$$
$$V_w = W_m' \ FR \ Cos(\phi + \theta) \qquad (10)$$

where FR is a radial distribution function that depends on r and RMW. The definition of FR was obtained from a nomogram found in NOAA Technical Report NWS 23 (1979). The sign convention of Equation 10 is consistent with the counterclockwise circulation around the eye of the storm.

Description of the Wave Model

21. Saipan is located 120 n.m. northeast of Guam and is geographically within the Guam Box. The distance between the two islands is small compared to the length scale of the Pacific Ocean. Furthermore, bathymetric conditions off Saipan are very similar to those off Guam. The fringing coral reefs along the west coast of both islands divide the water body into shallow nearshore and deepwater offshore regions. Because of the proximity and similarity between the two islands, wave information generated using the numerical wave model SHALWV (Hughes and Jensen, 1986) at locations outside Agana Bay, Guam (Mark in preparation) were assumed to represent conditions along the west coast of Saipan. The following is a brief description of the wave model and modeling procedure that were used for Agana Bay.

22. The SHALWV model was selected to simulate deepwater wave conditions for each typhoon. The primary physical processes modeled were wave growth and decay, wave propagation, and wave refraction and shoaling. Since the model is based on finite difference methods, solutions are computed at fixed points on a grid mesh that is used to discretize the domain of interest. The wind fields created by the SPH model were the primary model input to SHALWV at each grid point. The model output is a time history of two-dimensional energy spectra at selected grid points. The results needed for the Agana Bay study were the time-histories of significant wave heights, periods, and directions for selected gage locations outside the reef. These were calculated from the two-dimensional spectra.

23. A two-grid system was used in the wave modeling. A coarse grid was used for deepwater areas, and a much finer grid was used for the nearshore region. The deepwater wave modeling is analogous to modeling waves in a large two-dimensional wave flume of constant depth (deepwater). Typhoons are propagated along the longitudinal axis of the flume (along the predominant storm heading), and the time-histories of directional wave spectra are measured with an array of gages along the lateral axis of the flume. Twenty-four typhoons were simulated, representing all combinations of the typhoon parameters CPD, FS, RMW. The deepwater runs were not dependent on the track angle or landfall point. The resulting time-histories of spectra for selected points along the lateral axis of the grid were saved and used as boundary input for the nearshore grid.

?4. In the nearshore modeling, typhoon parameters of track angle and landfall point are very important. The path of the typhoon relative to the island determines the local wave climate along the west coast of Saipan, which is influenced by wave sheltering in the lee of the island, refraction, and shoaling. In the deepwater modeling, local coastal effects are too small to resolve. Therefore, an intermediate process was necessary before the deepwater output could be used as input for the nearshore grid. The intermediate process was to rotate the wave angles at the selected deepwater grid points consistent with the desired track angle and landfall point. The time-histories of the two-dimensional spectra saved for these selected deepwater grid points were then interpolated and used as boundary input for the nearshore grid. This process was repeated for each nearshore run. A total of 168 typhoons were simulated on the nearshore grid. As in the deepwater modeling, SHALWV generated two-dimensional wave spectra for each nodal point of the grid for each time step in the simulation. The time histories of energy spectra at two grid points outside the Agana Bay were saved and used to calculate the wave heights and periods at a deep water site adjacent to each of the five numerical gage locations at the Agana Bay, Guam. The wave data saved at gage 3 of the Agana Bay study (Mark in preparation) were selected and used to estimate the wave-induced ponding and wave setup water levels for the Saipan study.

PART IV: STORM SURGE SIMULATION

Storm Surge Model

25. The US Army Engineer Waterways Experiment Station (WES) Implicit Flooding Model (WIFM) was the hydrodynamic storm surge model used in this investigation. The numerical and hydrodynamic features of WIFM have been discussed by Butler (1978), and the application of WIFM to coastal studies has been successfully demonstrated in numerous previous investigations (e.g., Butler 1983). The WIFM solves the vertically integrated, dynamic, shallow water wave equations of motion by using an alternating direction, implicit, finite difference solution algorithm. The model allows subgrid barriers, such as barrier reefs (which can be either exposed or submerged) to be included in the grid. Also included in the model is the capability to flood or dry individual cells during a simulation. A major advantage of WIFM is the capability of discretizing the study region using a smoothly varying rectilinear grid that allows cells to be smaller in certain regions (e.g., area of interest) and larger in others. A piecewise reversible transformation (analogous to that used by Wanstrath, et al. (1976)) is used to map prototype, or real space, into computational space. The transformation takes the form

$$x = a + b\,\alpha^{c} \tag{11}$$

where a, b, and c are arbitrary constants, x is a real space coordinate and α is the corresponding transformed coordinate.

Numerical Grid Generation

26. The rectilinear variable grid system employed by WIFM is developed through the use of a computer code MAPIT. A computer code has been designed to calculate the mapping defined by Equation 11 allowing complete control of grid resolution at any point along each grid axis. Each axis is mapped independently. The entire real space x to be mapped is broken into regions defined by their end points X_1, X_2, ... X_n (for n-1 regions), and Equation 11 is applied to each of the n-1 regions. Continuity of slopes and

curvatures of real space coordinates, with respect to transformed coordinates, are forced at the interfaces of adjacent regions. Simultaneous solution of the equations representing the transformation and boundary conditions results in the calculation of values of the three coefficients (a, b, and c) for each of the n-1 regions. The coefficients computed from MAPIT are then used as input data to a computer code GRID to compute the complete mapping of the study area into a regular computational grid. The GRID program computes real space grid coordinates, which are then plotted on a CALCOMP pen plotter. The plot of the grid mesh is used as an overlay on bathymetric charts for digitizing bathymetric or topographic features.

27. The computational grid used in the Saipan project contains 1452 cells (Figure 9). It has 44 cells in the north-south direction and 33 cells in the west-east direction. The origin of the grid is located at approximately 145° 43.2′ E longitude and 15° 23.3′ N latitude. The eastern limit of the grid extends to Puntan Laggua Kattan, while the western limit is located at approximately 145° 33.8′ E longitude and 15° 10′ N latitude. The southern limit is located at 145° 41′ E longitude and 15° 5.2′ N latitude. Individual cell dimensions range from 625 x 2080 ft in the high resolution region along and near the west coast of Saipan to 3060 x 3750 ft near the origin of the grid.

28. Water depths and land elevations were assigned to grid cells based on information obtained from:

- a. Maps published by the Defense Mapping Agency Hydrographic/Topographic Center. The map numbers are DMA Stock No. 81076 (6th edition 1985) and Stock No. 81067 (4th edition 1984).
- b. Topographic map of the island of Saipan, published by U.S. Department of Interior, Geological Survey.

All water depths used as model input were referenced to MLLW.

29. Reef heights were set within the range of 1.4 to 2.5 ft below MLLW, and chosen based on topographic data obtained from the maps mentioned in paragraph above.

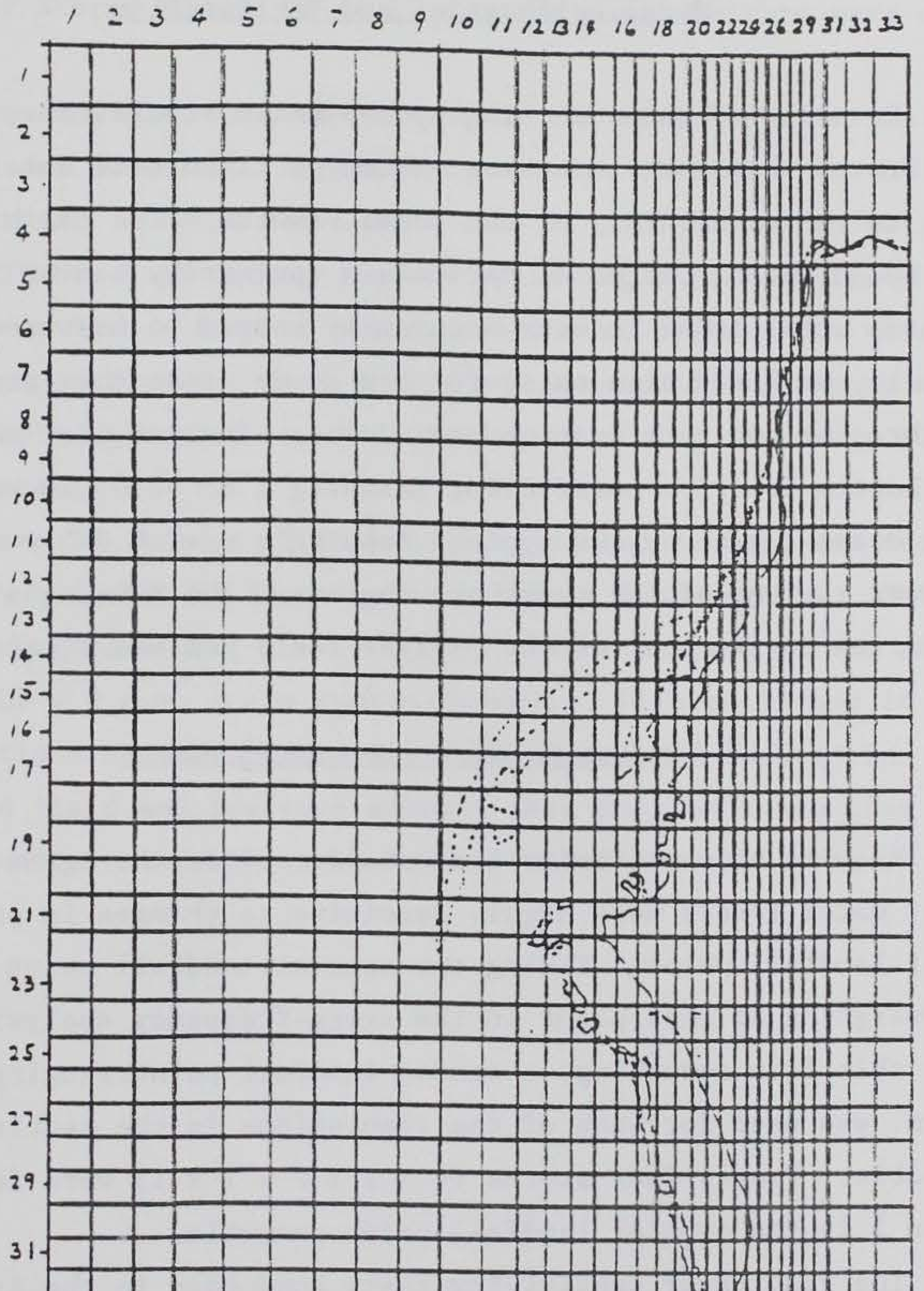


Figure 9. Numerical grid for the storm surge model, WIFM

Model Calibration and Verification

30. Normally, when conducting hydrodynamic simulations, the model is first calibrated then verified using prototype field data obtained from the study area to ensure accuracy of the model results. The calibration is performed by adjusting the model parameters (primarily bottom friction coefficients) until model results accurately reproduce measured field data. Unfortunately, no field data exist for the study area; this precludes the usual calibration and verification procedures. Instead, for the Saipan study, a typical bottom friction coefficient (Manning's n) of 0.025 was chosen for the deeper coastal waters, and typical Manning's n of 0.035 was chosen for the shallower regions of the nearshore lagoons. The Manning's n value for the bottom friction coefficient of the barrier reefs was set equal to 0.03.

