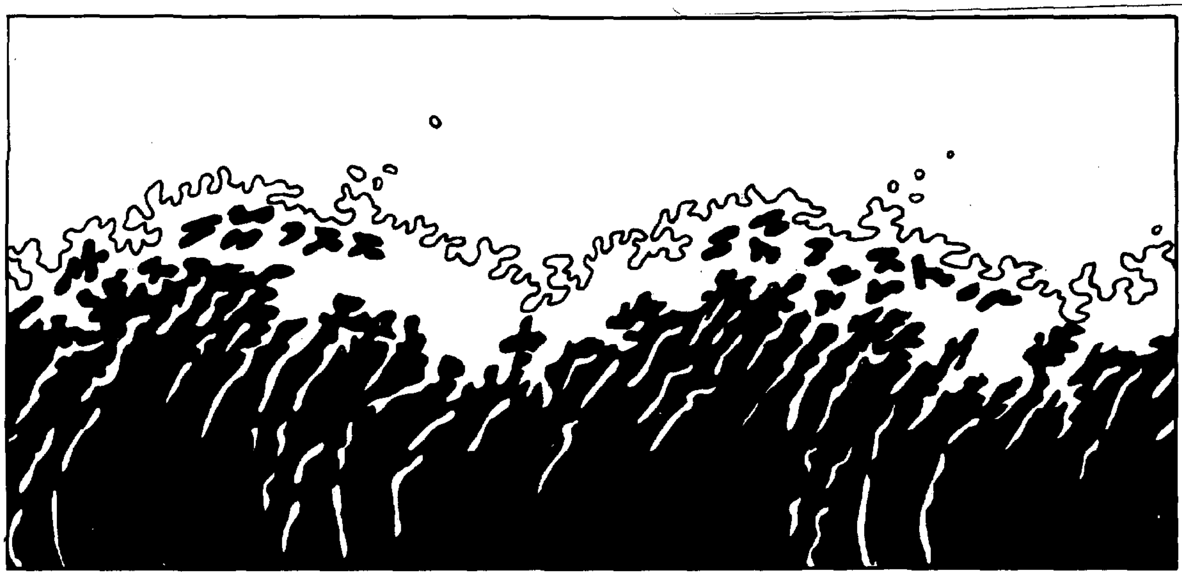
FY 1992 **FINAL PRODUCT** Task 18
Wave Energy Regimes



Design Wave Information for Chesapeake Bay and Major Tributaries in Virginia

by

David R. Basco, Ph.D., P.E.
and Cheol S. Shin

Report No. 93-1
December 1993

THE COASTAL ENGINEERING INSTITUTE

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This project was funded, in part, by the Virginia Department of Environmental Quality's Coastal Resources Management Program through Grant No. NA270Z0312-01 of the National Oceanic and Atmospheric Administration, Office of Ocean and Coastal Resource Management, under the Coastal Zone Management Act of 1972 as amended.

This project was also funded, in part, by the Virginia Department of Conservation and Recreation, Division of Soil and Water Conservation through contract No. C199-50311-93-5.

December, 1993

SUMMARY

Virginia has over 5,000 miles of Chesapeake Bay shoreline. Excessive water levels and accompanying wave action during storms causes shoreline erosion at many locations. The Shoreline Programs Section of the Department of Conservation and Recreation is responsible for giving advice to private property owners around the Bay as to alternatives available for shoreline stabilization. The economic design of each stabilization alternative (e.g. rock revetment, marsh vegetation, etc.) depends upon both the wave energy at the site and the value of the property, structures, investments, etc. to be protected.

Much of the property around the Bay is of relatively moderate value (farmland, single family dwellings, etc.). To provide for the minimum level of protection, moderate design wind speeds have been chosen for this study. From a historic wind data analysis for the Norfolk International Airport (1958-1973, 1979-1990) and the Patuxent Naval Air Station (1945-1983), a design wind speed of 35 mph was selected. This wind speed has about a 50 percent probability of exceedance in any one year and a duration of at least 6 hours.

Wave information is then hindcast using the simplified wind-generated, wave-growth formulas within the Automated Coastal Engineering System (ACES, 1992) as developed by the Coastal Engineering Research Center of the Corps of Engineers. These methods are essentially those described in the Shore Protectional Manual (1984) but updated to include the latest field data for calibration. The end product is twelve wave information maps showing iso-wave height contours (spectral, significant wave height) and associated wave periods (peak spectral period) for the Chesapeake Bay and its major tributaries in Virginia. The contours depict the largest waves at each location that could result from all possible wind directions (fetch distances and averaged water depths) that reach that location.

The results near the entrance to the Bay do not include ocean storm and swell waves which propagate into this region. Further refinement of these submaps (6, 7, 8, and 9) is recommended through use of a two-dimensional, wave spectrum transformation model. The limited amount of funding available precluded the use of these wave models for this project.

The design wave information as presented on the submaps of this report will be used by the Shoreline Programs Section of the Department of Conservation and Recreation to improve the accuracy and consistency of their shoreline erosion control advice. They will also aid in the implementation of management measures governing shoreline erosion control expected to be imposed by Section 6217 of the Coastal Zone Act Reauthorization Amendments of 1990. These maps are not recommended for general design use for all coastal engineering problems around the Bay.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the help of students in CE 482/582, Introduction to Coastal Engineering, during the spring 1993 semester at Old Dominion University for their initial try at sub-map development.

The contract was administrated by the Old Dominion University Research Foundation under Project No. ODURF 534251 between 1 Dec. 1992 and 31 Dec. 1993. Partial funding under Grant No. NA270Z0312-01 was provided by the Office of Ocean and Coastal Resource Management within the NOAA. This project was also funded in part by the Division of Soil and Water Conservation of Virginia's Department of Conservation and Recreation (DCR) through contract No. C199-50311-93-5. The financial support of these organizations is appreciated.

Mr. Carlton Lee Hill, Chief Shoreline Engineer was the project monitor for the DCR and assisted by Mr. Joe Baumer. The authors wish to thank these gentlemen for their help and advice during the project and for their diligent review of this final report. We also appreciate the comments and suggestions for improvement of this report as provided by Mr. Scott Hardaway of the Virginia Institute of Marine Science.

The maps were drawn by Ms. Debbie Miller, Publications and Graphics Department, Old Dominion University. The meticulous efforts of Ms. Miller are greatfully acknowledged.

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1.0 INTRODUCTION

1.1 Background

The Shoreline Programs Section of the Department of Conservation and Recreation needs consistently derived design wave information when providing advice for shore protection alternatives for over 5,000 miles of Chesapeake Bay shoreline. To accurately describe the wave climate within the Chesapeake Bay, two different techniques can be employed. One is wave gaging and the other is wave hindcasting. Although a network of wave gages* might eventually provide a good data source, the expense involved would make it economically prohibitive. A viable alternative to wave gaging is to hindcast the wave climate using historical wind data.

A variety of techniques are presently available to estimate water wave information from wind data. These methods are essentially two-dimensional, numerical models requiring computer solution or simple charts and formulas. The simplified, wind-generated, wave growth formulas within the Automated Coastal Engineering System (ACES, 1992) as developed by the Coastal Engineering Research Center of the Corps of Engineers was utilized as the wave hindcasting method in this project. The shallow-water formulations of ACES are based partly upon the fetch-limited, deep-water forms but do not encompass duration effects. The methods described in ACES are essentially those in Vincent (1984), the Shore Protection Manual (SPM, 1984), and Smith (1991), but updated to included the latest field data for calibration of the semi-theoretical, wave growth formulas.

Long term wind data from both the Norfolk International Airport (NIA) and the Patuxent Naval Air Station (PNAS) were obtained and statistically analyzed for the selection of a design wind speed. From the various storm probability curves, directional design wind speed and wind duration were obtained. Also, the analyses of tide and storm surge data were carried out for modification of the local water depth. A map of the entire Chesapeake Bay by the Virginia Institute of Marine Science (VIMS, 1977) was utilized for the bathymetric calculations and the geometries of water bodies although the analysis was confined to Virginia waters.

As the final product, twelve wave information maps were developed showing both iso-wave height contours (spectral significant wave height, H_{mo}) at one-half foot intervals and wave periods (peak period, T_p) covering all the water areas of the Chesapeake Bay and its major tributaries in Virginia. The local wave height shown is the largest that can be developed from all fetch directions but restricted to wind speeds with a fifty-percent exceedance probability level in any one year.

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* Wave data is available at a few selected locations and for limited time periods as collected by Dr. John Boon of the Virginia Institute of Marine Science.

1.2 Objectives

The goal of this project was to divide the Chesapeake Bay and tributary rivers into wave energy regimes based on the wave heights and periods predicted to be generated by a storm of a given exceedance probability. The results of this project is a tool to provide consistent shoreline management advice to the citizens and communities around the Bay. The wave energy maps developed in this study provide a source of accurate, scientifically determined wave characteristics (heights and periods) for use in the design of coastal structures for the shoreline of Virginia.

1.3 Work Tasks

Task No.1 included two major subtasks. One developed the coastal design philosophy for which the wave energy maps are applicable and determined the exceedance probability for wind speed that matched the design philosophy. The second subtask developed the methodology to determine the wave energy which included: summaries of wind statistics from regional airports; determination of appropriate design wind speeds; determination of dominant and non-dominant fetch directions; calculation of average water depths for given fetches; and finally the calculation of wave characteristics using the wind-generated, wave hindcasting model.

Task No.2 developed the organizational structure, numbering system and map scales to be used to display the predicted wave energy regimes.

Task No.3 developed one wave energy map for a limited area as a test case to validate the previously developed methodology.

Task No.4 developed wave energy maps for the Chesapeake Bay and tributary rivers in the Commonwealth of Virginia.

1.4 Limitations

The wave information maps developed in this study do not consider *nearshore* wave transformation processes such as shoaling, refraction and wave breaking processes in surf zones. Therefore, the information provided can be considered as boundary conditions for use in a nearshore wave transformation model. The iso-wave height contours shown on the maps are not those predicted from one storm with a 50 percent exceedance probability but are *synthesized* from all possible storm directions at the 50 percent level.

Ocean swell waves entering through the Chesapeake Bay entrance are not considered in this study.

2.0 WIND-WAVE HINDCAST MODELS

2.1 Types

Three basically different methods are available to hindcast wind-waves in coastal and bay waters. One approach (Hasselmann *et al.*, 1976) requires large, main-frame computers to solve the two-dimensional, wave propagation and transformation equations (growth, spread, decay, interaction) for the directional, energy density spectrum. Parameterization of the directional spectrum shape reduces the computational effort so that a second approach that also uses a two-dimensional grid, (Holthuijsen *et al.*, 1989) can be efficiently developed for the PC/workstation environment. The MIKE 21 NSW model as developed at the Danish Hydraulic Institute, Horsholm is an example of the latter approach. This model recently (September, 1993) has been installed within the Computing Laboratory of the Civil and Environmental Engineering Department at Old Dominion University.

The third approach further reduces the spectral shapes into a common family that together with field data have been converted into formulas and nomographs for wind-wave hindcasting purposes. Wave characteristics (height and period) are determined from three wind parameters (speed, duration and fetch distance) in deep water and have been modified to include depth-limiting effects (i.e., dissipation) for shallow water. These formulas are essentially one-dimensional estimates for wave characteristics along a dominant fetch direction and directional spreading of wave energy is implicitly included in the formulations. The wave-hindcast formulas as specified in the SPM (1984) and as incorporated and refined within the ACES (Version 1.07) software package are employed for this project. The water waves are characterized by the spectral, significant wave height, H_{mo} and the peak spectral period, T_p.

2.2 ACES 1.07

The methodologies represented in the latest formulation (Version 1.07) of ACES provide quick and simple estimates for wave growth over open-water and restricted fetches in deep and shallow water. Also, improved methods (over those given in the SPM, 1984) are included for adjusting the observed winds to those required by wave growth formulas. Wind-waves grow as a result of a flux of momentum and energy from the air above the waves into the wave field. The frictional effects due to the presence of the water and the land surface distort the wind field thus, wind speed and direction become dependent upon elevation above the mean surface, roughness of the surface, air-sea temperature difference, and horizontal temperature gradients.

For this project, the elevations have been corrected to the standard, 10 m reference level and all temperature corrections are taken at the default values as specified by ACES (1.07).

All wave conditions generated assume constant water depths over the storm duration, therefore, changes in the water elevation caused by the tides during each storm event are neglected. The wave growth formulations which follow are separated into four categories. Both deep- and shallow-water forms for both simple open water fetches and complex, limiting geometries designated as restricted fetch conditions are considered.

In open water, wave generation is limited by the dimensions of the meteorological event under investigation and fetch widths are of the same order of magnitude as the fetch length. The formulas for wave growth under open water fetch conditions do not include fetch width or shape effects. The more limiting or complex geometries of water bodies such as lakes, rivers, bays, and reservoirs have a significant impact on wind-wave generation.

The restricted fetch methodology applies the concept of wave development in off-wind directions and considers the shape of the basin. Radial fetch lengths and angles measured from the point of interest are used to describe the geometry of the basin. Figure 1 illustrates the relevant geometric data required for the restricted fetch approach. The conventions used for specifying wind direction and fetch geometry are illustrated in Figure 2.

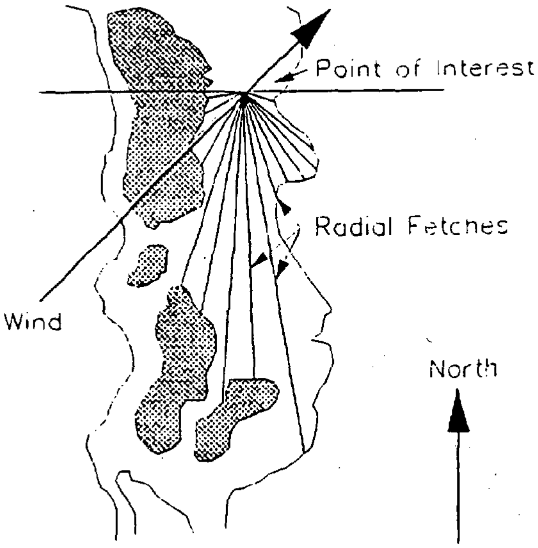

Figure 1 Restricted Fetch Geometry Data.

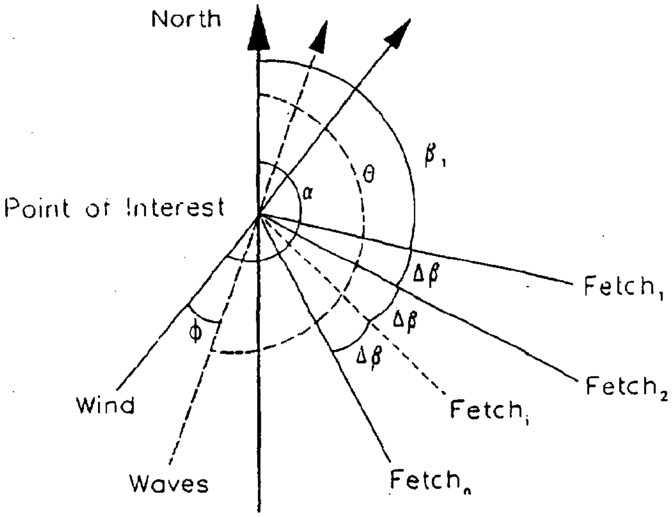

Figure 2 Restricted Fetch Conventions

The approach wind direction, α as well as the first radial fetch angle, β_1 and the radial fetch increment, $\Delta\beta$ are specified in a clockwise direction from north at the point of interest where wave growth prediction is required.

Hindcasting procedures are as follows for the restricted fetch method.

1. *select a point of interest*
2. *define the longest fetch length and direction from all possible direction*
3. *input the wind direction from the longest fetch direction*
4. *compute mean water depth along the longest fetch by the weighted-average method*
5. *measure radial fetch lengths and angles to describe the geometry of the basin*
6. *input all data into ACES.*

2.3 Limitations

The major assumptions and limitations regarding the use of the simplified ACES (1.07) model include;

- *energy from the presence of other existing wave trains (e.g. ocean swell) is neglected,*
- *relatively short fetch geometry (F $\leq$ 75 miles),*
- *relatively constant wind speed and direction,*
- *wind prescribed at the 10 meter elevation,*
- *neutral stability condition,*
- *fixed value of drag coefficient,*
- *nearshore wave transformations are not considered,*
- *depth-induced wave breaking and surf zone process are not defined.*

3.0 WIND DATA AND ANALYSIS

3.1 Time and Spacial Variation of Wind Speeds

3.1.1 Airport Reported Wind Speeds

Generally, the airport reported wind speeds are the fastest mile wind speed. The fastest mile wind speed, because of its short duration, should not be used to determine the wind speed for wave generation. Therefore, the fastest mile wind speeds must be converted to the one-hour average wind speed using methodology outlined in the Shore Protection Manual (SPM, 1984). Figure 3 shows the relationship between the fastest mile wind speed and the one-hour average wind speed with a regression line and an equation as determined by the SPM (1984) methodology.

3.1.2 Spacial Variation of Wind Data

Figure 4 shows the location of two, long term meteorological sites: Norfolk International Airport (NIA) Norfolk, Virginia for representation of the lower Chesapeake Bay wind field and the Patuxent Naval Air Station (PNAS) Patuxent, Maryland for the upper Chesapeake Bay wind field. PNAS is located on the western shore of the Bay at the mouth of the Patuxent River. The Norfolk Airport is close to the Chesapeake Bay entrance as shown in Figure 4. Also, a very limited amount of wind data was obtained from Wallops Island, Virginia but this site was not considered as a wind source due to insufficient length of data.

ACES assumes a constant wind speed and duration over the water body. Because of the size and length of the Chesapeake Bay, this assumption may be of concern. The rectangular box area in Figure 5 represents the boundaries of the Chesapeake Bay and its major tributaries as superimposed over the wind velocity vectors for the October 31, 1991 (Halloween Northeaster) storm event as modelled for the Mid-Atlantic Ocean (from Jensen *et al.*, 1993) The figure shows the frictional velocity contour (m/sec) and mean wind direction vector plot from the Fleet Numerical Oceanography Center (FNOC) wind stress fields as employed in the directional, discrete wave spectral model (3GWAM). From this example it can be seen that both the magnitudes (arrow length) and directions of the wind field remain *fairly uniform* within length scales of the Chesapeake Bay but, of course, change in magnitude and direction over length scales for the Atlantic Ocean. Therefore, the wind-wave hindcast results from ACES 1.07 for Chesapeake Bay should give reasonable results for storm events.

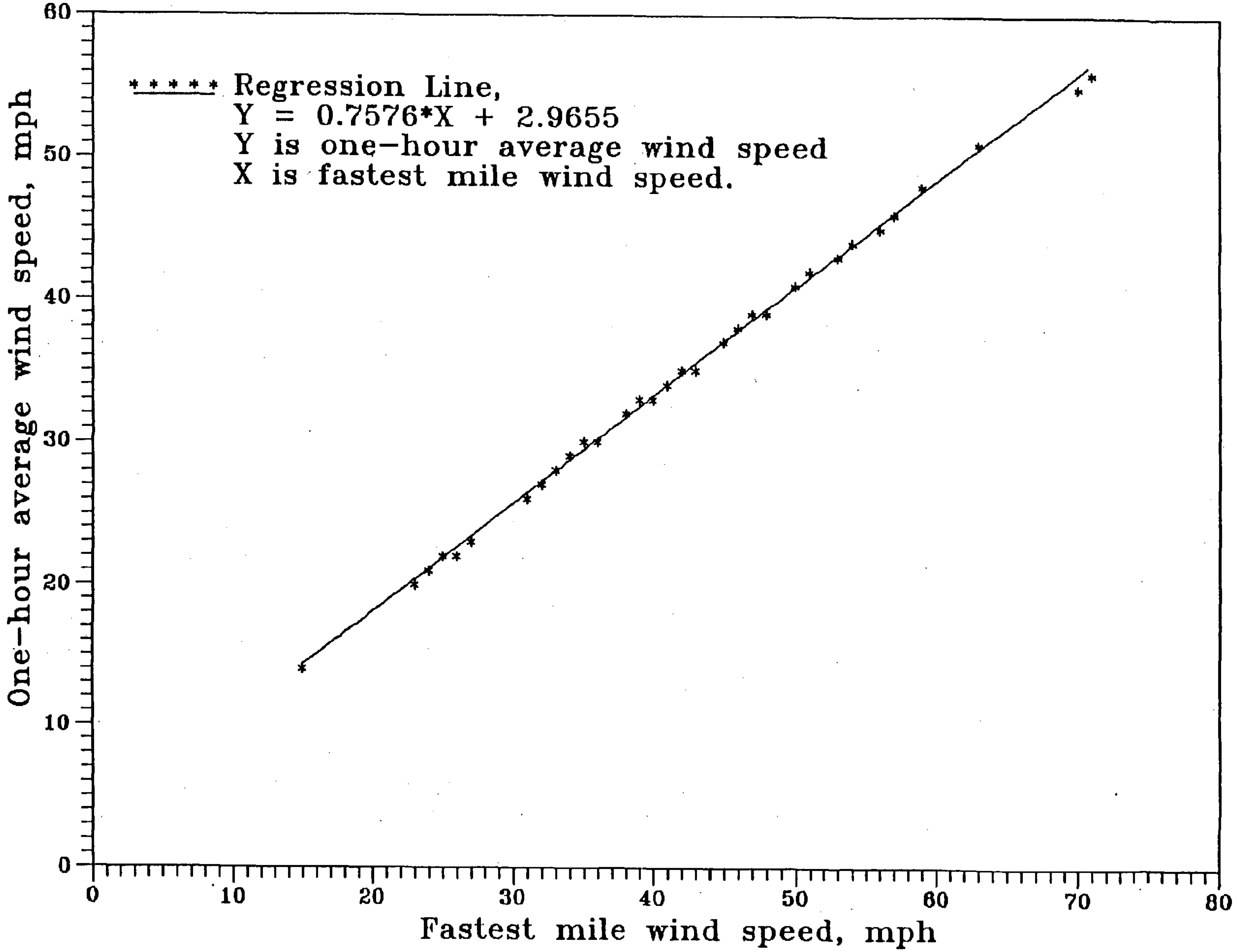

Figure 3 The Relationship Between the Fastest Mile Wind Speed and the One Hour Average Wind Speed.

