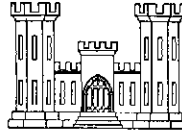


DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS

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HURRICANE SURGE PREDICTIONS
FOR CHESAPEAKE BAY

Miscellaneous Paper No. 3-59

September 1959

BEACH EROSION BOARD
OFFICE OF THE CHIEF OF ENGINEERS

John M. Darling

FOREWORD

In connection with its activities as an advisory agency to the various Corps of Engineer offices on design criteria for hurricane protection, the Board was requested by the North Atlantic Division of the Corps of Engineers to make preliminary estimates of hurricane surge elevations in the Chesapeake Bay region for the Norfolk, Washington, and Baltimore Districts of the Corps. This report presents the results of these computations, and indicates the methods employed.

The author of this report, Charles L. Bretschneider, is a Hydraulic Engineer in the Research Division of the Beach Erosion Board. At the time of publication of this report, Joseph M. Caldwell was Chief of the Research Division and Major General W. K. Wilson, Jr. was President of the Board.

Funds for the work discussed in this report were provided through the North Atlantic Division by the three interested Districts from hurricane funds allocated to them, and from Special Studies (hurricane) funds allocated directly to the Beach Erosion Board.

Views and conclusions expressed herein are not necessarily those of the Beach Erosion Board.

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SYMBOLS

- A = cross sectional area of vertical section through the entrance from Atlantic Ocean into Chesapeake Bay (square feet)
- A_U = upper limit or range of A
- A_L = lower limit or range of A
- B = breadth of Continental Shelf from the coast to the continental slope (nautical miles)
- C = coefficient of discharge
- C_1 = $\sqrt{gd_1}$, long wave celerity at depth d_1 (feet per second)
- C_0 = $\sqrt{gd_0}$, long wave celerity at depth d_0 (feet per second)
- \bar{C} = $1/2 (C_1 + C_0)$ (feet per second)
- F = fetch length (nautical miles)
- g = acceleration of gravity (32.2 ft./sec.²)
- h = surge hydrograph elevation (primary surge) (feet)
- h_0 = surge hydrograph elevation (primary surge) on open coast (feet)
- $h_1, h_2, h_3, \dots, h_{10}$ = h at sections 1, 2, 3, ..., 10 (feet)
- k = 3.0×10^{-6} stress parameter
- P = ratio of ordinates of assumed hydrographs to model hydrograph
- Q = discharge, cfs, through entrance of Chesapeake Bay
- R = radius of maximum wind (nautical miles)
- r = radial distance from center of hurricane to position of interest (nautical miles)
- S = $h + \Delta S$, resultant surge elevation (primary surge plus component due to cross winds) (feet)

- S_o = resultant surge elevation on open coast, including component due to atmospheric pressure reduction from normal (feet)
- S = resultant surge elevation within Chesapeake Bay (feet)
- S = response factor
- T = period of free wave across the Continental Shelf $T = B/\bar{C}$ (hours)
- t, t_1, t_2 = time
- U = wind speed (miles per hour)
- U_r = root mean square wind speed
- \bar{v} = mean velocity through entrance of Chesapeake Bay $\bar{v} = Q/A$ (feet per second)
- V = volume of water (ft.³) above mean water level
- $V_1, V_2, V_3 \dots V_{10}$ = volume of water above mean water level for sections of Chesapeake Bay as shown on Figure 1
- V_T = sum of V for all ten sections
- W_m = maximum wind speed (miles per hour)
- Z = $\cosh \theta$ = function in cubic equation
- ΔF = increment of fetch length
- ΔP = atmospheric pressure reduction from normal (inches of mercury)
- Δt = $t_2 - t_1$, increment of time
- ΔS = increment of wind set-up

HURRICANE SURGE PREDICTIONS FOR CHESAPEAKE BAY

by

Charles L. Bretschneider

Research Division, Beach Erosion Board

I-INTRODUCTION

This report presents a comprehensive investigation of hurricane surge problems for the Chesapeake Bay area. Methods and techniques are presented, and are calibrated with available surge data, so that the computational procedures result in reasonable estimates of maximum hurricane surge for design purposes. It is believed that the final results given in this report can only be refined by use of additional hurricane surge data, suitable for furthering the present investigation. Such additional hurricane surge data are not available at present, but might become available from future hurricanes affecting the Chesapeake Bay area. In addition theoretical studies, the formulas and techniques of which must also be calibrated, performed in the future, might tend to refine the surge results presented in this report.

The steps involved in the solution of any hurricane surge problem will differ from one situation to the next. One set of rules applicable to a certain area of interest may not necessarily be suitable for some other area. A classification of the problem, such as given by Bretschneider (1)* should be the first step in the solution of any hurricane surge problem. The problem for the Chesapeake Bay area overlaps a number of the classes outlined in reference 1.

Briefly, the problem consists of: reviewing data on all past hurricanes which affected the Chesapeake Bay area; establishing and calibrating formulas and techniques using data from the past hurricanes; and applying the formulas and techniques to hypothetical hurricanes. The process entails computing the surge on the open coast, routing this primary surge through the entrance to Chesapeake Bay, up the bay to various river mouths, then up those rivers to sites of interest. Allowance must be made for convergence and friction along the river channels, and modifications of the primary surge due to additional wind stress on the surface of the primary surge. For computational purposes Chesapeake Bay was divided into ten sections between Norfolk and Baltimore, as illustrated in Figure 1.

Details of the procedures are discussed in Section II of this report. Section III discusses the hurricane surge in regard to the

* Numbers in parentheses indicate references on page 50

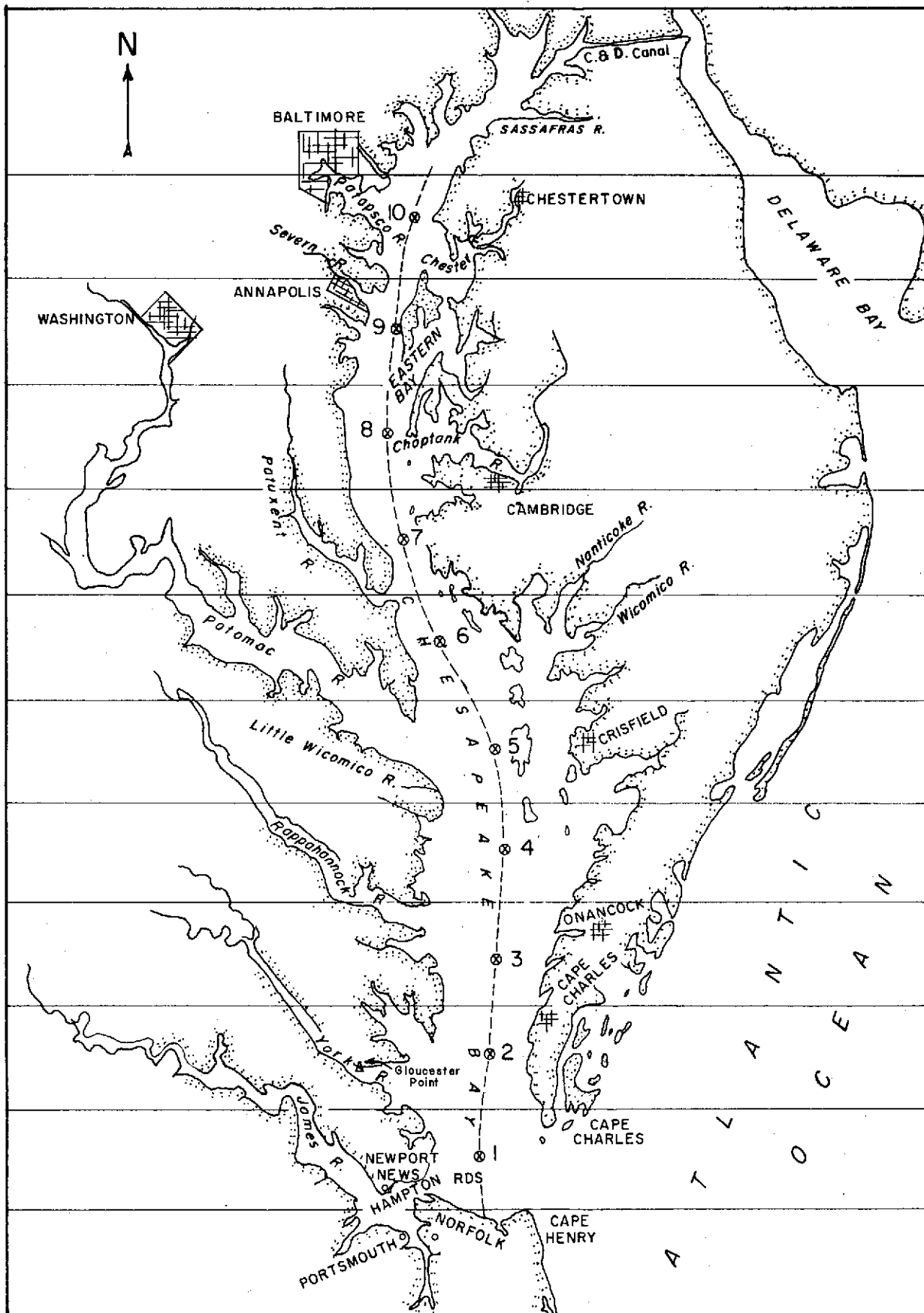


FIGURE 1. MAP OF CHESAPEAKE BAY AREA.

general area of Chesapeake Bay. Section IV discusses special predictions for the Norfolk, Washington, and Baltimore areas, and Section V summarizes the results of the computations.

Reference is made to a similar report on Hurricane Surge for the Delaware Bay area, since the two reports, Delaware Bay and Chesapeake Bay, have much in common (see reference 6).

II-PROCEDURE

General. The procedure used in this report consists of the following steps:

- a. A review of all past hurricanes for which data are available and which had significant effect on the Chesapeake Bay area.
- b. A selection of a hurricane from the above review, which might have possessed critical conditions for producing its maximum surge within Chesapeake Bay. Such a hurricane might then be used as a model hurricane for calibration purposes, for predicting surge heights for a standard project or design hurricane.
- c. A series of hydraulic computations for the entrance to Chesapeake Bay to determine the amount of surge which might pass through the entrance from the open ocean.
- d. Determination of surge on open coast coincident with that within Chesapeake Bay.
- e. A selection of prediction curves for obtaining surge elevations for a standard project or design hurricane.

Past Hurricanes. Detailed studies of past hurricanes affecting Chesapeake Bay have been made by the U. S. Weather Bureau. These studies are given in HUR Memorandums numbered 7-14, 7-18, 7-19, and 7-32. Additional wind and tide data obtained with the aid of other governmental agencies and local interests are available from the files of various U. S. Army Engineer Districts.

Of all the past hurricanes affecting the Chesapeake Bay, only four are sufficiently documented for this particular study. The dates of these hurricanes are:

- a. August 22 - 24, 1933
- b. August 11 - 13, 1955 (Connie)
- c. August 15 - 18, 1955 (Diane)
- d. October 14 - 17, 1954 (Hazel)

The above hurricanes do not necessarily represent the most severe one which might have occurred over Chesapeake Bay during past history, and certainly do not represent the most severe which could occur in the future. A brief summary of pertinent data for these four hurricanes is given in Table I, but greater details are available in appropriate HUR Memorandums. Figures 2 through 5 represent the surge hydrographs for these hurricanes. The predicted astronomical tide elevations have been eliminated leaving only that component of water level rise due to the hurricane influence, wind stress and atmospheric pressure reduction. Each of these four hurricanes is discussed below.

a. Hurricane of August 22 - 24, 1933 (Figure 2). Of the four storms, the August 1933 hurricane is ranked the third most intense in regard to maximum winds and central pressure anomaly over the open ocean, the second most intense in regard to maximum winds over Chesapeake Bay, and the most intense in regard to maximum surge within Chesapeake Bay. The storm center travelled up the west side of Chesapeake Bay. The surge hydrographs are relatively smooth, because the hurricane moved up the bay at a speed very nearly equal to that of a free wave travelling up the bay. This hurricane moved at a near critical speed for producing its maximum surge. If the hurricane had moved more rapidly, it would have moved over the primary surge and regenerated a secondary surge ahead of the primary surge. The result would have been a surge with two peaks, neither of which would have been as great as the actual condition.

b. Hurricane of August 11 - 13, 1955 (Figure 3). This hurricane was of greater intensity over the open ocean than was the August 1933 storm. The storm center traversed the east side of Chesapeake Bay. Within the bay, the maximum winds were somewhat less than those of the August 1933 storm. This storm moved more slowly than the August 1933 storm. Since its speed was also less than that of the free wave and as it moved up the east side of the bay, a double peak in the surge hydrograph resulted. The first peak is due to cross winds adding to free surge ahead of the hurricane's center. The second peak represents a resurgence effect. If the center of this hurricane had moved up the west side of Chesapeake Bay, the winds might have been more favorable to producing a greater surge than existed during the August 1933 hurricane, and in this case a smoother hydrograph would have been expected.

c. Hurricane of August 15 - 18, 1955 (Figure 4). The center of this hurricane passed about 100 miles west of Chesapeake Bay. The surge from the open ocean was not a maximum at the entrance to Chesapeake Bay; and the winds up the bay were not as strong as for the other three storms under discussion. As a result, the surge elevations were less. The storm moved at a speed slightly less than that of the free wave, and the hydrographs show only minor second peaks.

TABLE I
 BRIEF DESCRIPTION OF FOUR PERTINENT HURRICANES
 (See HUR 7-14, -18, -19, -32 for additional information)

Figure Number References	2 HUR 7-14	3 HUR 7-19	4 HUR 7-19	5 HUR 7-18
Dates	Aug. 22-24 1933	Aug. 11-13 1955 Connie	Aug. 15-18 1955 Diane	Oct. 14-17 1954 Hazel
Path of Storm Center	Just West of Chesapeake Bay westside	Just West of Chesapeake Bay eastside	About 100 miles west of Chesapeake Bay westside	About 100 miles west of Chesapeake Bay westside
Radius of Maximum wind, R, N. Miles	54	45	45	36
Central Pressure Anomaly ΔP, inches of Mercury	0.85	1.37	0.71	1.66
Forward Speed Over Ocean, Knots	23	12	21	55
Forward Speed Over Chesapeake Bay, Knots	13	10	12	36
Maximum Wind Speed Over Ocean, MPH	61	72	54	92
Maximum Wind Speed Over Chesapeake Bay, MPH	50	45	35	70
MAXIMUM HURRICANE SURGE ABOVE PREDICTED ASTRONOMICAL TIDE IN FEET AT STATIONS LISTED				
Hampton Roads, Va.	6.6	4.4	0.6	1.8
Gloucester Point, Va.		4.5	2.3	2.9
Solomons Island, Md.		4.2	2.2	2.8
Annapolis, Md.	5.8	4.9	3.2	4.2
Baltimore, Md.	7.2	5.2	3.7	4.8

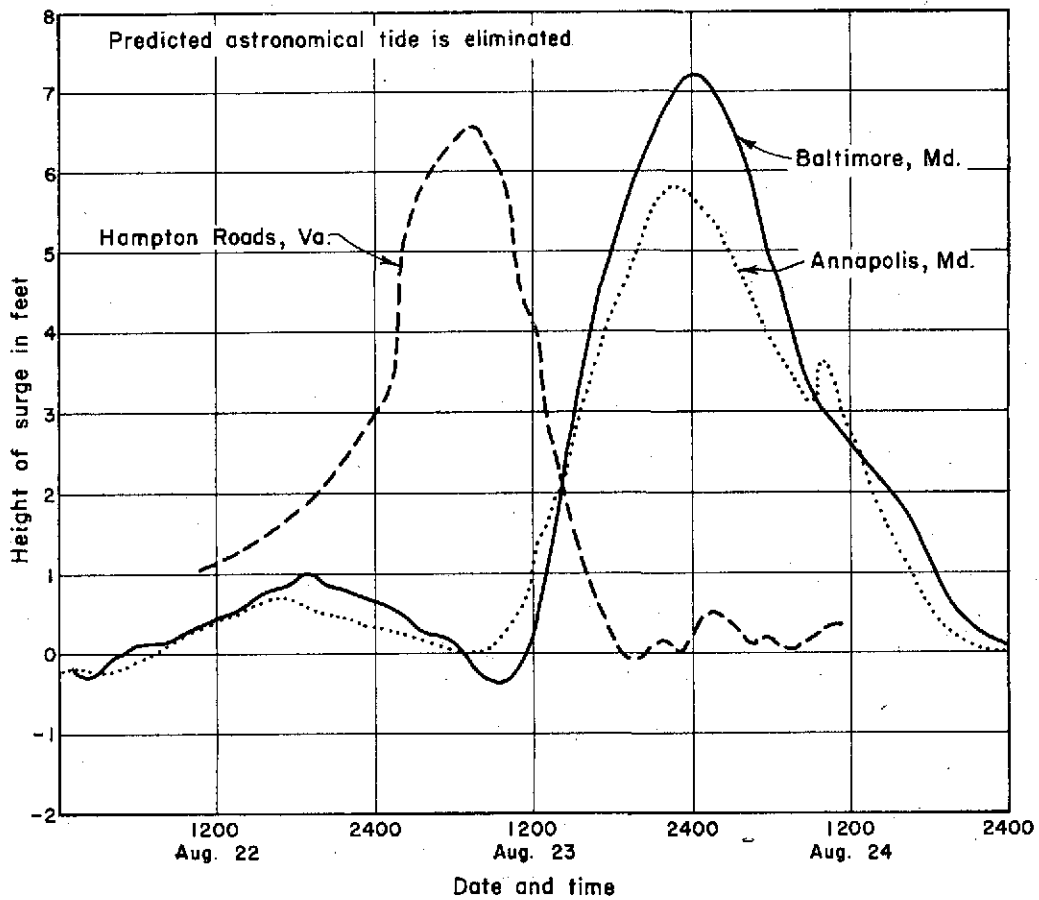


FIGURE 2. HURRICANE SURGE OF AUGUST 22-24, 1933

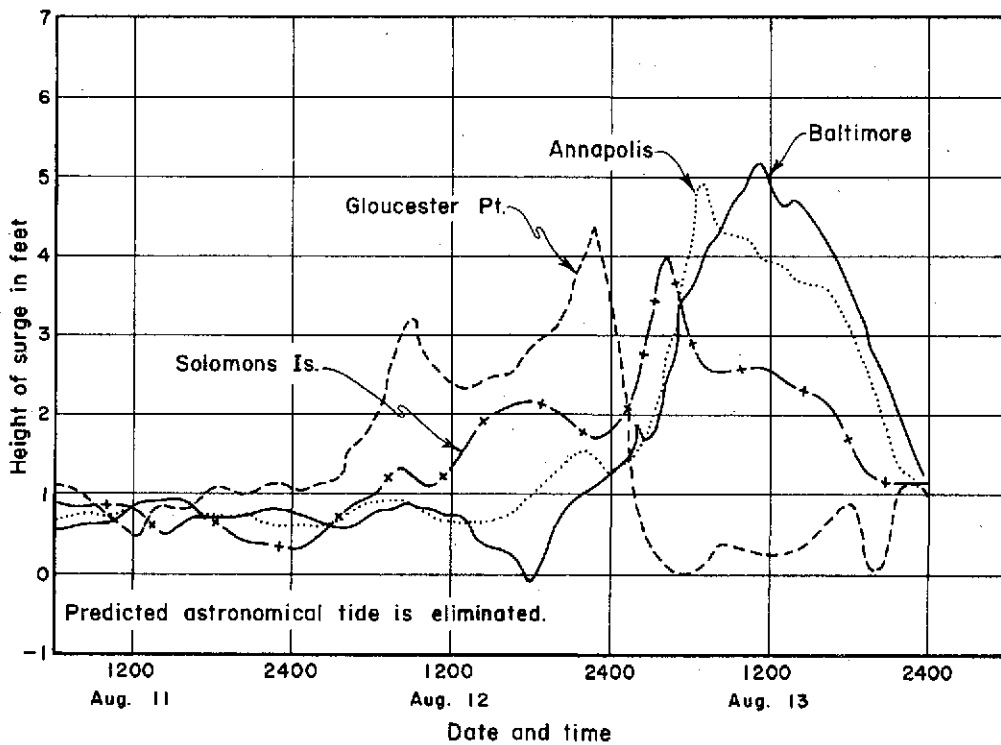


FIGURE 3. HURRICANE SURGE OF AUGUST 11-13, 1955 (CONNIE)