Simulation of the Events Ensemble

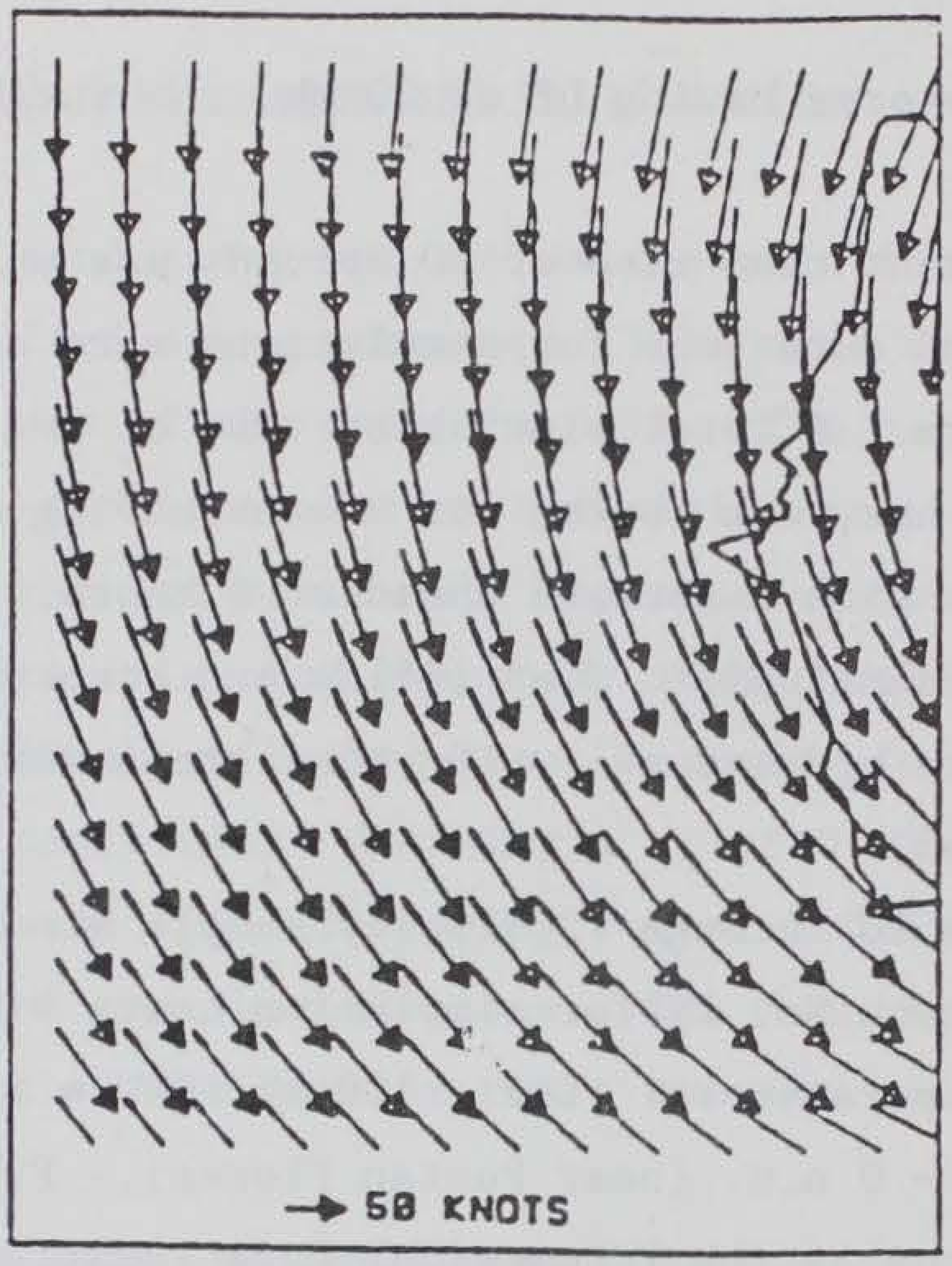
31. Results of sensitivity tests conducted in the Agana Bay study showed that water levels were highly sensitive to changes in pressure at the central landfall point. Fixing the central landfall point would cause excessive weighing of this point in the stage-frequency analysis. To prevent this from occurring, a random landfall point ranging from -12.5 to 12.5 n.m. was used for each of the simulations in the central landfall point ensemble. Twenty-four storms (6 x 2 x 2 x 1 x 1) were formed according to Equation 3 in the central landfall point ensemble.

32. The results of sensitivity tests conducted in the Agana Bay Study (Mark in preparation) have also shown that for conditions where atmospheric pressure deficit is the dominant mechanism causing storm surges (i.e., for storms with landfall points far from the island), water levels will increase linearly with a linear decrease in barometric pressure deficit and vice versa. Therefore, only storms having CPD of 40 mb and 120 mb were simulated for this study. A total of 72 hypothetical typhoons were simulated, 24 storms in the central landfall point ensemble and the 48 storms having a CPD of either 40 or 120 mb. The surge heights for storms having CPD of 60, 80 and 100 mb, were interpolated from simulated results for storms with CPD of 40

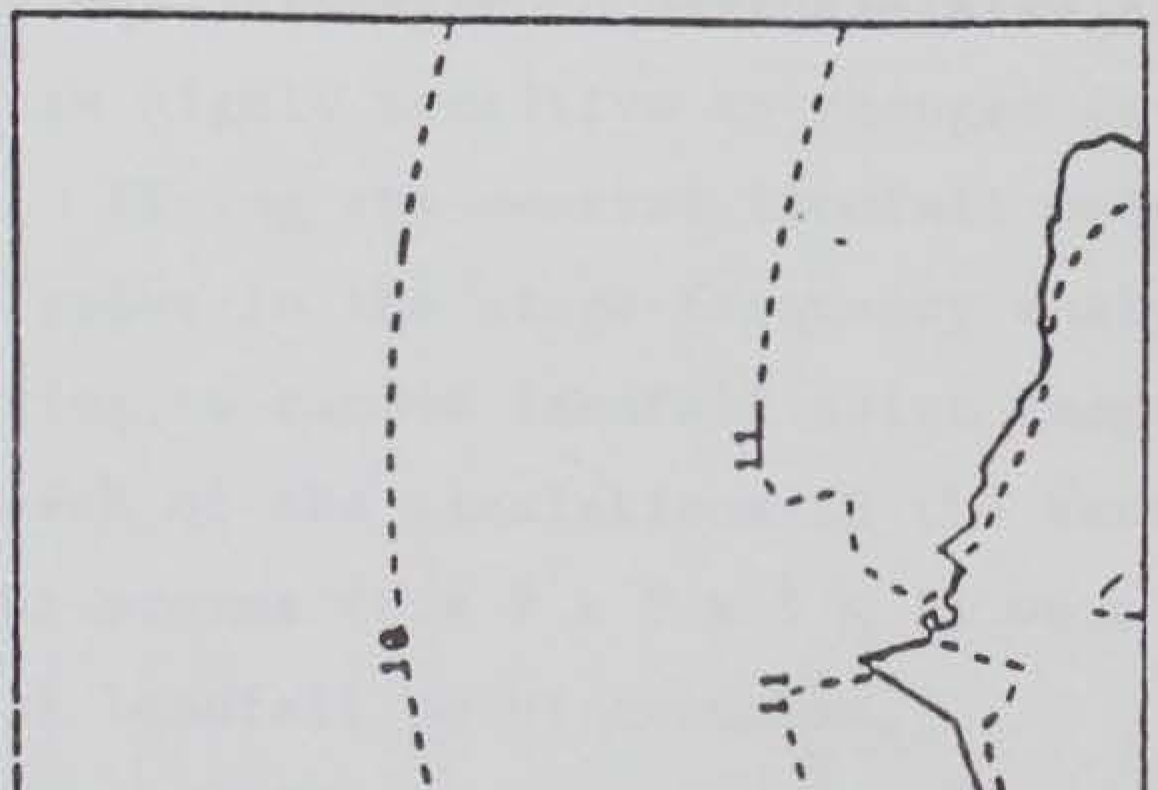
and 120 mb. For storms having DP of 20 mb, the surge heights were obtained by extrapolation.

33. A constant time step of 60 seconds was used for all simulations. Prototype times and durations for simulations were dependent on the forward speed of each storm. A total simulation time of 20.5 hrs, with a time to landfall of 6.125 hrs, was chosen for storms having a forward speed of 16 knots. For storms with a forward speed of 8 knots, these times were 31.0 and 10.25 hrs, respectively. Wind fields and atmospheric pressure anomalies for all storms were updated every 10 time steps during the surge simulations, or every 10 minutes.