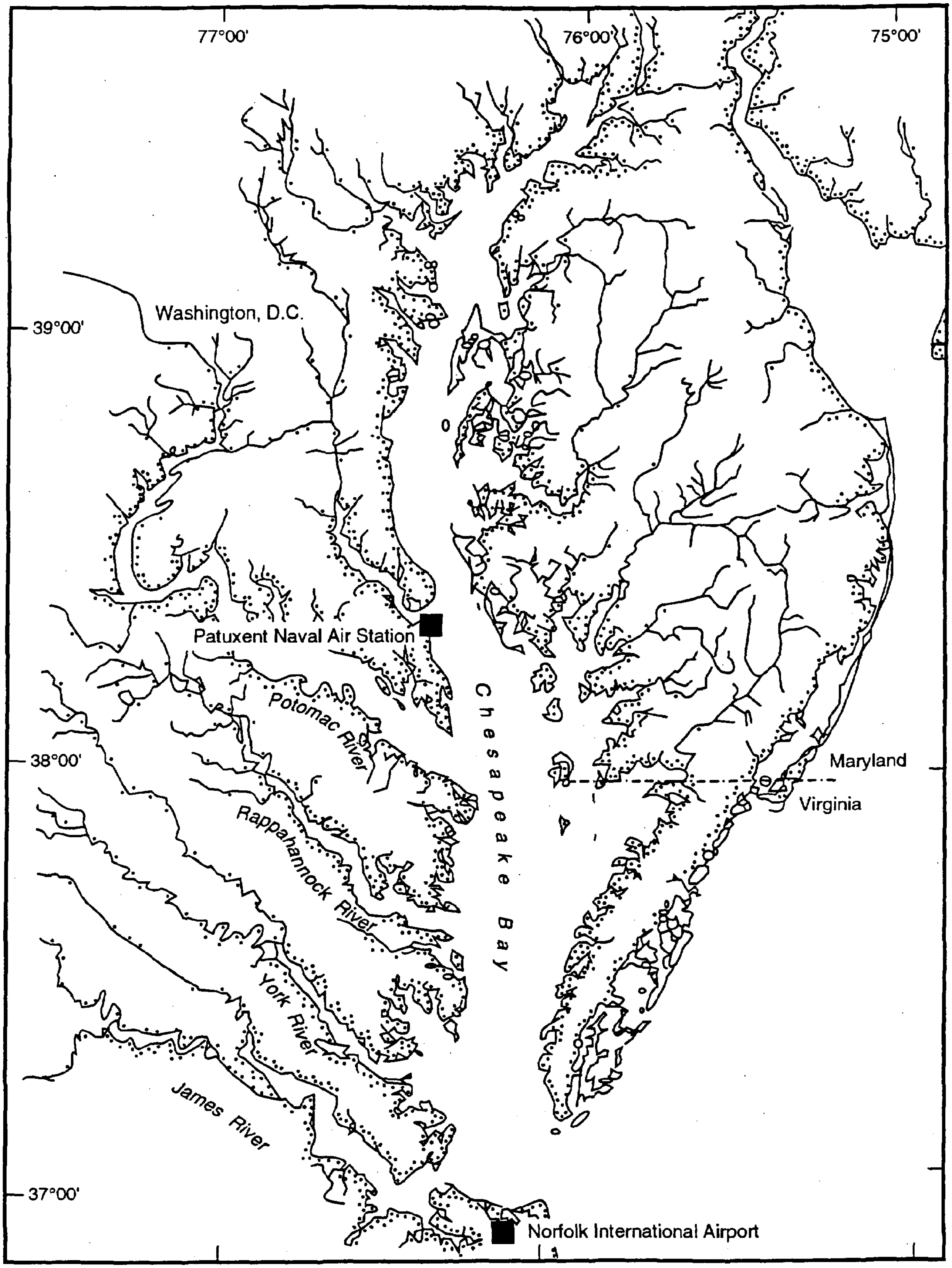

Figure 4 Chesapeake Bay and Wind Observation Sites.

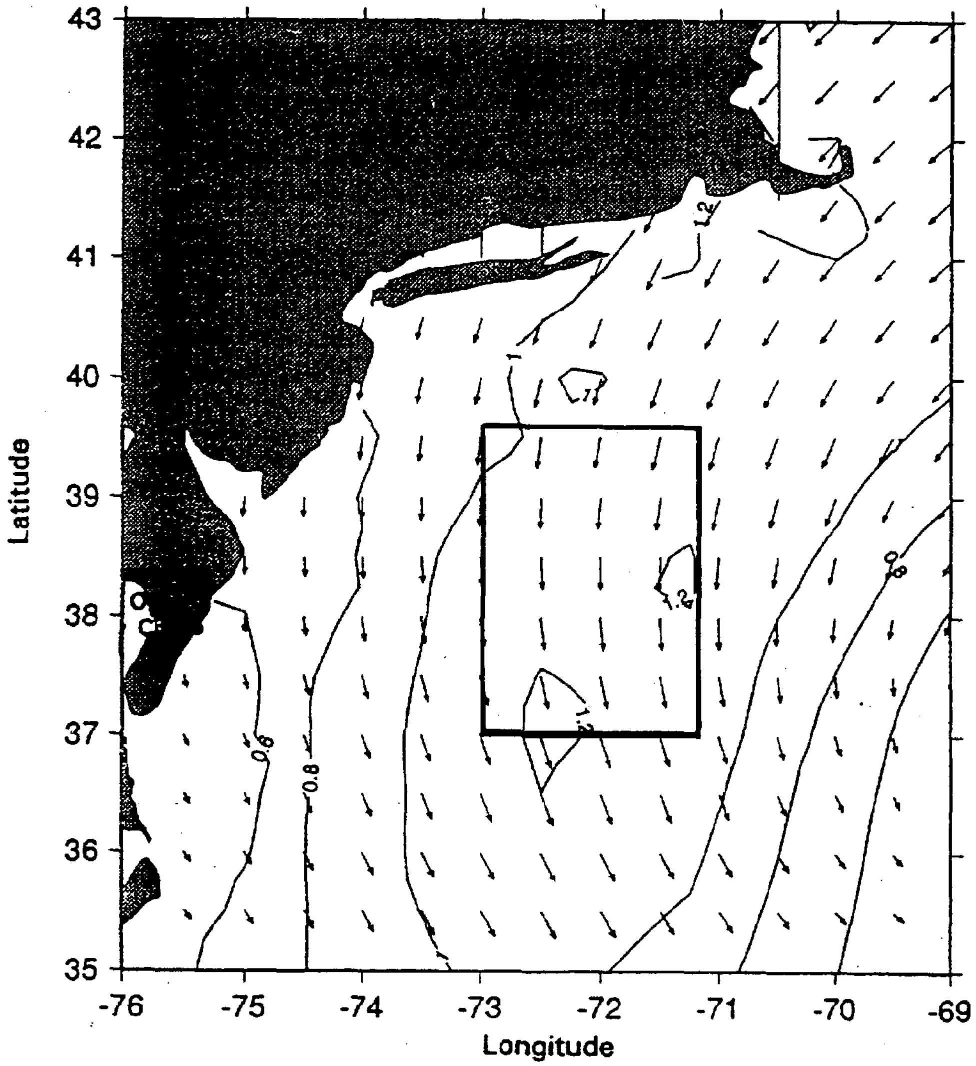

Figure 5 Frictional Velocity Contour and Mean Wind Direction Vector Plot from FNOC Wind Stress Fields and 3GWAM Model Simulations, Oct. 31, 1991 (Jensen *et al.*, 1993). The Rectangular Box Area Represents the Spatial Extent of the Chesapeake Bay.

3.2 Norfolk International Airport Data

3.2.1 Wind Duration Analysis

A total of thirty-two years of wind data observed at the NIA was obtained from the National Climate Data Center (NCDC) with fifteen years of summarized data from October 15, 1958 through August 23, 1973; five years of data from August 24, 1973 through December 31, 1978, and twelve years of hourly digitized wind observations from January 1, 1979 through December 31, 1990. The digitized wind data from 1979 through 1990 were analyzed for the directional storm probability curves.

Figures 6, 7, and 8 show duration histograms for various ranges of wind speed during 1958 through 1973. It is apparent from these figures that the sustained wind duration diminishes with increased wind speeds. For this study, three possible lengths of storm events considered were 6 hour, 12 hour, and the variable duration model as given in Table 1.

Table 1 Variable Wind Speed Range Versus Wind Durations Selected for This Study

Wind Speed Range (mph)	*Duration (hour)*
< 8.9	24
9.0 - 17.9	15
18.0 - 26.9	9
27.0 - 35.9	6
> 36.0	3

3.2.2 Exceedance Frequency Distributions

The number of storm events per year was calculated from the analyses of the probability of exceedance. Figures 9 and 10 show storm probability curves for these three storm durations during 1958-1973 (15 years) and 1979-1990 (12 years), respectively. From Figures 9 and 10 it was concluded that :

- *variable storm duration gives more representative results,*
- *both Figures 9 and 10 show consistent trends over a twenty-seven year span,*
- *the 100 percent exceedance probability storm wind speed equals 33 mph, and*
- *the 50 percent exceedance probability storm wind speed equals 36 mph.*

Figures 11 and 12 show storm probability curves for the four main compass directions (North, East, South, and West) for both 1958-1973 and 1979-1990 periods, respectively. Directional wind speeds were obtained from the directional probability analyses. From these analyses, it was concluded that :

- *winds from the North and West dominate,*
- *both time periods shows similar trends,*
- *the 100 percent probability storm wind speed equals 27 mph for the North direction, and*
- *the 50 percent probability storm wind speed equals 31 mph for the North direction.*

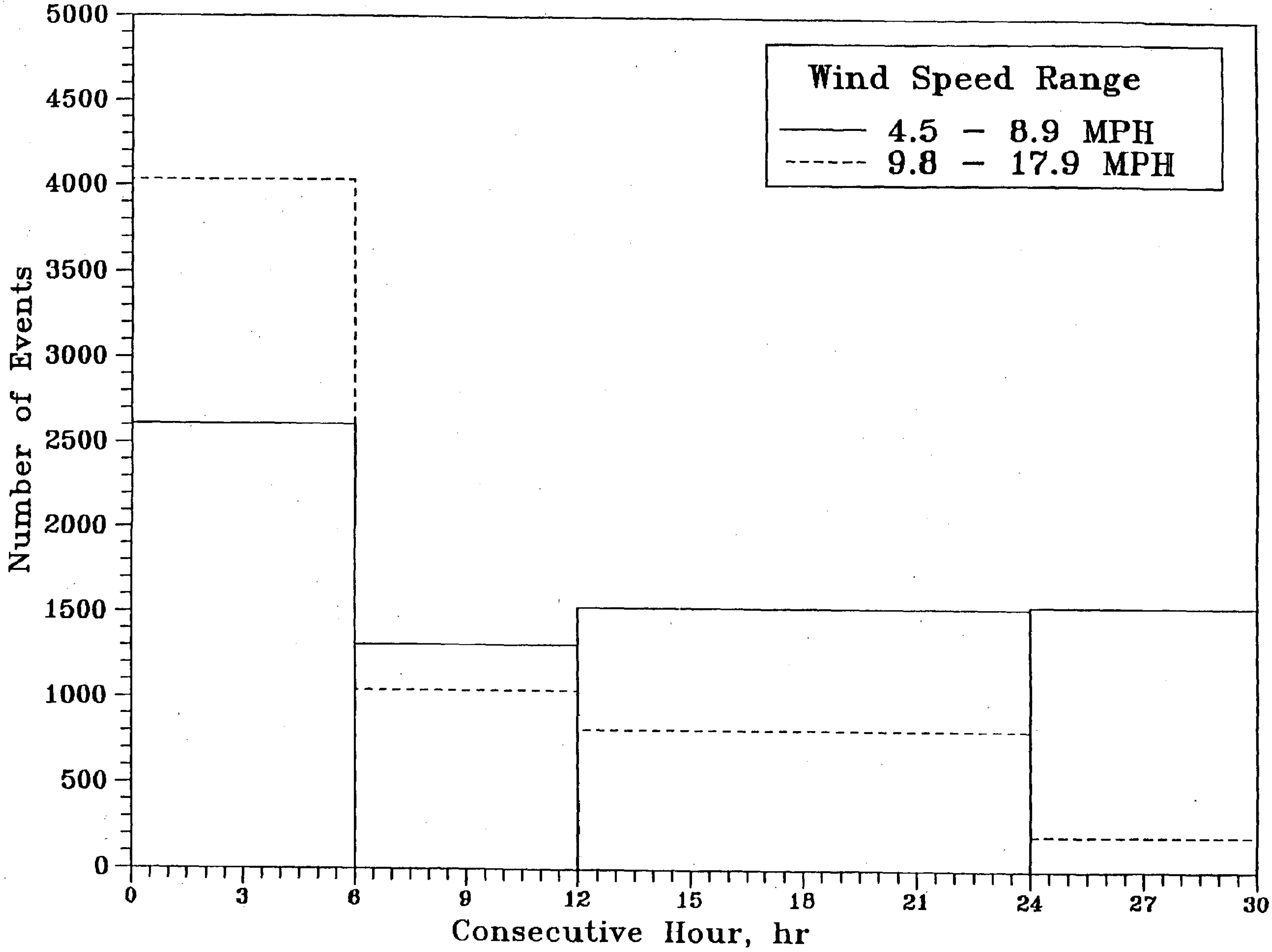

Figure 6 The Histogram of the Wind Speed Versus Duration, Norfolk (1958-1973).
(Wind Speed in 4.5 - 17.9 MPH Range)

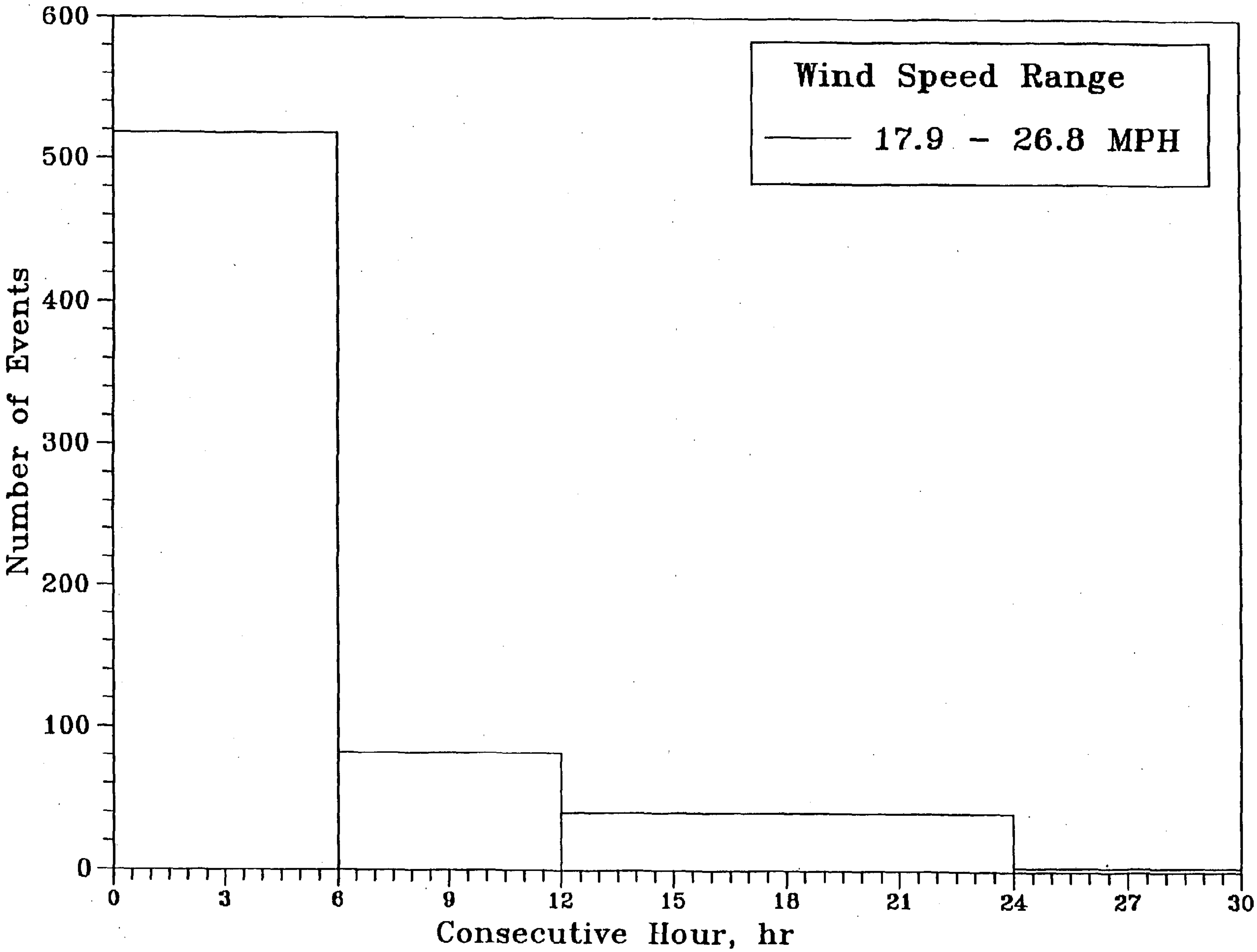

Figure 7 The Histogram of the Wind Speed Versus Duration, Norfolk (1958-1973).
(Wind Speed in 17.9 - 26.8 MPH Range)

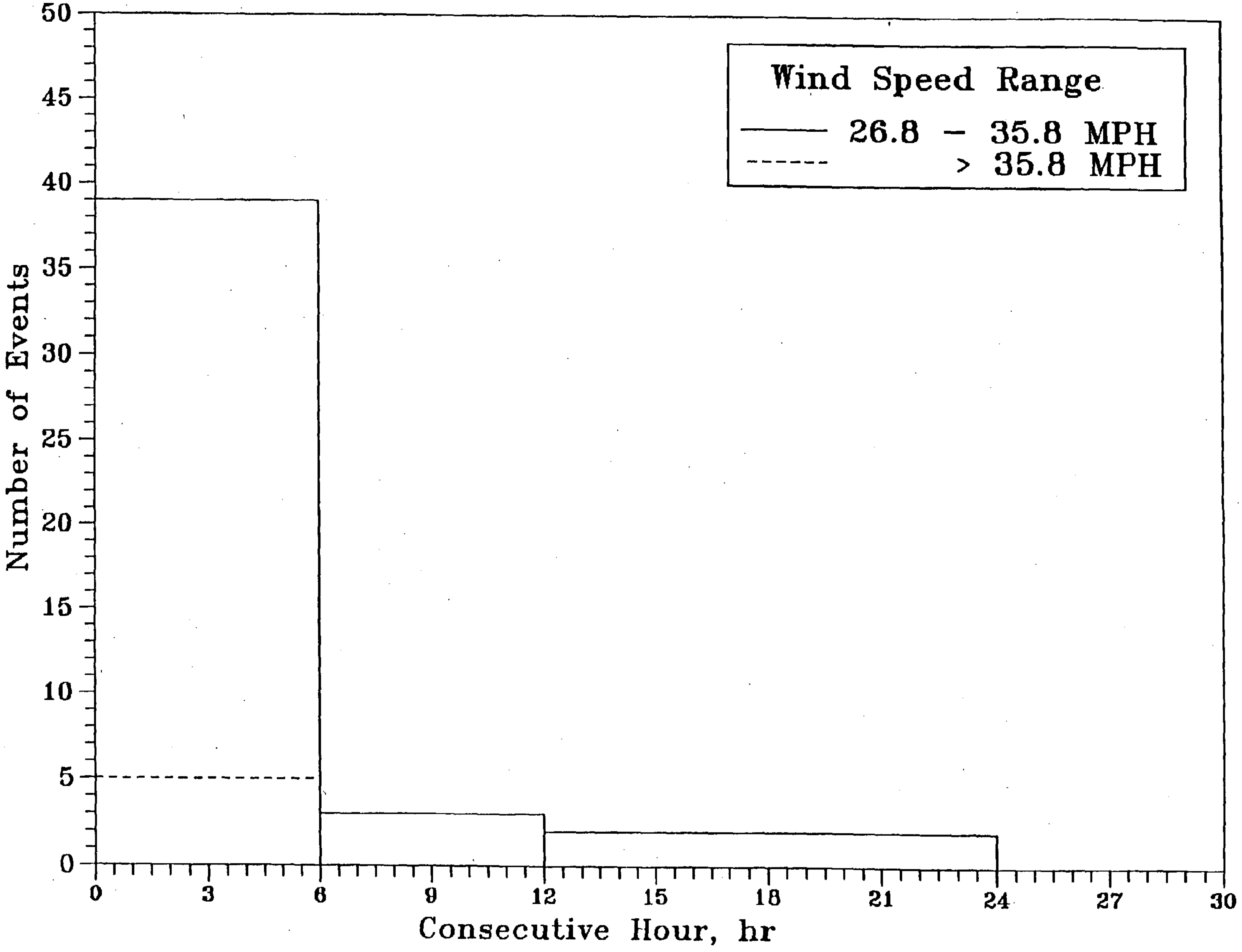

Figure 8 The Histogram of the Wind Speed Versus Duration, Norfolk (1958-1973).
(Wind Speed in 26.8 - 35.8 MPH and Greater Range)

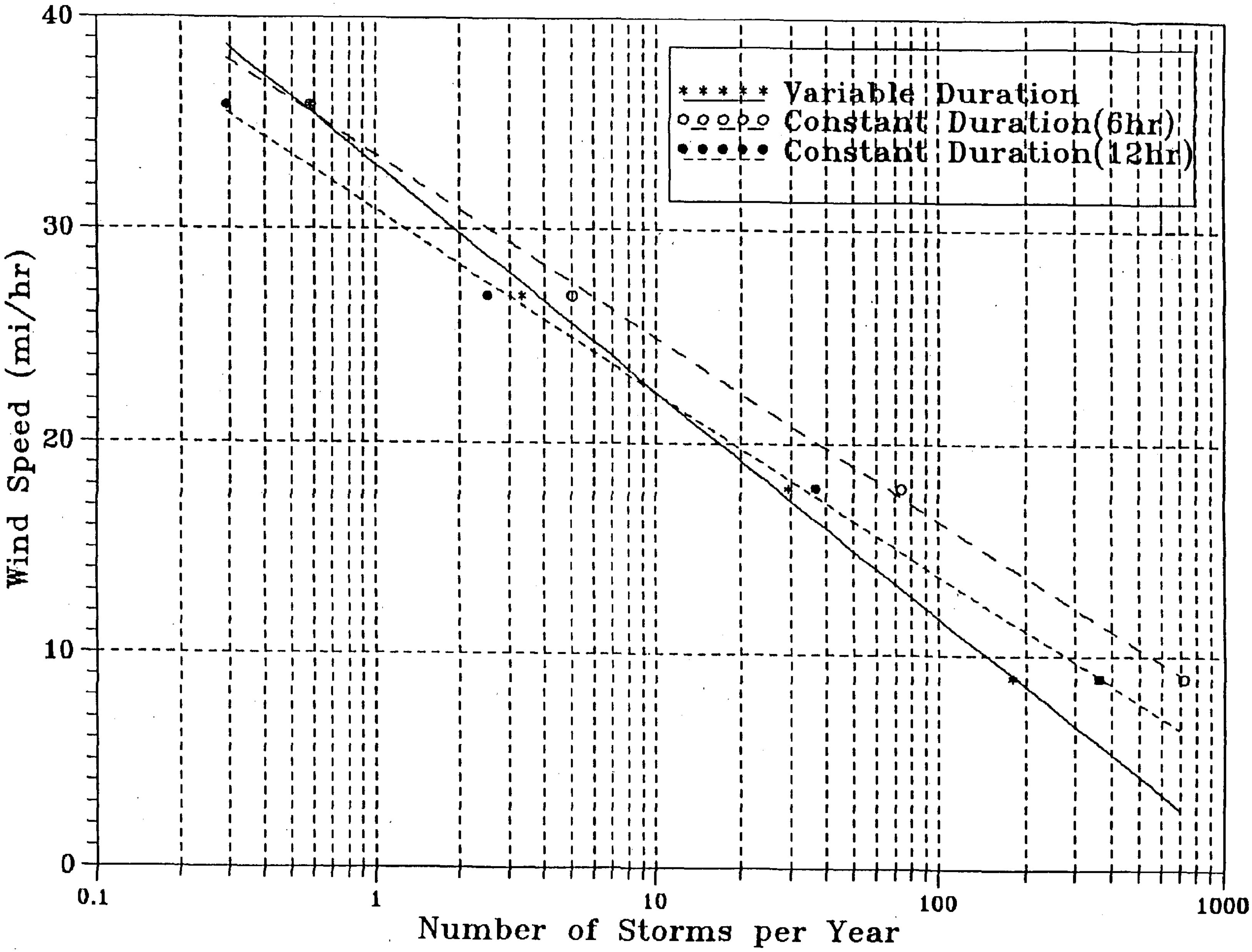

Figure 9 Number of Storm Events Versus Wind Speed under Various Durations, Norfolk. (1958-1973)