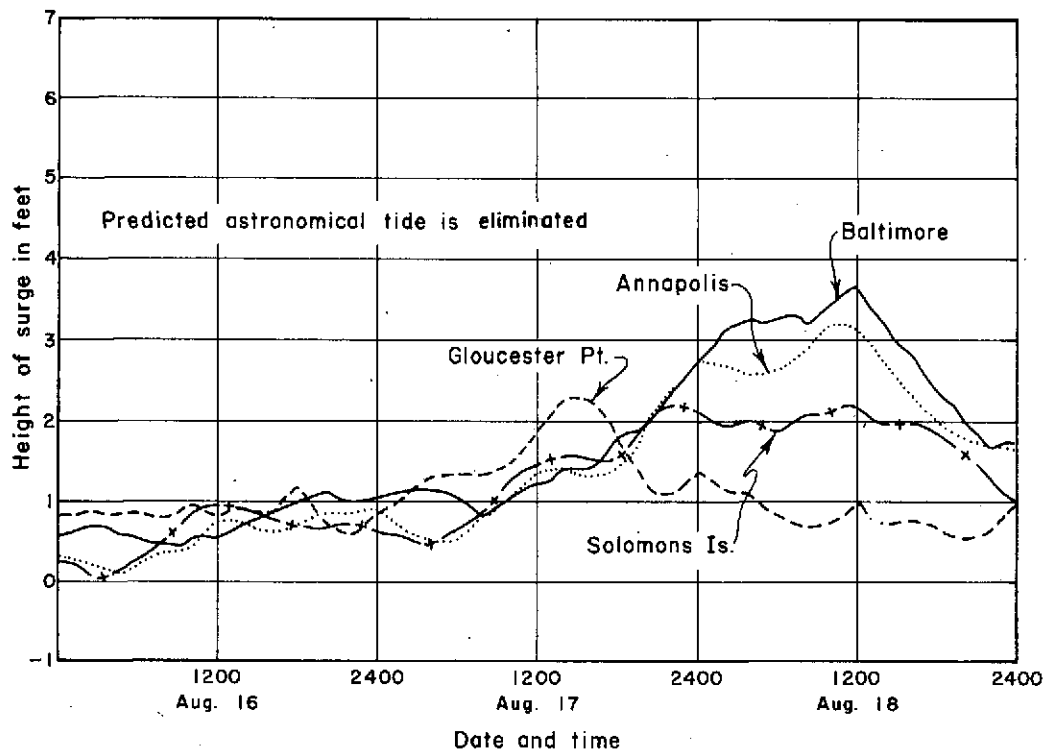


FIGURE 4. HURRICANE SURGE OF AUGUST 16-18 1955 (DIANE.)

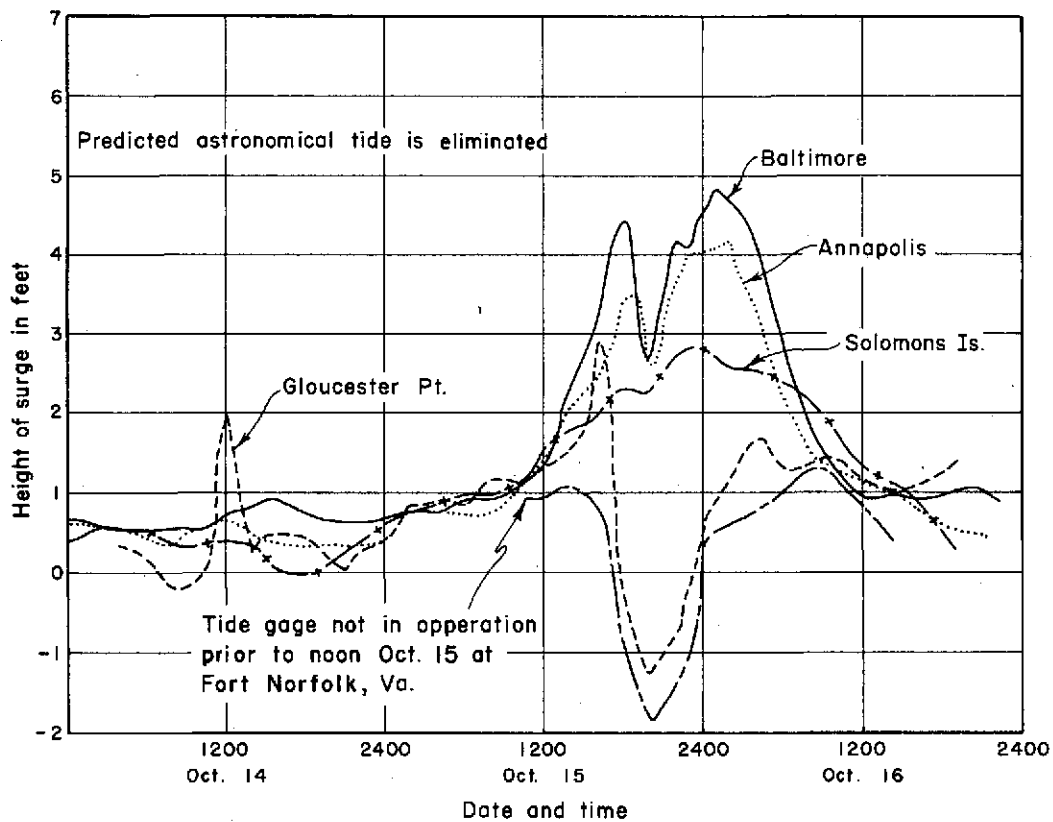


FIGURE 5. HURRICANE SURGE OF OCTOBER 14-16, 1954 (HAZEL)

d. Hurricane of October 14 - 17, 1954 (Figure 5). The center of this hurricane passed about 100 miles west of Chesapeake Bay as did the August 15 - 18, 1955 hurricane, but its path was more curved. The winds up Chesapeake Bay were much greater during the October 1954 hurricane than during any of the other three hurricanes being 70 mph for the former, but only 35 mph for the August 15 - 18, 1955 hurricane. However, there was no great difference in the maximum surges generated by these storms. The reason for the above condition is that the October 1954 hurricane had a forward speed of 36 knots, three times that for the other storms. As a result, the storm moved ahead of the primary surge, regenerating additional secondary surges. If this storm had moved more slowly and yet retained the same wind field over the bay, the highest surge elevations on record might have been experienced. However, if the storm had moved more slowly, the winds would have diminished because of the longer period of time the hurricane would have been over land. Also, the center of the storm was too far westward.

Selection of Model Hurricane. The hurricane of August 22 - 24, 1933 was selected as the one which appeared most usable as a model hurricane for calibration purposes. This hurricane was not associated with the strongest winds over Chesapeake Bay, but was associated with the highest surge elevations for which surge data and hydrographs are available. The fact that this hurricane followed very nearly a critical path and travelled very nearly at a critical speed makes this hurricane suitable as a model. In Figure 6 isolines of surge height were constructed from the hydrographs in Figure 2. Interpolations between Hampton Roads and Annapolis, and between Annapolis and Baltimore are based on available high water data. Figure 7, showing surge profiles along Chesapeake Bay, was prepared from cross plots of Figure 6. Section numbers correspond to those shown in Figure 1. The curves give a picture of the surge as a wave travelling up Chesapeake Bay, each curve representing the surface profile at a particular time. The dashed curve gives the profile and position of the surge crest at the time of maximum volume of water in Chesapeake Bay. This is also the time when the net flow of water through the entrance of the Chesapeake Bay reached zero.

For computational purposes, Chesapeake Bay was divided into ten sections of equal length along the center axis (see Figure 1). Figure 6 was then used to obtain a mean (interpolated) hydrograph for the center of each of the ten sections. An attempt was made through smoothing of the data to allow a small contribution of rise in water level due to cross wind effects. These hydrographs, given in Figure 8, represent model hydrographs which are used later for hydraulic computations and hurricane surge predictions for storm intensities greater or less than, but of the same speed and path, as that of the August 1933 hurricane. Table II gives values of the surge elevations for the ten sections for half-hour increments of time.

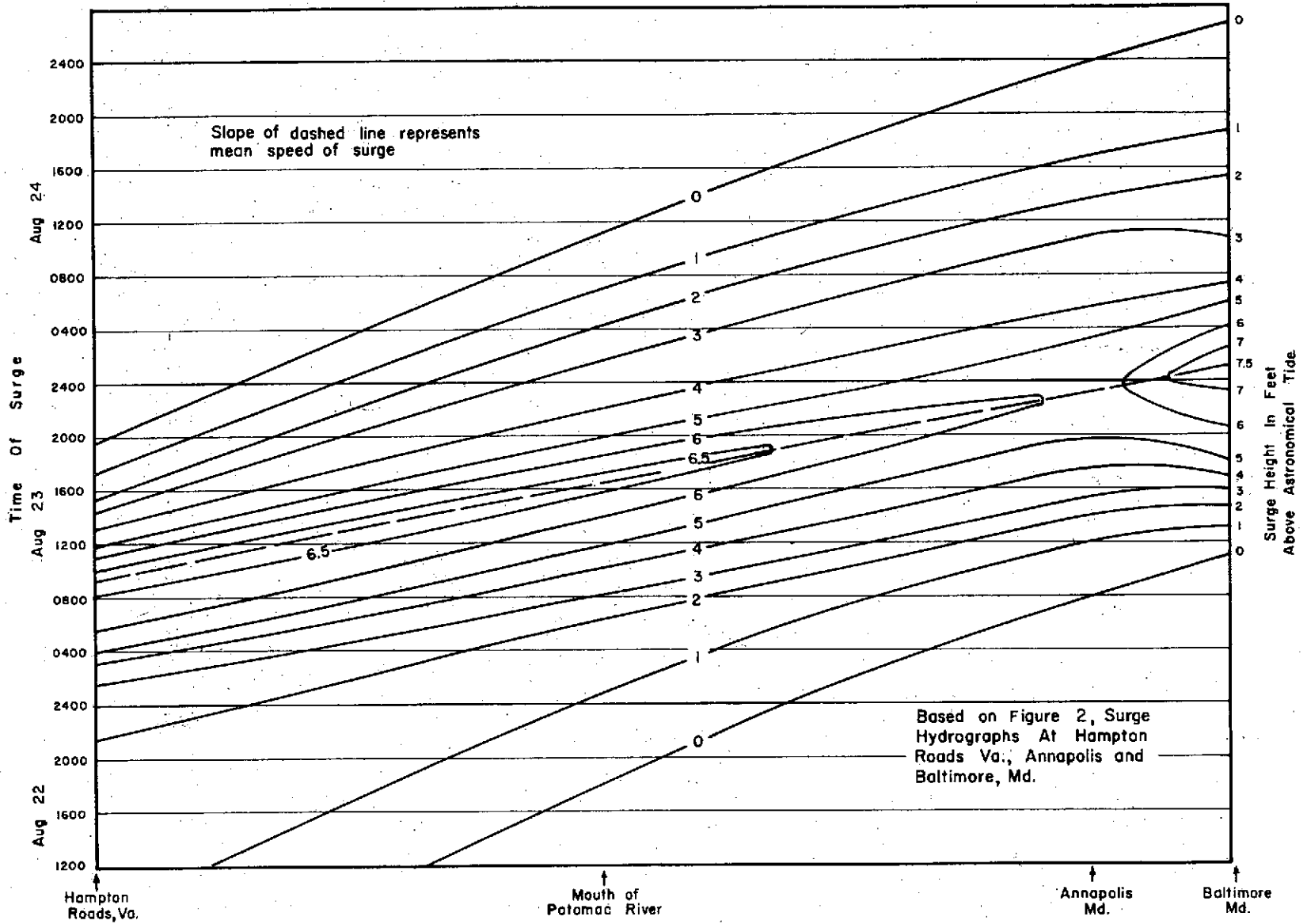


FIGURE 6. ISOLINES OF SURGE HEIGHT VERSUS TIME AND POSITION OF OCCURRENCE (1933 HURRICANE).

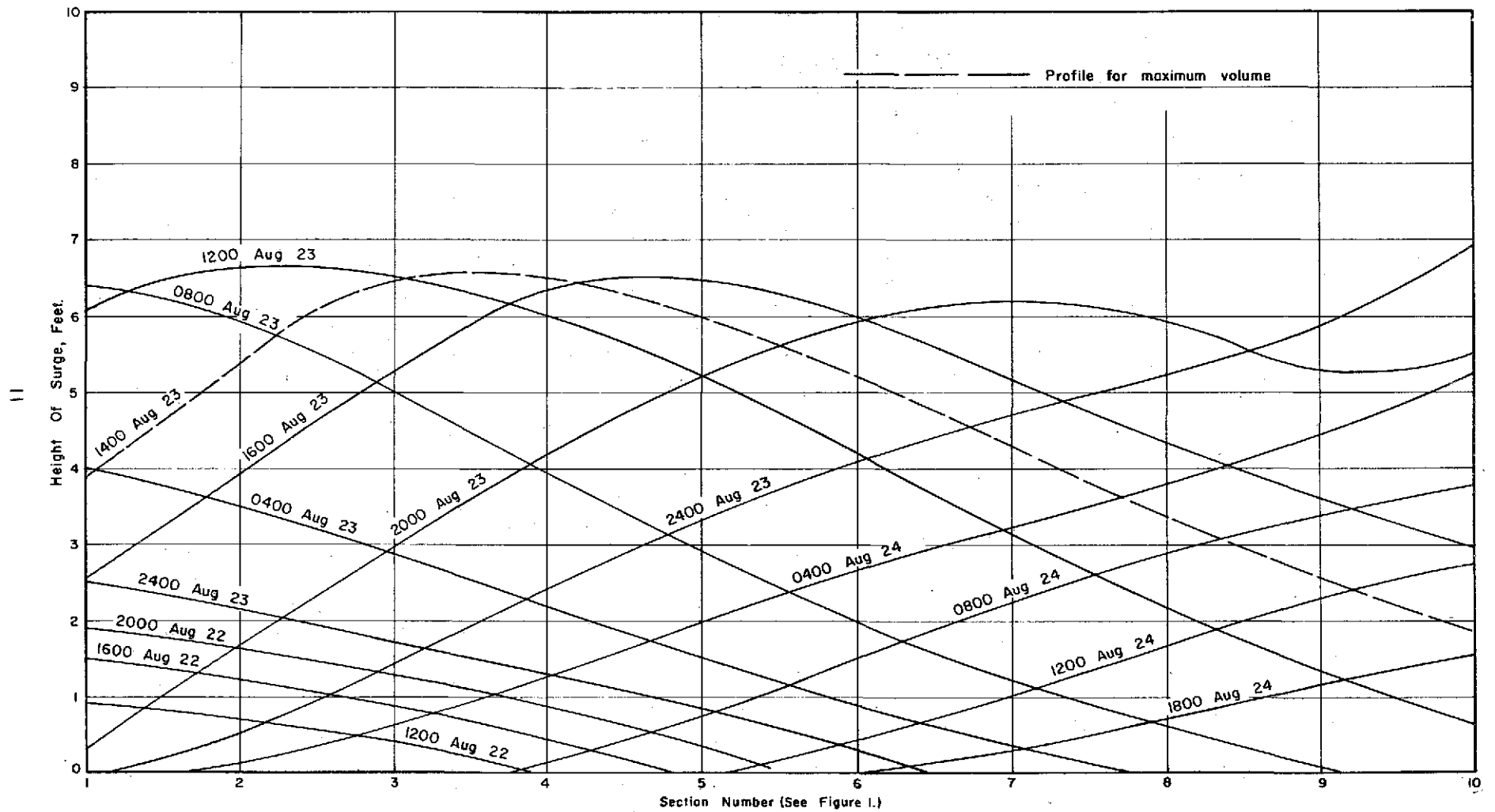


FIGURE 7. SURGE PROFILES ALONG CHESAPEAKE BAY BASED ON FIGURE 5 (1933 HURRICANE).