34. Figures 10 through 12 display sample wind vectors and isovels for synthetic typhoon No. 29 for simulation hours 9 through 11. This storm had the following parameters: CDP = 100 mb, RMW = 8 n.m., FS = 8 knots, TA = 120°, and LP = 0 n.m. (near Puntan Flores). Figures 13 and 14 present the surge elevations at the 7 numerical gage locations computed for the same storm. The wind field and pressure anomaly data and the surge time histories at 10-min intervals were archived on magnetic tape for each storm.

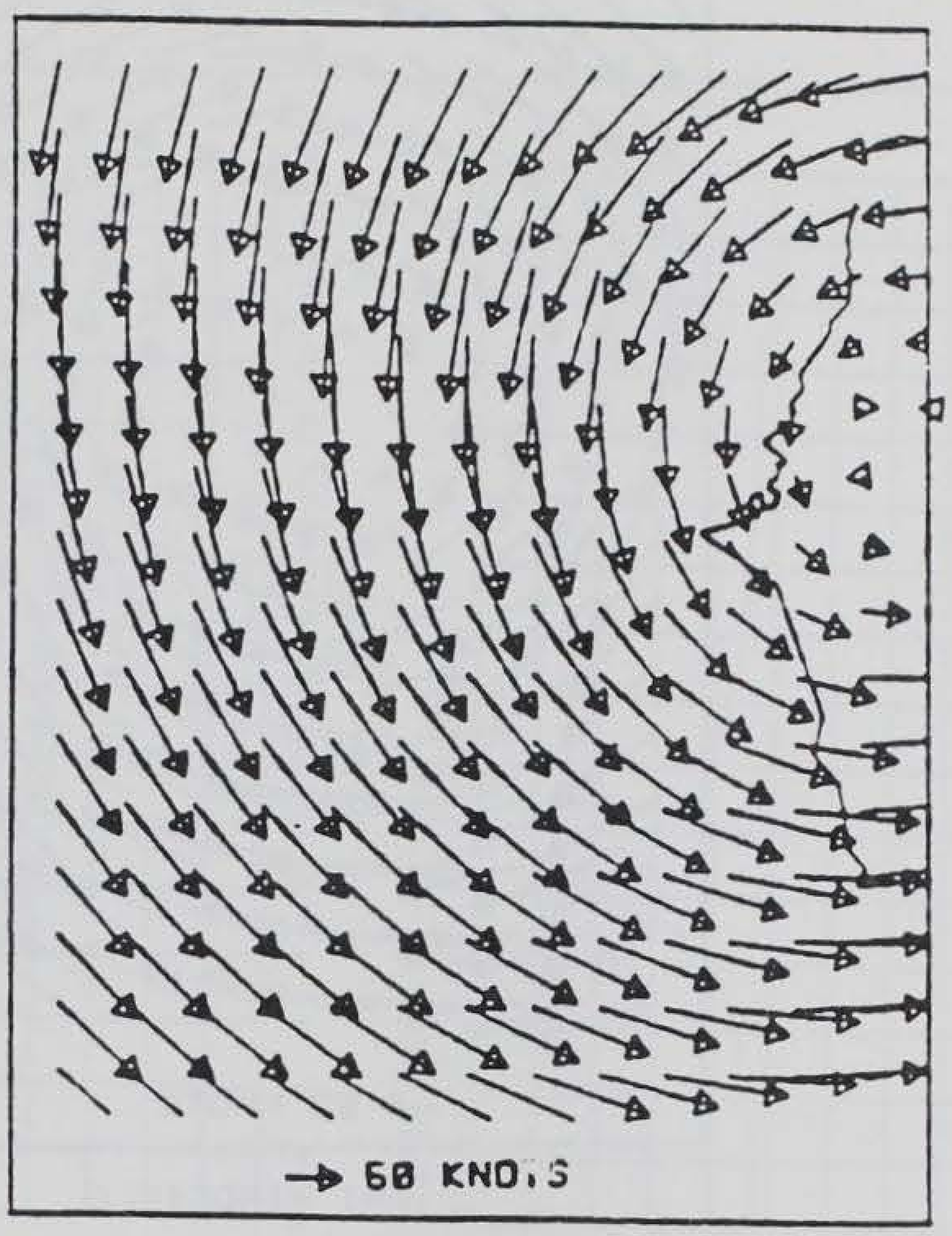


(A) WINDFIELD

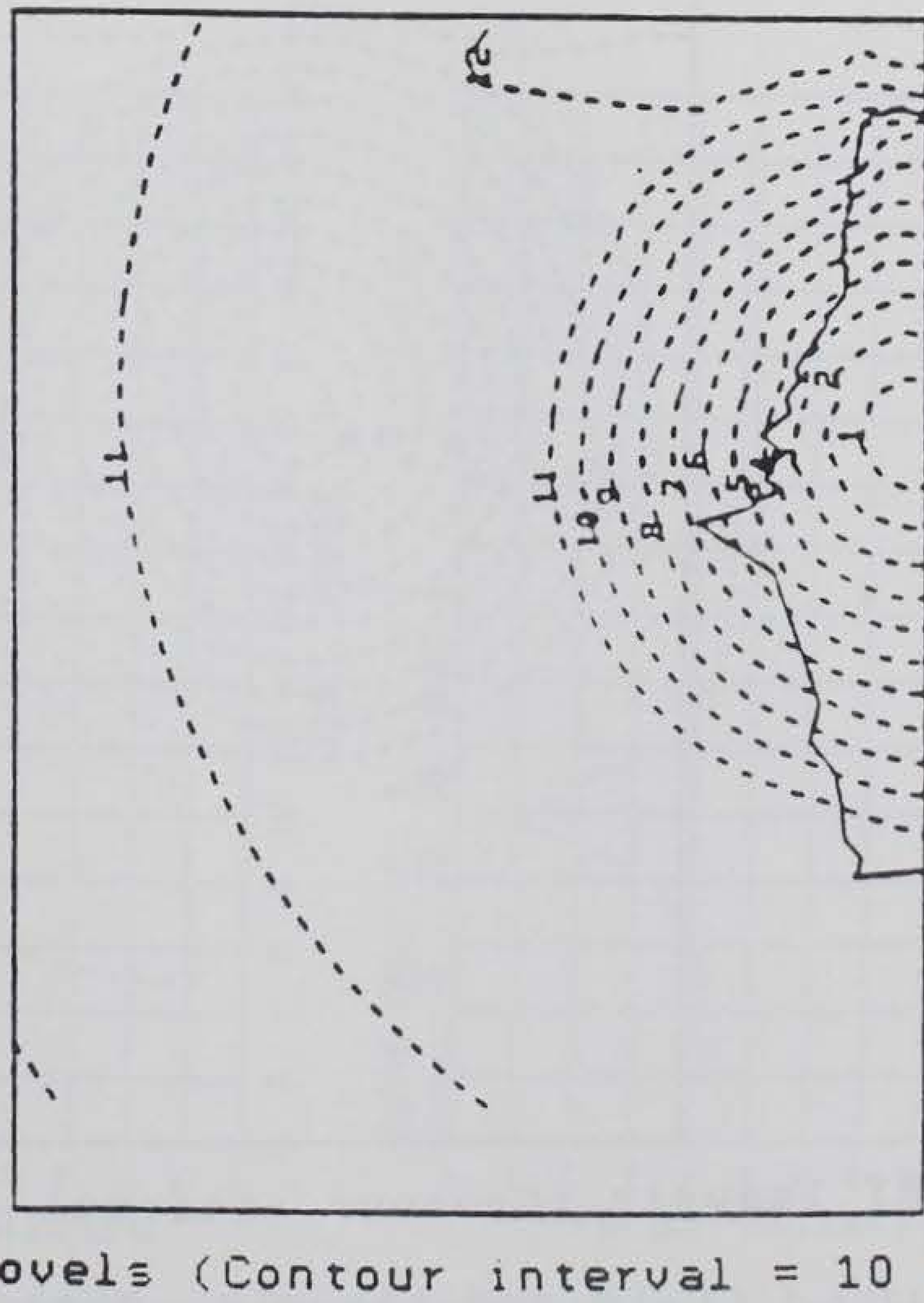


(B) Isovels (Contour interval = 10 Knots)

Figure 10. Wind field and isovels, design storm No. 29, hour 9

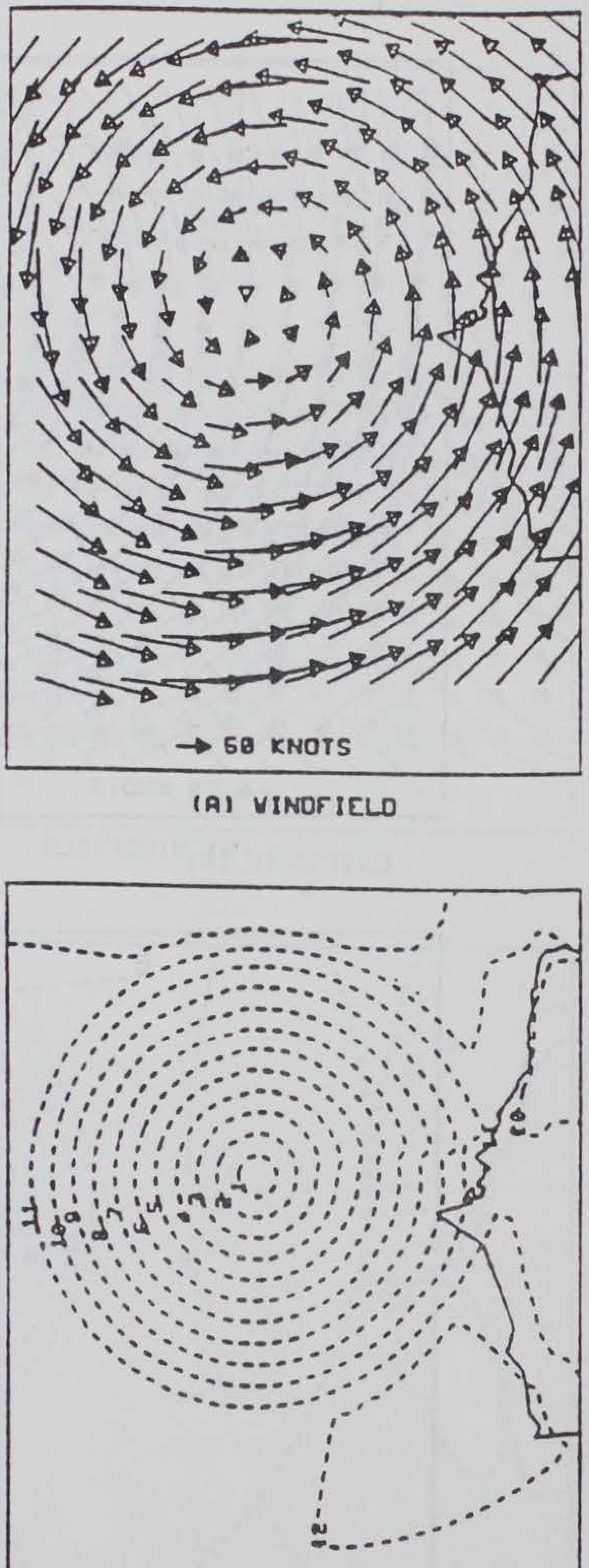


(A) WINDFIELD



(B) Isovels (Contour interval = 10 Knots)