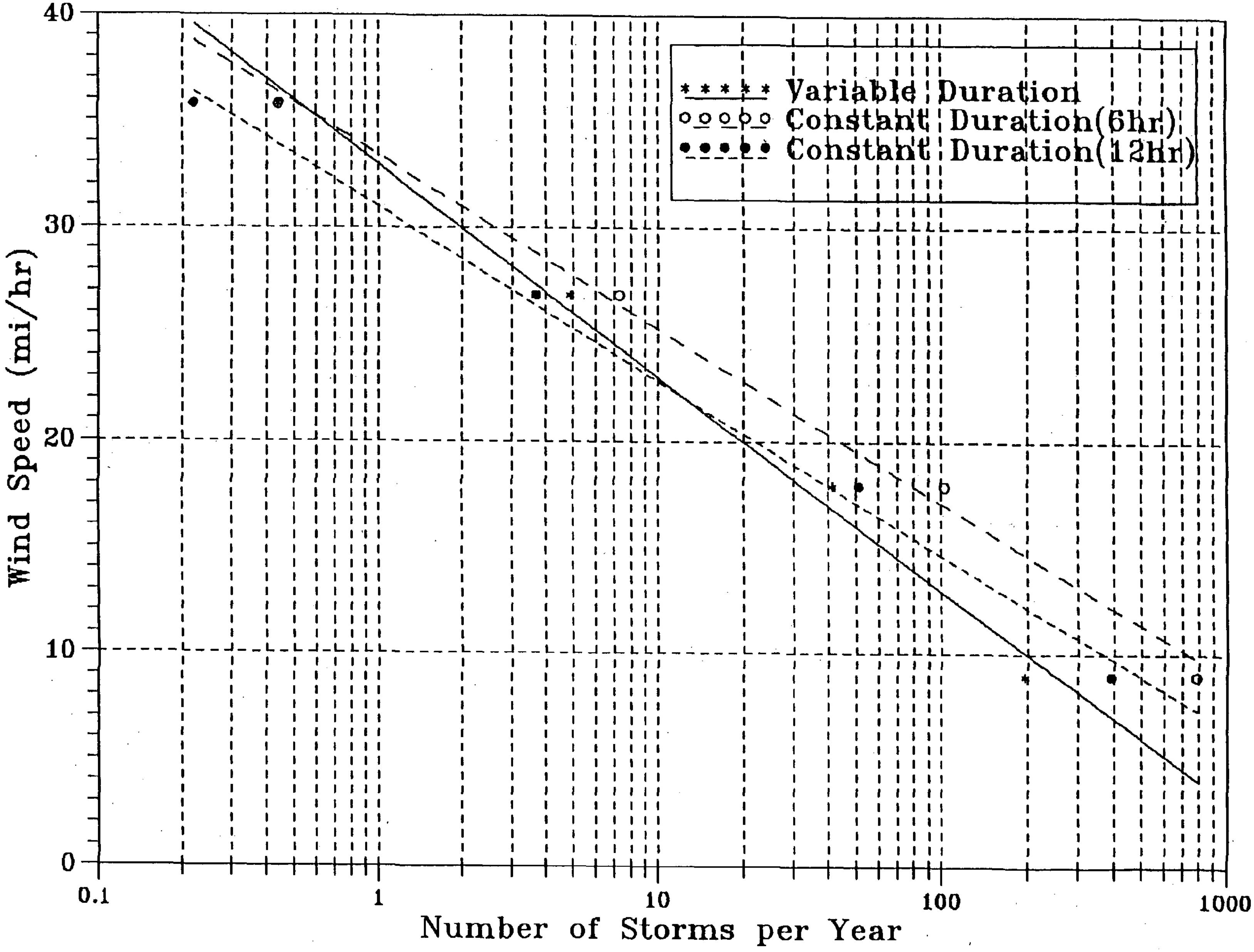

Figure 10 Number of Storm Events Versus Wind Speed under Various Durations, Norfolk. (1979-1990)

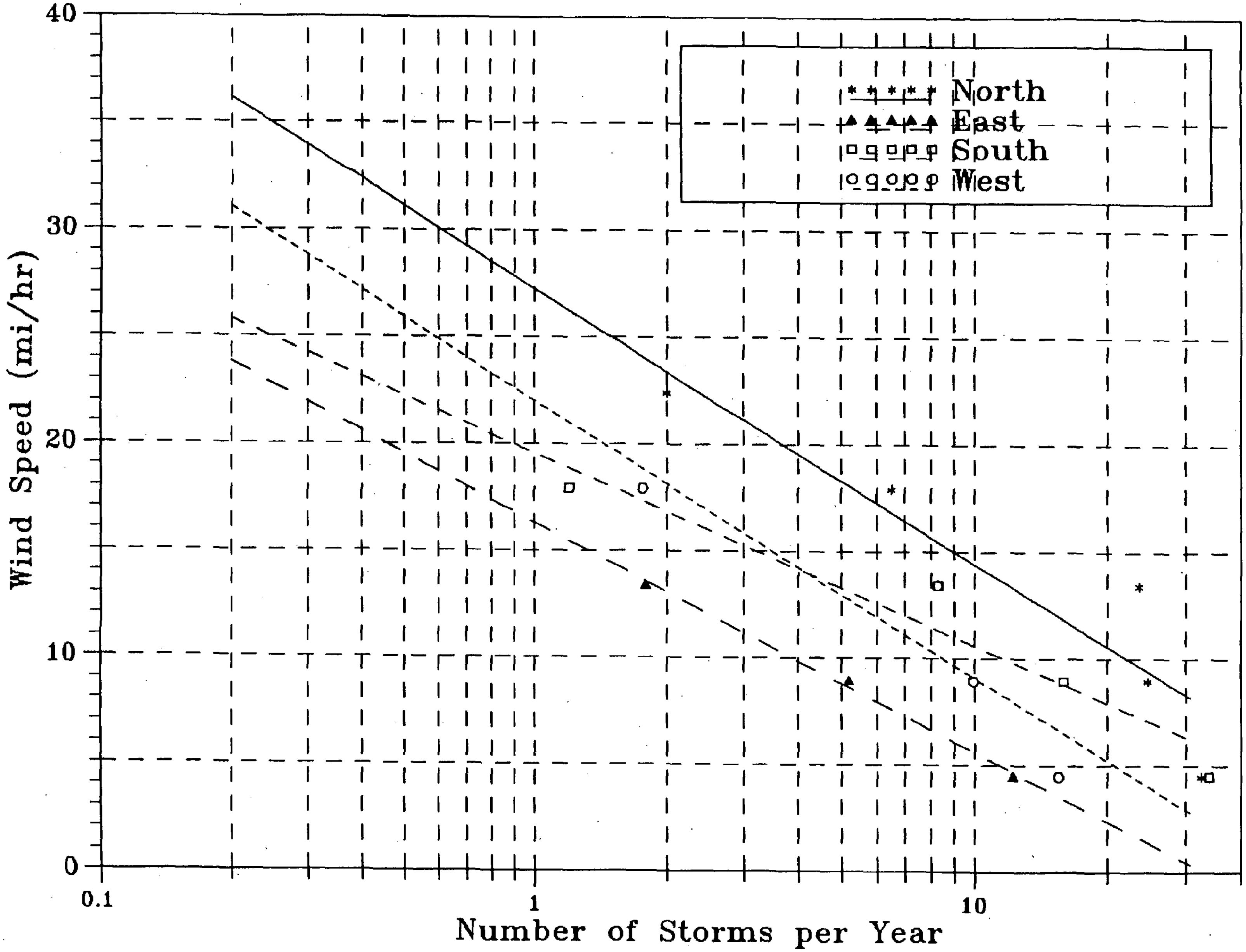

Figure 11 Number of Storm Events Versus Wind Speed, Norfolk (1958-1973).
(North, East, South, and West Directions)

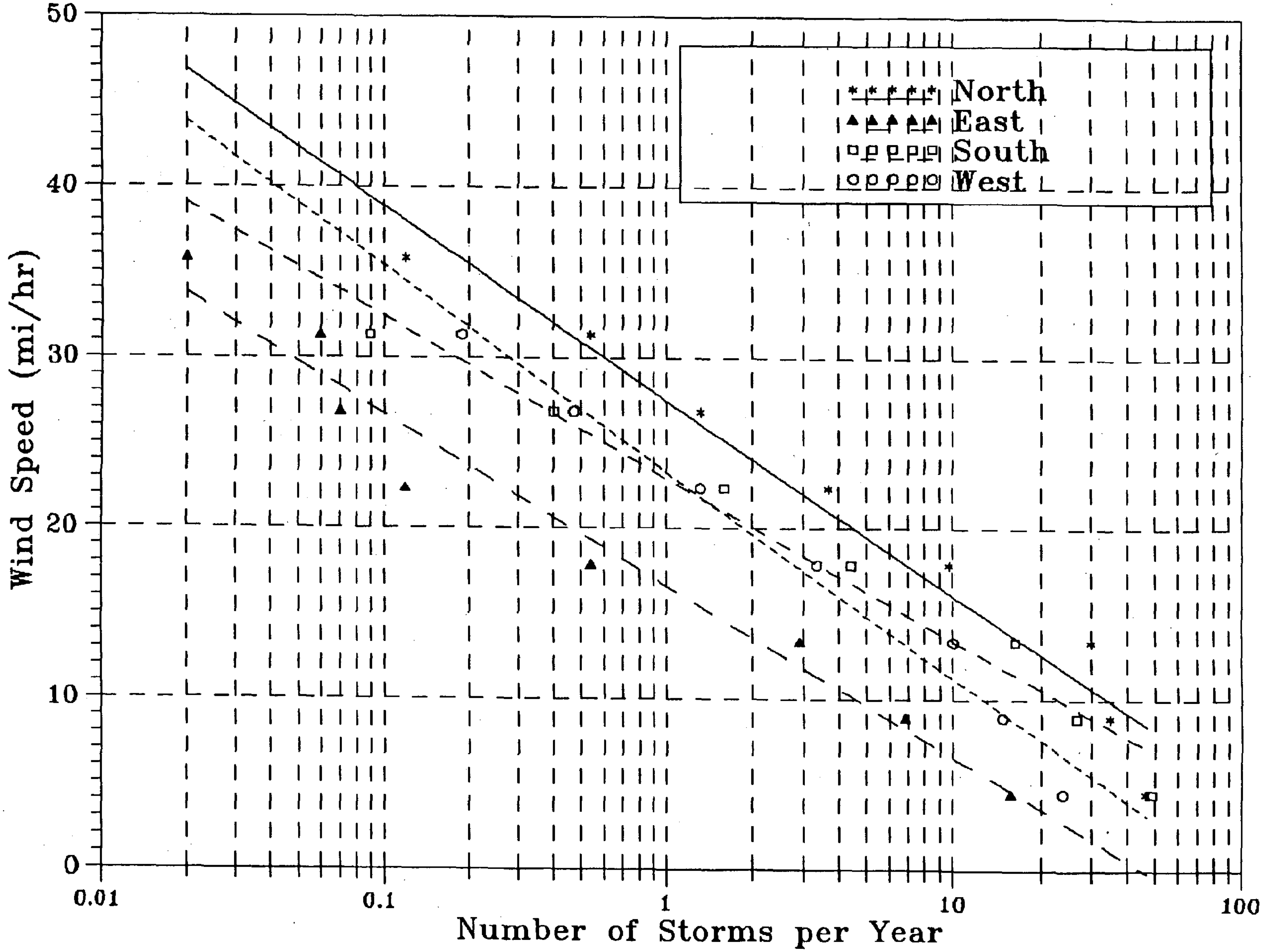

Figure 12 Number of Storm Events Versus Wind Speed, Norfolk (1979-1990).

(North, East, South, and West Directions)

Figures 13 and 14 show storm probability curves for four sub-compass directions[**] (North-West, North-East, South-East, and South-West) for both 1958 - 1973 and 1979 - 1990 periods, respectively. From these analyses, it was concluded that :

- *winds from the North-East and North-West dominate,*
- *the 100 percent probability storm wind speed equals 28 mph for the North-East direction, and*
- *the 50 percent probability storm wind speed equals 31 mph for the North -East direction.*

Table 2 shows the number of storm events per year with directional wind speed for both the 1958-1973 and 1979-1990 analysis periods.

3.3 Patuxent Naval Air Station

A total of 39 years of pre-analyzed wind data were obtained from the Chesapeake Bay Shoreline Erosion Study Report (1990). It was assumed that three possible lengths of storm events were 6 hour, 12 hour, and the variable storm duration from Table 1.

Figure 15 presents the storm probability curves for three durations during 1945 - 1983. From this analysis, it was concluded that :

- *variable duration is more realistic,*
- *the 100 percent probability storm wind speed equals 36 mph, and*
- *the 50 percent probability storm wind speed equals 40 mph.*

Figure 16 displays storm probability curves for four main compass directions (North, East, South, and West) for the 1945 - 1983 period. From this analysis, it was concluded that :

- *winds from the North and East dominate,*
- *the 100 percent probability storm wind speed equals 22 mph for the North direction, and*
- *the 50 percent probability storm wind speed equals 24 mph for the North direction.*

Figure 17 presents storm probability curves for the four sub-compass directions (North-West, North-East, South-East, and South-West) for the 1945-1983 period. From this analysis, it was concluded that :

[**] For this report, we have employed an alternate spelling of northwest, northeast, etc. to emphasize that we are considering winds within the entire quadrant from the North-West, North-East, etc., directions.

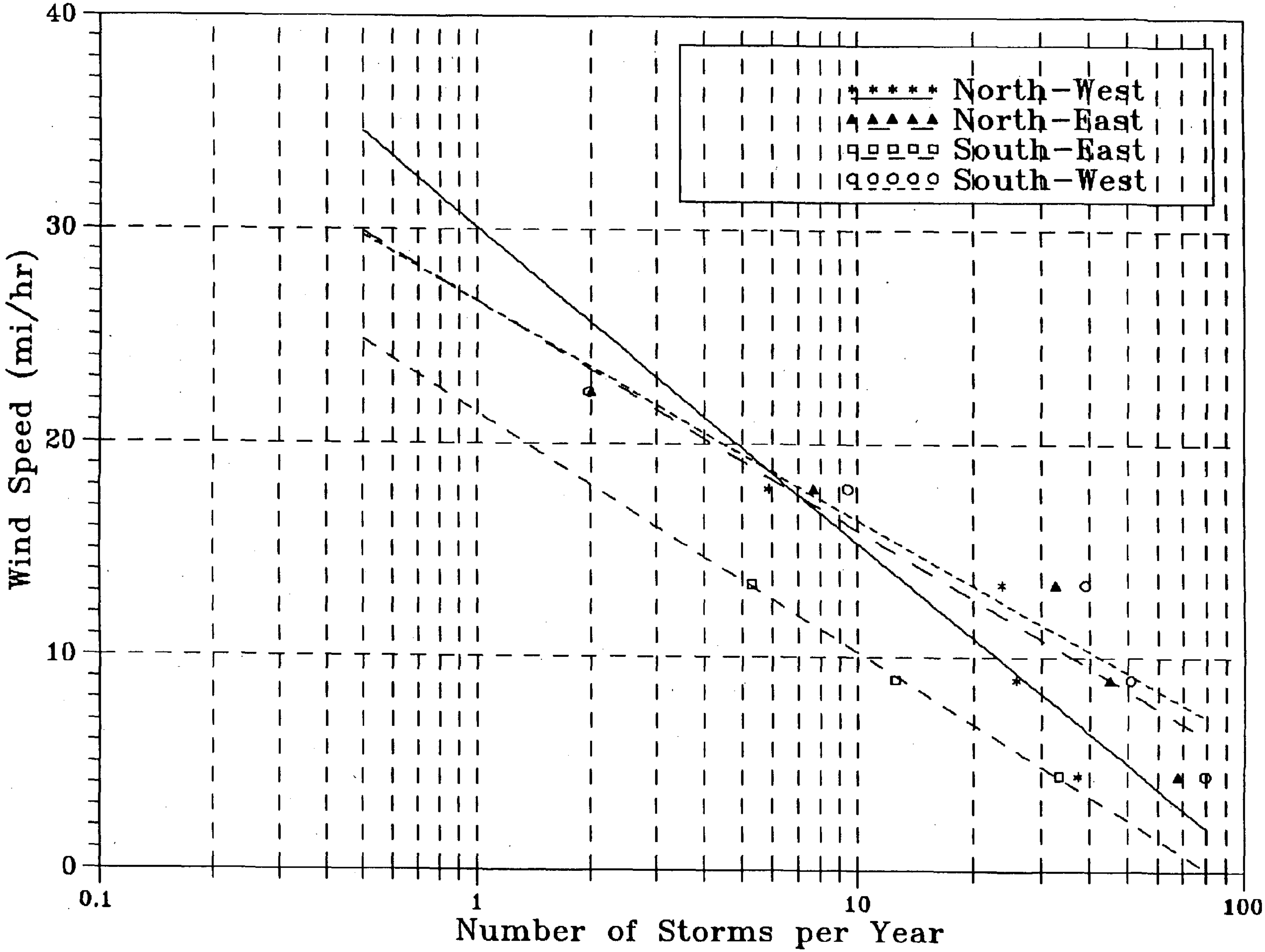

Figure 13 Number of Storm Events Versus Wind Speed, Norfolk (1958-1973).

(North-West, North-East, South-East, and South-West Directions)

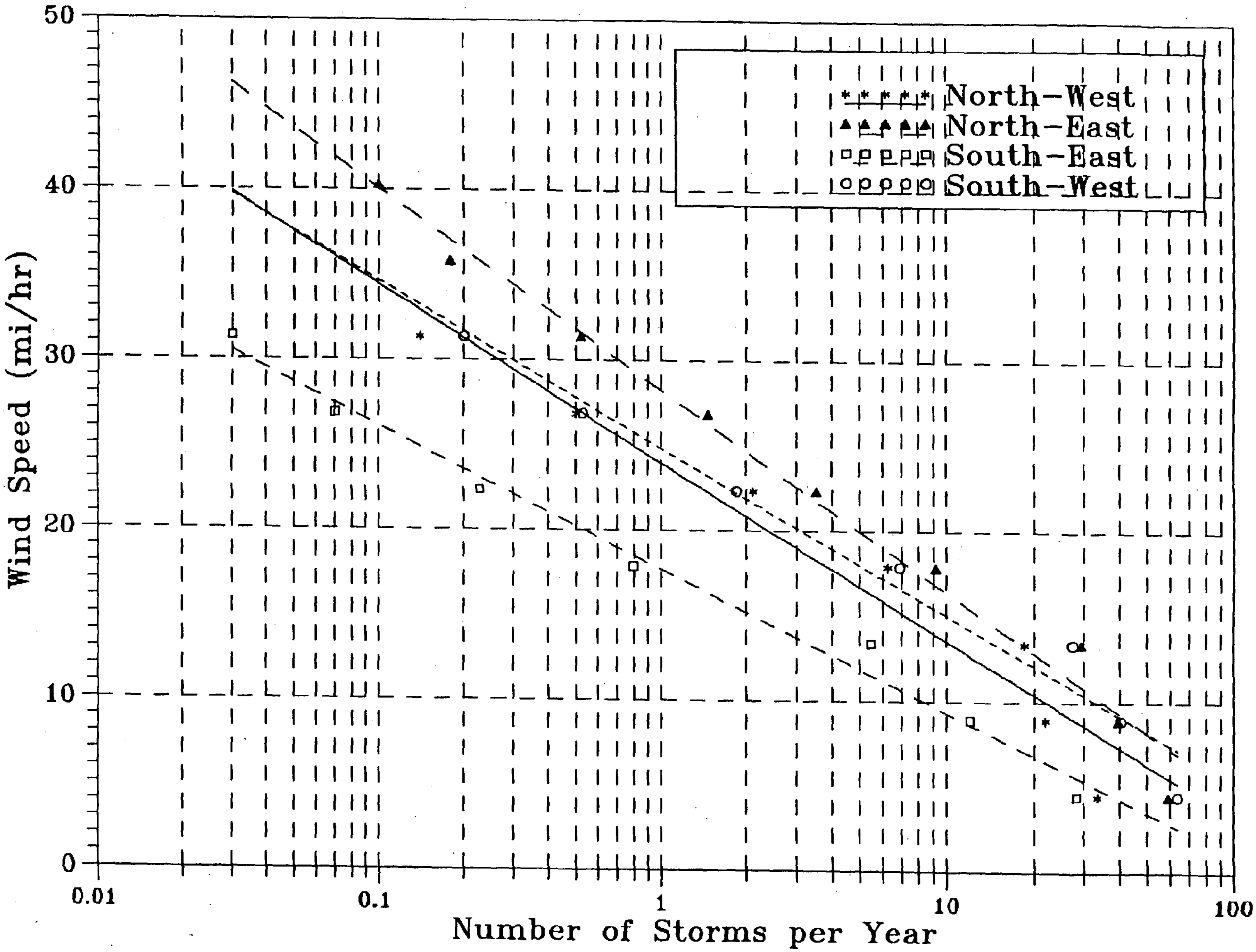

Figure 14 Number of Storm Events Versus Wind Speed, Norfolk (1979-1990).