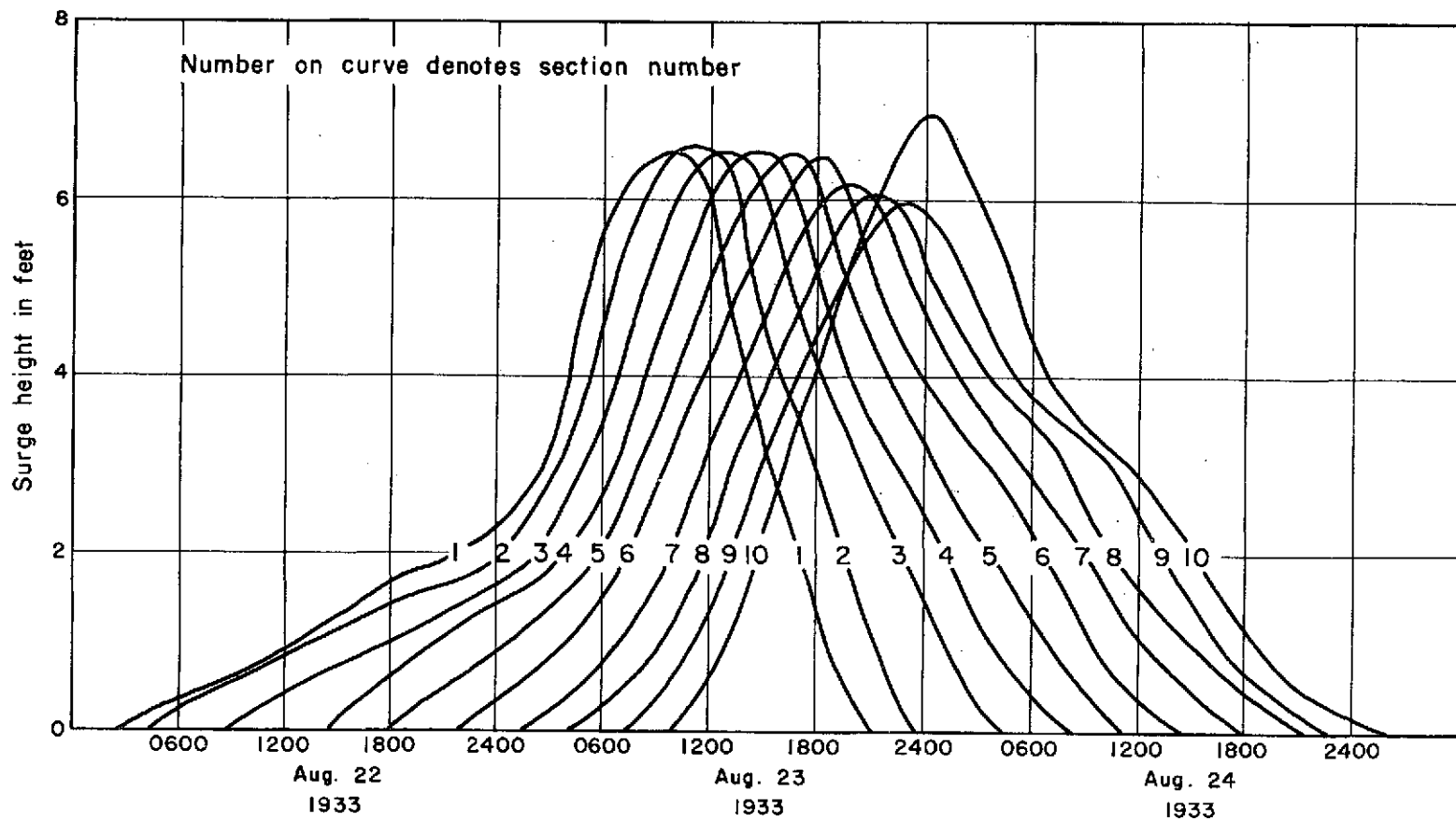


FIGURE 8. INTERPOLATED HYDROGRAPHS FOR TEN SECTIONS OF CHESAPEAKE BAY

TABLE II
 INTERPOLATED SURGE HYDROGRAPHS FOR TEN SECTIONS
 OF CHESAPEAKE BAY: HURRICANE AUGUST 22-24, 1933
 (values of h in feet above astronomical tide level)

Date	Elevations Section	h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8	h_9	h_{10}
		1	2	3	4	5	6	7	8	9	10
Aug. 22	EST										
	1200	0.90	0.90	0.45							
	1230	1.00	0.95	.50							
	1300	1.05	1.00	.55							
	1330	1.10	1.05	.60							
	1400	1.20	1.10	.65							
	1430	1.30	1.15	.70							
	1500	1.35	1.18	.75	0.10						
	1530	1.40	1.20	.78	.20						
	1600	1.45	1.30	.82	.25						
	1630	1.50	1.35	.87	.35						
	1700	1.60	1.38	.90	.45						
	1730	1.65	1.40	.95	.50						
	1800	1.70	1.45	1.00	.58	0.00					
	1830	1.78	1.48	1.07	.65	.10					
	1900	1.80	1.52	1.10	.75	.18					
	1930	1.85	1.58	1.15	.80	.21					
	2000	1.90	1.60	1.20	.90	.30					
	2030	1.92	1.65	1.25	1.00	.40					
	2100	1.95	1.70	1.30	1.05	.42	0.00				
	2130	2.00	1.73	1.35	1.10	.50	.01				
	2200	2.05	1.78	1.40	1.15	.60	.04				
	2230	2.10	1.80	1.45	1.21	.70	.10				
	2300	2.15	1.85	1.52	1.30	.78	.20				
2330	2.20	1.90	1.60	1.37	.82	.21					
2400	2.30	2.00	1.65	1.40	.90	.33					
Aug. 23	0030	2.40	2.20	1.70	1.50	.95	.40	0.00			
	0100	2.50	2.25	1.80	1.58	1.06	.43	.02			
	0130	2.60	2.40	1.85	1.60	1.17	.55	.10			
	0200	2.75	2.50	1.92	1.63	1.20	.60	.15			
	0230	3.00	2.65	2.00	1.70	1.30	.70	.20			
	0300	3.25	2.85	2.15	1.80	1.40	0.80	0.24			
	0330	3.60	3.20	2.40	1.86	1.50	.90	.33			
	0400	4.00	3.35	2.60	2.00	1.55	.98	.40	0.00		
	0430	4.60	3.50	2.80	2.10	1.62	1.05	.50	.10		
	0500	5.05	3.80	3.05	2.25	1.71	1.20	.60	.13		
	0530	5.50	4.20	3.30	2.42	1.83	1.37	.70	.20		
	0600	5.80	4.65	3.50	2.61	2.00	1.50	.80	.27		
	0630	6.00	5.00	3.70	2.80	2.20	1.60	.90	.37		
	0700	6.20	5.20	4.20	3.02	2.40	1.80	1.02	.43	0.00	
	0730	6.30	5.70	4.60	3.37	2.70	2.00	1.20	.55	.08	
	0800	6.40	6.00	4.90	3.60	2.94	2.15	1.38	.62	.18	
	0830	6.50	6.20	5.20	3.90	3.20	2.40	1.52	.77	.25	
	0900	6.55	6.35	5.55	4.40	3.42	2.60	1.63	.83	.38	
	0930	6.58	6.45	5.80	4.68	3.70	2.78	1.83	.83	.50	
	1000	6.58	6.55	6.00	4.93	4.00	3.10	2.02	1.20	.60	0.00
	1030	6.55	6.58	6.20	5.35	4.30	3.38	2.37	1.44	.80	.10
	1100	6.40	6.60	6.35	5.50	4.60	3.60	2.60	1.65	.90	.26
	1130	6.20	6.58	6.45	5.83	4.82	3.80	3.00	2.00	1.10	.50
	1200	6.00	6.55	6.50	6.00	5.10	4.10	3.23	2.20	1.21	.61
1230	5.40	6.50	6.58	6.20	5.30	4.45	3.50	2.45	1.60	.82	
1300	4.80	6.35	6.58	6.38	5.60	4.65	3.62	2.58	1.90	1.00	
1330	4.20	6.00	6.55	6.47	5.75	4.80	4.05	3.20	2.10	1.30	
1400	4.00	5.40	6.50	6.53	6.00	5.18	4.21	3.35	2.40	1.58	
1430	3.70	4.90	6.30	6.57	6.20	5.40	4.50	3.55	2.70	1.85	
1500	3.30	4.60	6.00	6.55	6.32	5.62	4.63	3.75	3.00	2.20	
1530	3.00	4.20	5.70	6.50	6.40	5.80	5.00	4.00	3.38	2.60	
1600	2.70	3.90	5.20	6.42	6.50	6.00	5.19	4.37	3.53	3.00	
1630	2.40	3.70	4.90	6.30	6.55	6.20	5.42	4.60	3.80	3.25	
1700	2.05	3.40	4.75	5.82	6.50	6.30	5.60	4.80	4.00	3.60	
1730	1.80	3.10	4.50	5.50	6.40	6.10	5.85	5.00	4.20	3.90	
1800	1.25	2.85	4.20	5.10	6.23	6.50	6.00	5.21	4.38	4.30	
1830	1.00	2.60	3.90	4.70	6.00	6.45	6.10	5.42	4.60	4.60	

TABLE II
(continued)

Date	Elevations Section	h_1 1	h_2 2	h_3 3	h_4 4	h_5 5	h_6 6	h_7 7	h_8 8	h_9 9	h_{10} 10
	EST										
	1900	0.70	2.20	3.65	4.38	5.60	6.42	6.15	5.61	4.80	5.00
	1930	.50	1.90	3.40	4.10	5.20	6.50	6.20	5.80	5.12	5.20
	2000	.30	1.60	3.15	3.86	4.95	5.82	6.19	5.90	5.25	5.45
	2030	.15	1.30	3.00	3.70	4.60	5.50	6.17	6.00	5.48	5.70
	2100	.00	1.00	2.80	3.50	4.40	5.20	6.02	6.03	5.60	5.85
	2130		0.80	2.60	3.37	4.20	4.90	5.85	6.04	5.78	6.10
	2200		.50	2.40	3.18	4.00	4.80	5.60	6.00	5.85	6.25
	2230		.30	2.10	3.00	3.90	4.50	5.30	5.90	5.97	6.60
	2300		.05	1.90	2.81	3.62	4.30	5.05	5.63	5.95	6.80
	2330			1.70	2.60	3.40	4.10	4.81	5.41	5.90	6.96
	2400			1.40	2.43	3.30	3.96	4.72	5.24	5.83	7.00
Aug. 24	0030			1.20	2.30	3.10	3.80	4.50	5.10	5.70	6.95
	0100			0.90	2.10	2.90	3.60	4.35	4.82	5.60	6.80
	0130			.70	1.81	2.70	3.55	4.12	4.60	5.40	6.60
	0200			.58	1.61	2.58	3.40	3.93	4.40	5.15	6.20
	0230			.40	1.42	2.50	3.30	3.80	4.22	4.92	6.10
	0300			.25	1.22	2.30	3.18	3.62	4.10	4.70	5.80
	0330			.15	1.10	2.10	3.00	3.50	4.00	4.50	5.50
	0400			.10	0.90	1.90	2.98	3.38	3.85	4.30	5.30
	0430				.74	1.75	2.70	3.20	3.70	4.10	5.10
	0500				.60	1.58	2.60	3.10	3.60	3.98	4.82
	0530				.50	1.40	2.40	2.95	3.50	3.81	4.55
	0600				.40	1.23	2.20	2.80	3.40	3.73	4.05
	0630				.24	1.10	2.03	2.68	3.30	3.62	4.05
	0700				.20	0.95	1.80	2.55	3.21	3.58	3.90
	0730				.11	.80	1.60	2.38	3.10	3.50	3.75
	0800				.70	1.40	2.20	2.98	3.40	3.40	3.65
	0830				.55	1.20	2.05	2.70	3.30	3.30	3.50
	0900				.40	1.10	1.98	2.50	3.20	3.20	3.45
	0930				.30	0.90	1.80	2.26	3.10	3.10	3.30
	1000				.20	.78	1.62	2.10	3.00	3.00	3.20
	1030				.10	.70	1.40	1.90	2.85	2.85	3.10
	1100					0.60	1.22	1.80	2.60	2.60	3.00
	1130					.45	1.10	1.58	2.50	2.50	2.90
	1200					.38	1.00	1.43	2.35	2.35	2.80
	1230					.30	0.90	1.40	2.22	2.22	2.70
	1300					.20	.70	1.25	2.04	2.04	2.50
	1330					.10	.65	1.16	1.99	1.99	2.35
	1400					.03	.58	1.08	1.77	1.77	2.20
	1430						.50	1.00	1.55	1.55	2.07
	1500						.40	0.90	1.40	1.40	1.90
	1530						.35	.80	1.30	1.30	1.70
	1600						.25	.70	1.08	1.08	1.60
	1630						.17	.57	0.90	0.90	1.40
	1700						.05	.50	.80	.80	1.26
	1730						.00	.40	.70	.70	1.10
	1800							.37	.62	.62	1.00
	1830							.30	.57	.57	0.90
	1900							.20	.43	.43	.79
	1930							.15	.37	.37	.70
	2000							.10	.31	.31	.60
	2030							.00	.25	.25	.50
	2100								.20	.20	.40
	2130								.10	.10	.35
	2200								.05	.05	.30
	2230								.01	.01	.22
	2300								.00	.00	.19
	2330										.13
	2400										.07

Hydraulic Computations. The hydraulic computations consist of a time history of the following variables:

- a. Surge or hydrograph on open coast.
- b. Discharge of water through the entrance of Chesapeake Bay.
- c. Surge profile up Chesapeake Bay. This gives the hydrograph for each of the ten sections, from which the volume of water in the bay and tributaries can be determined.
- d. Contribution of set-up due to cross winds.
- e. Contribution due to run-off and river flow (neglected in the computations, but should be taken into account for determining final elevations).

The problem includes the hydraulic characteristics of the Chesapeake Bay entrance and the hydraulics of the bay, or the speed and change in the form of the wave travelling up Chesapeake Bay and the capacity of the bay.

The volume of water which passes through the entrance of Chesapeake Bay must balance that represented by the time history of the stage curves. Figure 9 shows relationships for the volume of water above mean water level versus stage elevation for the ten sections of Chesapeake Bay. If the elevations are known at time t_1 , say from the model hydrographs, then the volume of water, V_1 in Chesapeake Bay can be computed. The volume of water V_2 in the bay at time t_2 can similarly be computed. The difference between V_2 and V_1 (neglecting run-off) represents that amount which must pass through the entrance of Chesapeake Bay during the time interval between t_2 and t_1 . This information, the hydrograph at the first section, and the hydraulics of the bay entrance can be used to compute the mean velocity head required on the open coast for the same period of time. The mean current velocity through the entrance of the Chesapeake Bay is given by

$$\bar{v} = C \sqrt{g |h_0 - h_1|} \quad (1)$$

where

\bar{v} = mean current velocity

C = coefficient of discharge

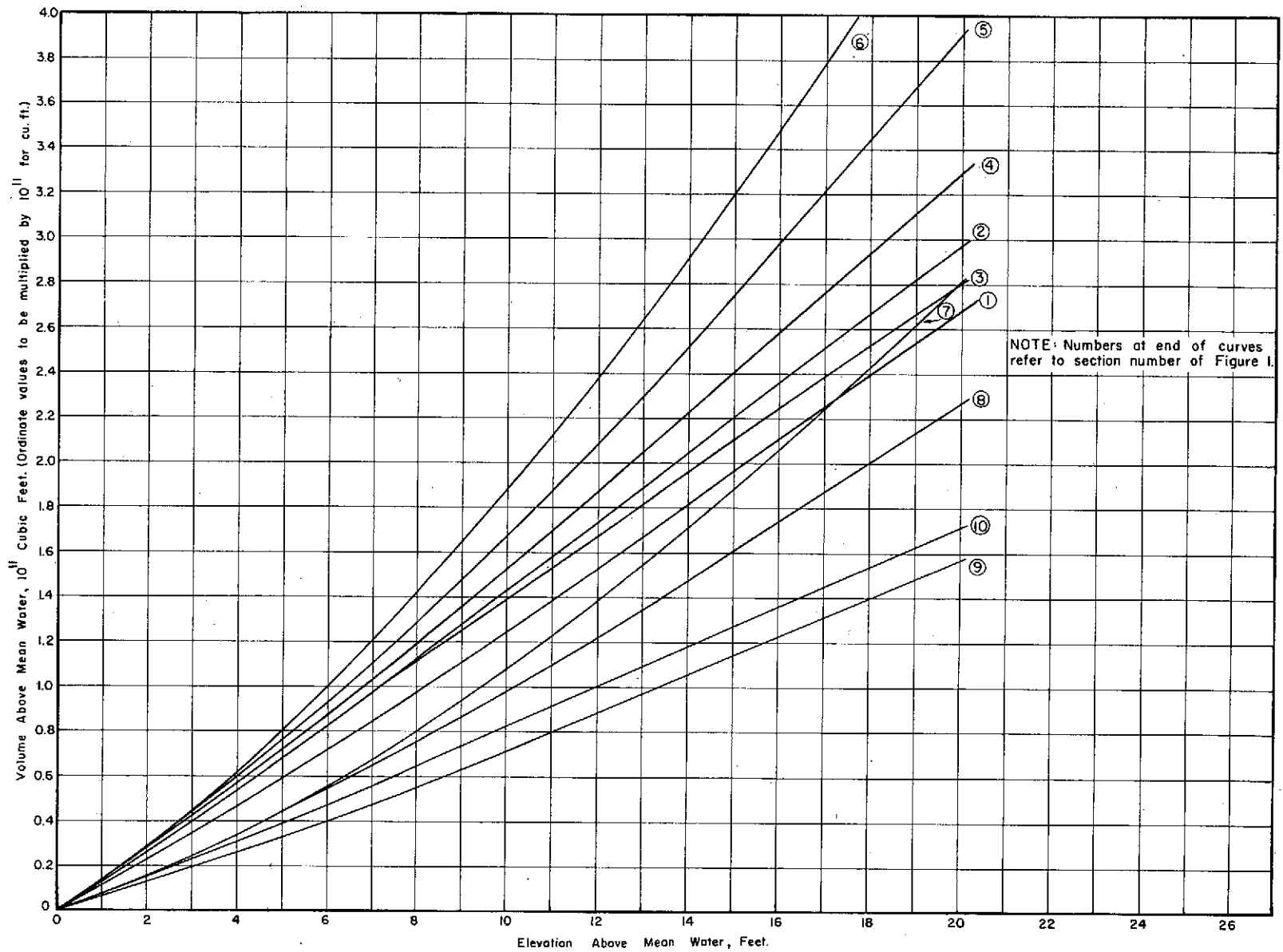


FIGURE 9. VOLUME OF WATER ABOVE MEAN WATER VERSUS ELEVATION FOR SECTIONS 1 THROUGH 10, CHESAPEAKE BAY.

g = acceleration of gravity, 32.2 ft./sec.²
 h_0 = surge elevation on open coast
 h_1 = surge elevation inside Chesapeake Bay (Section 1)
 when $h_0 - h_1 > 0$ the flow is into the bay.
 when $h_0 - h_1 = 0$ there is no flow
 when $h_0 - h_1 < 0$ the flow is out of the bay
 The absolute value $|h_0 - h_1|$ is required under the radical when
 $(h_0 - h_1) < 0$. Since h_0 and h_1 are functions of time, \bar{v} is also a function
 of time.