Figure 11. Wind field and isovels, design storm No.23, hour 10



(B) Isovels (Contour interval = 10 knots)

Figure 12. Wind field and isovels, design storm No.29, hour 11

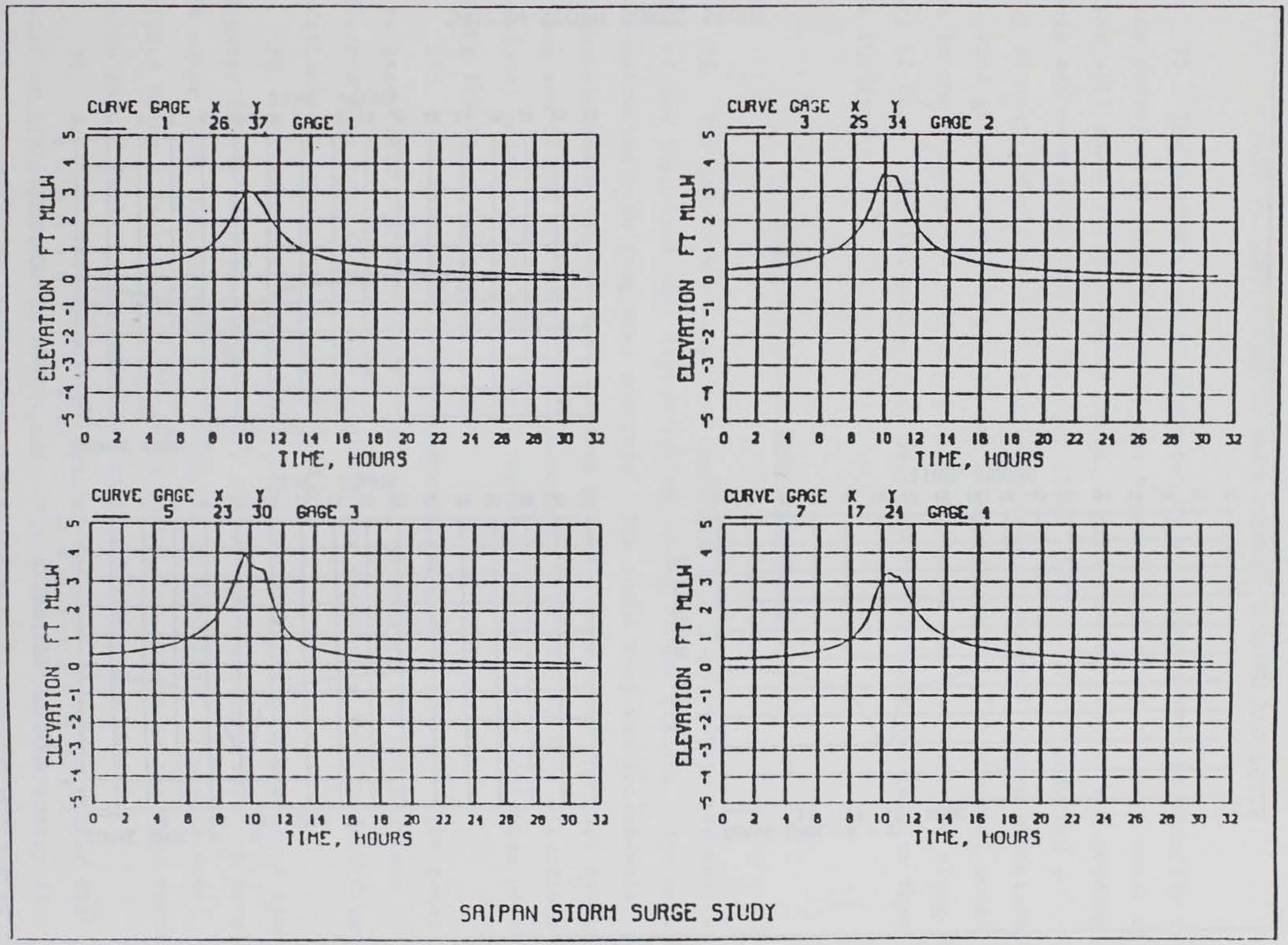


Figure 13. Surge elevations at gage 1-4

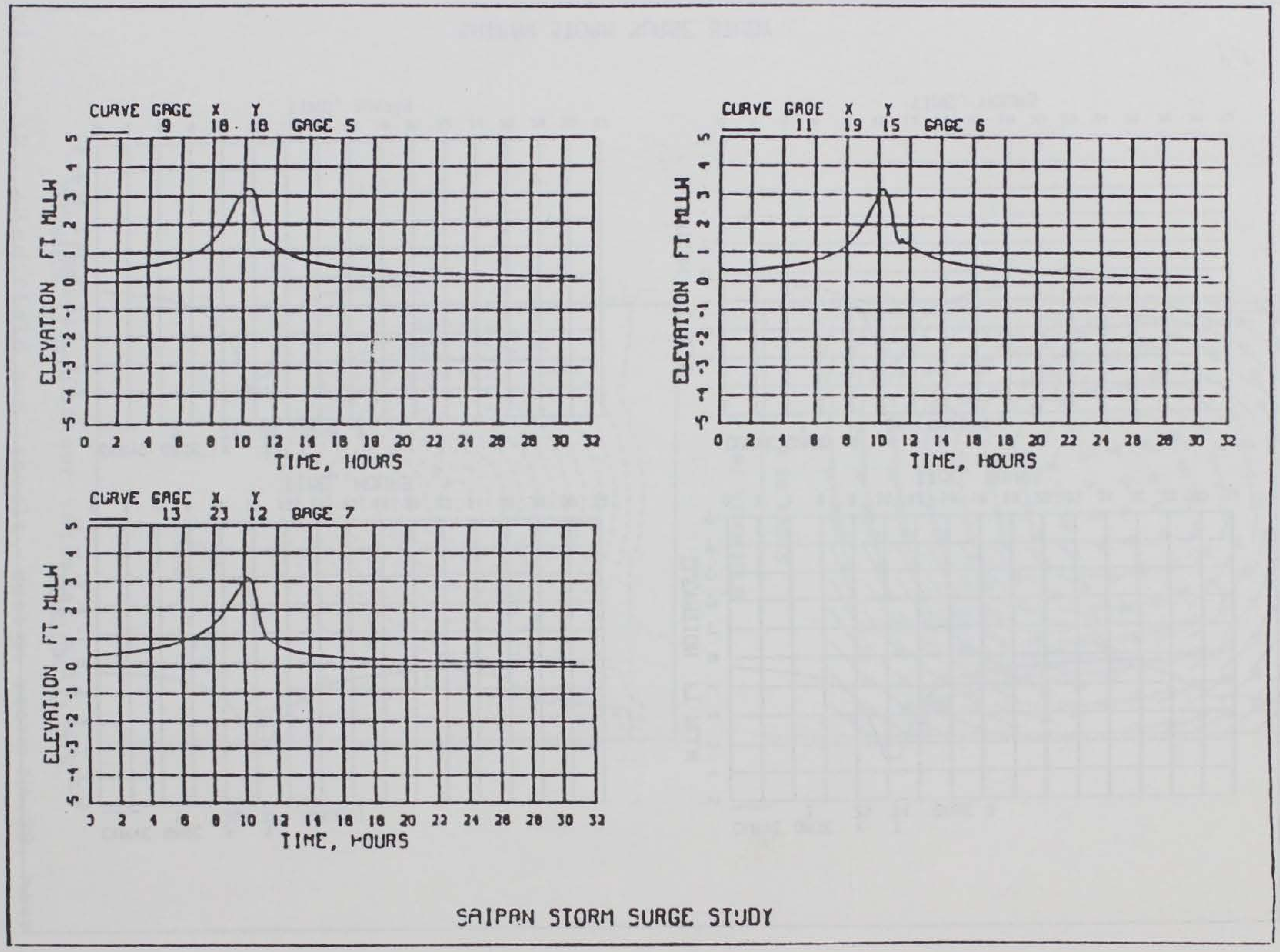


Figure 14. Surge elevations at gage 5-7

PART V: ESTIMATION OF WAVE-INDUCED PONDING AND SETUP

35. The deepwater waves generated by a typhoon cannot be directly used in the convolution process because the barrier reef along the west coast of Saipan will cause these waves to break, a process that affects the ponding levels and wave setup within the reef flat. Seelig (1983) conducted a study of wave-induced ponding on an idealized lagoon-reef system associated with wind generated monochromatic and irregular waves. The physical model used in the study had a reef cross section similar to that existing along the coast of Guam. The following is an overview of the study and results that were obtained.

Overview of the Ponding Level Technique

36. The laboratory study was conducted in a 1:64 undistorted physical model of the idealized reef lagoon system, using Froude scaling. The model was constructed with roughened concrete. The model reef was impermeable, did not contain channels, and had a uniform height. In general the reef systems of Guam and Saipan are very three-dimensional with varying reef elevations. Therefore, model results most likely represent conservative estimates of the ponding levels in the natural lagoon.