(North-West, North-East, South-East, and South-West Directions)

Table 2 Number of Storm Events per Year for Various Wind Speeds and Directions for the Norfolk International Airport Data Set.

a) NIA (1958 - 1973)
(Data in this table has been truncated during analysis by the NCDC.)

MPH	*North*	*East*	*South*	*West*	*N-W*	*N-E*	*S-E*	*S-W*
4.47	32.5	12.2	33.9	15.48	37.2	67.8	33.2	79.64
8.95	24.7	5.2	15.9	9.95	25.8	45.0	12.5	50.88
13.42	23.6	1.8	8.3	8.26	23.6	32.4	5.3	38.93
17.90	6.5		1.2	1.77	5.9	7.7		9.44
22.37	2.0					2.0		1.97
26.84								

b) NIA (1979 - 1990)
(Data in this table was analyzed as part of this study and was not truncated.)

MPH	*North*	*East*	*South*	*West*	*N-W*	*N-E*	*S-E*	*S-W*
4.47	46.13	15.64	48.60	23.71	33.44	59.31	28.13	63.84
8.95	34.51	6.82	26.50	14.74	21.88	39.38	12.09	40.16
13.42	29.84	2.92	16.30	10.60	18.62	29.26	5.48	27.31
17.90	9.72	0.54	4.40	3.36	6.24	9.19	0.80	6.90
22.37	3.70	0.12	1.60	1.32	2.12	3.54	0.23	1.85
26.84	1.32	0.07	0.40	0.47	0.50	1.46	0.07	0.53
31.32	0.54	0.06	0.09	0.19	0.14	0.52	0.03	0.20
35.79	0.12	0.02				0.18		
40.27						0.10		

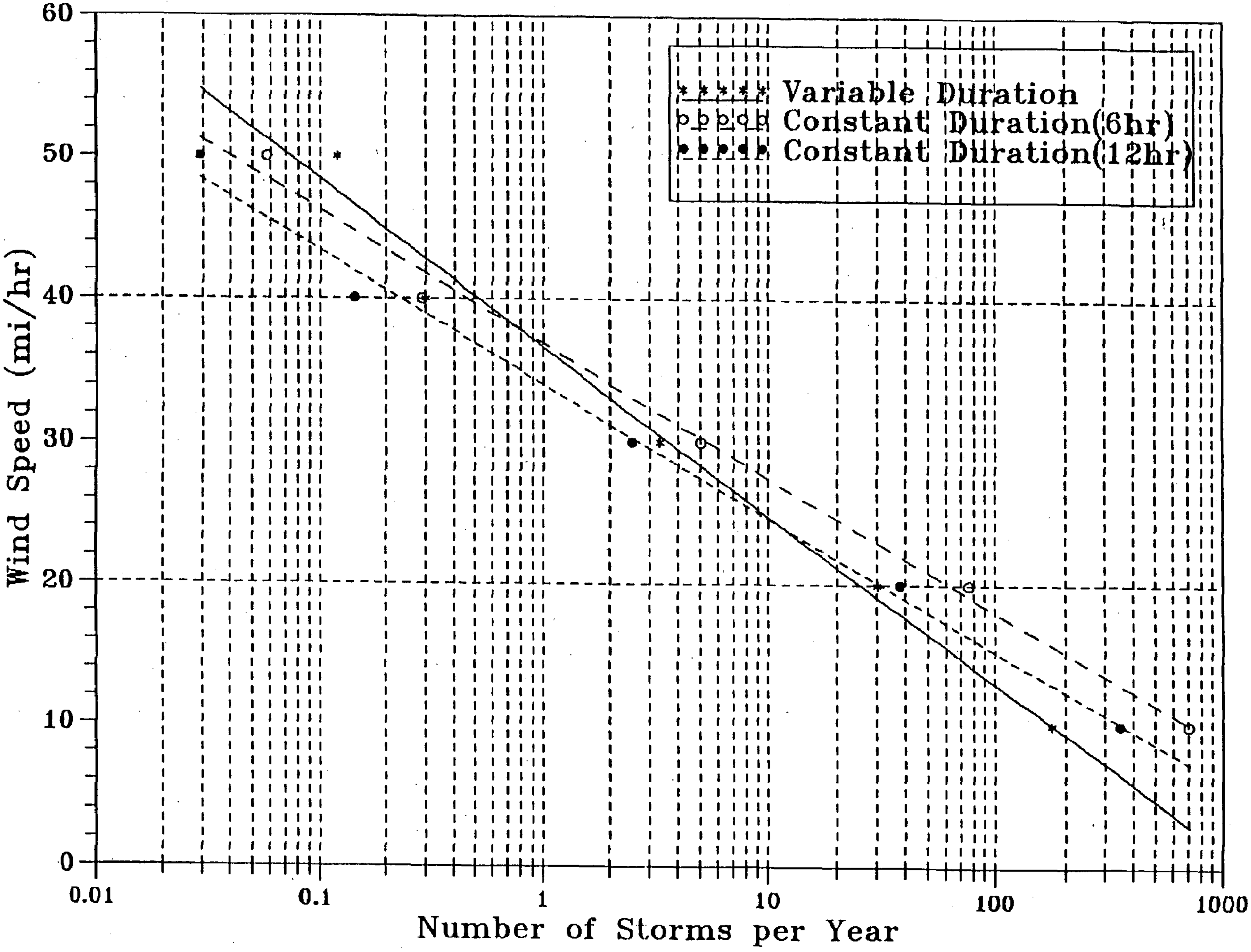

Figure 15 Number of Storm Events Versus Wind Speed under Various Durations, Patuxent. (1945-1983)

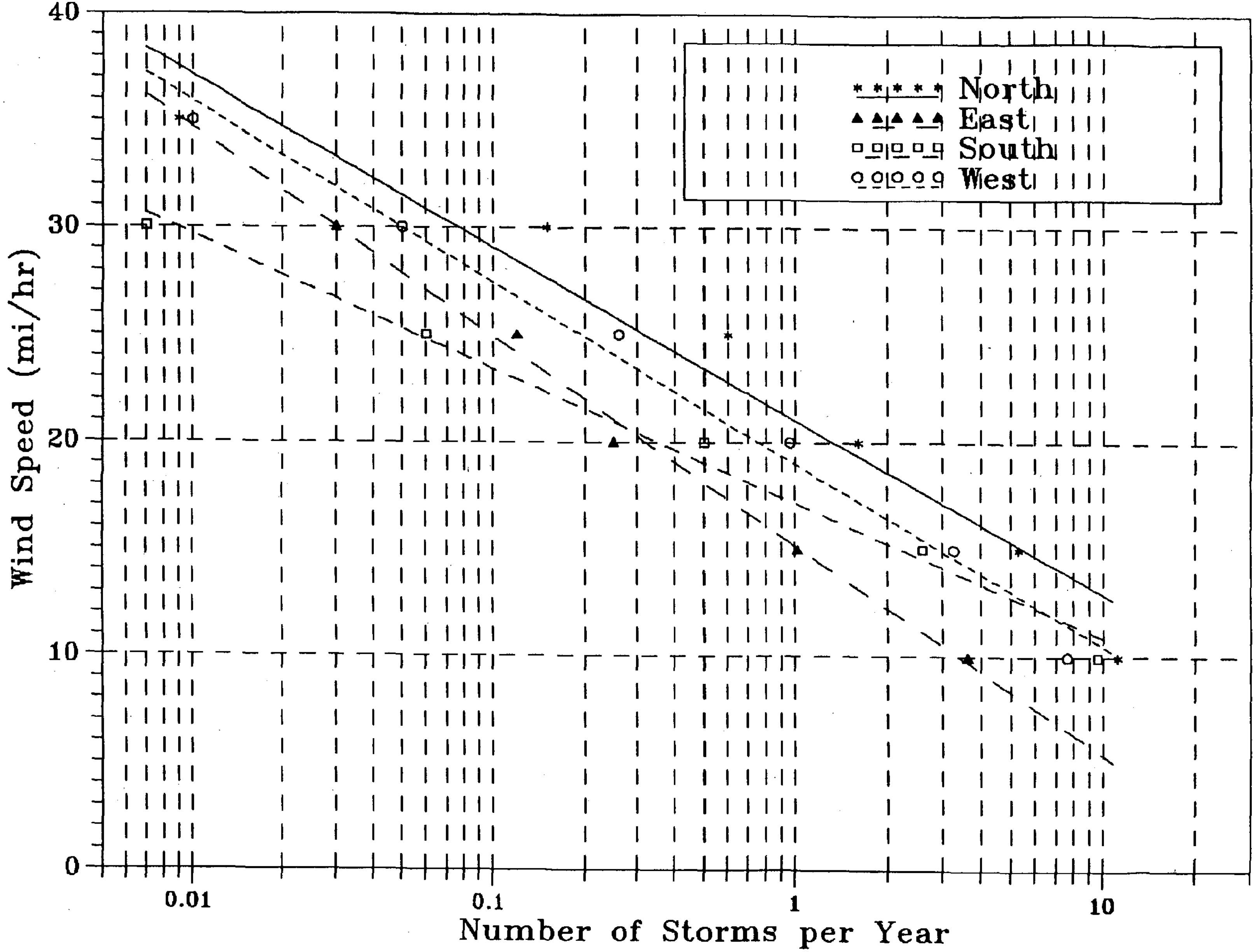

Figure 16 Number of Storm Events Versus Wind Speed, Patuxent (1945-1983).
(North, East, South, and West Directions)

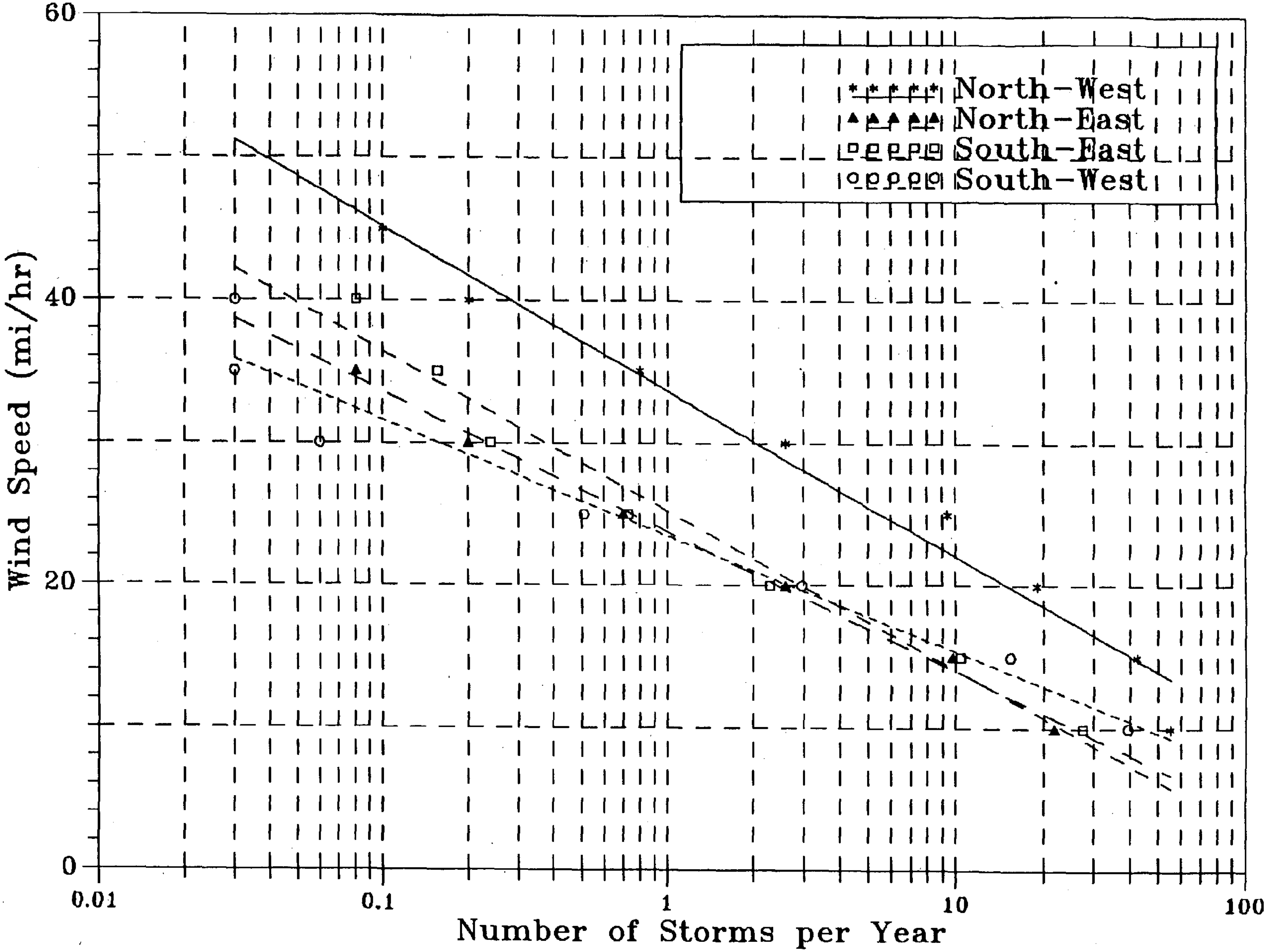

Figure 17 Number of Storm Events Versus Wind Speed, Patuxent (1945-1983).
(North-West, North-East, South-East, and South-West Directions)

- *winds from the North-West and South-East dominate at this location,*
- *the 100 percent probability storm wind speed equals 34 mph for the North-West direction, and*
- *the 50 percent probability storm wind speed equals 36 mph for the North-West direction*

Generally, the wind speeds at the PNAS are slightly stronger than at the NIA because the wind blows along the Patuxent River from the mountain ridge to the lower PNAS which is located at the mouth of the Patuxent River. Another possible reason is PNAS is located at a higher latitude. Table 3 summarizes the results of the number of storm events per year for various directional wind speeds at the PNAS.

Table 3 Number of Storm Events per Year for Various Wind Speeds and Direction, Patuxent (1945 - 1983).

MPH	*North*	*East*	*South*	*West*	*N-W*	*N-E*	*S-E*	*S-W*
10	11.20	3.60	9.60	7.64	55.10	21.80	27.40	39.39
15	5.30	1.02	2.60	3.27	42.40	9.70	10.40	15.45
20	1.60	0.25	0.50	0.96	19.10	2.60	2.30	2.97
25	0.60	0.12	0.06	0.26	9.40	0.70	0.73	0.51
30	0.15	0.03	0.01	0.05	2.60	0.20	0.24	0.06
35	0.01			0.01	0.80	0.08	0.16	0.03
40					0.20		0.08	0.03
45					0.10			
50								

3.4 Relation to Major Storms (1956-1978)

In the 1970's, three study reports documented major storms along the Virginia coast. Ho *et al.*, 1976 reported on storm tidal frequencies and this information was combined with wind speeds and durations by Pore and Richardson (1977) as Chapter 15 in a special report by the Virginia Institute of Marine Science (VIMS) as compiled and edited by Goldsmith *et al.*, 1977. These study reports became the basis for a 1979 report by the Coastal Erosion Abatement

Table 4 Summary of Major Storms at Virginia Beach, Virginia 1956 - 1978. (from Senate Document No.4, 1979)

Storm Description	*Date*	*Storm Surge (feet)*	*Wind Speed (knot)*	*Wind Speed (mph)*	*Direction*
	01/11/1956	3.4	33	38	N-E
	04/11/1956	4.3	62	71	N
	11/03/1956	2.0	29	33	N-E
	02/28/1957	2.4	33	38	N-E
	03/08/1957	2.2	27	31	N-E
	11/01/1957	2.7	28	32	N-E
	01/25/1958	2.3	44	50	E
	02/01/1958	2.2	30	34	W
	03/19/1958	2.2	21	24	N-E
	03/27/1958	2.6	20	23	N
	12/11/1958	2.1	27	31	N-E
	12/29/1958	2.3	38	43	E
	04/12/1959	2.5	45	51	N-E
	12/19/1959	2.1	29	33	N
	01/31/1960	3.0	42	48	N-E
	02/13/1960	2.3	49	56	N-E
	03/03/1960	2.4	52	59	E
	12/12/1960	2.0	40	46	W
	01/16/1961	2.0	13	15	W
	02/08/1961	2.4	27	31	N-E
	03/22/1961	2.2	33	38	E
	11/28/1961	2.0	23	26	N-W
	01/28/1962	2.2	37	42	N-E
Ash Wed.	03/07/1962	5.6	41	47	N-E
	03/22/1962	2.4	20	23	N
	11/03/1962	2.5	33	38	N
	11/26/1962	3.3	41	47	N
	02/08/1963	2.3	30	34	N-E
	11/06/1963	2.4	38	43	E
	01/04/1964	2.0	28	32	W
	01/12/1964	2.6	42	48	E
	02/12/1964	2.0	32	36	E
Cleo	09/01/1964	1.0	42	48	ESE
Dora	09/13/1964	0.3	61	70	N-E
Gladys	09/23/1964	2.3	44	50	N
Isabell	10/16/1964	2.6	50	57	N-E
	01/16/1965	3.9	35	40	N-E
	01/22/1965	3.0	36	41	E

Table 4 (Continued)

	01/29/1966	3.6	37	42	E
Alma	06/14/1966	2.3	31	35	N-E
	12/24/1966	1.0	40	46	N
	02/07/1967	2.6	33	38	N-E
	12/12/1967	2.0	30	34	E
	12/29/1967	2.0	31	35	W
Doria	09/16/1967	3.4	55	63	N
	01/14/1968	2.3	33	38	E
	02/08/1968	2.6	30	34	N-E
Gladys	10/20/1968	1.3	46	53	N-E
	11/10/1968	4.3	34	39	N
	11/12/1968	2.6	47	54	N-E
	03/02/1969	5.9	40	46	N
	11/02/1969	2.6	36	41	N-E
	11/10/1970	2.6	22	25	S-E
	12/16/1970	2.0	31	35	E
	03/27/1971	2.8	45	51	N-E
	04/06/1971	4.0	44	50	N-E
	10/19/1972	-	34	39	N
	02/11/1973	3.5	44	50	N
	03/21/1973	3.1	28	32	N
	03/02/1975	2.2	22	25	SSE
	10/14/1977	2.6	29	33	N-E
	10/30/1977	2.3	24	27	N-E
	04/28/1978	4.6	39	45	N-E

Commission to the Governor and General Assembly of Virginia called Senate Document No.4 (1979). Table 4 is the summary from Senate Document No.4, 1979 for the 23 year period 1956-1978 that included both tropical storms (named hurricanes) and extratropical storm (northeaster) events. Unfortunately, the criteria to define a "storm" event (i.e. storm surge level or threshold wind speed) were not specified.

The location and elevation of the wind gauge are unknown (Richardson, 1993, personal communication) and it was learned that the reported wind speeds are the fastest mile wind speed. Because of its short duration, the fastest mile wind speed must first be converted to a one hour average wind speed using the SPM (1984) methodology as summarized in Figure 3.

The wind speeds tabulated for the sixty-two major storms listed in Table 4 were converted to one hour averages and plotted in Figure 18. The mean was 33.4 mph with a standard deviation of ±8.3 mph at the 95 percent confidence level. As seen in Figure 9 for the Norfolk Airport over the same time period, this average wind speed is at the 100 percent probability

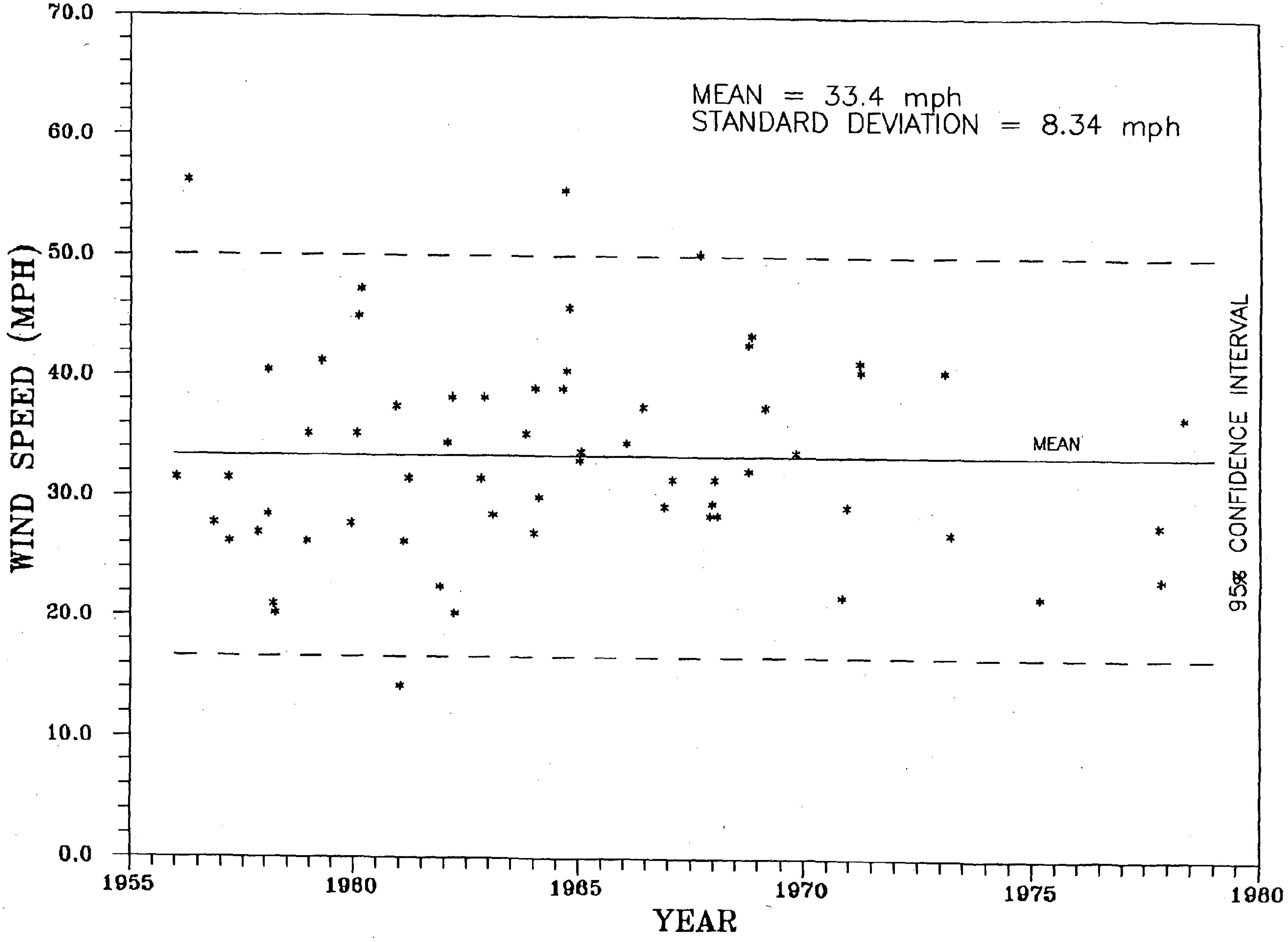

Figure 18 The Historical Record of Fastest Mile Wind Speeds, Virginia Beach (1956-1978).

level (one storm per year) in any one year. A similar result is evident in Figure 10 for the 1979-1990 analysis period. Thus the averaged, one hour wind speed for 62 major storms over a 23 year period has a 100 percent chance of occurrence each year and is about 33 mph.