The discharge through the entrance of Chesapeake Bay is given by

$$Q = A \bar{v} \quad (2)$$

where Q is in cubic feet per second, A is cross-sectional area of entrance in square feet, and \bar{v} is mean current velocity in feet per second. The increment of water volume ΔV passing through the entrance during a time interval $\Delta t = t_2 - t_1$ is given by

$$\Delta V = A \bar{v} \Delta t \quad (3)$$

The cross-sectional area of the entrance to Chesapeake Bay comprises two parts, a constant value plus a change due to change in elevation of the surge. Depending on the traverse selected across the bay entrance one obtains an area below mean water between 1,800,000 and 2,400,000 square feet. The increase in cross-sectional area due to surge elevation is between 70,000 and 80,000 square feet per foot of elevation. Thus, the cross-sectional area of the bay entrance will for all practical purposes fall between the ranges given by

$$A_L = 70,000 (25 + h_0) \quad (4)$$

and

$$A_U = 80,000 (30 + h_0) \quad (5)$$

where the subscripts L and U refer to the lower and upper ranges, respectively and h_0 is the surge elevation on the open coast above mean water elevation.

Since $h_0 = h_1 + \Delta h$, equations 4 and 5 become

$$A_L = 70,000 \left[(25 + h_1) + \Delta h \right] \quad (6)$$

$$A_U = 80,000 \left[(30 + h_1) + \Delta h \right] \quad (7)$$

Substituting equation 6 into equation 3 and using equation 1, one obtains the cubic equation in terms of Δh

$$(\Delta h)^3 + 2(25 + h_1)(\Delta h)^2 + (25 + h_1)^2 \Delta h - \left(\frac{\Delta V}{\Delta t C} \right)^2 \frac{10^{-8}}{98g} = 0 \quad (8)$$

Similarly by using equation 7, one obtains

$$(\Delta h)^3 + 2(30 + h_1)(\Delta h)^2 + (30 + h_1)^2 \Delta h - \left(\frac{\Delta V}{\Delta t C} \right)^2 \frac{10^{-8}}{128g} = 0 \quad (9)$$

Equations 8 and 9 bracket the range in Δh , the only unknown quantity, once the coefficient of discharge C has been assumed. h_1 and $\Delta V/\Delta t$ can be obtained from the surge hydrographs for Chesapeake Bay. The total volume of water V_t above mean water level in cubic feet in Chesapeake Bay and tributaries, based on planimetered area of the 0, 10 and 20-foot contours for each section shown on Figure 1, is given by

$$V_T = \sum_{N=1}^{10} V_N \quad (10)$$

where

$$V_1 = \left[0.9 h_1^2 + 116 h_1 \right] 10^8$$

$$V_2 = \left[1.05 h_2^2 + 135 h_2 \right] 10^8$$

$$\begin{aligned}
V_3 &= \left[0.05 h_3^2 + 140 h_3 \right] 10^8 \\
V_4 &= \left[1.05 h_4^2 + 140 h_4 \right] 10^8 \\
V_5 &= \left[2.95 h_5^2 + 141 h_5 \right] 10^8 \\
V_6 &= \left[3.10 h_6^2 + 157 h_6 \right] 10^8 \\
V_7 &= \left[3.40 h_7^2 + 73 h_7 \right] 10^8 \\
V_8 &= \left[1.55 h_8^2 + 88 h_8 \right] 10^8 \\
V_9 &= \left[1.55 h_9^2 + 48 h_9 \right] 10^8 \\
V_{10} &= \left[1.25 h_{10}^2 + 61 h_{10} \right] 10^8
\end{aligned}
\tag{11}$$

The above equations are shown by the curves given in Figure 9. The elevations, $h_1, h_2, \text{ etc.}$, are obtained from the corresponding hydrographs, and are functions of time. $V_1, V_2, \text{ etc.}$ are also functions of time, and finally equation 10 for V_T is a function of time. Thus, $\Delta V/\Delta t$ may be obtained from the resultant curve for equation 10.

It can be shown that the solution of the cubic equations (8 or 9) results in one real root and two conjugate imaginary roots. Only the summary equations are given here; the details of the derivation are given in Appendix A. (Also see reference 5, page 1-03.)

Referring to equation 8, the solution is obtained by computing

$$\cosh \theta = \left[1 + \left(\frac{\Delta V}{\Delta t C} \right)^2 \frac{10^{-8}}{98g} \left(\frac{3}{25+h_1} \right)^3 \right] = Z \tag{12}$$

Solve for $\theta = \lambda_n \left[Z + \sqrt{Z^2 - 1} \right]$

compute $\cosh \frac{\theta}{3}$

compute $y = \frac{2}{3} (25 + h_1) \cosh \frac{\theta}{3}$

$$\text{compute } \Delta h = y - \frac{2}{3} (25 + h_1)$$

$$\text{compute } h_0 = h_1 + \Delta h$$

Actually Δh is obtained from the following equation,

$$\Delta h = \frac{2}{3} (25 + h_1) \left[\cosh \frac{\theta}{3} - 1 \right] \quad (13)$$

where

θ is obtained from arc cosh Z, using equation 12.

The above equations were applied to the Chesapeake Bay area using the model hydrographs given in Figure 8 and the volume-stage curves given by equation 11. Computations were made for discharge coefficients $C = 0.5, 0.55, 0.60,$ and 0.65 . Figure 10 shows the results for $C = 0.60$. The dashed curve is for h_0 , the hydrograph for the ocean outside of Chesapeake Bay, and the solid curve is for h_1 , the model hydrograph on the inside of Chesapeake Bay. The upper curves are based on equation 8 for the lower limit of cross-sectional area of the entrance and the lower curves on equation 9 for the upper limit of cross-sectional area of the entrance.

Figure 11 shows similar results when the model hydrographs are multiplied by $P = 1.5$, and Figure 12 is for $P = 2.0$. P is the ratio of the ordinates of the assumed hydrograph to those of the model hydrographs.

Similar computations were made for the model hydrographs multiplied by $P = 0.25, 0.50, 1.0, 1.5, 2.0, 2.5,$ and 3.0 using $C = 0.5, 0.55, 0.60,$ and 0.65 and the two values of cross-sectional area of the entrance to Chesapeake Bay. Thus a total of $2 \times 4 \times 7 = 56$ sets of computations were made, taking advantage of the speed of an electronic computer.

Prediction Relationships. Graphs similar to Figures 10, 11, and 12 were prepared for all fifty-six sets of computations, and the maximum or peak values were determined for each condition. Figures 13 and 14 are based respectively on the lower and upper limits of cross-sectional area of the bay entrance. Peak values for these computations are given in the following Table III.

TABLE III
PEAK VALUES OF HURRICANE SURGE
ON OPEN COAST AND JUST INSIDE CHESAPEAKE BAY

Entrance Condition	C	Values of $(h_o)_{max}$ Feet for Various P (open coast)				
		P = 0.25	P = 0.5	P = 1.0	P = 1.5	P = 2.0
A_L	0.50	1.87	4.17	9.43	15.2	21.0
A_U	0.50	1.82	3.96	8.80	14.1	19.7
A_L	0.55	1.83	4.00	9.02	14.4	20.0
A_U	0.55	1.78	3.85	8.47	13.5	18.7
A_L	0.60	1.80	3.88	8.63	13.8	19.0
A_U	0.60	1.76	3.75	8.17	13.0	17.9
A_L	0.65	1.77	3.80	8.32	13.2	18.3
A_U	0.65	1.74	3.69	7.98	12.5	17.3

		Values of $(h_1)_{max}$ Feet (Inside Bay)				
		P = 0.25	P = 0.5	P = 1.0	P = 1.5	P = 2.0
A_L and A_U	C = 0.50 to C = 0.65	1.64	3.29	6.59	9.90	13.1

$$A_L = 70,000 (25 + h_o)$$

$$A_U = 80,000 (30 + h_o)$$

Figure 15 represents the final results, prediction curves for the peak of the hydrograph on the open coast versus that at section 1 inside the Chesapeake Bay entrance. The center curve is based approximately on the mean of the two curves for C = 0.6 from Figures 13 and 14. Similarly, the upper curves are based on C = 0.55 and the lower on C = 0.65.

In order to use the prediction curves, one must obtain the surge on the open coast. For example, if the surge on the open coast is computed to be $h_o = 12.0$ feet, then the surge inside at section 1 obtained from Figure 15 will be $h_1 = 9 + 0.5$ feet. The surge elevations at the various sections will be proportional to those given by the model hydrographs presented in Figure 8. In fact this would also give the complete hydrograph for each section. To the surge elevations, which apply along the center axis of Chesapeake Bay, one must add the component due to cross wind effects. Finally, the total water elevation is obtained by adding the predicted astronomical tide and the increase in elevation due to river flow and run-off to the hurricane surge elevation and the cross wind set-up. These factors are discussed in more detail next for the general surge predictions.