37. Wave measurements were conducted using five parallel-wire gages. Three gages were placed seaward of the reef to measure the incident and reflected wave conditions. The remaining two gages were used to record wave conditions and water levels in the lagoon.

38. For each test, waves were generated for 40 min of prototype time, and water levels were sampled for 34.1 min at a 0.5-sec intervals. A total of 4096 water level data points were collected at each gage. The data were analyzed using a Fast Fourier Transform routine to determine the wave spectrum at each gage. Table 2 summarizes the range of conditions tested.

39. Seelig (1983) found that most of the wave energy is either dissipated or transmitted into the lagoon; only a fraction of the energy is reflected. Furthermore, the ponding levels within the lagoon increase as

Table 2

Range of Conditions Tested by Seelig (1983)

Variable	Range
Still water depth at reef crest (d_r)	0.0 m - 2.0 m
Wave period (T and T_p)	8 sec - 16 sec
Lagoon width (W)	150 m - 525 m
Irregular deep water significant wave height (H_o)	2.5 m - 10.7 m

deepwater wave power increases, and ponding levels decrease as depth of water over the reef increases. Table 2 indicates that the lagoon widths tested are smaller than widths found along the west coast of Saipan. However, Seelig found that lagoon width had no significant effect on the ponding water level within the test range he used. Seelig proposed the following equation to predict ponding levels in a lagoon:

$$\eta = a_1 + a_2 \log (H_o^2 T) \qquad (12)$$

where H_o is the significant deepwater wave height, and T is the wave period. Values for coefficients a_1 and a_2, for irregular waves, are presented in Table 3 for different depths of water at the reef crest.

Table 3

Ponding Water Level Coefficients

d_r(m)	a_1	a_2
0.0	-0.92	0.77
2.0	-1.25	0.73

40. Ponding level time-histories for this study were computed using Equation 12 in conjunction with the surge and tide and incident wave information. The ponding level is computed in three steps: (a) ponding water levels are computed for reef water depths of 0.0 and 2.0 m using the

significant wave heights and periods calculated from the wave model, (b) the surge and tide levels were added to estimate the water depth at the reef crest, and (c) the ponding level associated with the surge-plus-tide level was interpolated/extrapolated using the ponding levels calculated for depths of 0.0 and 2.0 m.

Estimation of Wave Setup

41. Another potential contributor to water level during a severe storm, besides tide, surge and ponding, is setup due to wave breaking along the beach. The following section describes the procedure used in this study to estimate the wave setup:

a. First the wave length L and deepwater wave length L_o are computed using the expressions provided in the Coastal Engineering Technical Notes (CETN).

$$L_o = \frac{gT^2}{2\pi} \tag{13}$$

$$L = T \sqrt{\frac{gd}{F}} \tag{14}$$

$$F = G + \frac{1}{1.0 + 0.6522G + 0.4622G^2 + 0.0864G^4 + 0.675G^5} \tag{15}$$

$$G = 2\pi \left(\frac{d}{L_o}\right) = \left(\frac{2\pi^2}{T}\right)\frac{d}{g} \tag{16}$$

where T is the deepwater wave period and d is the total water depth at the reef crest. Both T and d are known values.

b. After L and L_o are computed, the ratio of group velocity to individual wave velocity (n) and wave height (H) at the reef crest are obtained from the equations below

$$n = \frac{1}{2}\left[1 + \frac{4\pi d / L}{\sinh(4\pi d / L)}\right] \tag{17}$$

$$H = H_o \sqrt{\frac{1}{2}\,\frac{1}{n}\,\frac{1}{L/L_o}} \tag{18}$$

c. By assuming a bottom slope m equal to 1/10.6 or 0.0943 (characteristic of the seaward reef face), the incipient wave breaking height (H_b) is computed from the following equations

$$H_b = \frac{bd}{1 + a\ (\ d\ /\ gT^2\ )} \tag{19}$$

$$a = 43.75\ (\ 1 - e^{-19m}\ ) \tag{20}$$

$$b = \frac{1.56}{(1 + e^{-19.5m})} \tag{21}$$

d. If $H \geq H_b$, wave breaking is assumed to take place on the reef crest and wave setup (S_w) is computed using Equation 22

$$S_w = 0.15\ d \tag{22}$$

where d is the total water depth at the reef crest.

e. If $H < H_b$, wave breaking is assumed to take place on the beach slope, the breaking wave height is estimated to be the wave height at the reef, and wave setup (S_w) is calculated using the following equations

$$d_b = \frac{H}{b - [\ a\ (\ H/gT^2)]} \tag{23}$$

$$S_w = 0.15\ d_b \tag{24}$$

where d_b is the depth of water at breaking. Equations 17 to 21 and Equation 23 are obtained from the SPM (1984). Note in Equations 22 and 24, which are Equation 3-77 of the SPM, the setdown at the breaking location is neglected, which results in a conservative estimate for setup.

PART VI: COMBINING SURGE, TIDE, AND WAVE EFFECTS TIME HISTORIES

42. Nineteen-year astronomical tide time histories for Saipan were constructed from tidal constituents obtained from "Tidal Harmonic Constants, Pacific and Indian Oceans, TH-2, April 1942", published by the U.S. Department of Commerce, Coast and Geodetic Survey, Washington. The tidal elevations were computed at 10-min intervals for the 19 year period from 1960 to 1978. The output was saved on 19 separate files for use as input files to the convolution process.

43. The storm surge, astronomical tide and deepwater wave time histories were combined in a manner identical to that used in the Agana Bay, Guam study. The algorithm of the computer code is briefly described as follows:

- a. a set of random numbers was generated on the computer. All surge and corresponding deepwater wave time histories were read into separate arrays.
- b. The starting time for the astronomical tide was randomly chosen, based on a stored random number. The time series was stored in an array.
- c. Surge time-histories, also computed at 10-minute intervals, were then added to the astronomical tide time-histories to form the surge-plus-tide total water level time history.
- d. Ponding level time-histories were computed using equation 12, and then added to surge-plus-tides water level to form surge plus tide plus wave-induced ponding total water level.
- e. Wave-induced setup time histories were computed using equations presented in Paragraph 41, and then added to the water level from d to obtain surge plus tide plus ponding and setup total water level.
- f. Since the surge time histories produced by each simulated storm were combined with 100 randomly chosen astronomical tides, steps b through d were carried out 100 times for each of the 168 storms. This procedure resulted in 16800 maximum water level values from which the stage-frequency curves were generated.

PART VII: STAGE-FREQUENCY CURVES

44. The ultimate objective of this study was to determine the 100-yr flood elevations at seven numerical gage locations on the west coast of Saipan. The method used to develop the stage-frequency curves is identical to that developed for the study of Agana Bay, Guam (Mark, in preparation). For each numerical gage, an array of stage intervals, each with a bandwidth of 0.1 ft, was created. The probability of each storm event was added to the cumulative probability associated with the interval which bracketed the maximum water level computed for that event. The probability of each storm event was computed as the product of the probabilities of the five JPM parameters assigned to that event and the yearly probability of typhoon occurrence. The exceedance, or cumulative probability, for each interval was calculated by adding its probability to the cumulative probability of the next higher interval whose stage is one increment greater.

45. Figures 15 through 21 present the computed stage-frequency curves for the seven locations of interest (shown in Figure 2) along the west coast of Saipan. The total water level, represented by the solid line, was developed from the astronomical tide, storm-surge, and ponding due to waves breaking on the reef. The total water level plus wave-induced setup is shown in the figure as a dashed line.

46. The total water level with and without wave-induced setup for all seven locations at return periods of 10, 50, 100, and 500-years are shown in Table 4. It is shown that for the total water level without setup, the 100-yr water level varies from 6.3 ft at gage location 4 to 6.7 ft at gage location 3. For total water level plus wave-induced setup, it is shown that the 100-yr water level varies from 7.2 ft at gage location 4 to 7.7 ft at gage location 3.