3.5 Selection of Design Wind Speed

The economic design of shoreline stabilization alternatives (e.g. a rock revetment, vegetated marshes) depends upon (1) the wave energy at the site (2) the water level at the site and (3) the value of the property, structure, investments, etc. to be protected. The coastal engineering design philosophy adopted for this study is simply that the *benefits* resulting from storm damage protection are roughly equivalent to the *costs* for shore protection in any one year. And, since much of the property value for the 5,000 mile shoreline of Virginia around the Bay is of relatively moderate value, this translates into a relatively moderate wave energy level to provide for the *minimum level* of protection. Site specific locations where shoreline erosion threatens high value property (marinas, roads, major buildings, infrastructures, etc.) are not considered as applicable for the wave information reported herein. Special oceanographic engineering analyses of the design wave conditions are required for these cases.

From the historic wind data analyses for both the Norfolk and Patuxent locations, the 100 and 50 percent chance probability storm winds speeds are about 30 and 35 mph, respectively for winds of all directions. However, the relatively narrow tributary estuaries are generally aligned along the South-East (or North-West) direction for longest fetch considerations. At the same 100 and 50 percent probability levels, wind speeds are about 20 and 25 mph, respectively from the South-East direction.

These wind speeds were tested for Submap No.8 (see Section 4) to determine the relative difference in hindcast wave heights for the 30 and 35 mph conditions. It was found that for northern winds aligned along the entire Bay, the additional 5 mph wind speed increased the wave height by one foot or less. Other directions produce less than one-half foot increase in wave heights for the extra 5 mph wind speed.

All the above mentioned results were presented and discussed at a meeting with the Shoreline Programs Office. At this meeting (8 July, 1993) the design wind speed of 35 mph was selected for use to hindcast wave information for the Bay and all the major tributaries. This wind speed has about a 50 percent probability of exceedance in any one year or a 2 year recurrence interval. This design wind speed is compatible with the average wind speed occurring during 62 major storms over a 23 year period.

The 35 mph design wind speed is used for winds blowing from all directions along all possible fetches in the Bay and major tributaries. However, a 25 mph design wind speed has been employed for the South-East direction along the axis of the relatively narrow major tributaries when this direction is being used in the hindcast procedure.

3.6 Wind Duration

The shallow-water, wave growth formulations of ACES are based partly upon the *fetch-limited* deepwater forms and do not encompass duration effects. Consequently, it is assumed that all waves are fetch-limited in size and that wind durations are sufficient so as to *not* to limit wave growth.

Histograms of number of events versus consecutive hour durations are presented in Figures 6, 7, and 8 for various wind speeds and were used to derive Table 1 as previously discussed. A six hour duration storm is consistent with wind speeds in the 35 mph range. About 40, six hour storms with speeds in the 27-36 mph range occurred over the 16 year period (1958-1973). Hence it is conservative to assume that six hour duration events can occur with a 50 percent probability each year.

Longer fetch distances require longer duration storm events to reach fully arisen seas. The wave growth formulations in ACES are said to give reasonable results for fetch distances under 75 miles. Although ACES shallow-water formulations do not encompass duration effects, the shallow-water forcasting curves in SPM were utilized to estimate the minimum durations. From these results, it was concluded that a six hour duration is sufficient for fully arisen sea conditions for fetches less than 75 miles. Therefore for some areas of the lower Chesapeake Bay where fetch distances exceed 100 miles, longer than 6 hour duration events are probably needed. Or conversely, a 6 hour duration means that the waves are possibly *duration-limited* in this region. As seen in Figure 8, consecutive hour winds blowing longer than 6 hours are rare. Hence, the assumption that all waves are fetch-limited for this study simply means that the wave heights reported for the lower Bay are conservative, namely larger in size than if duration-limited growth formulas are applied.

4.0 BATHYMETRIC MAPS, TIDAL RANGES, AND MEAN WATER DEPTHS

4.1 Bathymetric Maps

The bathymetric chart of the Chesapeake Bay as developed by the Virginia Institute of Marine Science (VIMS, 1977) was used for the bathymetric determination. The scale of this map is 1 : 224,700. Bathymetry of this chart is based on depths from National Ocean Survey Sounding Sheets and contoured to Mean Low Water (MLW) datum. Land forms are also adopted from National Ocean Survey Charts. It was assumed that the land forms and the depth contours have not changed appreciably since 1977.

4.2 Tidal Ranges

An estimation of the Mean Tidal Range (MTR) is essential for the calculation of a local mean water depth because the bathymetric chart is contoured to Mean Low Water (MLW) datum. Therefore, one half of the MTR is added to the local water depth. Tidal information was obtained from a VIMS report (Boon *et al.*, 1978). For the boundary between different tidal stations, linear interpolation techniques were employed to achieve a smooth transition of the MTR. Table 5 presents the MTR for each submap (see Section 5 for submap locations).

4.3 Storm Surge

During each storm event, the wind stress field on the water surface will also create an increase in local water level, i.e. the storm surge. The statistical distribution of the directional wind speed and resulting hindcast wave field is *not* identical to the storm surge probabilities although the two factors (waves and water levels) are related.

Table 4 of the 62 major storms between 1956 and 1978 also includes measured, maximum storm surge for Virginia Beach, Virginia. These values are plotted in Figure 19 which shows that the mean storm surge was 2.6 feet with a 0.94 foot standard deviation at the 95 percent confidence level. A histogram of these storm surge events is plotted as Figure 20. The greatest number of storms (23) were in the 2.0-2.5 feet class interval.

A formal, statistical analysis of extratropical, storm surge heights for the five primary tide stations on the Bay can be found in Boon *et al.*, 1978 (Figure 7.7, p.107). For a 2.5 feet surge the annual exceedance frequency varied over the Chesapeake Bay. It is at the 0.65 level for Hampton Roads (Sewells Point), drops to only 0.05 at Solomons Island and then increases again to 0.25 at the Baltimore tide gauge. For ease in analysis, it was decided to use a uniform 2.5

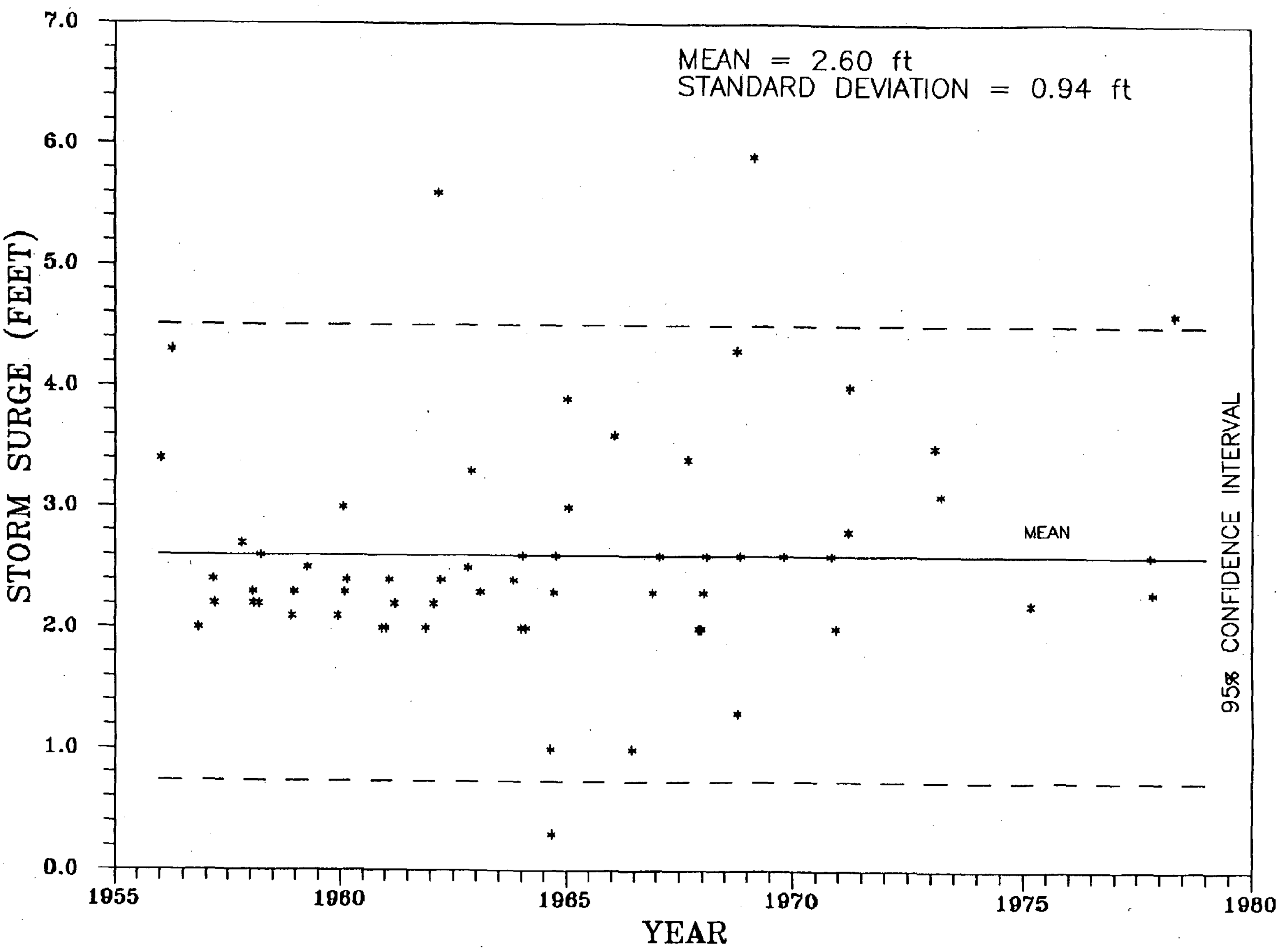

Figure 19 The Historical Records of Storm Surge, Virginia Beach (1956-1978).

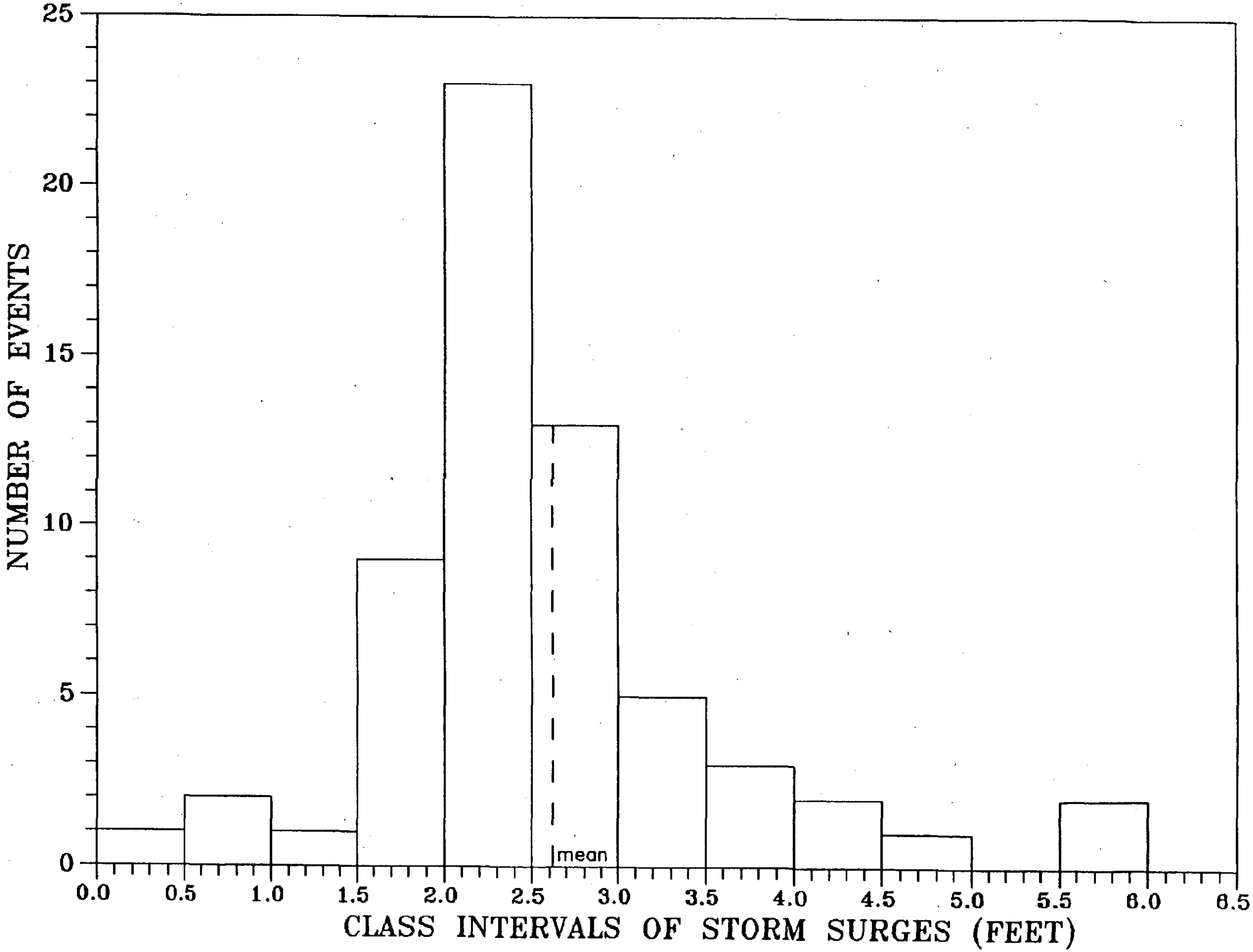

Figure 20 The Histogram of Storm Surge, Virginia Beach (1956-1978).

Table 5 The Average Mean Tidal Range for Each Submap.

Submap No.	*Mean Tidal Range, R (feet)*
1	R = 2.3
2	Potomac River : R = 1.5
	Rappahannock River : R = 2.1
3	R = 1.7
4	R = 2.8
5	R = 2.2
6	R = 2.5
7	R = 2.6
8	York River and Mobjack Bay : R = 2.5
	Piankatank River Area : R = 1.2
9	R = 1.9
10	R = 1.4
11	R = 1.6
12	R = 1.6

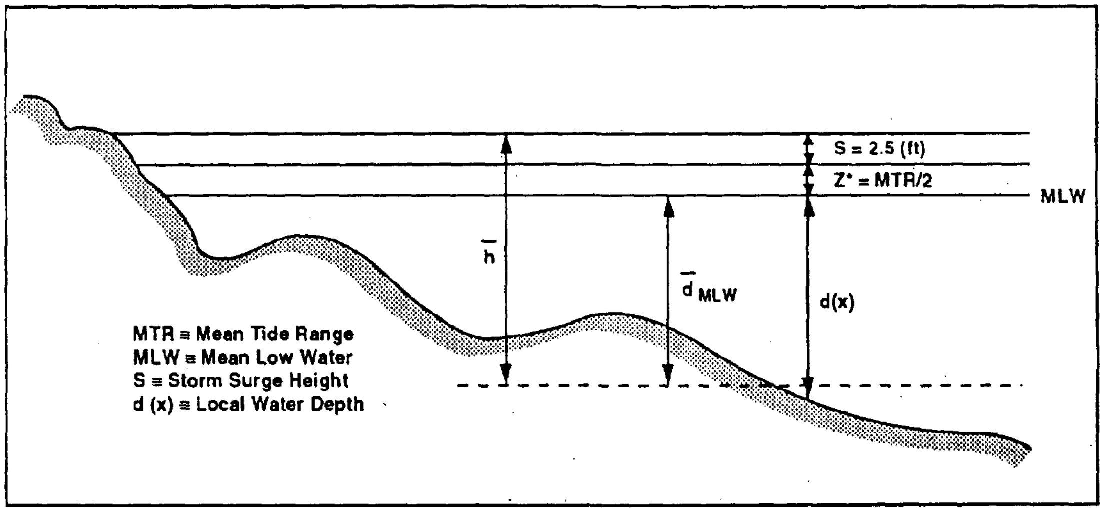

Figure 21 Definition Sketch for Water Depth.

feet storm surge for all mean water depth calculations over the entire Bay and tributaries. This storm surge level can be considered as arising from a moderate storm event with a similar probability of exceedance as that for the wind speeds.

4.4 Mean Water Depths

The mean water depth is defined as the summation of the weighted-averaged water depth below MLW along the wind fetch, plus half of the mean tidal range, plus the storm surge height. Weighted-averaged water depths along each dominant fetch direction are found by summing the products of each local depth times its individual fetch length and dividing the total by the fetch length in that direction. This is the most time consuming aspect of the entire study. Figure 21 is a definition sketch for the vertical elevation. The mean water depth, $\bar{h}$ for ACES application is defined as

$$\bar{h} = \bar{d}_{MLW} + z^* + 2.5 \,, \quad z^* = MTR/2 \qquad (1)$$

4.5 Submaps for Display of Results

The bathymetric chart of the Chesapeake Bay by VIMS (1977) at a scale 1 : 224,700 (one inch equals 3.5465 miles) was utilized as the basis for developing a series of submaps of wave information. Twelve submaps were established to cover the Chesapeake Bay and the major tributaries. Each submap is on 8.5 inch by 11 inch paper with half-inch margins so that each submap will be 7.5 inch by 10.0 inch. Figure 22 shows submaps numbering (No.1 - 12) of Chesapeake Bay and adjacent area. Map numbering begins with No.1 covering the headwater of the Potomac River at Washington, D.C. and ends at No.12 which covers the entrance region of this same river. Table 6 is the submap coordinate system in which coordinates of the top (left, right) and bottom (left, right) for each submap to the nearest degree, minute, and second in latitude and longitude are presented. Submap No.8 was selected as the test case to study the entire methodology for wave information development as discussed in the following section of this report.

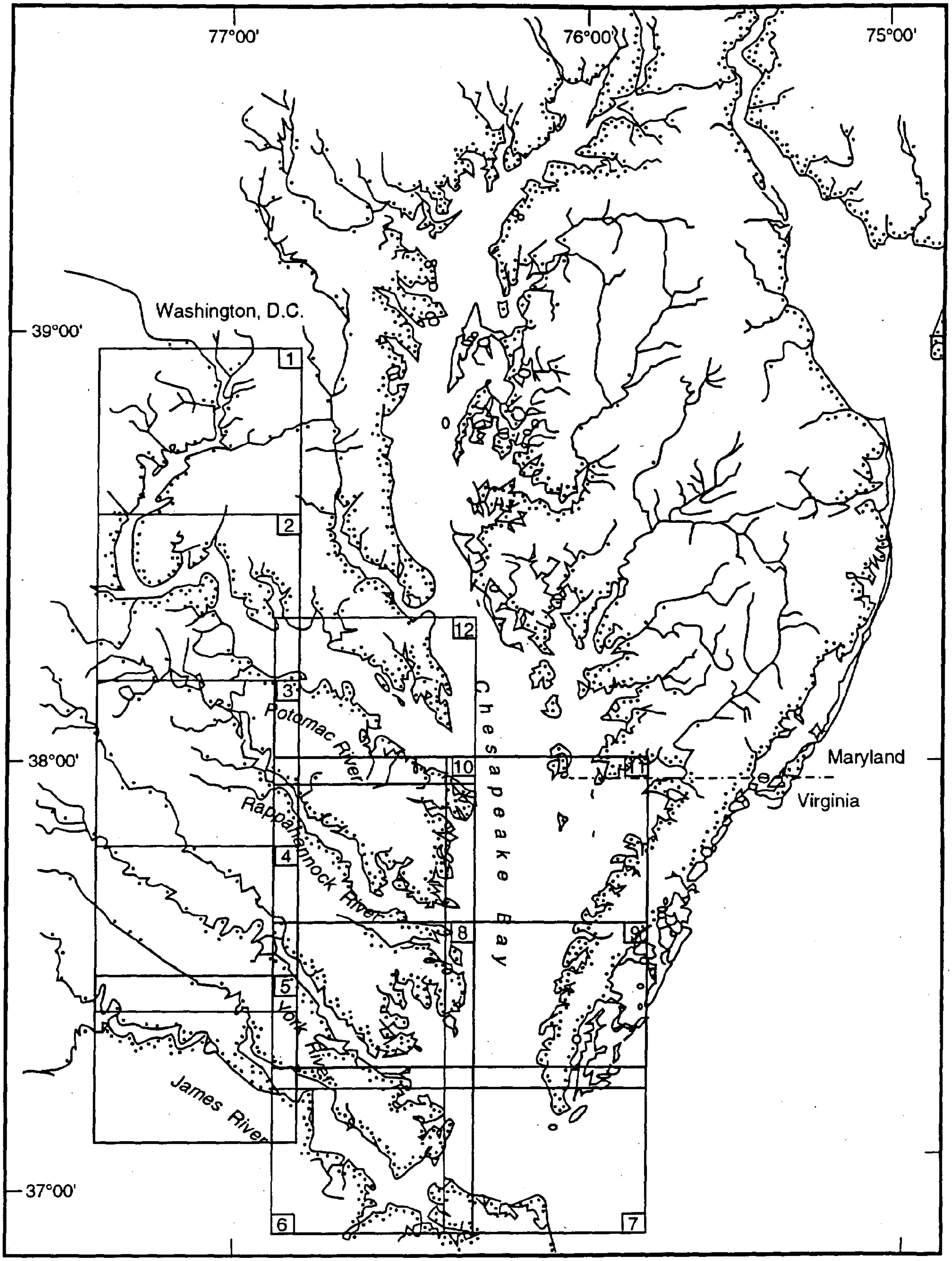

Figure 22 Numbered Submaps for Chesapeake Bay and Adjacent Water Bodies.

Table 6 Submap Coordinate System.