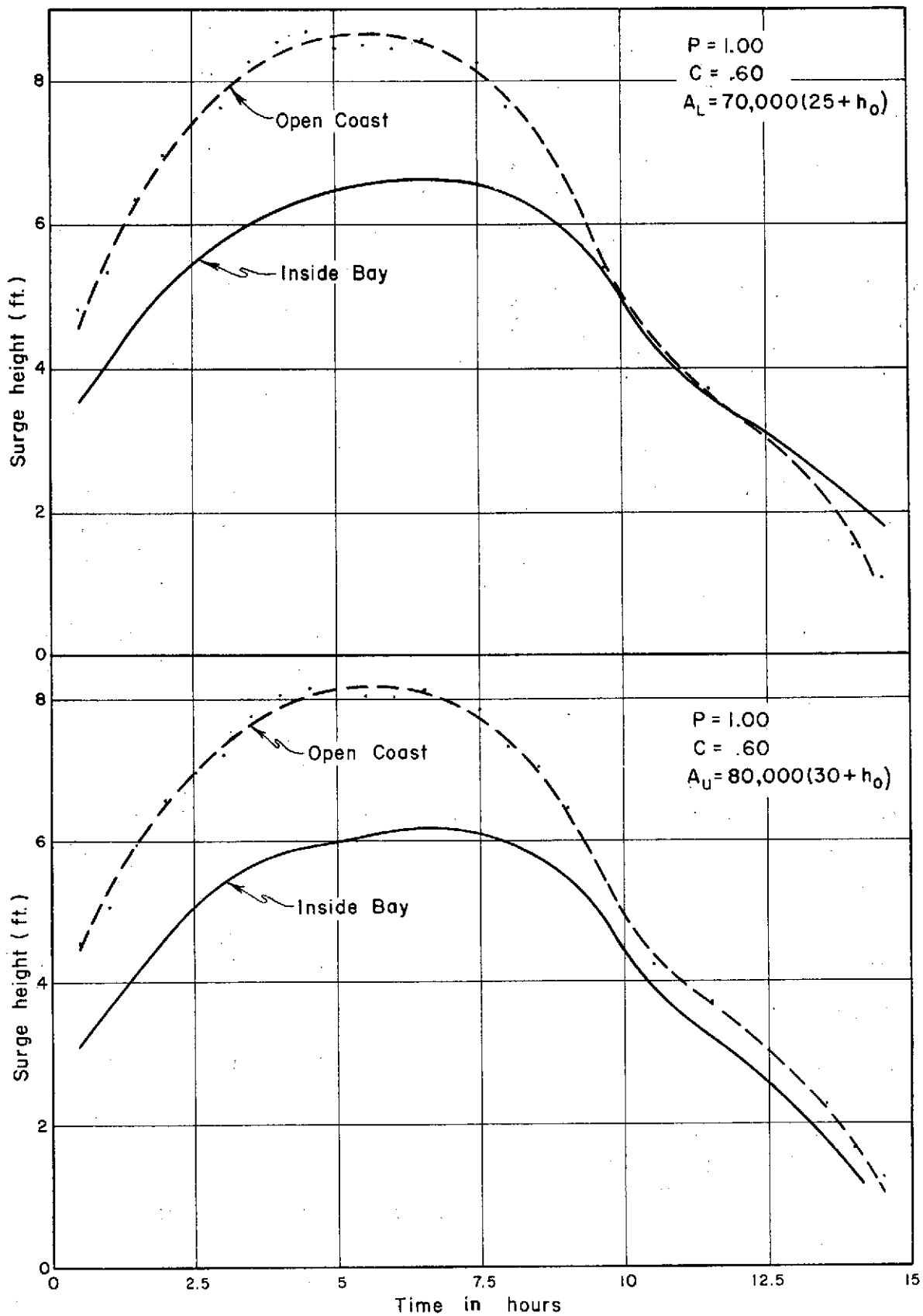


FIGURE 10. COMPUTED SURGE ON OPEN COAST VERSUS MODEL SURGE JUST INSIDE CHESAPEAKE BAY

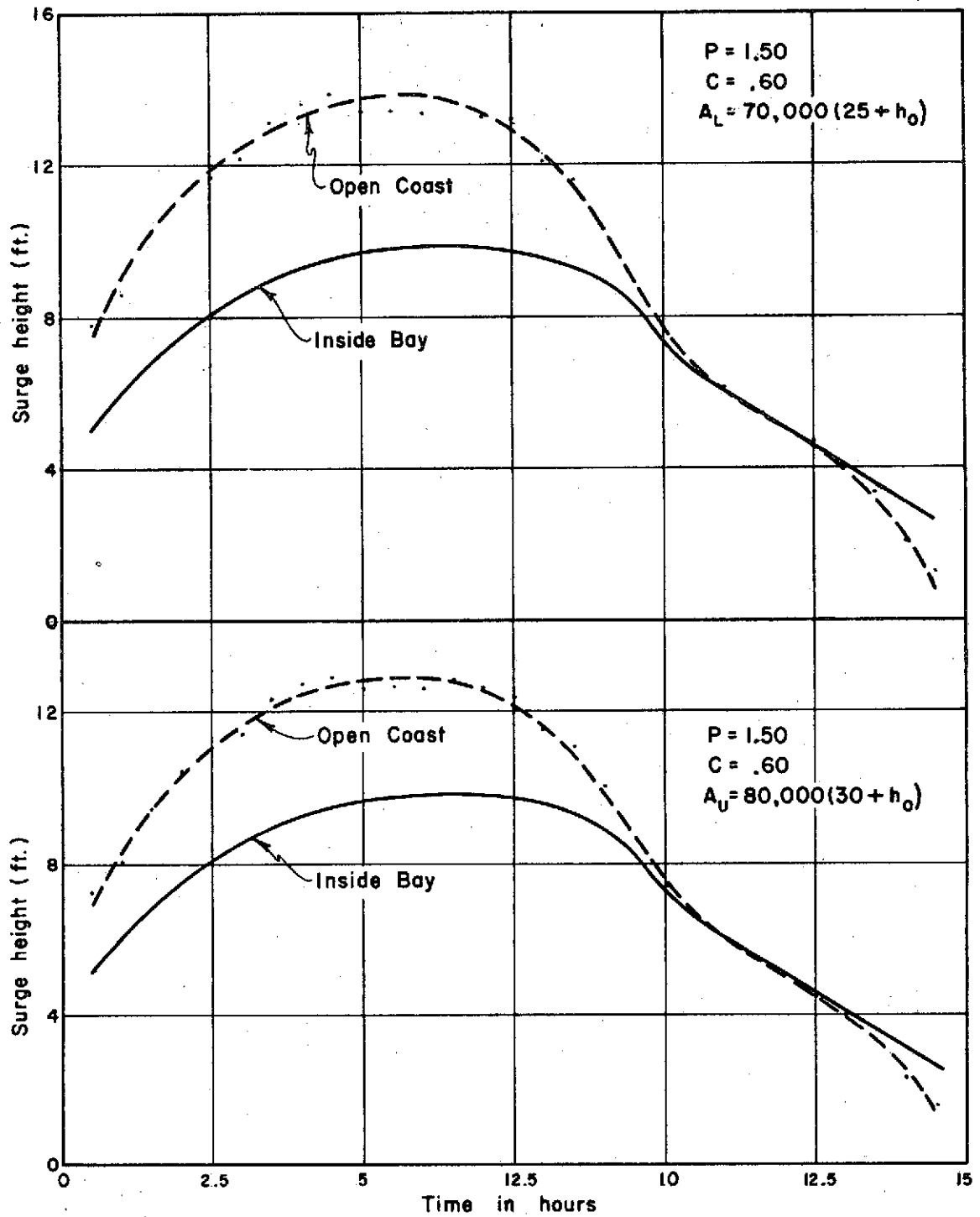


FIGURE 11. COMPUTED SURGE ON OPEN COAST VERSUS 1.5 TIMES MODEL SURGE JUST INSIDE CHESAPEAKE BAY

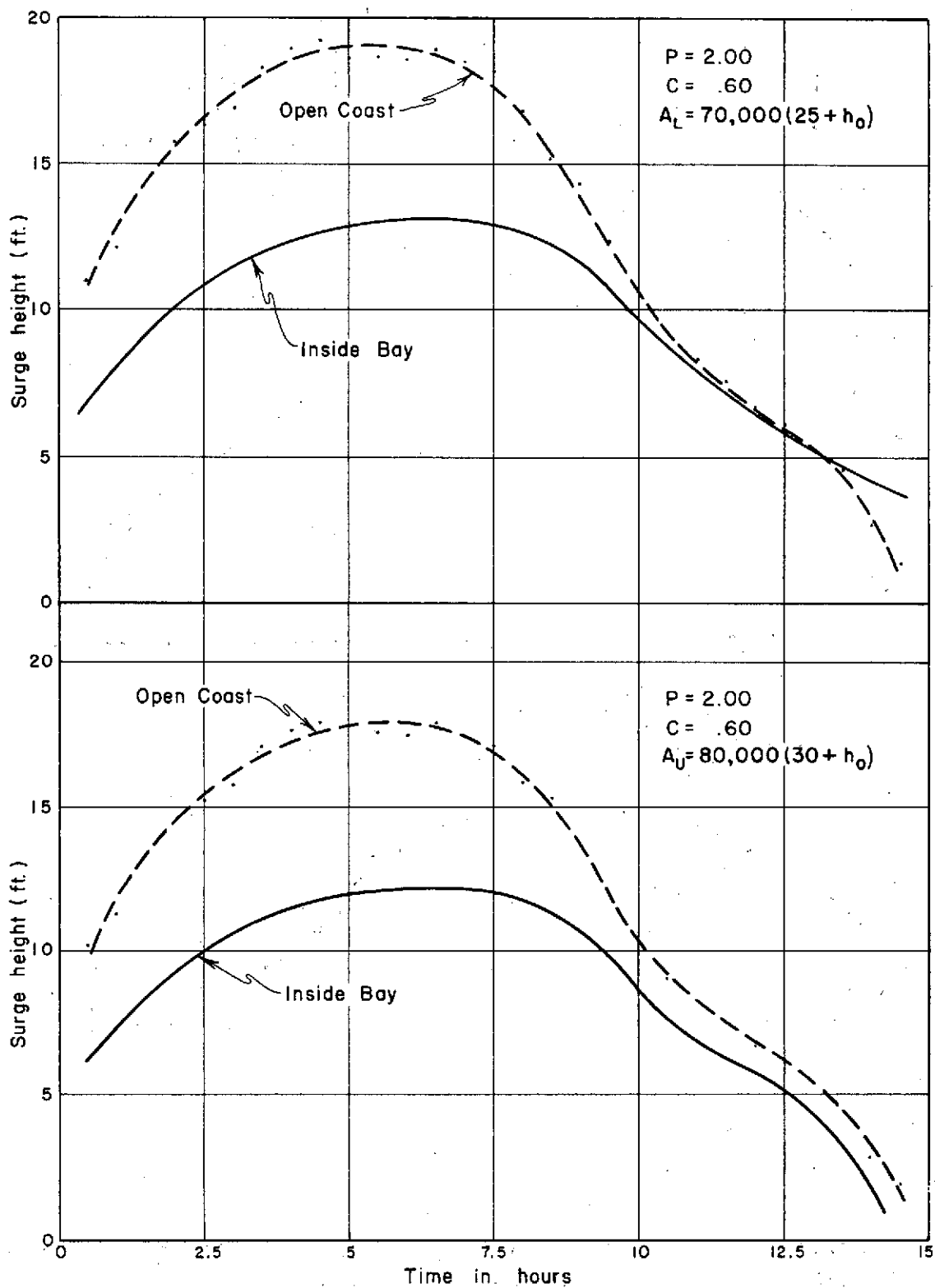


FIGURE 12. COMPUTED SURGE ON OPEN COAST VERSUS 2.0 TIMES MODEL SURGE JUST INSIDE CHESAPEAKE BAY

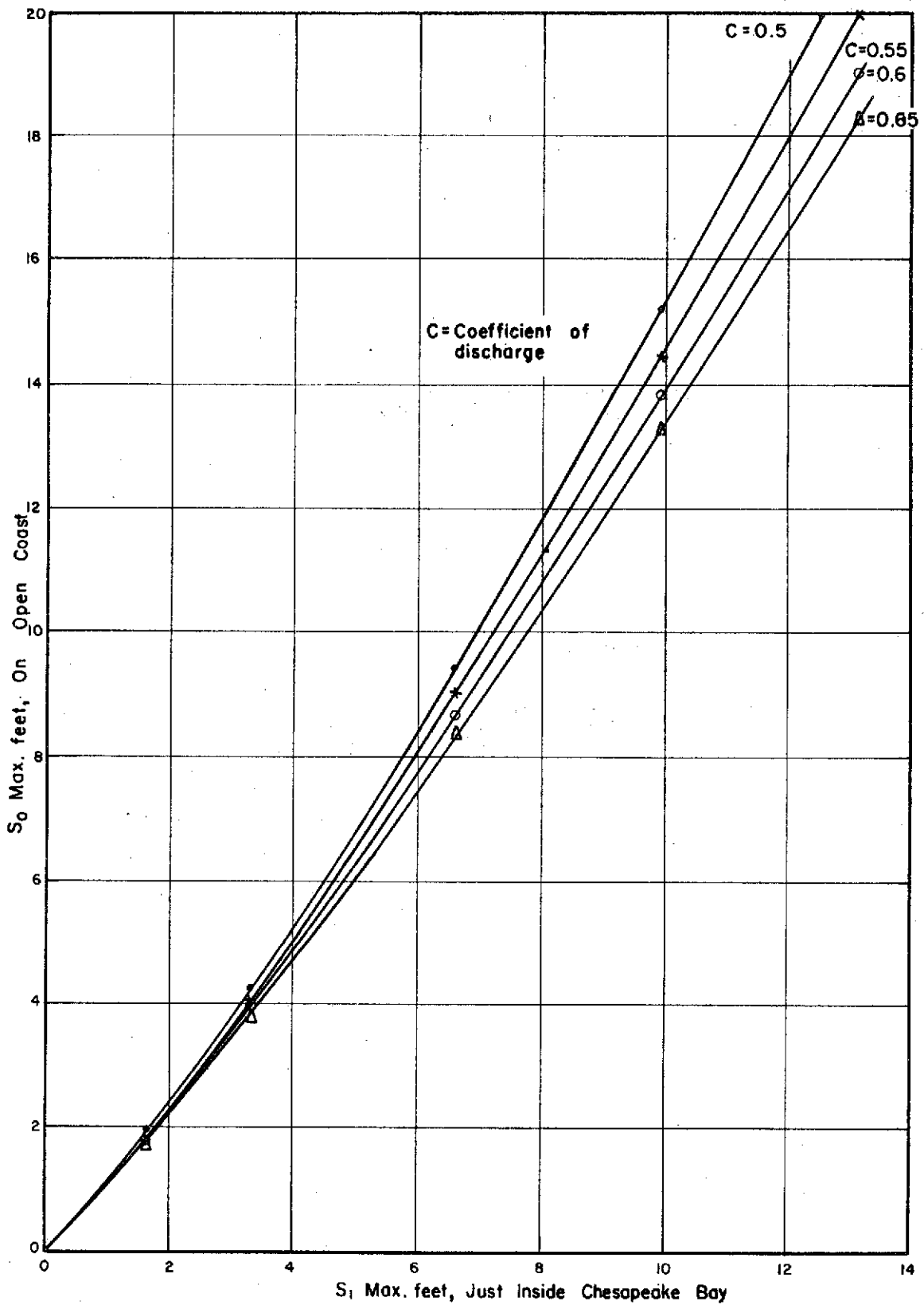


FIGURE 13. PEAK OF SURGE HYDROGRAPH ON OPEN COAST VERSUS PEAK OF SURGE HYDROGRAPH JUST INSIDE CHESAPEAKE BAY. FOR $A_L = 70,000 (25 + h_0)$

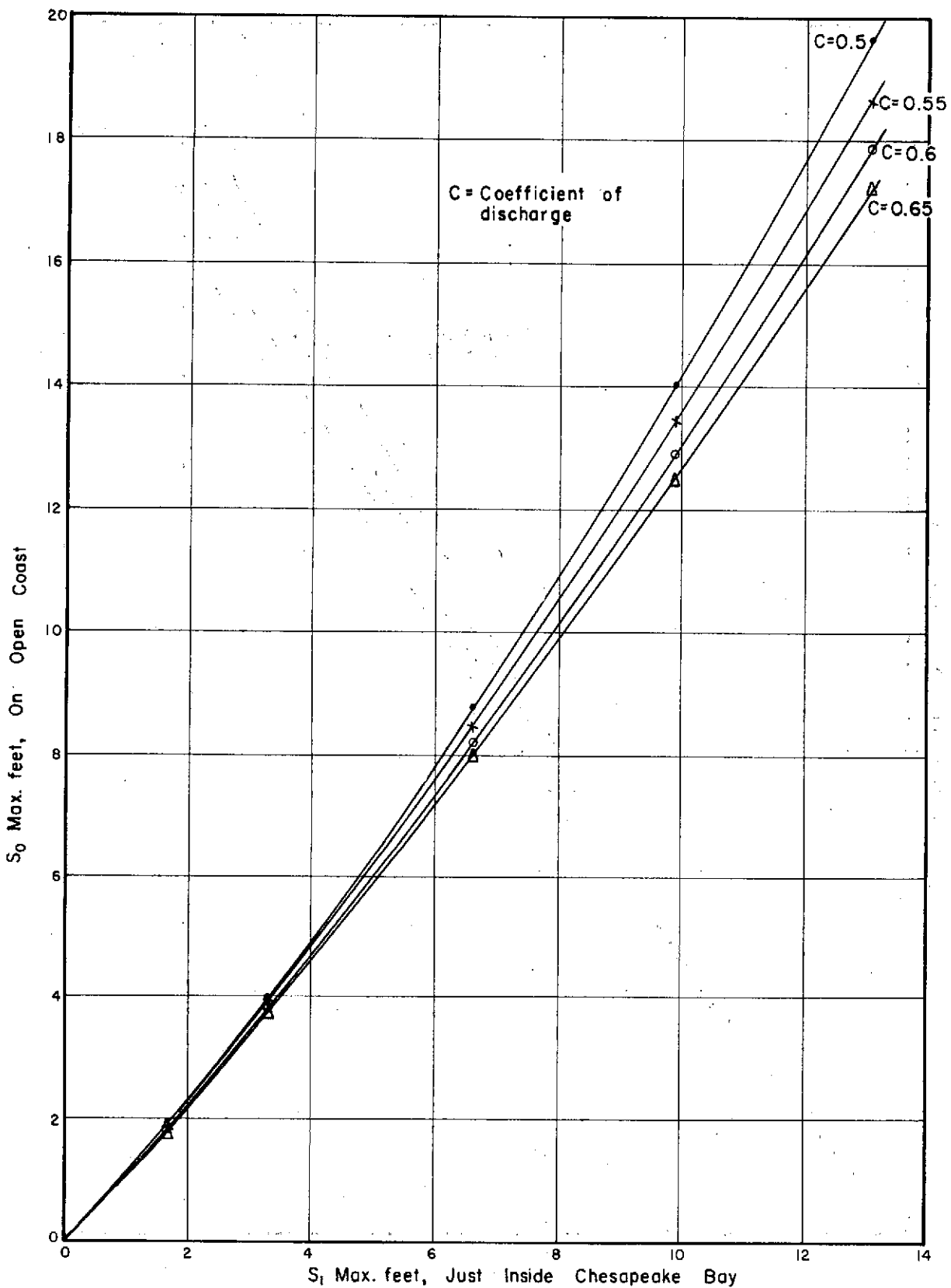


FIGURE 14. PEAK OF SURGE HYDROGRAPH ON OPEN COAST VERSUS PEAK OF SURGE HYDROGRAPH JUST INSIDE CHESAPEAKE BAY. FOR $A_u = 80,000 (30 + h_0)$

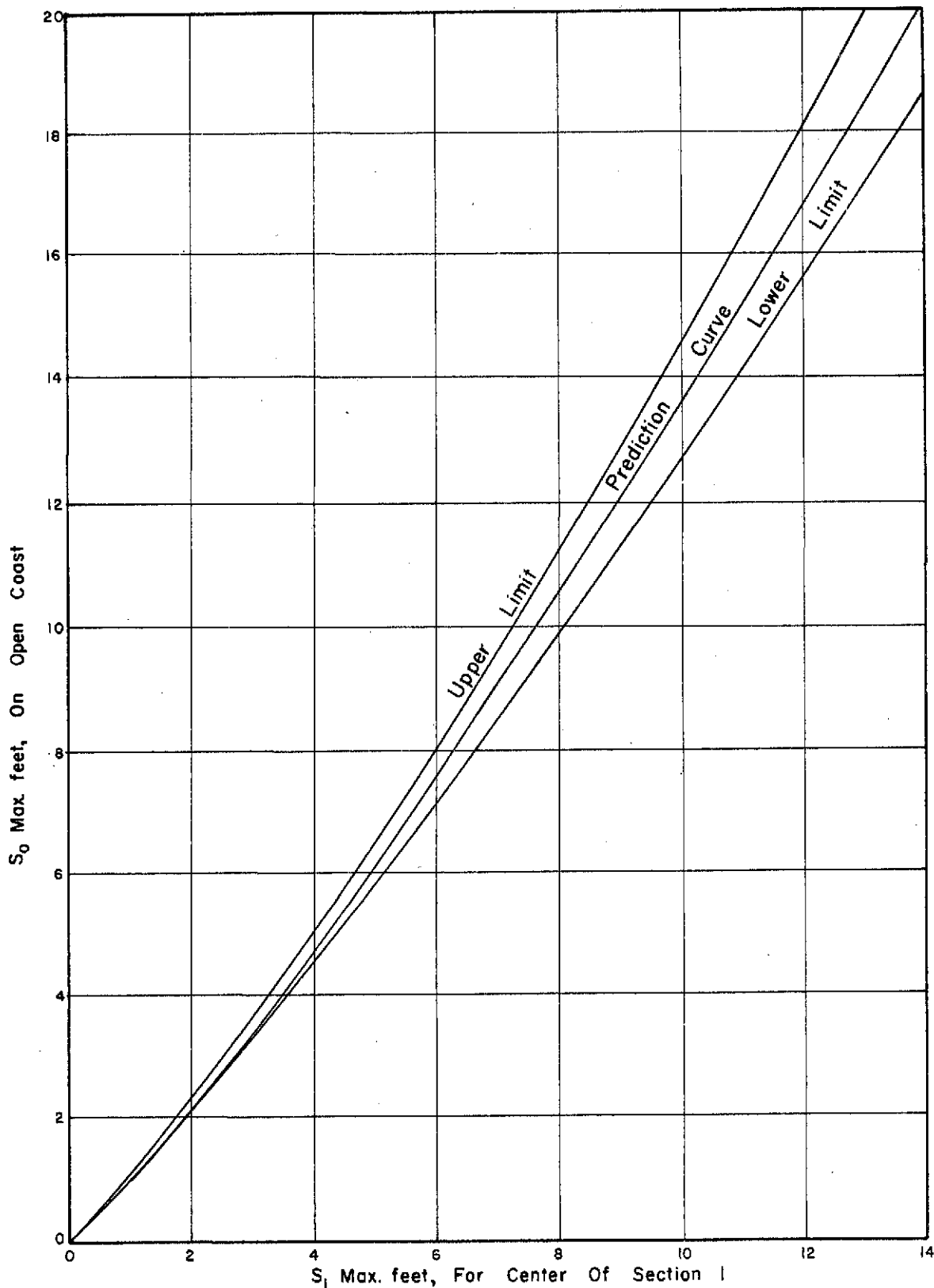


FIGURE 15. PREDICTION CURVES FOR PEAK OF HYDROGRAPH ON OPEN COAST VERSUS THAT AT SECTION NO.1 INSIDE CHESAPEAKE BAY.

III-HURRICANE SURGE, GENERAL DESIGN PREDICTIONS FOR CHESAPEAKE BAY

Discussion. The discussion at this time is intended to serve a number of purposes. The primary purposes are to discuss the method of approach and the tools of application and to justify the means by which the final answers may be obtained.

First of all, in order to use Figure 15 to obtain the hurricane surge within section 1 of Chesapeake Bay, it is necessary to obtain the surge on the open coast. The next step is to compute the surge along the center axis of the bay, and then add the components due to cross wind effects. The surge along the center axis (see Figure 1) of Chesapeake Bay may be determined from the surge in section 1 and surge ratios given in Table IV below. For example, the surge elevation about half-way across Chesapeake Bay between the mouth of York River and the town of Cape Charles is 99% of that half-way across Chesapeake Bay between Hampton Roads and the mouth of Chesapeake Bay.

TABLE IV SURGE RATIOS ALONG CENTER AXIS OF CHESAPEAKE BAY

<u>Center Axis Location Between</u>	<u>Ratio</u>
Hampton Roads and entrance to Chesapeake Bay	1.0
Mouth of York River and Town of Cape Charles	0.99
Mouth of Rappahannock River and Onancock	0.98
Mouth of Potomac River and Crisfield	0.97
Mouth of Severn River and Chester River	0.95
Mouth of Patapsco River and Chester River	1.02

The above ratios are based on the interpolated or model hydrographs, Figure 8.

As far as the surge travelling up Chesapeake Bay is concerned, the August 1933 hurricane may be considered as a model. However, it is difficult to make the same statement for the surge on the open coast, since the direction of movement and wind components on the open coast are such that no simple method or formulas are available for computing exactly the surge on the open coast from the wind and pressure fields, except perhaps when the situation is idealized.

The predicted hydrographs, Figures 10, 11, and 12 for the open coast, are based on the time history of volume changes within Chesapeake Bay and the interpolated or model hydrographs for ten sections along the center axis of the bay. Figure 10 represents that surge which might have been experienced on the open coast during the August 1933 hurricane. To complete the problem, including calibration of the formulas, it is necessary to verify the predicted surge hydrograph for the open coast given by Figure 10.

Since no hydrograph is available for the open coast near the entrance to Chesapeake Bay for the August 1933 hurricane, it becomes necessary to predict the appropriate hydrograph in agreement with that given by Figure 10, using the wind and pressure field for the August 1933 hurricane. This process might well be termed the calibration of formulas and techniques for surge computation on the open coast, and is discussed under the next topic.

Calibration of Formulas and Techniques. The calibration of formulas and techniques for predicting the surge elevations on the open coast entails a certain amount of subjectiveness. It must be borne in mind that the final formulas selected and calibrated will be used for the design and/or the standard project hurricane. Now the design or project hurricane will be one of relatively great intensity and will move on a critical path and at a critical speed such that maximum surge conditions will be reached within Chesapeake Bay. Such a hurricane will move more-or-less perpendicular to the coast with the center passing just southwest of the bay entrance, and after entering the coast will proceed northward with the center following a path just west of the bay.

For a traverse perpendicular to the open coast, the conventional set-up formula, exclusive of dynamic effect and of the component due to atmospheric pressure reduction is given by:

$$\frac{ds}{dx} = \frac{kU^2}{g(d+s)} \quad (14)$$

where

ds/dx = slope of water surface
 k = 3.0×10^{-6} stress coefficient
 U = wind speed
 d = depth of water
 g = acceleration of gravity

Equation 14 must be solved by numerical means, since the Continental Shelf is variable in depth. Use of equation 14 is illustrated by Bretschneider (1) in regard to surge computations resulting from Hurricane Audrey (1956) in the Gulf of Mexico.

The formula for dynamic storm tide on a sloping Continental Shelf, exclusive of the component due to atmospheric pressure reduction, is given by Reid (3) as follows:

$$\eta_m = k \frac{T}{C_1} \left(\frac{d_1}{d_0} \right)^{\frac{1}{4}} W_m^2 S \quad (15)$$

where

- η_m = maximum rise in water level
 d_1 = mean water depth at seaward edge of the Continental Shelf, just landward of the sharp increase in depth on the Continental slope
 d_0 = mean water depth at shoreward edge of the Continental Shelf, just seaward of the sharp decrease in depth in the nearshore zone
 k = 3.0×10^{-6} stress parameter
 C_1 = $\sqrt{gh_1}$, speed of free wave at d_1
 C_0 = $\sqrt{gh_0}$, speed of free wave at d_0
 \bar{C} = $(1/2)(C_0 + C_1)$
 T = B/\bar{C} , period of travel of free wave over Continental Shelf
 B = breadth of Continental Shelf between the locations of d_1 and d_0
 W_m = maximum sustained wind speed
 S = response factor depending on the ratio of fetch length to breadth of Continental Shelf, and the ratio of the forward speed of the hurricane to the propagational speed of the free wave, \bar{C}

Equation 15 applies for conditions when the hurricane moves perpendicular to the coast. Equation 14 applies for a stationary storm when the wind field is perpendicular to the coast. In regard to the August 1933 hurricane, neither of the two equations apply since both the wind field and the path of the hurricane movement are oblique to the coastline. For the oblique case there is a component of hurricane surge due to Coriolis effect, whence equations 14 and 15 will give surge values too low for the August 1933 hurricane, when using the component of wind perpendicular to the coast. Using a traverse parallel to the wind (oblique to the coast) may result in surge heights too high. There is another factor which tends to increase the surge height above that predicted by the above equations and that is the additional set-up due to wave action.