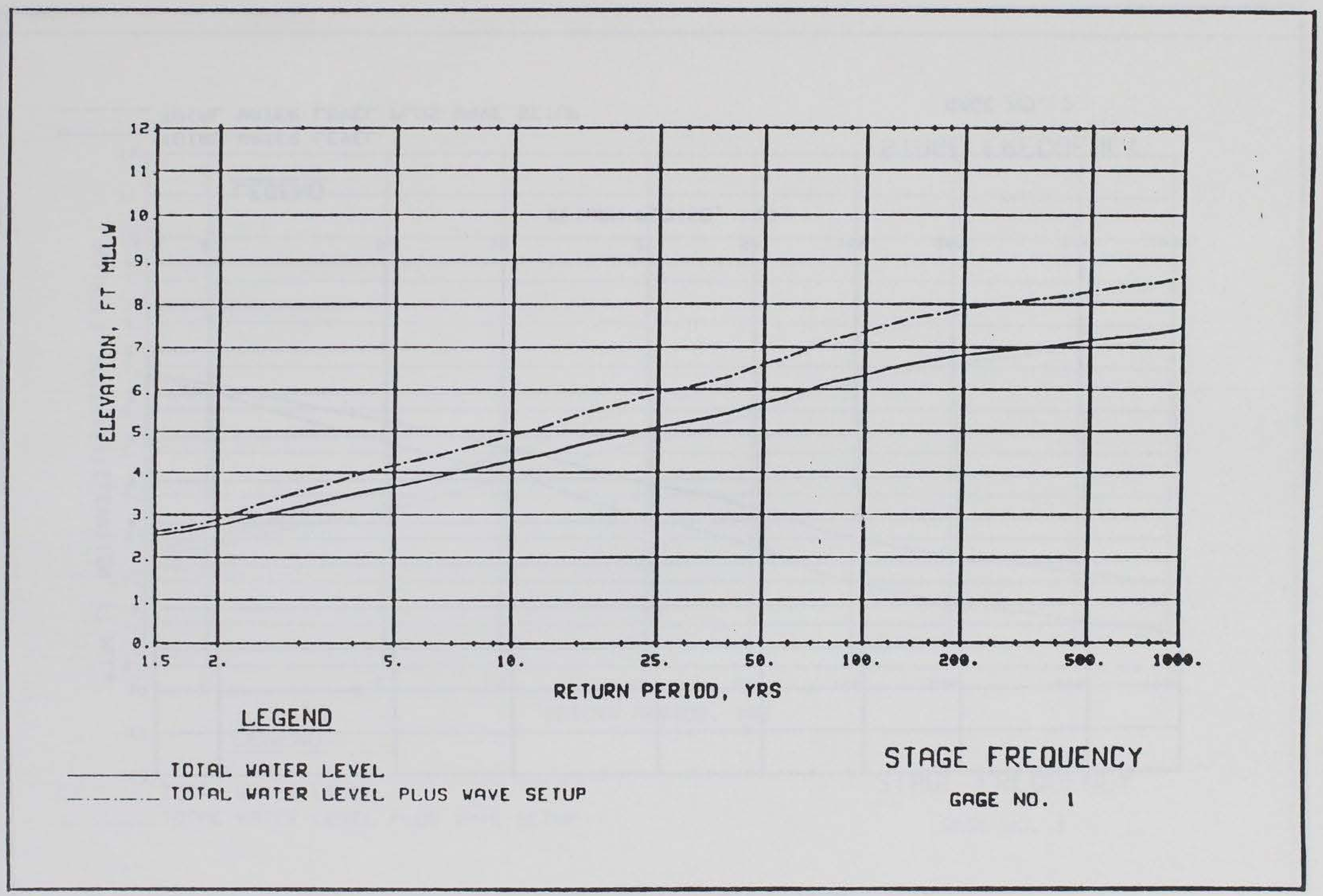


Figure 15. Stage-frequency curve for gage 1

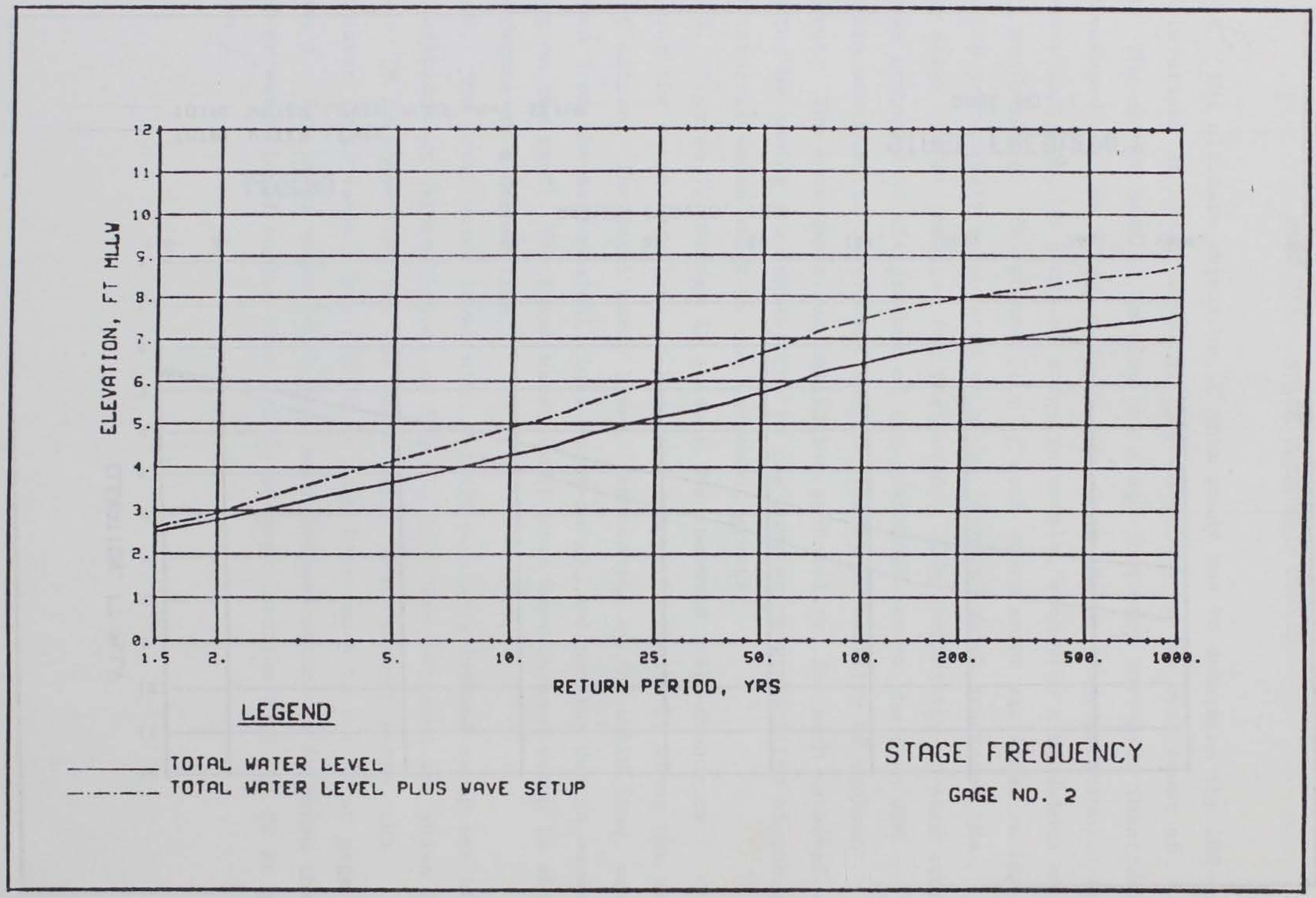


Figure 16. Stage-frequency curve for gage 2

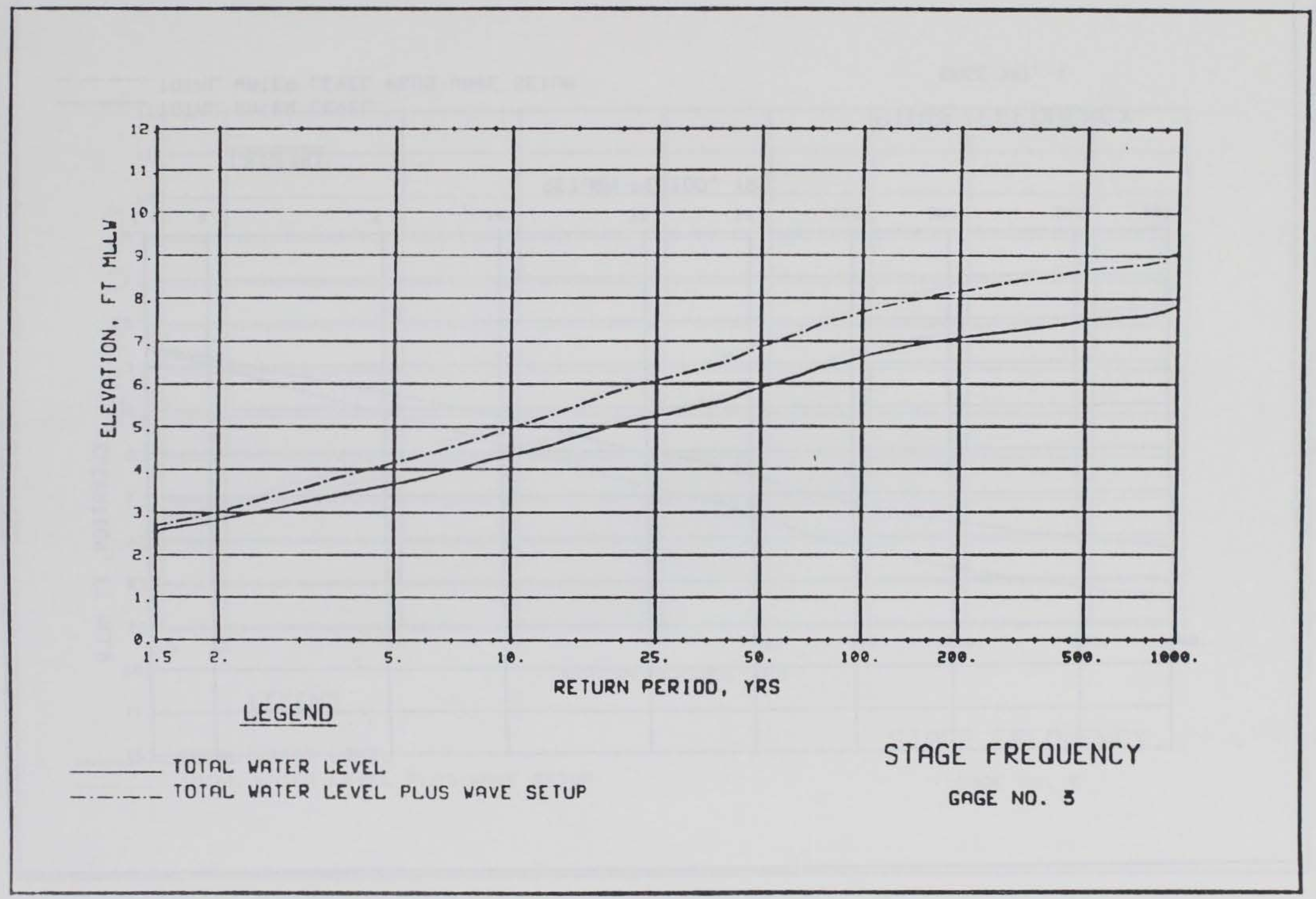


Figure 17. Stage-frequency curve for gage 3

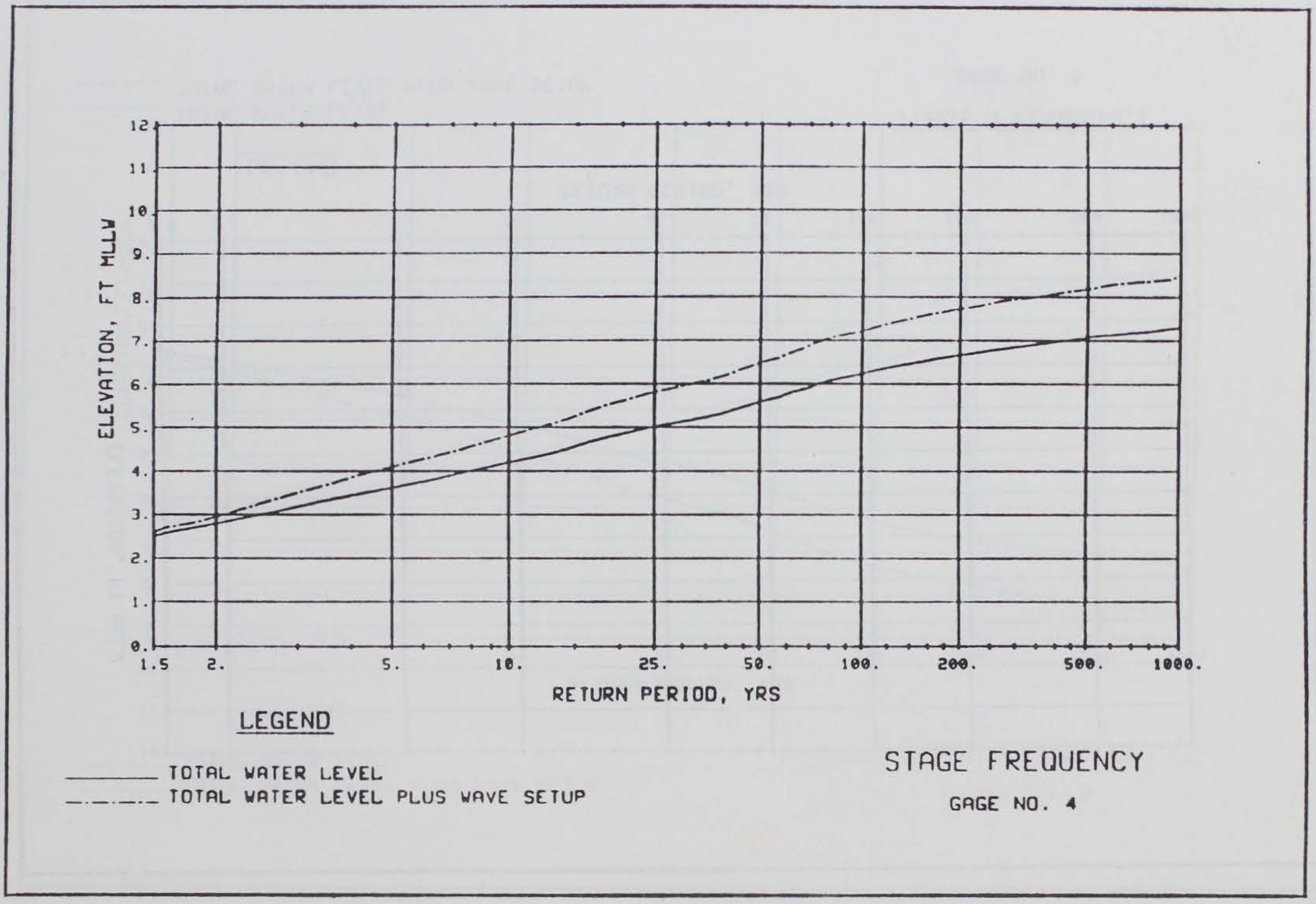


Figure 18. Stage-frequency curve for gage 4

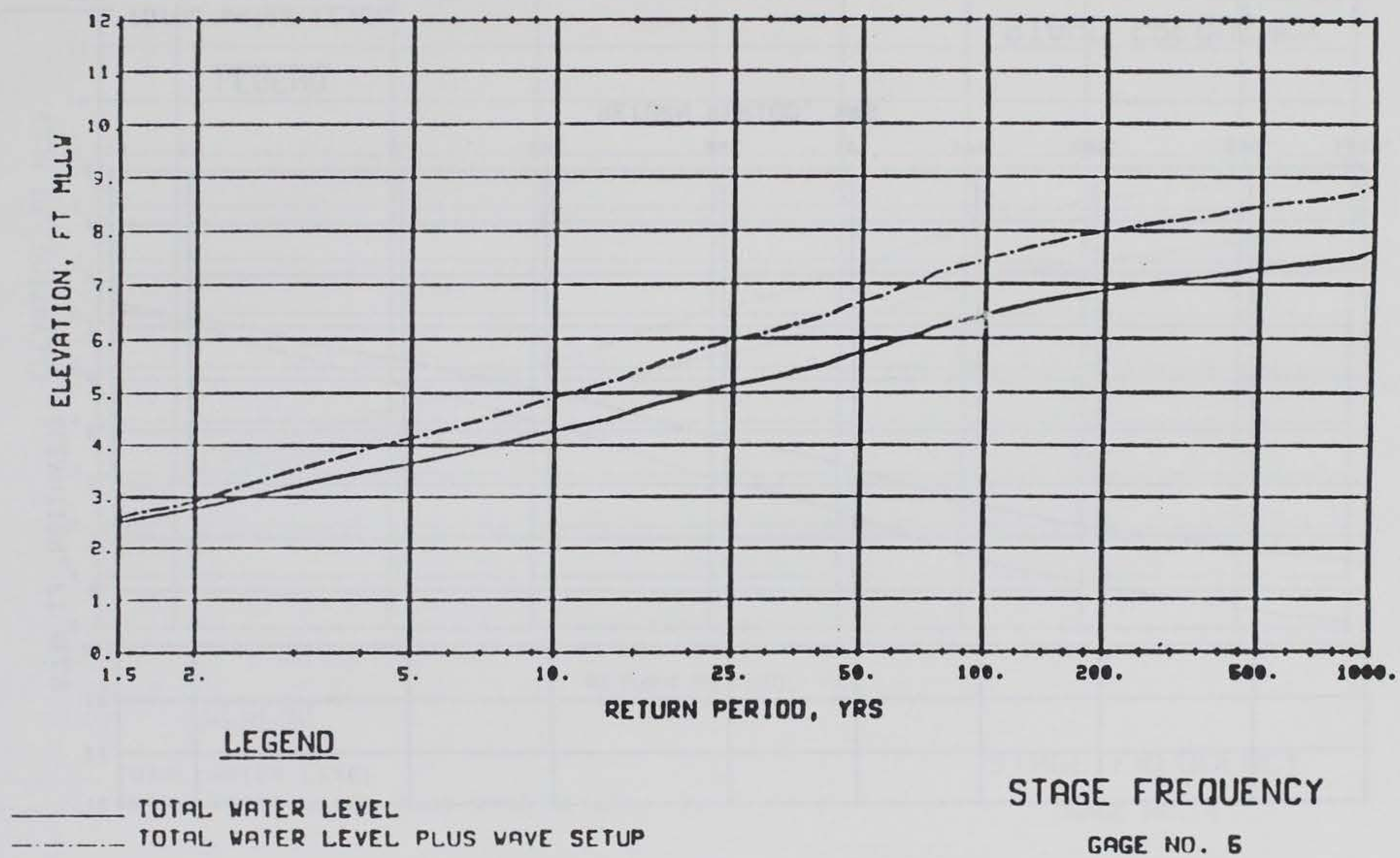


Figure 19. Stage-frequency curve for gage 5

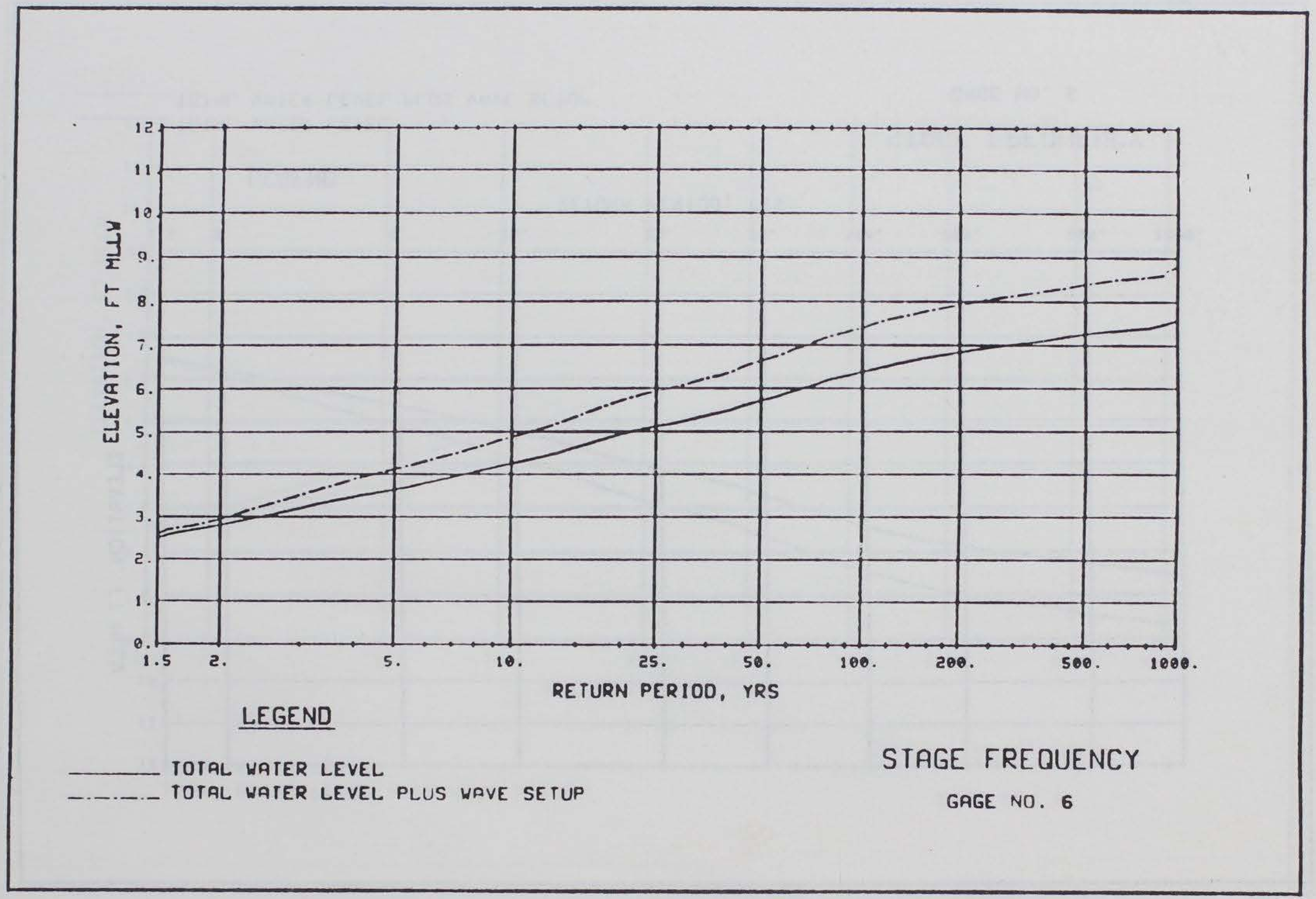


Figure 20. Stage-frequency curve for gage 6

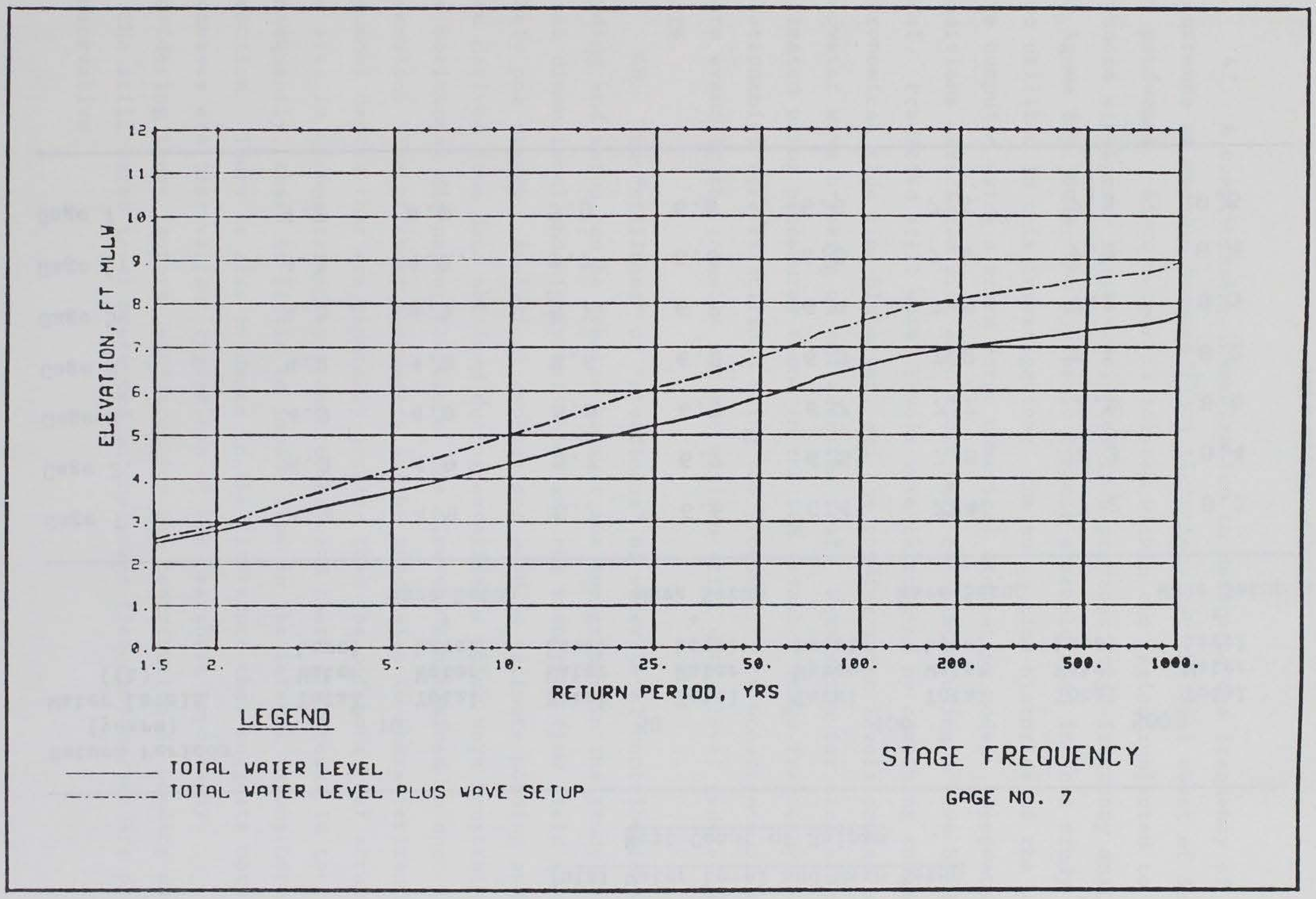


Figure 21. Stage-frequency curve for gage 7

Table 4

Return Periods for

Total Water Level and Wave Setup

West Coast of Saipan

Return Periods (years) Water Levels (ft)	10		50		100		500	
	Total Water Level	Total Water Level + Wave Setup	Total Water Level	Total Water Level + Wave Setup	Total Water Level	Total Water Level + Wave Setup	Total Water Level	Total Water Level + Wave Setup
Gage 1.	4.3	4.9	5.7	6.6	6.4	7.4	7.2	8.3
Gage 2.	4.3	4.9	5.7	6.7	6.5	7.5	7.3	8.4
Gage 3.	4.3	4.9	5.9	6.9	6.7	7.7	7.5	8.6
Gage 4.	4.2	4.8	5.6	6.5	6.3	7.2	7.1	8.2
Gage 5.	4.3	4.9	5.7	6.7	6.4	7.5	7.2	8.5
Gage 6.	4.3	4.9	5.7	6.6	6.5	7.4	7.3	8.4
Gage 7.	4.3	4.9	5.8	6.8	6.6	7.6	7.3	8.5

PART VIII: SUMMARY

47. A comprehensive investigation to determine the frequency of occurrence of typhoon-induced flood elevations for the west coast of Saipan was performed. Since Saipan is located within the region subjected to typhoons similar to those considered in a previous stage-frequency analysis for Agana Bay, Guam, the synthetic typhoon ensemble used in that study was also utilized in this investigation. The surge time-histories of the storms were computed using a storm surge numerical simulation model. Deepwater wave conditions associated with each storm were calculated using a wave hindcast model. Predicted still water levels were calculated by combining surge and astronomical tide time-histories, and the ponding water levels caused by deepwater wave breaking on and over the reef. Wave setup for each storm was estimated using procedures found in the SPM (1984). Stage-frequency relationships were established using the probability of occurrence of each storm event in the ensemble and the maximum still water level generated by the storm.