Submap No.		*Top Left*	*Top Right*	*Bottom Left*	*Bottom Right*	*Remarks*
1	La.	38° 55′ 37″	38° 55′ 37″	38° 32′ 30″	38° 32′ 30″	Scale : 1:224,700 1 inch = 3.5465 mile. La= latitude Lo=longitude *Use Top and Left Scale on the Map.
	Lo.	77° 25′ 47″	76° 45′ 56″	77° 25′ 47″	76° 45′ 56″	
2	La.	38° 32′ 30″	38° 32′ 30″	38° 09′ 01″	38° 09′ 01″	
	Lo.	77° 25′ 47″	76° 45′ 56″	77° 25′ 47″	76° 45′ 56″	
3	La.	38° 09′ 01″	38° 09′ 01″	37° 45′ 59″	37° 45′ 59″	
	Lo.	77° 25′ 47″	76° 45′ 56″	77° 25′ 47″	76° 45′ 56″	
4	La.	37° 45′ 59″	37° 45′ 59″	37° 23′ 03″	37° 23′ 03″	
	Lo.	77° 25′ 47″	76° 45′ 56″	77° 25′ 47″	76° 45′ 56″	
5	La.	37° 27′ 23″	37° 27′ 23″	37° 04′ 05″	37° 04′ 05″	
	Lo.	77° 25′ 47″	76° 45′ 56″	77° 25′ 47″	76° 45′ 56″	
6	La.	37° 14′ 16″	37° 14′ 16″	36° 50′ 48″	36° 50′ 48″	
	Lo.	76° 51′ 43″	76° 11′ 54″	76° 51′ 43″	76° 11′ 54″	
7	La.	37° 14′ 16″	37° 14′ 16″	36° 50′ 48″	36° 50′ 48″	
	Lo.	76° 17′ 36″	75° 37′ 36″	76° 17′ 36″	75° 37′ 36″	
8	La.	37° 35′ 24″	37° 35′ 24″	37° 12′ 12″	37° 12′ 12″	
	Lo.	76° 51′ 43″	76° 11′ 54″	76° 51′ 43″	76° 11′ 54″	
9	La.	37° 35′ 24″	37° 35′ 24″	37° 12′ 12″	37° 12′ 12″	
	Lo.	76° 17′ 36″	75° 37′ 36″	76° 17′ 36″	75° 37′ 36″	
10	La.	37° 58′ 20″	37° 58′ 20″	37° 35′ 24″	37° 35′ 24″	
	Lo.	76° 51′ 43″	76° 11′ 54″	76° 51′ 43″	76° 11′ 54″	
11	La.	37° 58′ 20″	37° 58′ 20″	37° 35′ 24″	37° 35′ 24″	
	Lo.	76° 17′ 36″	75° 37′ 36″	76° 17′ 36″	75° 37′ 36″	
12	La.	38° 17′ 15″	38° 17′ 15″	37° 54′ 00″	37° 54′ 00″	
	Lo.	76° 51′ 43″	76° 11′ 54″	76° 51′ 43″	76° 11′ 54″	

5.0 TEST CASE DEVELOPMENT - SUBMAP NO.8

5.1 Grid Scales and Application of ACES 1.07

Submap No.8 was selected to use as the test case. Figure 23 shows the boundaries of this map and the grid employed to make wave hindcasts at each node on the grid. A grid scale of one centimeter by one centimeter *(1 cm ≡ 1.4186 mile in actual)* was used for the relatively broad Bay area. However, for the narrow York River area, finer grid sizes were employed. Approximately one hundred grid points were selected to estimate fetch information, mean water depth, and wave information. Design wind speed of 35 mph with 6 hour duration was employed based upon the storm probability analysis. However, for South-East winds over the York River a wind speed of 25 mph was employed because it has the same design exceedance probability. A storm surge height of 2.5 feet was used. Also, a MTR of 2.5 feet was used for the York River and Mobjack Bay area, and a MTR of 1.2 feet was used for the Bay and the Piankatank River area. In order to apply the ACES wave hindcast model, the selection of the fetch condition (open or restricted fetch) and the determination of the mean water depth are essential. These are discussed in the following sections.

5.2 Restricted Fetch Versus Open-Water Fetch Results

In open water, wave generation is limited by the dimensions of the meteorological event under investigation and fetch widths are of the same order of magnitude as the fetch length. The restricted fetch methodology applies the concept of wave development in off-wind directions and considers the shape of the basin.

Tests at several nodes in Submap No.8 were conducted using both the open-water and restricted fetch modes of wave hindcasting in ACES 1.07. Open-water conditions produced larger wave heights than restricted fetch condition: on the order of 0.1 to 1.0 foot for the test nodes. However, the open-water fetch condition is not suitable because open-water conditions with fetch width equal or greater than fetch lengths are generally not found in the Chesapeake Bay for the dominant fetch distances involved.

5.3 Variable Water Depth Results

ACES 1.07 requires constant water depth along the fetch distance. Therefore, a weighted-averaged method is employed to calculate the representative, mean water depth. Weighted-averaged water depths along each dominant fetch direction are found by summing the products

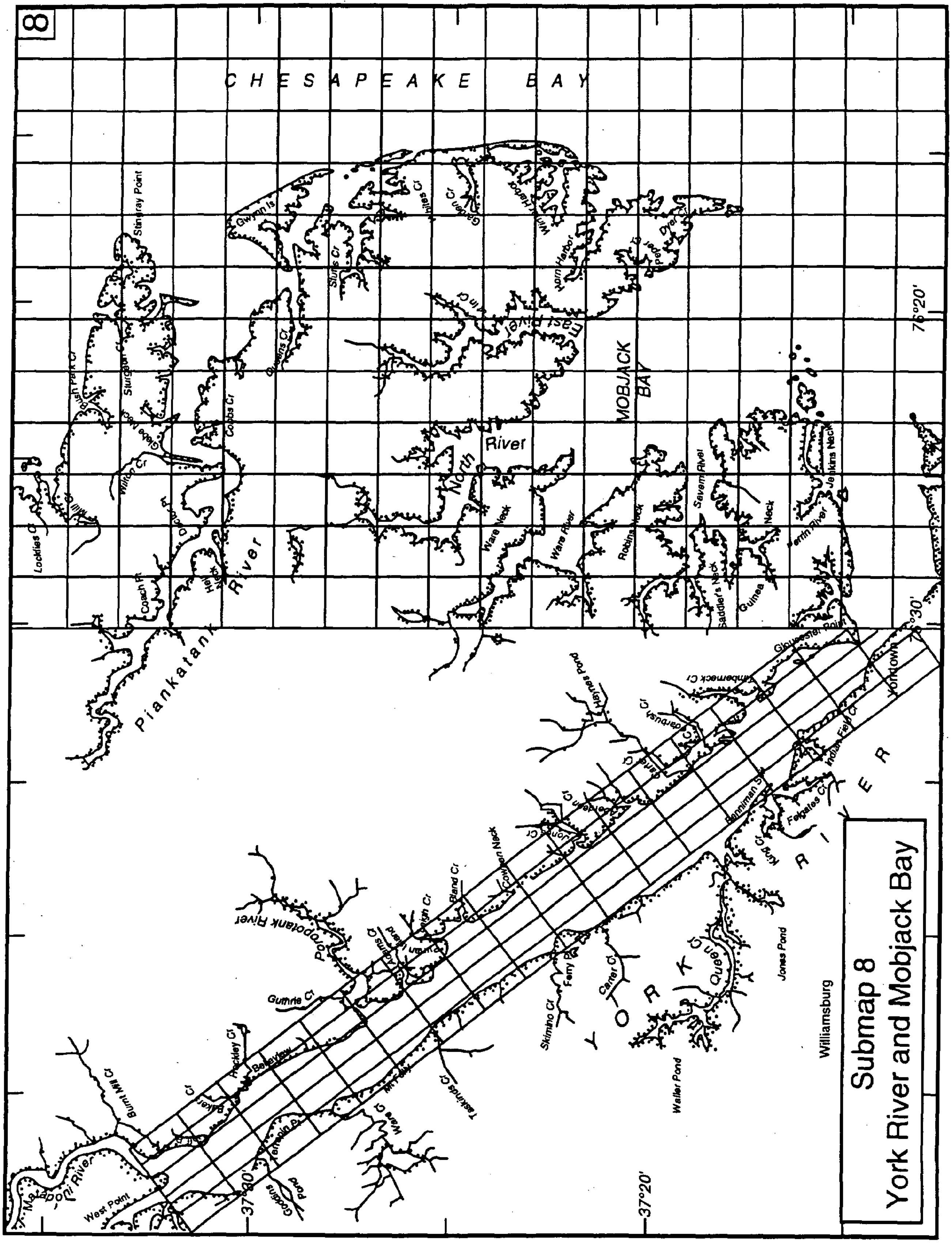

Figure 23 Grid System for Submap No.8

of each local depth times its individual fetch length and dividing the total by the fetch length in that direction. Tests at several nodes in Submap No.8 were conducted using both (1) the averaged-depth over the dominant fetch direction, and (2) the averaged-depth over all the radial fetch distances. The restricted-fetch method using averaged-depth over the dominant fetch distances produced slightly higher wave heights than when the depths are averaged over all the radial fetch distances. For this project, the averaged-depth over the dominant fetch direction was selected. This is the suggested method in the ACES 1.07 documentation, requires far less work and produces slightly more conservative, yet realistic results.

5.4 Composite Wave Height Map

The wind direction is assumed to be identical with the longest fetch direction. Therefore, wave heights at the points of interest are the maximum possible from all directions under the design wind speed.

Figure 24 shows a wave information map with iso-wave height contours (spectral significant wave height, H_{mo}) at one-half foot intervals covering all the water areas on Submap No.8. Wave periods (peak spectral periods, T_p) associated with these wave heights appear below the wave heights in parenthesis. Figure 25 presents a relationship between the spectral significant wave height and wave spectral peak period under the design wind speed, U_w = 35 mph. This relationship was obtained from the wave heights and wave periods using ACES at all grid points in Submap No.8.

5.5 Conclusions

In general, the wave hindcasting results for Submap No.8 are reasonable because major changes in wave height are hindcasted fairly well. A coarser sub-grid could have been employed for the broad Bay area but the finer sub-grid is still needed for the narrow York River area.

It was concluded that the restricted-fetch method using a weighted-averaged water depth over the dominant fetch direction provides the most reasonable wave information for enclosed bays, estuaries and river areas. These methods were applied to all other submap regions.

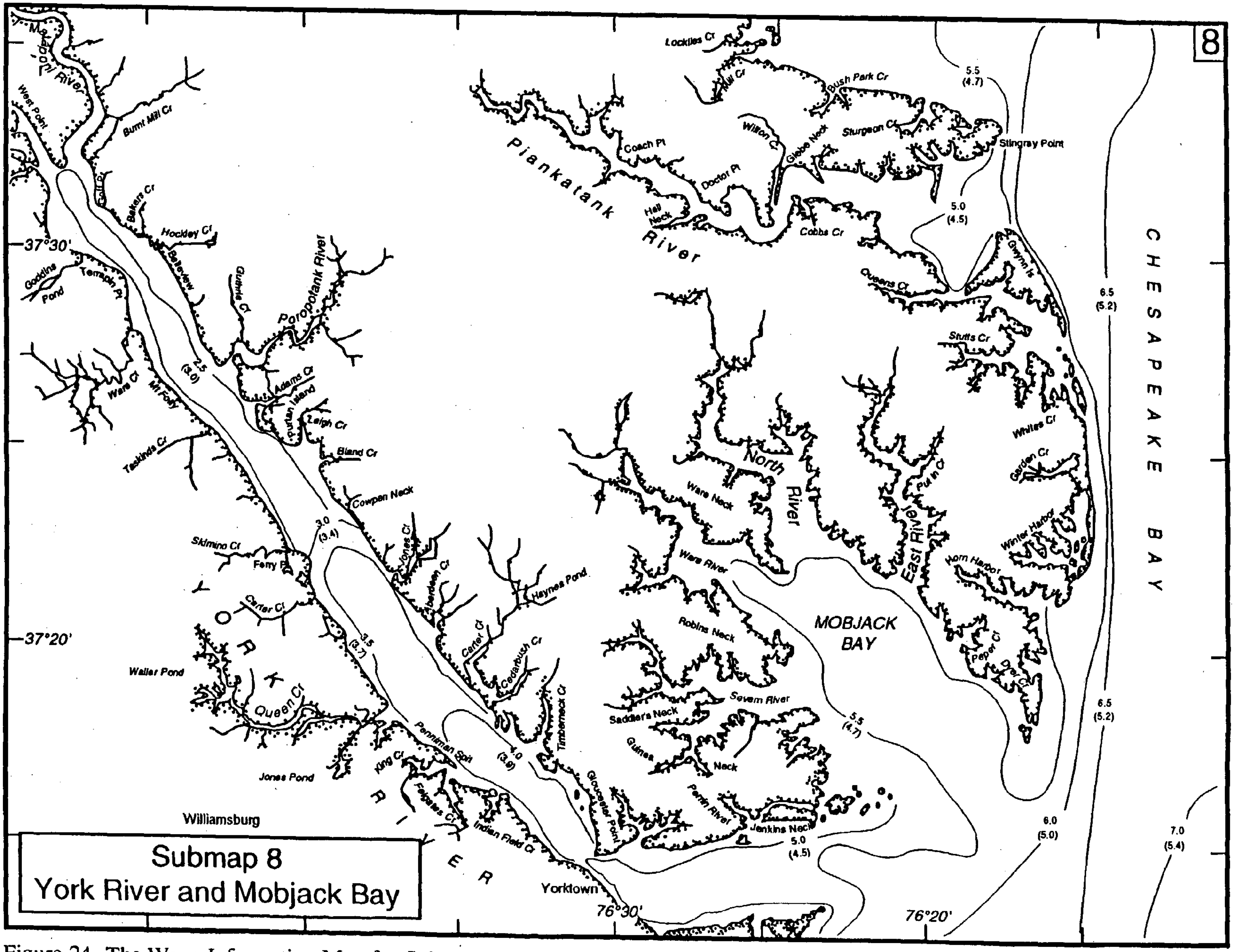

Figure 24 The Wave Information Map for Submap No.8 Showing Iso-Wave height Contours With Wave Periods in Parentheses.

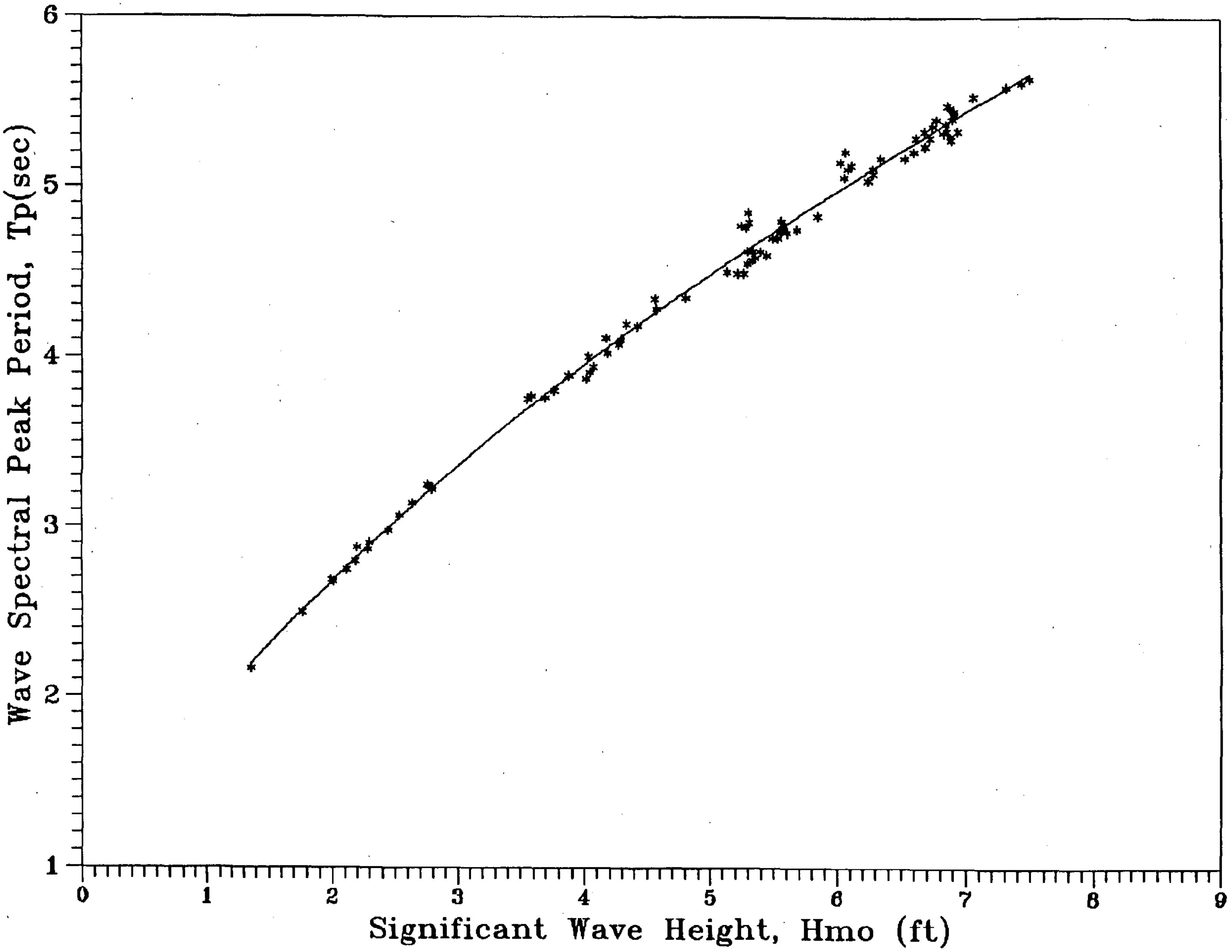

Figure 25 The Relationship Between H_{mo} and T_p for U_w=35 mph.

6.0 DEVELOPMENT OF WAVE INFORMATION MAPS

6.1 Discussion

Each submap was treated in detail, since errors on one could alter the results for adjacent areas. All submaps were combined on one large layout to insure that all wave heights were consistent from region to region on each submap. The submaps show iso-wave height contours at one-half foot intervals with wave periods covering all the water area with the fifty percent exceedance probability wind speed in any one year. Wave heights less than one foot are not shown. Wave height contours were obtained by linear interpolation among each adjacent node. Also, wave periods associated with each wave height were obtained from the statistical results of ACES output for the Submap No.8 as shown in Figure 25. Submap No.8 included all possible conditions encountered and the results shown in Figure 25 were also spot-checked for wave period throughout the study.

6.2 The Final Product

All final wave information maps with submap numbering are included as the Appendix for this report. Map numbering begins with No.1 covering the headwaters of the Potomac River at Washington, D.C. and ends at No.12 which covers the entrance region of this same estuary.

6.3 Limitations

The ACES hindcast model is a simplified, wave generation model that assumes a constant, weighted-average water depth over the entire wind field region. Because water depth is a key independent variable for wave transformation over two-dimensional bathymetry, this assumption is a primary limitation of the ACES methodology. Variable water depths permit the waves to shoal and refract and these transformations must be empirically incorporated within the calibration coefficients of the wave formulas employed. Wave energy spreading is also not explicitedly controlled by the user of the ACES model.

Near the shoreline, wave breaking and energy loss further complicates the process. Therefore the wave height contours presented should not be used at the shoreline. Surf zone energy loss models must be used in this region. These models must include shoaling, refraction, wave breaking energy loss, and wave induced set up on the local water levels.

In the center of the Bay near the lower end where fetch distance is greater than 75 miles, the height contours become aligned with the dominant fetch direction because wave height becomes controlled by mean water depth, not increasing fetch distance. This illustrates the point that the contours depict the largest waves at each location that could result from all possible wind directions. At some locations shorter fetch distances over deeper water produce bigger waves than that from the longest fetch direction.

Wave heights (and periods) in Submaps No.6, 7, 8, and 9 do not include waves from distant storms which enter the Bay from the Atlantic Ocean. Recent wave data measurements by Dr. John Boon at the Virginia Institute of Marine Science in the lower Bay at Thimble Shoal Light (Submap No.7) have shown double peaked energy density spectrums. Higher frequency energy associated with storm waves comes from the north and lower frequency energy associated with swell waves comes from the Bay entrance. This study only considers the storm wave component in the energy density spectrum and the associated spectral significant wave height and peak spectral period.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Much of the 5,000 mile shoreline of Virginia around the Bay consists of relatively moderate property value (farmland, single family dwellings, etc.) and this translates into relatively moderate wave energy levels for the design of coastal shore protection alternatives. From the historic wind data analysis, the design wind speed of 35 mph was selected which has about a 50 percent probability of exceedance in any one year. These can be considered for design to provide minimum property protection.

Submaps No.1 through No.12 in the Appendix present iso-wave height contours and associated wave periods for the Chesapeake Bay and its major tributaries in Virginia. Maximum wave heights were 8 feet with periods about 5.8 seconds and are found near the middle of both the upper and lower reaches of the Bay. Wave heights decrease along the tributary rivers. Wave heights less than one foot are not shown.

The design wave information presented on these twelve maps are considered to resonably reflect the results expected for the design wind conditions.

7.2 Recommendations

These results are recommended for use in providing consistent, wave information climates for shoreline property owners around the Bay.

Results shown on submaps near the entrance to Chesapeake Bay (6,7,8, and 9) do not include ocean waves propagating into the Bay. It is recommended that a second phase of this study be initiated using the parametric, spectral wind-wave model MIKE 21 NSW that is presently installed in the Computing Laboratory of the CE Department at ODU. This two-dimensional model can study how ocean wind-waves from coastal storms and ocean swell waves propagate into the Bay. The combined results can then be incorporated into an updated version of Submaps 6,7,8, and 9 for the entrance region of the Bay.

The spectral wind-wave model MIKE 21 NSW can also be used to make *site specific,* nearshore wave transformation studies (shoaling, refraction, etc.), including energy losses due to surf zone wave breaking. Boundary conditions for fine-grid, two-dimensional models can be the results of this study or generated separately from a large grid model of the entire Bay that is presently under development.

Finally, it is recommended that for locations where shoreline erosion threatens high value property such as public infrastructure (roads, pipelines, transmission lines, etc.) or private property (major buildings, marinas, etc.) that site specific, coastal engineering studies be conducted to determine the appropriate probability level for the design wind speeds. Higher value property will suffer larger damages during storm events so that it may be economically feasible to consider rarer storms with stronger winds for these situations. Thus the design wave information as presented on the submaps of this report are specifically for the Shoreline Programs Section of the Department of Conservation and Recreation of the Commonwealth of Virginia and are *not* recommended for general design use for all coastal engineering problems around the Bay.