In spite of the above difficulties, it is of interest to compute surge elevations by use of either equations 14 and 15. Using equation 14, for example, one obtains a rise in water level due to wind stress of 4.7 feet, which when added to a component of about 0.7 foot due to atmospheric pressure reduction gives a total maximum surge height of 5.4 feet on the open coast. From Figure 15 for $(S_0)_{\max} = 5.4$ feet one obtains $(S_1)_{\max} = 4.2$ to 4.65 feet at the center of section 1 inside Chesapeake Bay. Since Hampton Roads is about 8 nautical miles from the center of section 1, there will be an additional rise due to wind over this part of the bay. This additional rise is computed to be 1.0 foot, whence the predicted value at Hampton Roads is between 5.2 and 5.7 feet above predicted astronomical tide. The observed height at Hampton Roads

was about 6.6 feet above predicted astronomical tide. It is assumed that Coriolis effect and/or wave set-up results in an additional rise of 1.6 feet on the open coast, then $S_0(\text{max})$ will be approximately $5.4 + 1.6 = 7.0$ feet, and from Figure 15, $S_1(\text{max}) = 5.3$ to 5.9, and that at Hampton Roads 1.0 foot higher or between 6.3 and 6.9 feet. It appears that the component due to Coriolis effect and/or wave set-up is noticeable. Thus, the predicted surge on the open coast for the August 1933 hurricane is 7.0 feet above astronomical tide.

The use of equation 15, depending on the selection of the response factor, gives essentially the same results as those above obtained by use of equation 14.

The surge in feet at Baltimore including wind set-up will be approximately 1.02 times $5.6 + 0.3 + \Delta S = 5.7 + 0.3 + \Delta S$, where ΔS is that component due to wind blowing up the Patapsco River toward Baltimore, and where the ratio 1.02 is from Table IV. The Patapsco River component is computed to be 1.4 feet, whence the maximum water level above astronomical tide at Baltimore is computed to be $5.7 + 0.3 + 1.4 = 7.1 + 0.3$ feet for the August 1933 hurricane. The observed value at Baltimore was 7.2 feet above astronomical tide.

The surge in feet at Annapolis including wind set-up will be approximately 0.95 times $5.6 + 0.3 + \Delta S = 5.3 + 0.3 + \Delta S$, where ΔS is that component due to wind blowing up the Severn River and the ratio 0.95 is from Table IV. That component due to wind blowing up the Severn River is computed to be 0.4 foot, whence the maximum water level above astronomical tide at Annapolis is computed to be $5.3 + 0.3 + 0.4 = 5.7 + 0.3$ feet for the August 1933 hurricane. The observed value at Annapolis was 5.8 feet above astronomical tide.

The surge height in feet at the mouth of the Potomac River will be 0.97 times $5.6 + 0.3 = 5.4 + 0.3 + \Delta S$, where ΔS is that component due to wind blowing across Chesapeake Bay to the mouth of the Potomac River. That component due to the wind is $\Delta S = 0.6$ feet, whence the surge at the mouth of the Potomac River is $6.0 + 0.3$ feet. The observed value at Little Wicomico near the mouth of the Potomac River was 6.0 feet.

Thus, it appears that the August 1933 hurricane is satisfactory as a model for determining surge heights within Chesapeake Bay, provided allowance can be made on the open coast to take into account that component due to Coriolis effect and/or wave set-up.

As far as maximum surge on the open coast is concerned, the critical path of approach should be more or less perpendicular to the coast, in which case the Coriolis effect is minimized and only that component due to wave set-up must be considered. Perhaps at least approximately that

component due to wave set-up might be included in the wind set-up formula provided a calibration of the formula can be made.

Although Hurricane Audrey (1956) was in the Gulf of Mexico, this storm approached perpendicular to the coast and was very well documented with wind and tide data, and is therefore suitable for calibration purposes. The details of this documentation are given by Harris (3). Using available information on Hurricane Audrey, Bretschneider (1) was able to verify by computation the observed maximum water level rise, provided a stress parameter $k = 3.0 \times 10^{-6}$ and a response factor of $S = 1.0$ were used. When a hurricane moves at critical speed, the response factor is normally greater than 1.0, but when the Continental Shelf is of great breadth and relatively shallow, the damping effect will be such that the response factor will not deviate too much from $1.0 \pm 10\%$, which is within the order of accuracy of the computational procedures and the meteorological data.

Since the formula given by Bretschneider (1) is calibrated based on data from Hurricane Audrey it can be assumed that the set-up computed therefrom includes the damped dynamic effect and the contribution due to wave set-up, provided the limits of accuracy are set at $\pm 10\%$, and the equation is applied to similar or near similar offshore meteorological and physical features. In view of the above, surge computations can now be made for the open coast.

Surge Computations for the Open Coast. Surge computations for the open coast are made for two hypothetical hurricanes, either of which might be comparable nearly to a design or standard project hurricane. The first, hereafter called Hurricane "A" is the September 14, 1944 hurricane transposed to the Chesapeake Bay area, but not adjusted for filling. The meteorological data for Hurricane "A" are given in Weather Bureau Memorandum HUR 7-20. In particular for the open ocean the radius of maximum wind is $R = 33.5$ nautical miles, the atmospheric pressure anomaly at the center is 2.2 inches of mercury, and the maximum sustained wind speed at R is equal to 105 mph. The path of movement over the open ocean can be assumed more or less perpendicular to the coast and the forward speed equal to about 15 to 25 mph. After crossing the coast, the path of movement curves and proceeds northward along the west side of the Chesapeake Bay, and the speed of movement reduces to about 12 to 15 mph. The wind speed over Chesapeake Bay decreases as the storm moves northward as shown by HUR 7-20. Actually the decrease in wind speed as the storm moves northward will be greater, as given in HUR 7-26.

The second storm, hereafter called Hurricane "B" is exactly the same as Hurricane "A" except that all wind speeds are 5 mph greater. That is, the maximum sustained wind for Hurricane "B" is 110 mph. Furthermore, over the Chesapeake Bay maximum winds, for example of 90 mph for Hurricane "A", will be 95 mph for Hurricane "B", etc.

Figure 16 shows the wind stress diagram for over ocean through the radius of maximum wind and parallel to the path of the hurricane center for Hurricane "B", maximum sustained wind of 110 mph. The stress diagram for Hurricane "A" can be obtained very nearly by multiplying the values of Figure 16 by the factor $(105/110)^2 = 0.91$. The stress coefficient $k = 3.0 \times 10^{-6}$ was used for both Hurricanes "A" and "B". (Previous computations on hurricane surge assumed a stress coefficient $k = 3.3 \times 10^{-6}$. It therefore might be interpreted that Hurricane "B" is identical to Hurricane "A" except that a stress coefficient of $k = 3.3 \times 10^{-6}$ is used instead of 3.0×10^{-6} .)

As outlined in reference 1, the stress diagram is moved over the traverse perpendicular to the coast and surge computations are made, based on steady state conditions for each position. The assumption of steady state conditions appears reasonable, since the storm is moved at a relatively slow speed. The use of the cumulative curve or the integral of the stress diagram $k/g \int |U| U_x dx$ facilitates computational procedures.

Figure 17 is a segmented smoothed version of the bottom profile from the mouth of Chesapeake Bay to the edge of the Continental Shelf. Three traverses, parallel to each other from the coast to the Continental Shelf, were averaged to obtain Figure 17. The three traverses encompassed the north and south boundaries of the mouth of Chesapeake Bay and one through the center of the entrance.

The stress diagram, Figure 16, was placed at various positions along the profile of Figure 17 and computations were made for wind set-up, using the procedures of reference 1. In addition, that component due to atmospheric pressure reduction was also computed, based on the distance that the hurricane center was from the coast for each position of the stress diagram over the bottom profile. The results of these computations are given below in Table V.

TABLE V, SURGE COMPUTATIONS FOR OPEN COAST AND CHESAPEAKE BAY FOR HURRICANES "A" & "B"

		Hurricane "A"			Hurricane "B"	
X_0	r	S_0^A	S_0^B	S_0^C	S_0^D	S_0^E
N. Miles	N. Miles	Feet	Feet	Feet	Feet	Feet
0	55.5	1.13	5.18	6.31	5.75	6.88
10	47.8	1.26	7.06	8.32	7.84	9.10
20	41.2	1.41	8.26	9.67	9.18	10.59
30	36.5	1.54	9.15	10.69	10.17	11.71
40	33.8	1.59	9.53	11.12	10.63	12.21
50	34.5	1.57	9.12	10.69	10.11	11.68
60	37.5	1.49	8.40	9.89	9.34	10.83
70	42.5	1.37	6.95	8.32	7.73	9.10
80	49.6	1.28	6.06	7.34	6.73	8.01
90	57.5	1.12	4.84	5.96	5.37	6.49

In the above table, X_0 is the distance that the front of the hurricane is inland from the coast, or where U is parallel to the coast. S_0'' is that rise in water level due to atmospheric pressure reduction at the coast from normal and S_0' is the rise in water level due to wind stress. S_0 is the total rise in water level (or surge elevation) above astronomical tide level on the open coast and is obtained from $S_0 = S_0'' + S_0'$.

Figure 18 shows predicted surge elevation S_0 , versus position X_0 of the front of the hurricane with respect to the entrance of Chesapeake Bay.

Similar computations were made for Hurricane "A" using 0.91 times the stress diagram, Figure 16 and a maximum surge for Hurricane "A" of 11.1 feet was computed. Maximum surge for Hurricane "B" was 12.2 feet. The ratio of the surge heights for the two hurricanes is $11.1/12.2 = 0.91$, which is the same ratio as that given for the square of the two maximum wind speeds. Within the range of say ± 15 to 20 mph from the above maximum wind speeds, for a hurricane moving more or less perpendicular to the coast at a speed of 15 to 20 mph, the maximum surge on the open coast at Chesapeake Bay can be predicted from the following equation.

$$(S_0)_{\max} = 0.001 W_m^2 \pm 10\% \quad (16)$$

where S_0 is in feet and W_m is in miles per hour.

If the design or standard project hurricane is selected, for which the radius of maximum wind is nearly that used for Hurricanes "A" and "B" and the speed of forward movement is about 15 to 20 mph, then critical conditions or near critical conditions will exist, and equation 16 can be used to predict the maximum surge on the open coast. It might be noted that equation 16 includes the component of surge due to atmospheric pressure reduction, as reflected in the wind speed. For example, if the maximum sustained wind is 100 mph, then $(S_0)_{\max} = 10.0$ feet and if the maximum sustained wind is 120 mph then $(S_0)_{\max} = 14.4$ feet, on the open coast at Chesapeake Bay.

Hurricane Surge Within Chesapeake Bay. The maximum surge elevation above predicted astronomical tide for any location within Chesapeake Bay, neglecting river flow and run-off, consists of two components: (a) that which enters through the mouth of Chesapeake Bay, known as the primary surge and travels up the bay only to be modified by the surge ratios given in Table IV; and (b) the additional tilt or rise due to local wind stress and other local effects. Surge heights on the open coast were computed to be 11.1 and 12.2 feet, respectively for Hurricanes "A" and "B". Figure 15 can be used to obtain the surge elevation for the center of section 1. The additional rise or fall as the case may be due to the cross wind can be computed from the one-step formula

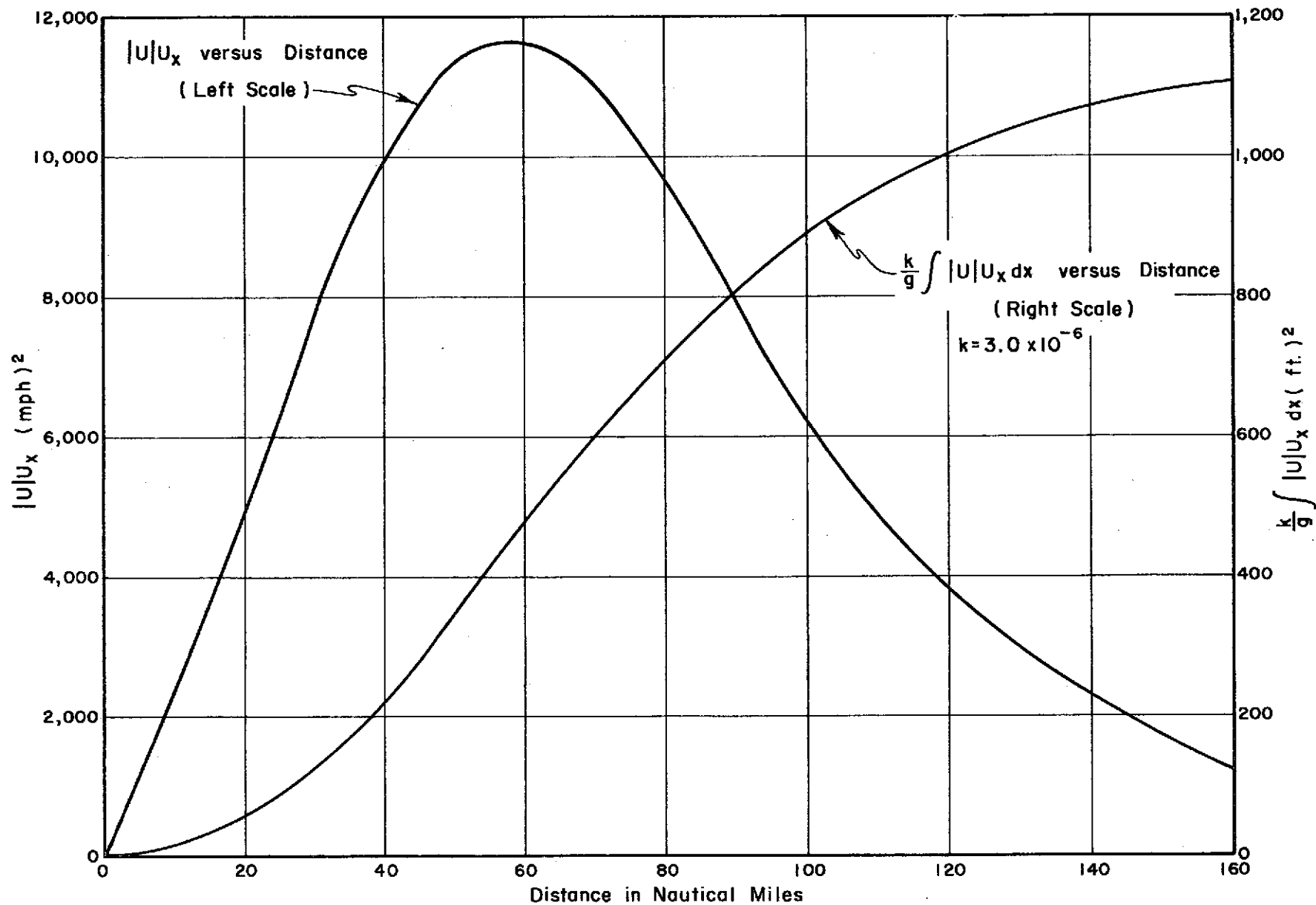


FIGURE 16. WIND STRESS DIAGRAM FOR HURRICANE "B".