48. The "stillness" or "steadiness" of water level contributions due to ponding and setup can be debated because the topography in the study area is three-dimensional and highly variable, and the resulting flow field is most likely not steady. Analytical expressions used to estimate ponding and setup were derived from data obtained during experiments which were constrained in one horizontal dimension; therefore, the flow was constrained in one dimension. The offshore bathymetry at the study site is characterized by lagoonal depths that are generally greater than the offshore reef structure, the area is unconstrained by promontories, and there are breaks in the reef. Consequently, there is little to impede flow in the lateral (alongshore) direction. There is also evidence in the literature that suggests both processes are time-variant regardless of the nearshore topography. Considering these factors, estimates for the contribution of ponding and setup to the still water level presented in the stage-frequency curves are probably conservative.

REFERENCES

Butler, H. L. 1978. "Coastal Flood Simulations in Stretched Coordinates," Proceedings, 16th International Conference on Coastal Engineering, Hamburg Germany.

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

Butler, H. L., Prater, M.D. "Innovative Determination of Nearshore Flood Frequency," Twentieth Coastal Engineering Conference, Proceedings of the International Conference, Vol III, November 9-14, 1986, Taipei, Taiwan

Mark, D. In preparation. "Typhoon Analysis for Agana Bay, Guam," Technical Report, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hardy, A. T. and Crawford, P. L. 1986. "Frequency of Coastal Flooding at Roughans Point, Broad Sound, Lynn Harbor, and the Saugus-Pines River System," Technical Report, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kraus, N. C. et al. 1988. "Coastal Processes at Sea Bright