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Virginia Institute of Marine Science (VIMS), Bathymetry of the Chesapeake Bay, 1977.(map)

APPENDIX

WAVE INFORMATION MAPS FOR CHESAPEAKE BAY IN VIRGINIA

(Wind Wave Hindcast For Sustained Wind Speed At The 50 Percent Exceedance Probability Level, U_w = 35 mph)

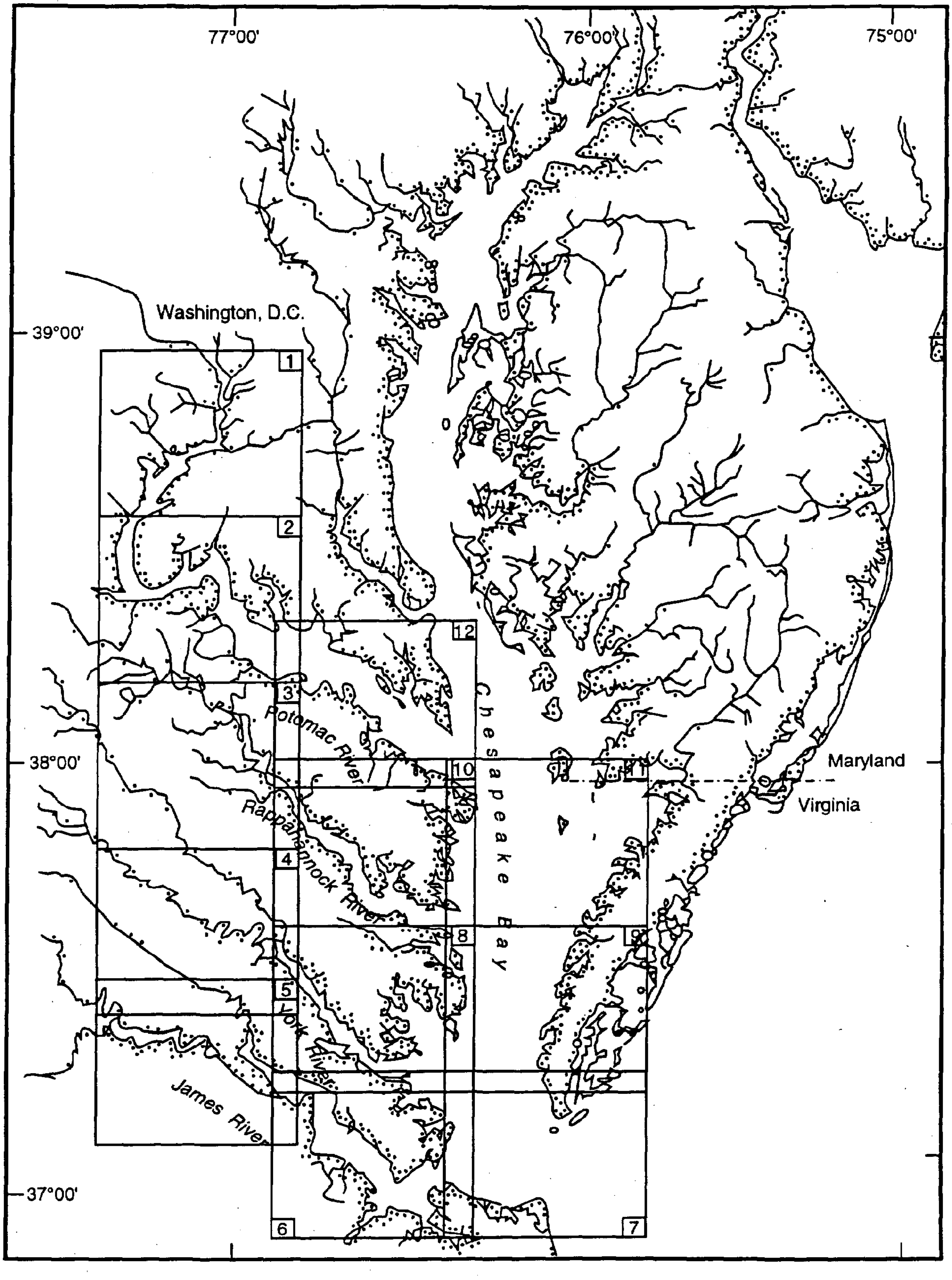
- Scale : 1 inch ≡ 3.5465 miles
- Date : December, 1993
- Notes : 1. Wave heights and periods (in parenthesis) are in general, generated along the longest fetch at the point of interest.

  H_{mo} = Spectral significant wave height,

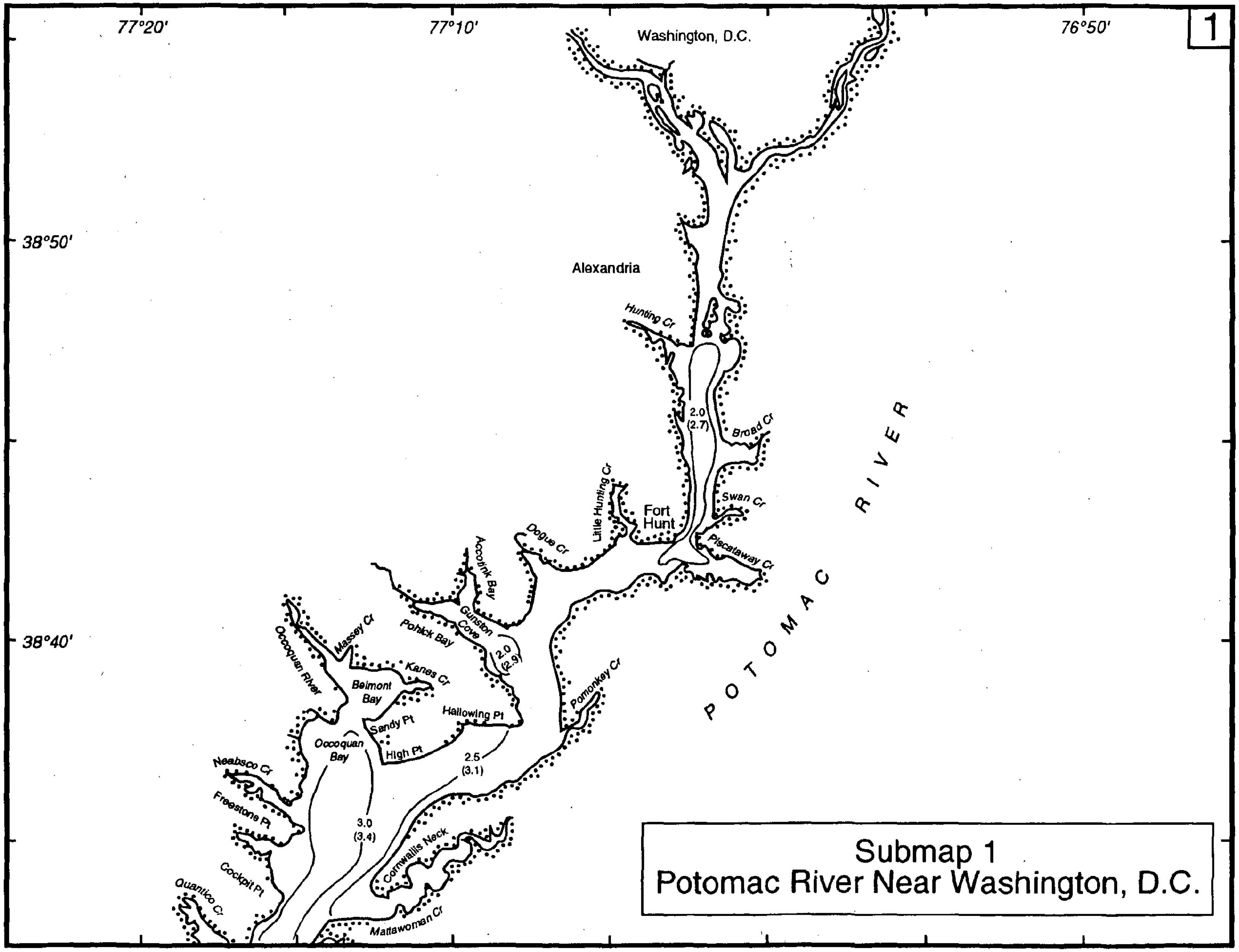
  T_p = Peak spectral period,

  2. Bathymetry from VIMS (1977) chart.

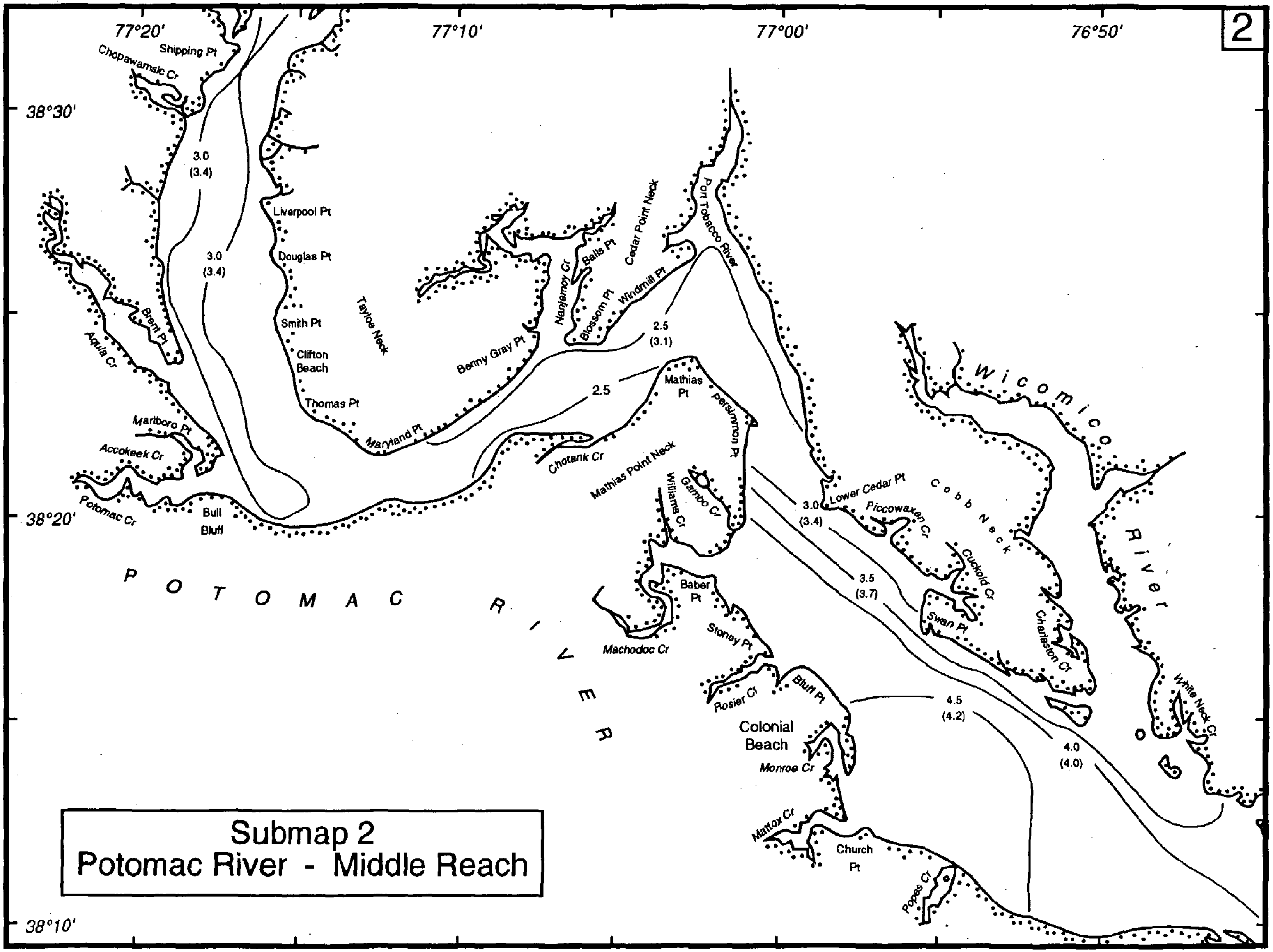
  3. Storm surge height is 2.5 feet.



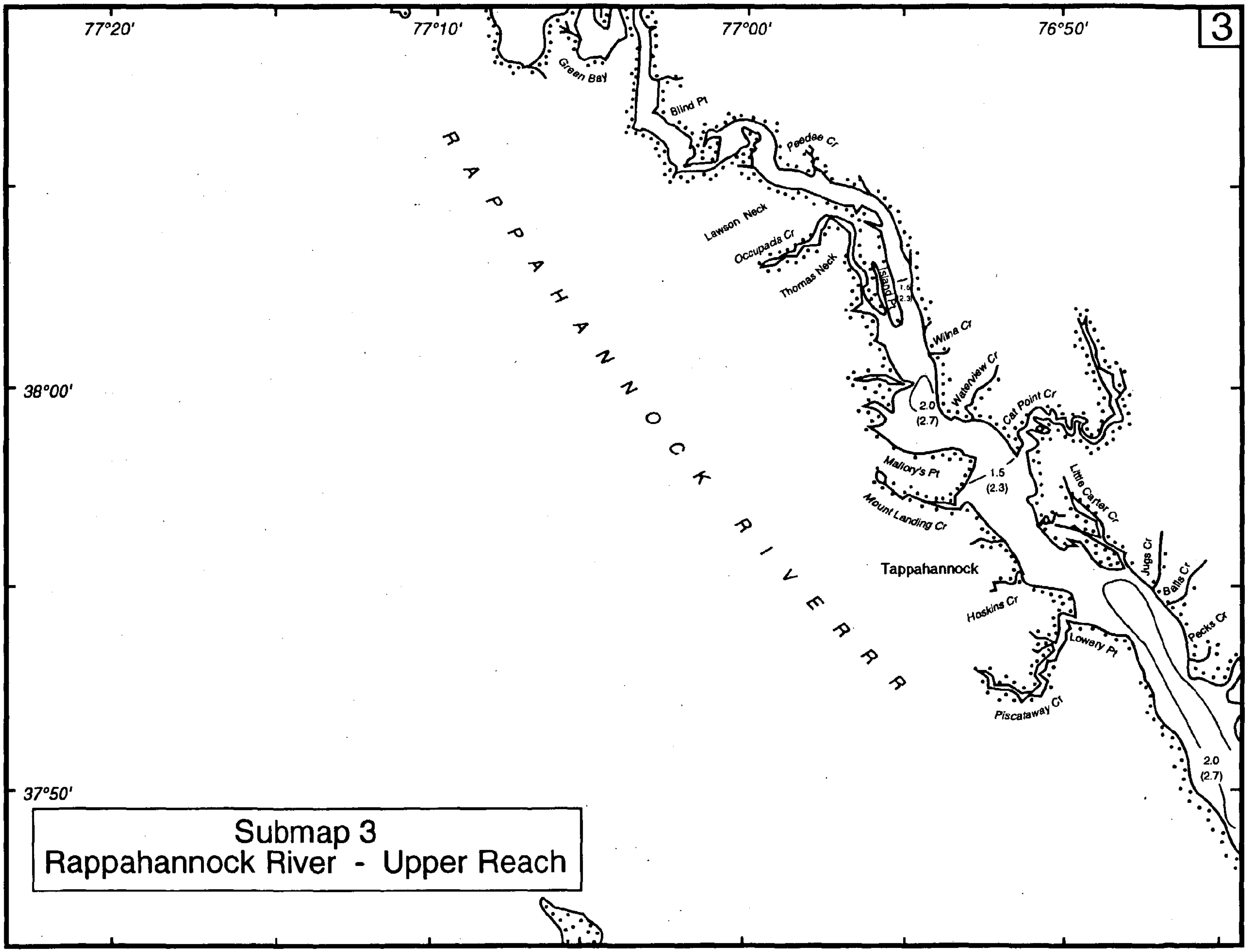
Numbered Submaps for Chesapeake Bay and Adjacent Water Bodies.



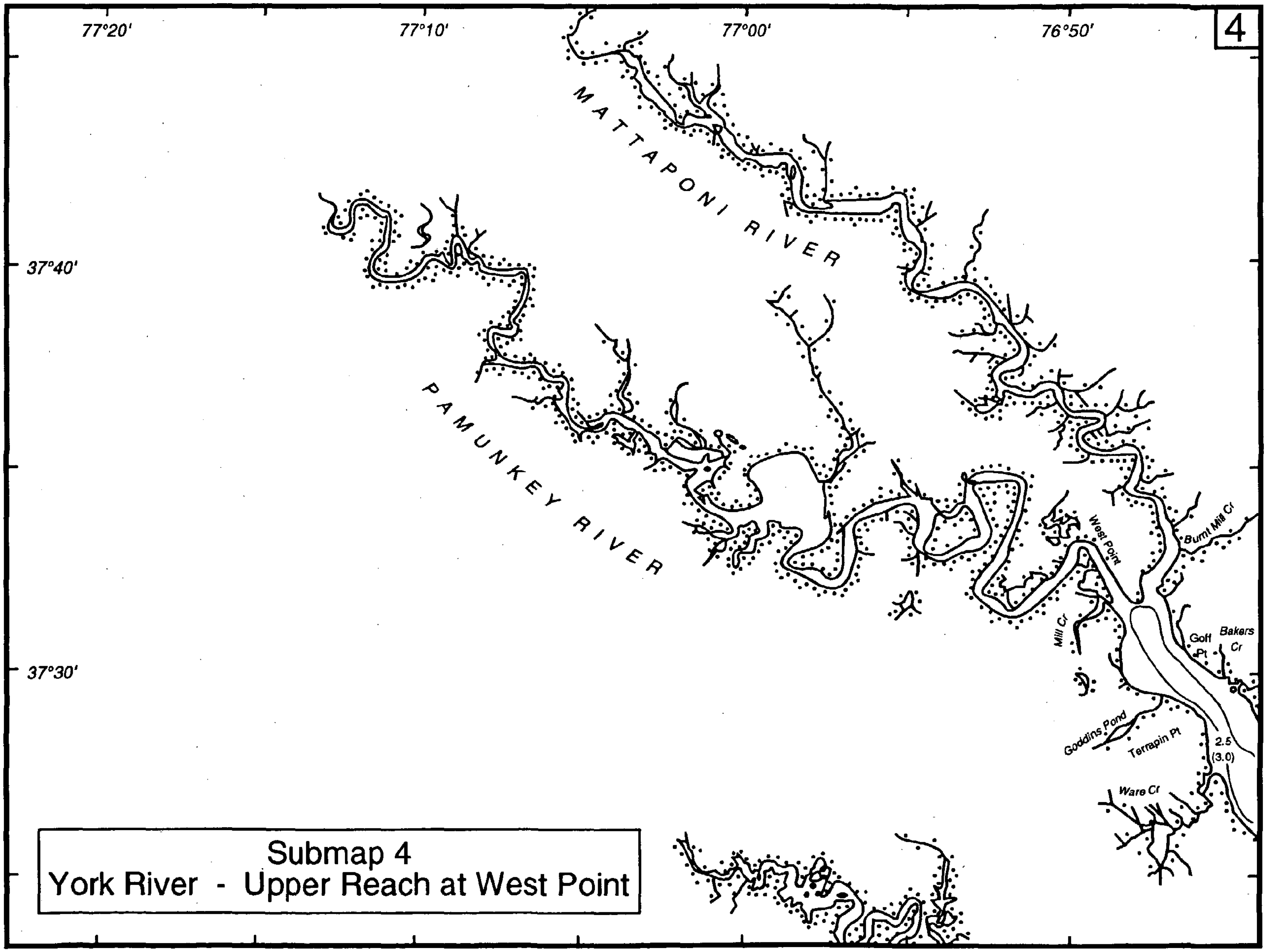
Submap 1
Potomac River Near Washington, D.C.