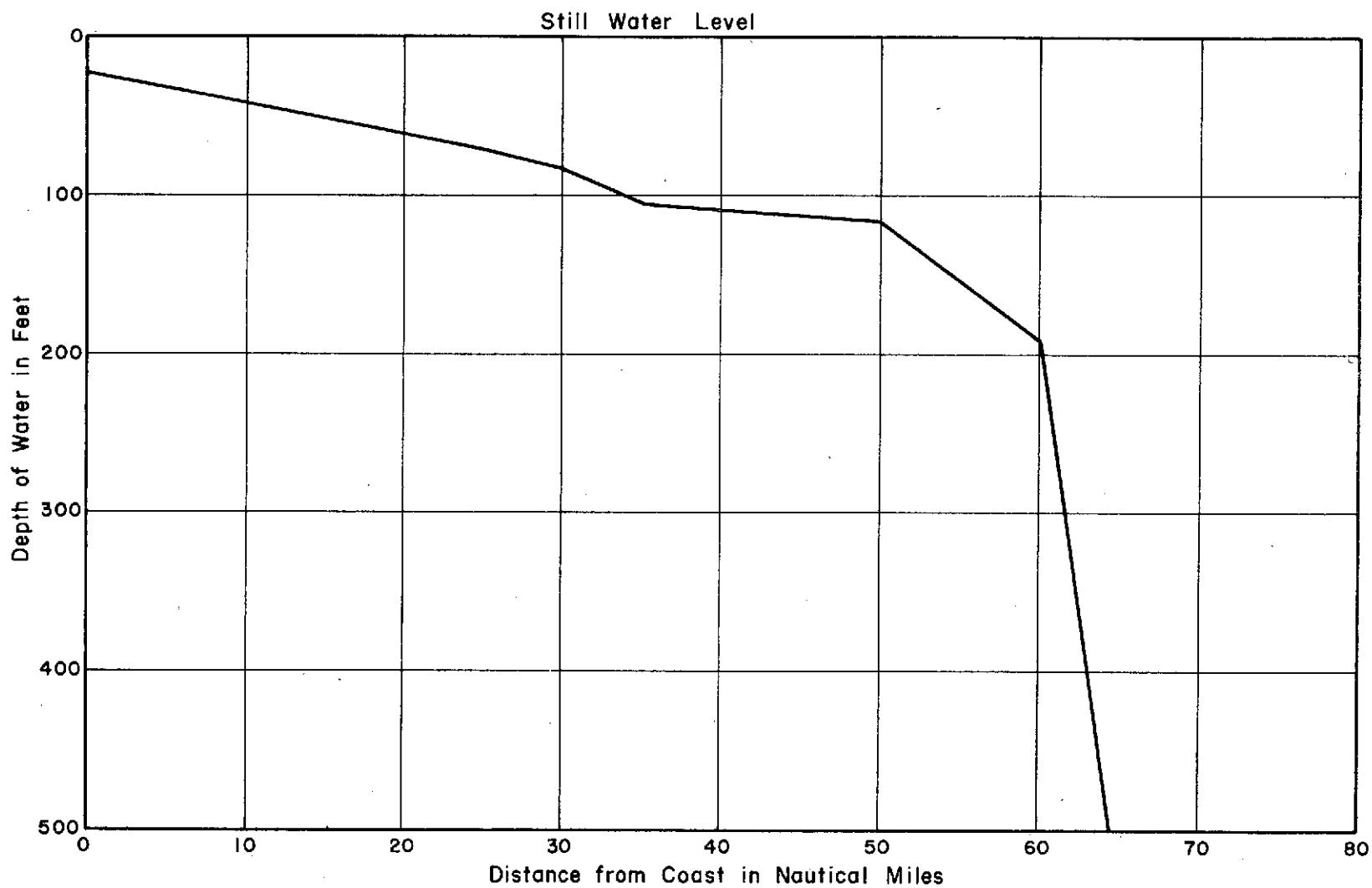


FIGURE 17. MEAN BOTTOM PROFILE OFF MOUTH OF CHESAPEAKE BAY

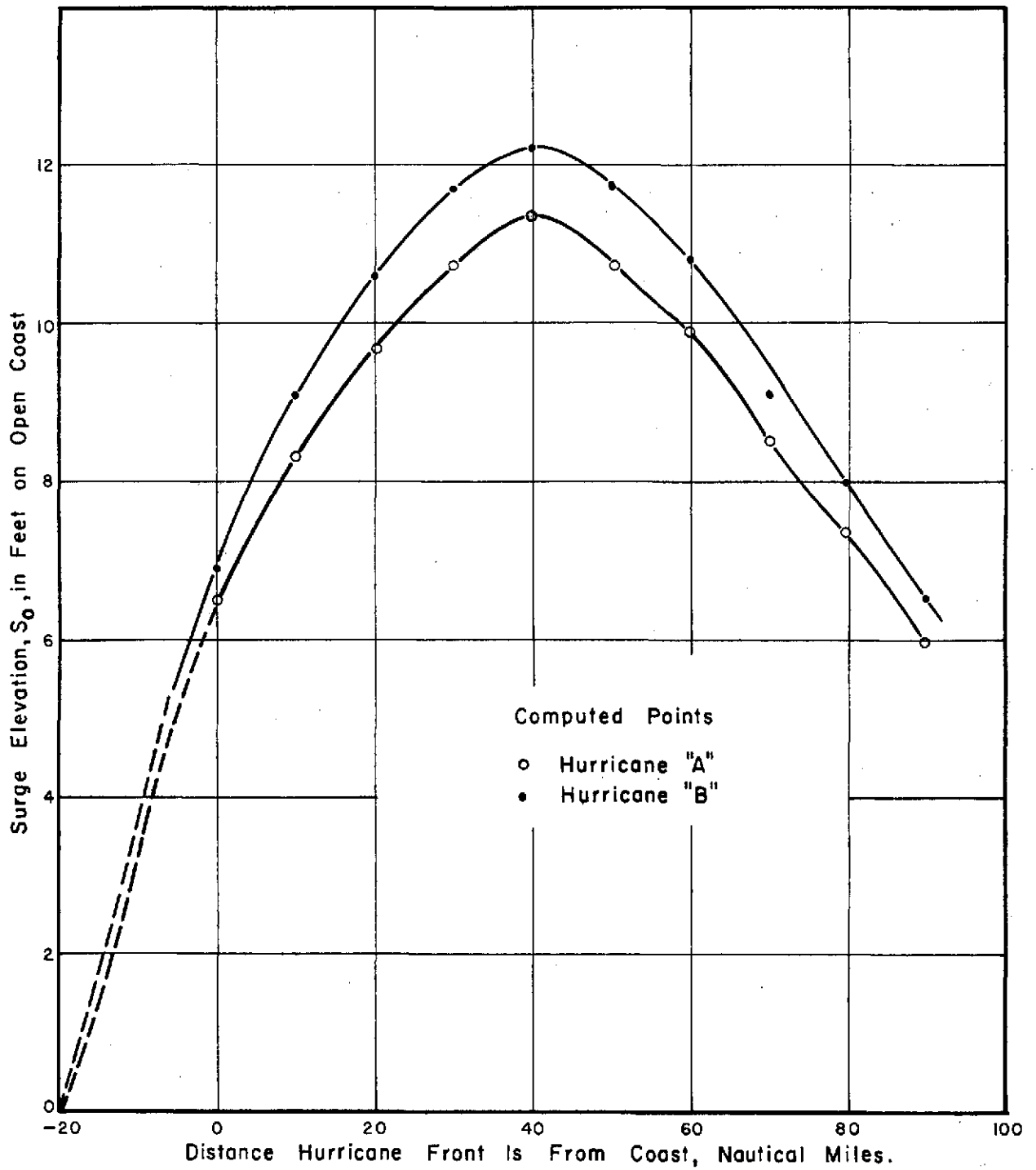


FIGURE 18. SURGE ELEVATION ON OPEN COAST CHESAPEAKE BAY ENTRANCE FOR HURRICANES "A" AND "B".

$$\Delta S = d_t \left[\sqrt{\frac{2kU^2 F}{gd_t^2} + 1} - 1 \right] \quad (17)$$

where d_t is the total mean water depth, excluding ΔS (but in this particular case, d_t is equal to the mean low water level plus astronomical tide plus surge height from the open coast); (i.e., d_t for section 1 is an average depth from the center axis of section 1 to Hampton Roads). The above assumes that the nodal line for cross tilt follows the center axis of the Bay, and this is approximately true since the cross wind effect is small compared with the mean depth. The symbols used in equation 17 are dimensionally homogenous. If $2F$ is replaced with W the mean width of the section in nautical miles, U is the mean cross wind component of the section in miles per hour, and $g = 32.2$, equation 17 reduces to:

$$\Delta S = \pm d_t \left[\sqrt{\frac{0.0122U^2 W}{d_t^2} + 1} - 1 \right] \quad (18)$$

The plus sign indicates set-up in the downwind direction and the minus sign set-down in the upwind direction.

Computations for the cross wind effects have been made for a number of locations along the western side of Chesapeake Bay. For example, consider Hampton Roads.

Using Figure 15, and $(S_o)_{max} = 11.1$ feet for Hurricane "A" and 12.2 feet for Hurricane "B" one obtains, respectively for the center of section 1, primary surge of 8.3 ± 0.4 feet and 9.0 ± 0.4 feet. The primary surge for the other locations is obtained by use of the surge ratios given in Table IV. The mean width across section 1 is approximately $W = 14$ nautical miles. The mean depth of water over section 1, exclusive of surge elevation is about 25 feet. The total mean water depth is $d_t = 25 + 8.3 = 33.3$ feet for Hurricane "A", and $d_t = 25 + 9.0 = 34.0$ feet for Hurricane "B".

From HUR 7-26 it is seen that the maximum cross wind over section 1 is about 100 mph, corresponding to Hurricane "A". The maximum cross wind for Hurricane "B" is given by $100 + 5 = 105$ mph.

Using the above information, and equation 18, one obtains

$\Delta S = 2.5$ feet for Hurricane "A"

$\Delta S = 2.7$ feet for Hurricane "B".

Thus the surge elevation on the west side of Chesapeake Bay at Hampton Roads is

$$S = 8.3 + 2.5 = 10.8 \pm 0.4 \text{ feet for Hurricane "A"}$$

and

$$S = 9.0 + 2.7 = 11.7 \pm 0.4 \text{ feet for Hurricane "B" .}$$

For the east side of Chesapeake Bay the minus ΔS cannot be used for section 1, since the surge entering the Bay already established an elevation between 11.1 and 8.3 for "A" and 12.2 and 9.0 for "B" for the conditions set forth. The minus ΔS can only apply for the east side of Chesapeake Bay for the sections which are not directly influenced by the entrance flow conditions.

Similar computations as those illustrated above have been made for the locations given in Table IV. Summary of these computations are given in Tables V-A and V-B.

Methods for Computing Surge Elevation for the East Side of Chesapeake Bay. Surge heights on the east side of Chesapeake Bay can be computed in a manner similar to that used for the west side. It must be remembered that when ΔS is positive for the west side ΔS will be negative on the east side, and vice versa depending on whether the wind is from the east or west.

Because of the particular path and speed of the hurricane selected, the peak of the primary surge from the open coast will coincide approximately with the maximum cross winds from the east; but the peak of the primary surge may not necessarily be close in phase with the maximum cross winds from the west, which follow behind the hurricane. From Figures 10, 11, and 12, it is seen that for about 5 hours the primary surge will be within one-half to one foot below the peak. It appears then for a first approximation that the maximum resultant for the east side of the bay will be equal to the peak of the primary surge minus about 1/2 to 1 foot plus ΔS , where ΔS is that component computed due to the cross wind from the west. This method will probably not apply for the east side of section 1.

In order to obtain more accurate estimates, it would be necessary to consider the time history of the primary surge and the time history of the wind field within Chesapeake Bay superimposed thereon; and then compute the time history of ΔS due to cross wind components, east or west.

TABLE V-A
SUMMARY OF SURGE COMPUTATIONS HURRICANE "A"

<u>Location</u>	<u>W N. Miles</u>	<u>Primary surge (ft.)</u>	<u>mean low water depth ft.</u>	<u>d_t ft.</u>	<u>cross wind MPH</u>	<u>ΔS feet</u>	<u>S feet</u>
Hampton Roads, Va.	14.0	8.3 ± 0.4	25	33.3	100	2.5	10.8 ± 0.4
Mouth of York River	17.5	8.2 ± 0.4	33	41.2	92	2.1	10.3 ± 0.4
Mouth of Rappahannock River	18.0	8.1 ± 0.4	40	48.1	87	1.7	9.8 ± 0.4
Mouth of Potomac River	14.0	8.0 ± 0.4	40	48.0	80	1.1	9.1 ± 0.4
Mouth of Severn River	5.5	7.9 ± 0.4	45	52.9	75	0.4	8.3 ± 0.4
Mouth of Patapsco River	8.0	8.5 ± 0.4	18	26.5	70	0.9	9.4 ± 0.4

40

TABLE V-B
SUMMARY OF SURGE COMPUTATIONS HURRICANE "B"

Hampton Roads, Va.	14.0	9.0 ± 0.4	25	34.0	105	2.7	11.7 ± 0.4
Mouth of York River	17.5	8.9 ± 0.4	33	41.9	97	2.4	11.3 ± 0.4
Mouth of Rappahannock River	18.0	8.8 ± 0.4	40	48.8	92	1.9	10.7 ± 0.4
Mouth of Potomac River	14.0	8.7 ± 0.4	40	48.7	85	1.3	10.0 ± 0.4
Mouth of Severn River	5.5	8.6 ± 0.4	45	53.6	80	0.5	9.1 ± 0.4
Mouth of Patapsco River	8.0	9.2 ± 0.4	18	27.2	75	1.0	10.2 ± 0.4

IV HURRICANE SURGE, SPECIAL PREDICTIONS

Discussion. The preceding sections of this report carried the surge problem from the open coast, through the entrance of Chesapeake Bay, and up the bay to points just inside various main river mouths along the west side of the Chesapeake Bay.

The problem of special surge predictions is an attempt to obtain reasonable surge elevations upstream from the mouths of these rivers. In particular, the areas around Washington, D. C. and Baltimore, Maryland are important. The area around Norfolk, Virginia is also a special problem, since the present hurricane investigated may not necessarily be that which might produce the highest water level in downtown Norfolk, where strong winds from the northeast might be critical. The three areas of interest are discussed below.

Surge Prediction for Norfolk Area. Unless there are strong winds out of the north or northeast, the present investigation may lead to values too low for the hurricane surge for the Norfolk area. The present analysis gives a surge height on the open coast, opposite Norfolk, of 11.1 feet for Hurricane "A" and 12.2 feet for Hurricane "B"; and inside the Chesapeake Bay, the present analysis gives 8.3 ± 0.4 feet for Hurricane "A" and 9.0 ± 0.4 feet for Hurricane "B", which increases to 10.8 ± 0.4 feet and 11.7 ± 0.4 feet, respectively westward to Hampton Roads.

Isovel patterns for the standard project hurricane for the Norfolk area are given in HUR 7-44. The path of this hurricane was selected such that strong winds would be directed toward Norfolk from the northeast quarter. Such a hurricane would not produce the greatest surge entering Chesapeake Bay and advancing northward say toward Baltimore. From the upper reaches of Chesapeake Bay, the water would be driven southward, and if there is a strong onshore component of wind at the same time tending to pile up the water along the open coast near the mouth of Chesapeake Bay, then the surge would converge on the Norfolk area.

The wind set-up along the southern end of Chesapeake Bay between Hampton Roads and Norfolk due to northerly winds over the bay may be computed from the following formula:

$$S_1 = \frac{0.1 U_r^2}{45 + A_s + S_1/2} \cos \theta \pm 10\% \quad (19)$$

where S_1 is the wind set-up in feet ($\pm 10\%$)
 A_s is astronomical tide above mean water depth
 U_r^2 is average squared wind velocity in (mph)²

θ is an angle the wind direction makes with the long axis of lower Chesapeake Bay

It appears from HUR 7-44 that $U_r^2 \cos \theta$ will be approximately 4,000 (mph)² whence from equation 18, using $A_S = 0$, one obtains

$$S_1 = 8.1 \text{ feet } \pm 10\%$$

The atmospheric pressure reduction from normal over the area of interest will be about 1.7 inches of mercury corresponding to 1.9 feet of water. Thus the maximum surge for the Norfolk area for the standard project hurricane will be

$$S = 8.1 + 1.9 = 10.0 \pm 1.0 \text{ feet}$$

To the above value must be added the predicted astronomical tide.

If the wind speed is increased 10 percent the corresponding surge height would be increased by about 20 percent.

As far as the Norfolk area is concerned, consideration should be given to the maximum probable surge that might be experienced with a severe northeasterly storm. For example, HUR 7-41, gives isovels for the April 11-12, 1956 northeaster adjusted for maximum surge generation at Norfolk. For this storm it is seen that the isovel of maximum wind speed is 65 mph, corresponding very nearly to $U_r^2 = 4225 \text{ (mph)}^2$, which is slightly greater than that for the standard project hurricane for Norfolk. Using equation 18 and $U_r^2 = 4225 \text{ (mph)}^2$, one obtains for this northeaster

$$S_1 = 8.6 \text{ feet } \pm 10\%$$

If it is assumed that atmospheric pressure reduction from normal will produce about one and a half foot additional rise then the total surge produced by this northeaster will be comparable to that produced by the standard project hurricane.

If the standard project northeaster has greater intensity than the above northeaster, then the standard project hurricane is less critical than the standard project northeaster.

Surge Prediction for Washington, D. C. Area. The maximum surge elevation for the Washington area will be a resultant of the surge travelling up Potomac River from Chesapeake Bay and the additional change in elevation due to wind stress over the upper Potomac River near Washington. The surge entering Potomac River will be modified by shoaling, convergence, and bottom and side friction, and according to tide and surge data the net result would be to increase the surge height as it propagates up the river. The wind effect over the upper Potomac River may tend to increase or decrease the surge elevation depending on the direction that the wind is blowing.

It is difficult to separate entirely the above effects, except by use of a great amount of empirical data, which are as yet not available. The limited amount of empirical data are used to obtain surge prediction relationships for the Washington area. Table VI below presents surge data available from past hurricanes for both Washington and Dahlgren, Virginia.

TABLE VI
SURGE DATA FOR POTOMAC RIVER

<u>Date</u>	Surge Height in Feet Above Predicted Astronomical Tide		
	<u>Dahlgren</u>	<u>Washington</u>	<u>Mouth of Potomac (adjusted)</u>
22-24 Aug. 1933	6.5 (estimated)	7.6	6.0 (observed)
15 Oct. 1954	6.2	8.3	5.1
12-13 Aug. 1955	4.6	6.2	3.8
17-18 Aug. 1955	4.7	6.6	3.8
19-20 Sept. 1955	2.9	4.4	2.2

Except for the adjusted and estimated values, the above data were furnished by the U. S. Army Engineer District, Washington.

It was desirable to adjust the above data to apply at the mouth of Potomac River, instead of at Dahlgren, Virginia. Based on other available high water data, and the configuration of Potomac River, it is fairly reasonable to assume that the increase in surge from Dahlgren to Washington is approximately twice the increase in surge from the mouth of the Potomac to Dahlgren. For adjustment purposes, the surge at the mouth of the Potomac is estimated for the above storms from the following formula.

Surge at mouth of Potomac = surge at Dahlgren - $1/2$ (surge at Washington - surge at Dahlgren).

Applying the above formula, the surge heights become adjusted for the mouth of Potomac River, and the corresponding values are given in the last column of Table VI.

In regard to the August 1933 hurricane, the value of 6.0 feet for the mouth of Potomac River is in agreement with that observed at Little Wicomico, near the mouth of that river, and this is the same value predicted in the previous section of this report for the mouth of Potomac River.

Figure 19 shows the surge heights from Table VI for Washington versus those at Dahlgren. Figure 20 shows the surge heights for Washington versus those adjusted for the mouth of Potomac River. The ranges in astronomical mean and spring tides are also shown in the above figures for the corresponding locations.

Figures 19 and 20 show a remarkable correlation in surge elevations for the corresponding locations. The surge height for the August 1933 hurricane does not fall on the curve, and the reason is that little or no wind effect existed for that hurricane. The other hurricanes had moderate wind effects.

Figure 20 also shows the prediction curve for hurricane surge at Washington. The solid curve can be used to estimate the surge height (including wind effect) at Washington from the maximum surge predicted at the mouth of the Potomac. This assumes that the wind is in the direction to cause an increase in surge height. The dashed curve might be used to predict the surge height at Washington from that at the mouth of the Potomac, after which the wind effect over the upper Potomac River might be added. It is quite likely that the solid and dashed lines should intersect at the astronomical tide, for no wind.

The surge height at the mouth of Potomac River was computed in the previous section to be $9.1 + 0.4$ feet and $10.0 + 0.4$ feet, respectively for Hurricane "A" and Hurricane "B". Using the solid curve of Figure 20, the corresponding surge elevations at Washington will be 13.6 and 14.8 feet, respectively.

In order to establish more confidence in the above surge values, one might use the dashed curve of Figure 20 for predicting surge values and then add that component due to wind stress. Using the dashed curve, the surge height (not including the additional wind set-up) is equal to $10.6 + 0.4$ feet and $11.5 + 0.4$ feet, respectively for Hurricane "A" and Hurricane "B".