to Ocean Township, New Jersey," Technical Report, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hughes, S .A. and Jensen, R. E. 1986. "An User's Guide to SHALVW: Numerical Model for Simulation if Shallow-water Wave Growth, Propagation, and Decay," Instruction Report (in preparation), US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS.

Meyers, V. A. 1970. "Joint Probability Method of Tide Frequency Analysis Applied to Atlantic City and Long Beach Island, NJ, "ESSA Technical Memorandum WBTM HYDRO 11, US Department of Commerce, Environmental Science Service Administration, Weather Bureau, Silver Spring, MD.

National Weather Service. 1972. "Revised Standard Project Hurricane for the Atlantic and Gulf Coasts of the United States," Memorandum HUR 7-120, Hydrometeorologicl Branch, Office of Hydrology, Silver Spring, MD.

National Weather Service. 1979. "Meteorological Criteria for Standard Project Hurricane and Probable Maximum Hurricane Wind Fields, Gulf and East Coasts of the United States," Technical Report NWS 23, Washington, DC.

"Tidal Harmonic Constants, Pacific and Indian Oceans," TH-2, April 1942. US Department of Commerce, Coast and Geodetic Survey, Washington, DC.

Reid, R.O. et al. 1977. "Development of SURGE II Program with Application to the Sabine-Calcasieu Area for Hurricane Carla and Design Hurricanes," Technical Report No. 77-13, Coastal Engineering Research Center, CE, Fort Belvoir, VA.

Seelig, W. N. 1983. "Laboratory Study of Reef-Lagoon System Hydraulics," Journal of Waterway, Port, Coastal and Ocean Engineering, American Society of Civil Engineers, Vol 109, No 4, pp 380-391.

Shore Protection Manual. 1984. 4th ed., 2 vols, US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, US Government Printing Office, Washington, DC.

Wanstrath J. J. 1977. "Nearshore Numerical Storm Surge and Tidal Simulation," Technical Report H-77-17, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Weir, R. C. 1983. "Tropical Storms Affecting Guam (1671 - 1980)," Technical Note, US Naval Oceanography Command Center/Joint Typhoon Warning Center, San Francisco, CA.