That component due to wind set-up over the upper Potomac River can be obtained from equation 17 where the upper Potomac River is replaced

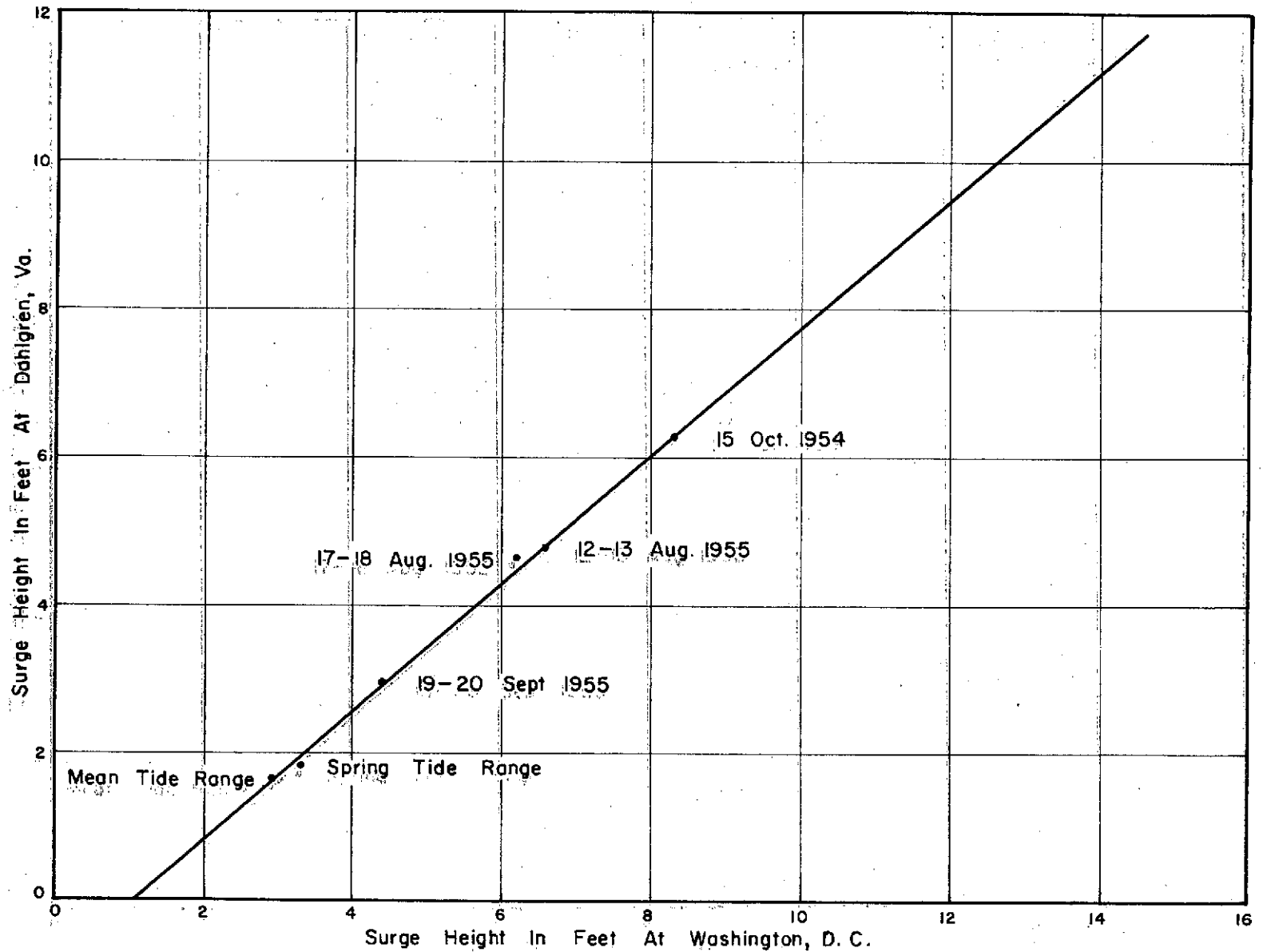


FIGURE 19. SURGE HEIGHT AT DAHLGREN, VA.
VS SURGE HEIGHT AT WASHINGTON, D.C.

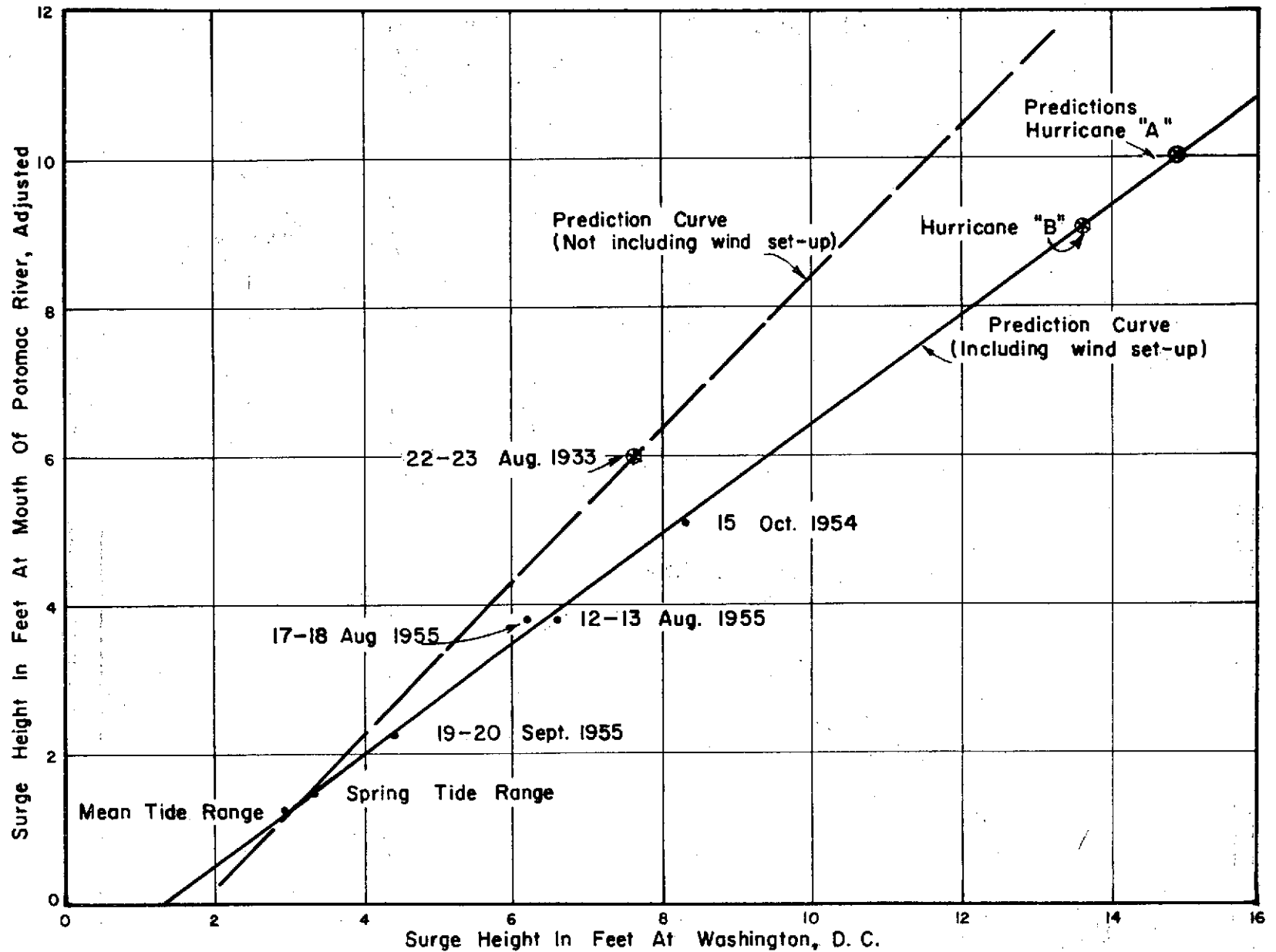


FIGURE 20. PREDICTION CURVE FOR HURRICANE SURGE AT WASHINGTON, D. C.

with an equivalent channel having the following dimensions:

length = 55,500 feet
width = 5,000 feet
depth = 10.5 feet

When computing the wind set-up component, the surge heights (10.6 and 11.5, above) must be added to the depth of 10.5 feet.

From Figure 9 of HUR 7-20 it is estimated for the upper Potomac River that the maximum wind is 60 mph for Hurricane "A" and 65 mph for Hurricane "B". Higher wind speeds might be used if the path of the storm is shifted more critical to the Washington area. Using equation 17 and the above wind speeds, fetch length, and mean water depth plus surge the corresponding set-up values are:

AS = 1.9 feet for Hurricane "A"
AS = 2.1 feet for Hurricane "B"

Whence the maximum surge elevation above predicted astronomical tide for Washington will be

S = 10.6 + 1.9 = 12.5 feet for Hurricane "A"
and
S = 11.5 + 2.1 = 13.6 feet for Hurricane "B"

It is seen that the above values are about a foot below those predicted from the solid curve of Figure 17. However, if maximum winds 75 mph and 80 mph were used for Hurricanes "A" and "B", respectively, then the maximum surge elevations above would be increased an additional foot.

It is believed, in addition to the accuracy of ± 0.4 foot at the mouth of Potomac River, that the accuracy up Potomac River is on the order of ± 0.5 foot, say ± 0.6 foot.

Finally, the maximum surge elevations for the Washington area are reasonably given as follows:

S = 13.6 \pm 1.0 feet for Hurricane "A"
S = 14.8 \pm 1.0 feet for Hurricane "B"

Surge Prediction for Baltimore Area. The maximum surge height for the Baltimore area is equal to that just inside the mouth of Patapsco River plus the additional rise due to wind stress up the river. The mean water depth, excluding surge height, is 18 feet, the fetch length

from just inside the mouth of Patapsco River to Baltimore is about 10 nautical miles, the wind speed (HUR 7-26) is 70 mph for Hurricane "A" and 75 mph for Hurricane "B".

Surge heights at the mouth of Patapsco River computed in the earlier section were $S = 9.4 + 0.4$ feet for Hurricane "A" and 10.2 feet for Hurricane "B", corresponding to $d_t = 27.4$ feet and 28.2 feet, respectively. Using equation 17 the additional set-up for Baltimore becomes

$$\Delta S = 2.1 \text{ feet for Hurricane "A"}$$

and

$$\Delta S = 2.3 \text{ feet for Hurricane "B"}$$

Thus, the maximum surge at Baltimore is

$$S = 9.4 + 2.1 = 11.5 \pm 1.0 \text{ feet for Hurricane "A"}$$

and

$$S = 10.2 + 2.3 = 12.5 \pm 1.0 \text{ feet for Hurricane "B"}$$

The limits of ± 1.0 foot for the surge elevations are considered reasonable, in view of the various steps required to bring the surge all the way from the open coast, through the entrance of Chesapeake Bay up that bay, thence up Patapsco River to Baltimore.

General Comments. It is believed that the surge heights computed for Hurricane "A" are reasonable and comparable to those which might be associated with a design or standard project hurricane and those for Hurricane "B" are maximum probable surges. However, for the Norfolk area, it is questionable whether the hurricane or the northeaster will be critical. If the standard project northeaster is about 10 percent greater in intensity than that given in item 3, above, then one should expect a surge height of about 12.0 ± 1.0 feet for the Norfolk area.

V SUMMARY

Summary of Surge Computations for Hurricane "A" and Hurricane "B".
 Hurricane "A" is the same as the September 14, 1944, Cape Hatteras Hurricane transposed to the Chesapeake Bay area to produce maximum surge entering that bay and propagating to the various points of interest (see HUR 7-20). Hurricane "B" is exactly the same in all respects as Hurricane "A" except that all wind speeds are increased by 5 mph. Table VII summarizes the computed surge elevations. The stress parameter used was $k = 3.0 \times 10^{-6}$.

TABLE VII
 SUMMARY OF SURGE PREDICTIONS FOR
 HURRICANE "A" AND HURRICANE "B"

<u>Location</u>	<u>Surge Elevations in Feet Above Predicted Astronomical Tide</u>	
	<u>Hurricane "A"</u>	<u>Hurricane "B"</u>
Open Coast	11.1	12.2
Hampton Roads, Virginia	10.8 ± 0.4	11.7 ± 0.4
Mouth of York River	10.3 ± 0.4	11.3 ± 0.4
Mouth of Rappahannock River	9.8 ± 0.4	10.7 ± 0.4
Mouth of Potomac River	9.1 ± 0.4	10.0 ± 0.4
Mouth of Severn River	8.3 ± 0.4	9.1 ± 0.4
Mouth of Patapsco River	9.4 ± 0.4	10.2 ± 0.4
Norfolk, Virginia	8.3 to 11.1 ± 0.4	9.0 to 12.2 ± 0.4
Washington, D. C.	13.6 ± 1.0	14.8 ± 1.0
Baltimore, Maryland	11.5 ± 1.0	12.5 ± 1.0

Surge Computations for Norfolk, Virginia for Standard Project Hurricane.
 Isovels for the standard project hurricane for Norfolk, Virginia are given in HUR 7-44. The maximum surge, due to wind blowing down Chesapeake Bay from the north, was computed to be 10.0 ± 1.0 feet for the standard project hurricane.

Surge Computations for Norfolk, Virginia for the April 11 - 12, 1956 Northeaster Adjusted for Maximum Surge Generation. Isovels for the above storm are given in HUR 7-41, and the maximum surge computed from the north is equal to 10.0 ± 1.0 feet.

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- HUR 7-20 Winds Over Chesapeake Bay for Hurricane of September 14, 1944 - Transposed.
- HUR 7-26 Winds Over Chesapeake Bay for Hurricane of September 14, 1944 - Transposed and Adjusted for Filling.
- HUR 7-27 Wind Speeds Over the Atlantic Ocean (30° - 42° Lat. 65° W. Long. - U. S. Coast) During the Northeaster of November 25, 1950.

- HUR 7-29 Wind Speeds Over the Atlantic Ocean (30° - 42° N Lat. 65° W. Long. - U. S. Coast) during the Northeaster of November 5-7, 1953.
- HUR 7-32 Meteorological Data Over the Sea in Hurricane of September 14, 1944.
- HUR 7-32a Hourly Wind Charts for Atlantic Hurricane of September 14, 1944.
- HUR 7-41 April 11-12, 1956 Northeaster Adjusted for Maximum Surge Generation at Norfolk, Virginia.
- HUR 7-43 Standard Project Hurricane Criteria and Isovel Patterns, East Coast U. S., Zone 3.
- HUR 7-44 Standard Project Hurricane Isovel Patterns, Norfolk Area.
- HUR 7-46 Characteristics of Northeasters as Related to Downtown Norfolk Area.
- HUR 8-1 Selected Weather Situations Related to High Tides.

APPENDIX A

The general solution of a cubic equation can be found in most handbooks on engineering, mathematics or physics. Reference (5) is used in the following material.

The solution to a cubic equation, which has one real root and two conjugate imaginary roots is given below.

Consider equation 8, which was given as follows:

$$(\Delta h)^3 + 2(25 + h_1)(\Delta h)^2 + (25 + h_1)^2 \Delta h - \left(\frac{\Delta V}{\Delta t C}\right)^2 \frac{10^{-8}}{98g} = 0 \quad \text{I-1}$$

The above equation has the form

$$aX^3 + 3bX^2 + 3cX + d = 0 \quad \text{I-2}$$

where

$$\begin{aligned} a &= 1 \\ b &= \frac{2}{3}(25 + h_1) \\ c &= \frac{1}{3}(25 + h_1)^2 \\ \text{and } d &= -\left(\frac{\Delta V}{\Delta t C}\right)^2 \frac{10^{-8}}{98g} \\ X &= \Delta h \end{aligned} \quad \text{I-3}$$

$$\text{Now let } X = \frac{1}{a}(y - b), \text{ whence} \quad \text{I-4}$$

$$y^3 + py + q = 0 \quad \text{I-5}$$

$$p = 3(ac - b^2)$$

$$q = a^2d - 3abc + 2b^3 \quad \text{I-6}$$

Substituting the relations for a, b, c, and d into equation I-6, one obtains

$$\begin{aligned} p &= -\frac{1}{3}(25 + h_1)^2 \\ q &= -\frac{2}{27}(25 + h_1)^3 - \left(\frac{\Delta V}{\Delta t C}\right)^2 \frac{10^{-8}}{98g} \end{aligned} \quad \text{I-7}$$

Now

$$D = \left(\frac{p}{3}\right)^3 + \left(\frac{q}{2}\right)^2 \quad \text{I-8}$$

Substituting equations I-7 into I-8, one obtains

$$D = \left[\frac{1}{2} \left(\frac{\Delta V}{\Delta t C} \right)^2 \frac{10^{-8}}{98g} \right]^2 + \frac{(25 + h_1)^3}{3} \left(\frac{\Delta V}{\Delta t C} \right)^2 \frac{10^{-8}}{49g} \quad \text{I-9}$$

From equations I-7 and I-9, it is seen that

$$\begin{aligned} p &< 0 \\ q &< 0 \\ D &> 0 \end{aligned} \quad \text{I-10}$$

For the conditions given by I-10, it can be found in reference (4) that there is only one real root and that the solution is given by

$$\begin{aligned} \cosh \theta &= -\frac{q}{2} \left(\frac{3}{-p} \right)^{3/2} \\ y &= 2 \sqrt{\frac{-p}{3}} \cosh \frac{\theta}{3} \end{aligned} \quad \text{I-11}$$

Thus

$$\begin{aligned} \Delta h &= \frac{2}{3} (25 + h_1) \left[\cosh \frac{\theta}{3} - 1 \right] \quad \text{where} \\ \cosh \theta &= \left[1 + \left(\frac{\Delta V}{\Delta t C} \right)^2 \frac{10^{-8}}{98g} \left(\frac{3}{25 + h_1} \right)^3 \right] = Z \\ \theta &= \ln \left[Z + \sqrt{Z^2 - 1} \right] \end{aligned} \quad \text{I-12}$$

The procedure for solution entails that $\Delta V/\Delta t$, C , and h_1 are given and Z is computed. Then compute θ , and finally compute Δh and it follows

$$h_0 = h_1 + \Delta h \quad \text{I-12}$$

HURRICANE TRACKING CHART

REMEMBER, hurricanes are large powerful storms that can suddenly change direction. Check frequently on the storm's progress until all Watches and Warnings for your area from the National Weather Service are canceled.

HURRICANE WATCH: hurricane may threaten within 36 hours

- Be prepared to take action if a warning is issued by the National Weather Service.
- Keep informed of the storm's progress

HURRICANE WARNING: hurricane expected to strike within 24 hours

- Leave beachfront and low-lying areas
- Leave mobile homes for more substantial shelter
- Stay in your home if it is sturdy, on high ground, and not near the beach, but if you are asked to leave by authorities, Go!
- Stay tuned to radio, NOAA Weather Radio, or television for hurricane advisories and safety information.



Scale
 0 50 100 150 200 Miles
 0 50 100 150 200 Kilometers