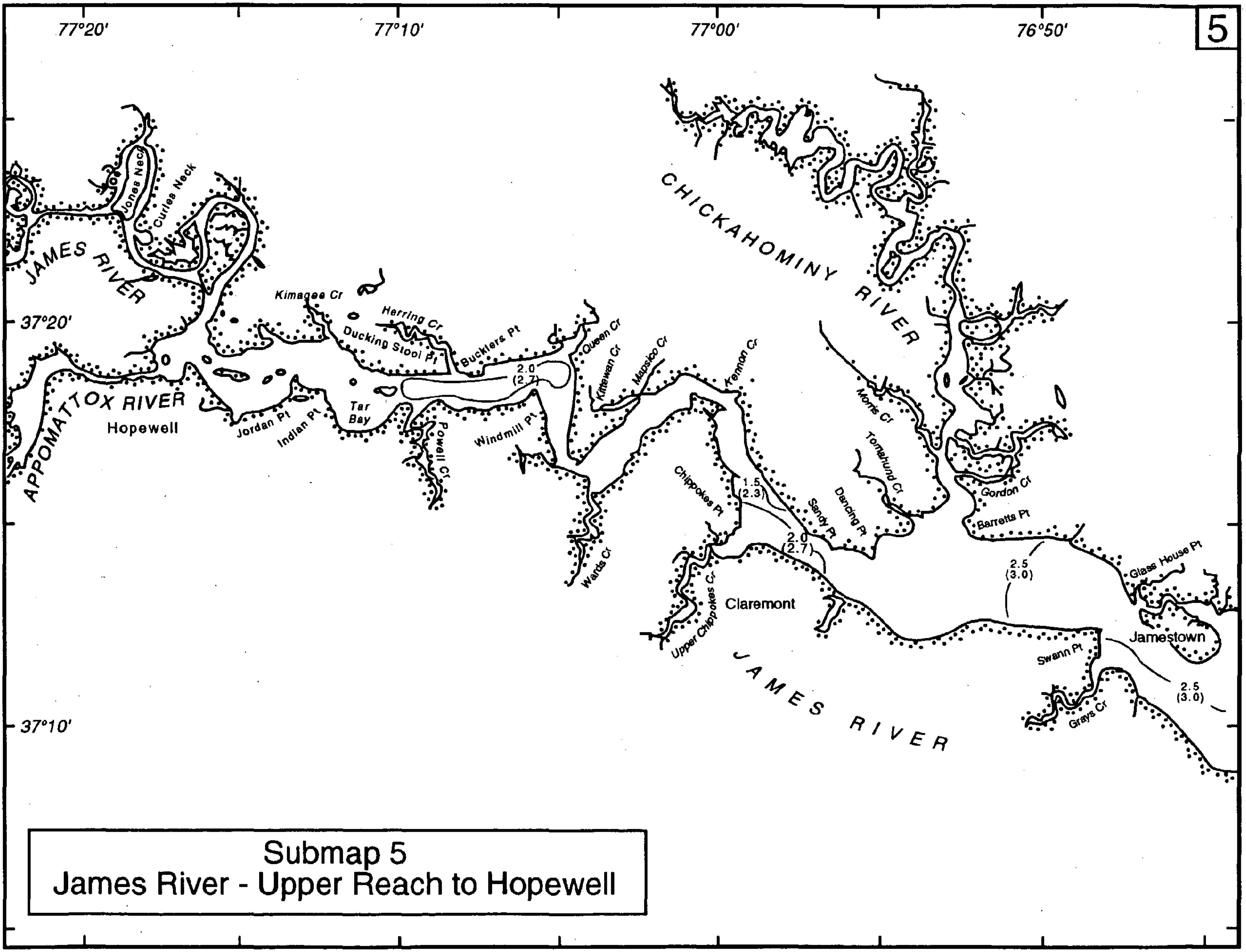
Submap 2
Potomac River - Middle Reach



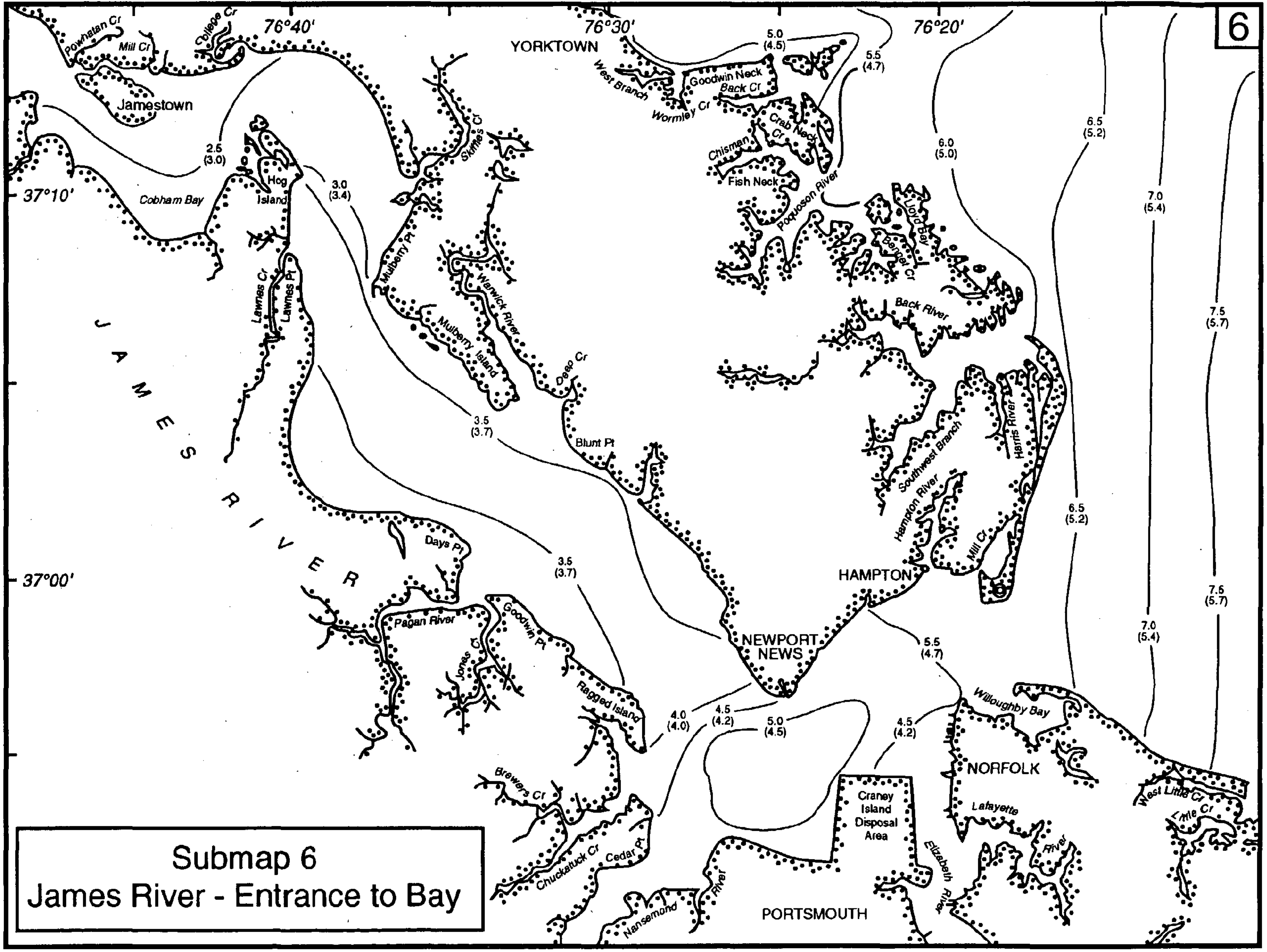
Submap 3
Rappahannock River - Upper Reach



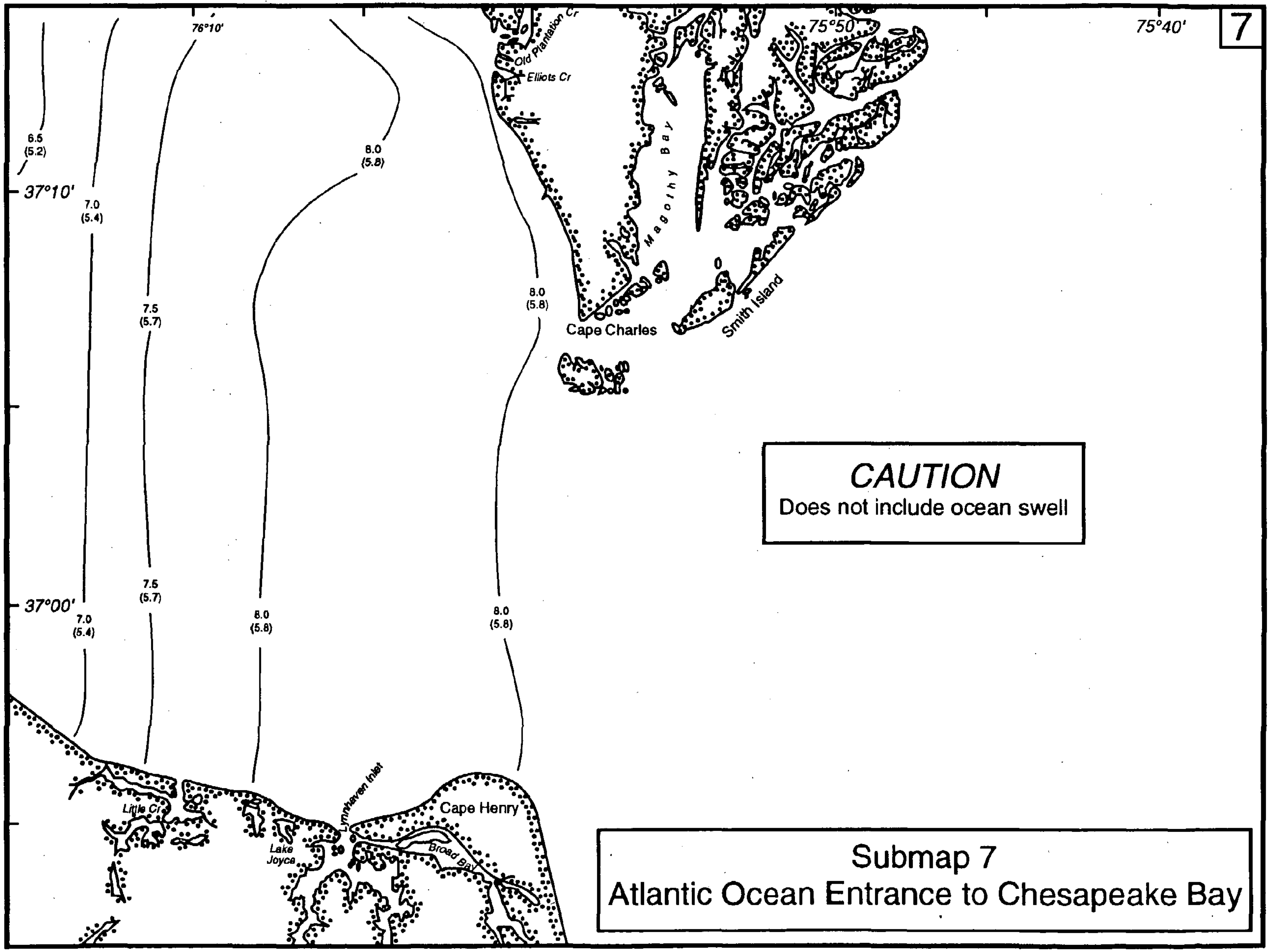
Submap 4
York River - Upper Reach at West Point



Submap 5
James River - Upper Reach to Hopewell

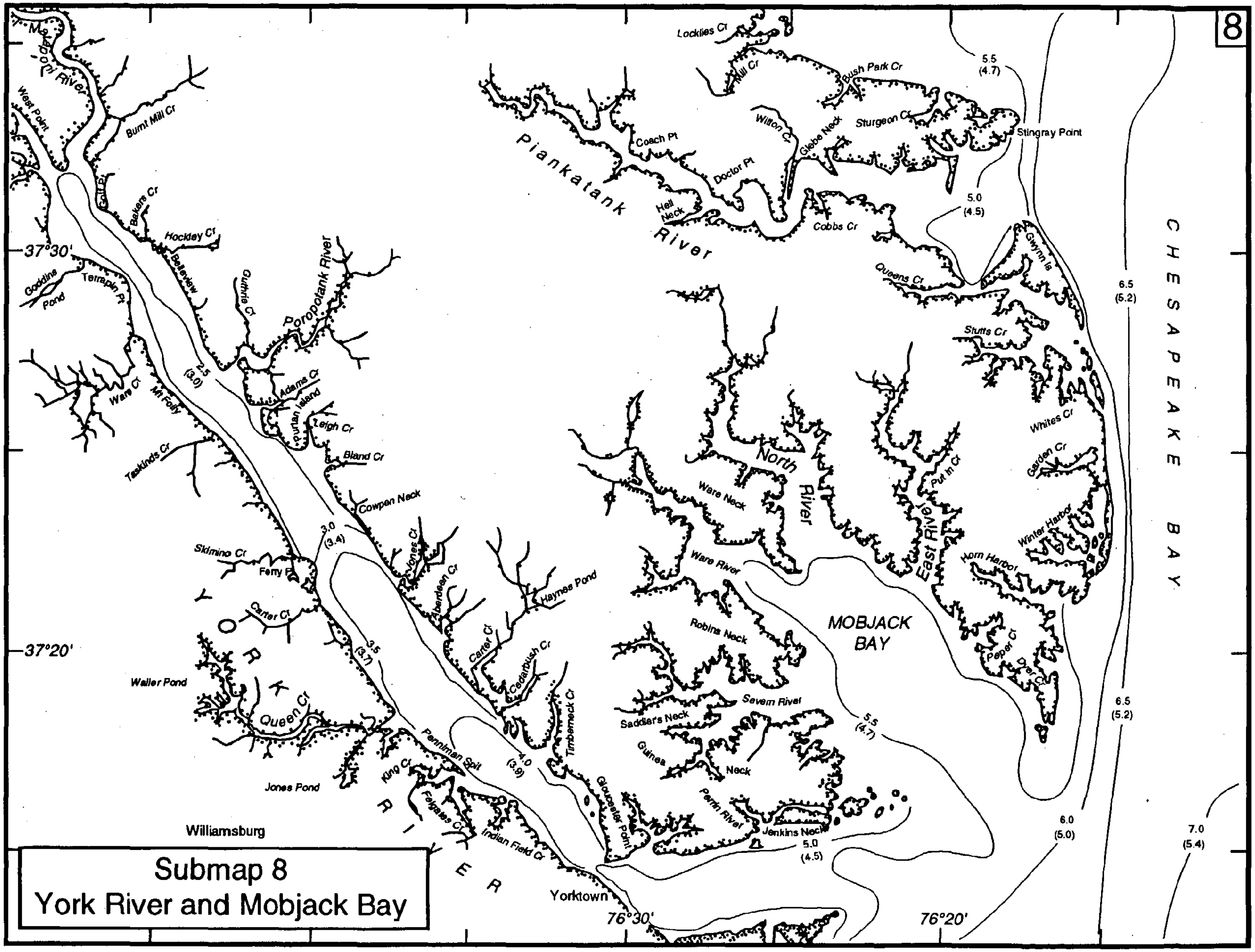


Submap 6
James River - Entrance to Bay

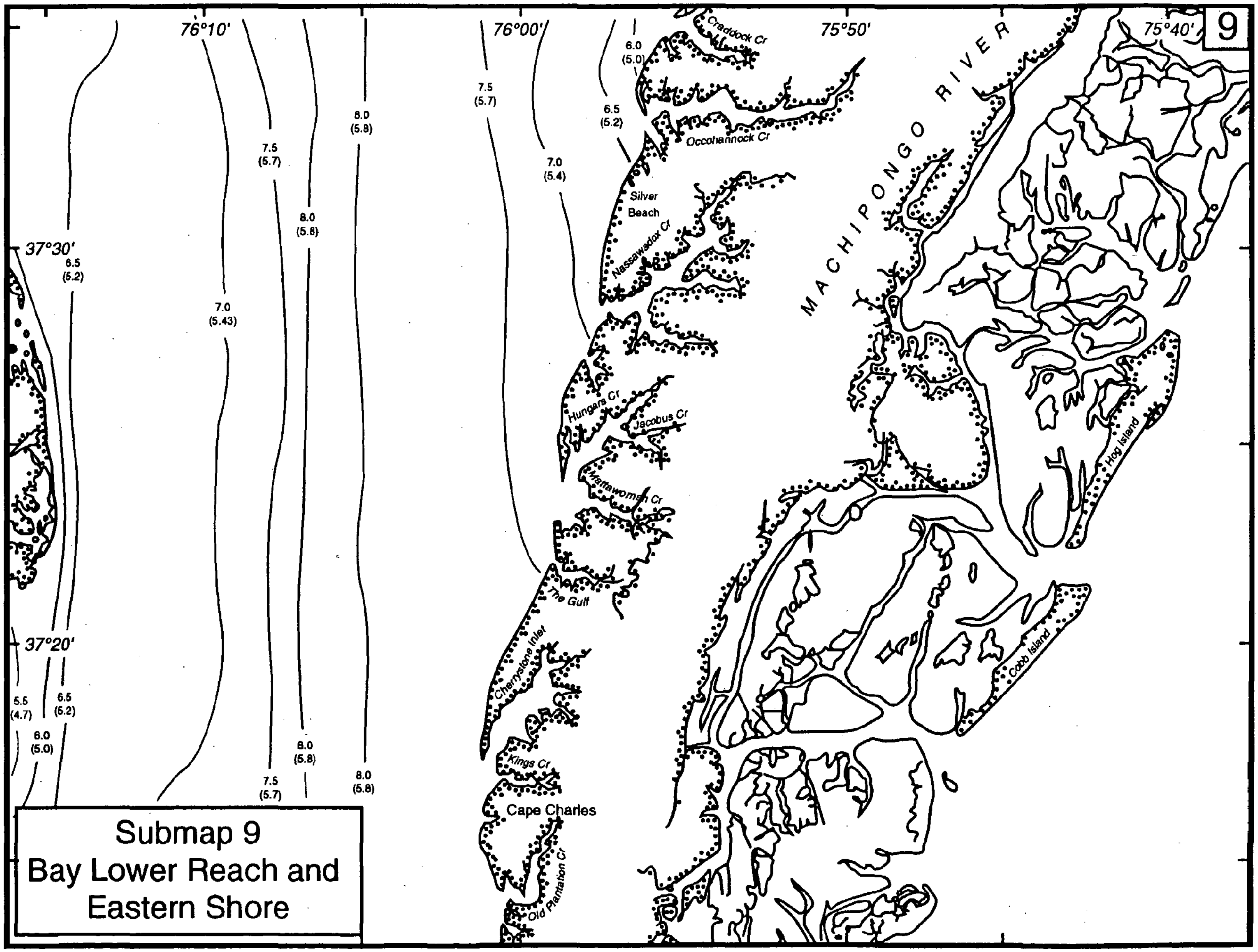


Submap 7
Atlantic Ocean Entrance to Chesapeake Bay

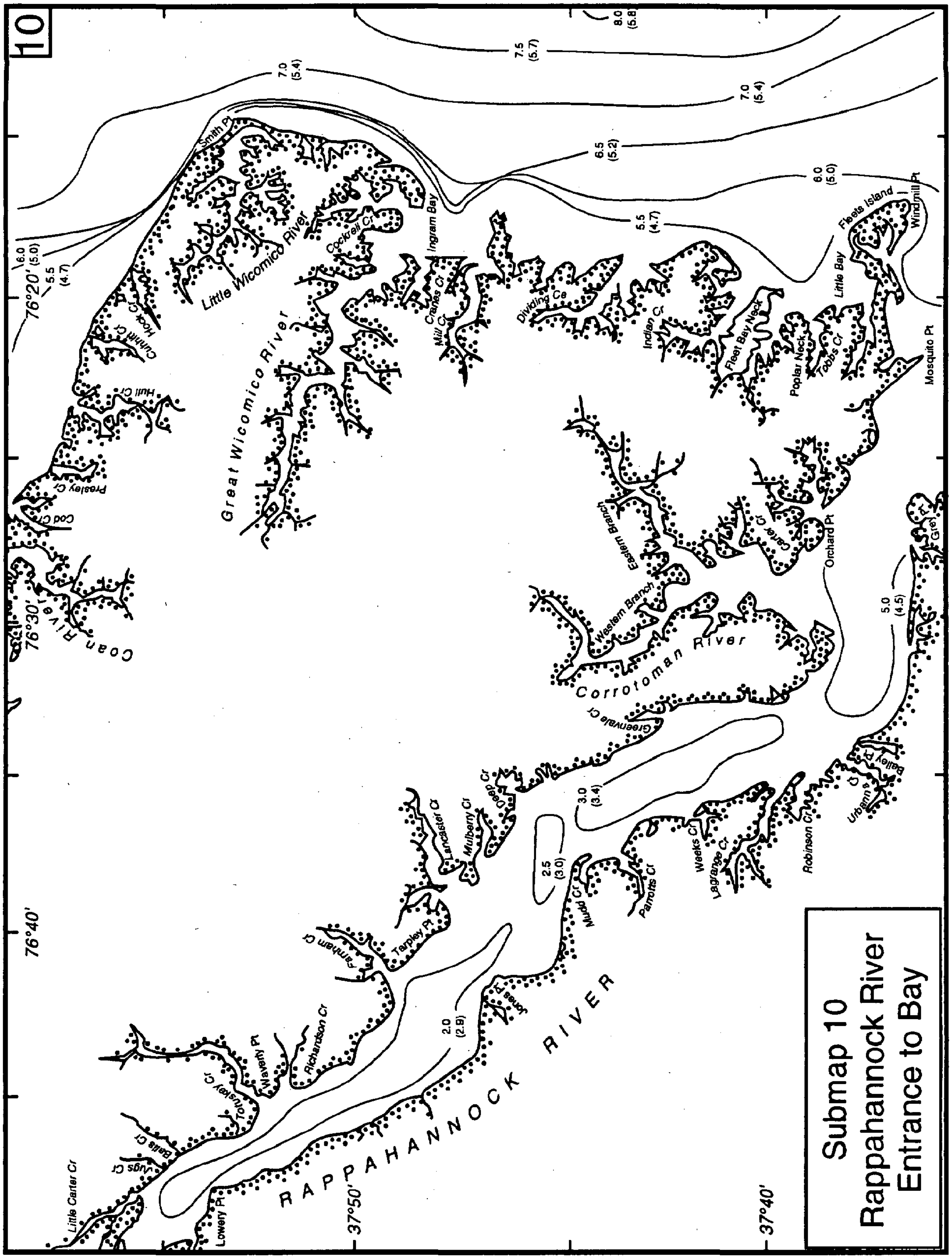
CAUTION
Does not include ocean swell

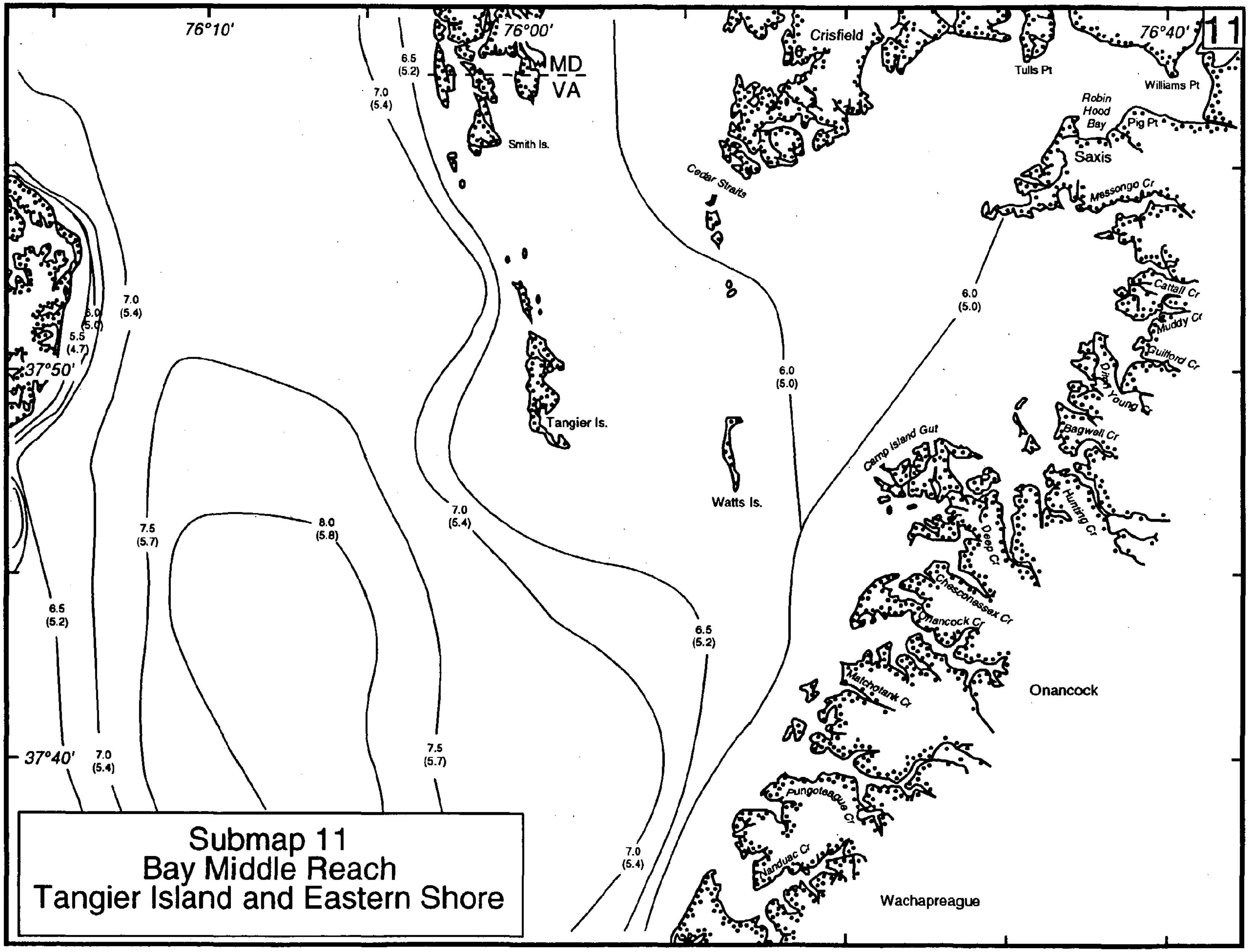


Submap 8
York River and Mobjack Bay

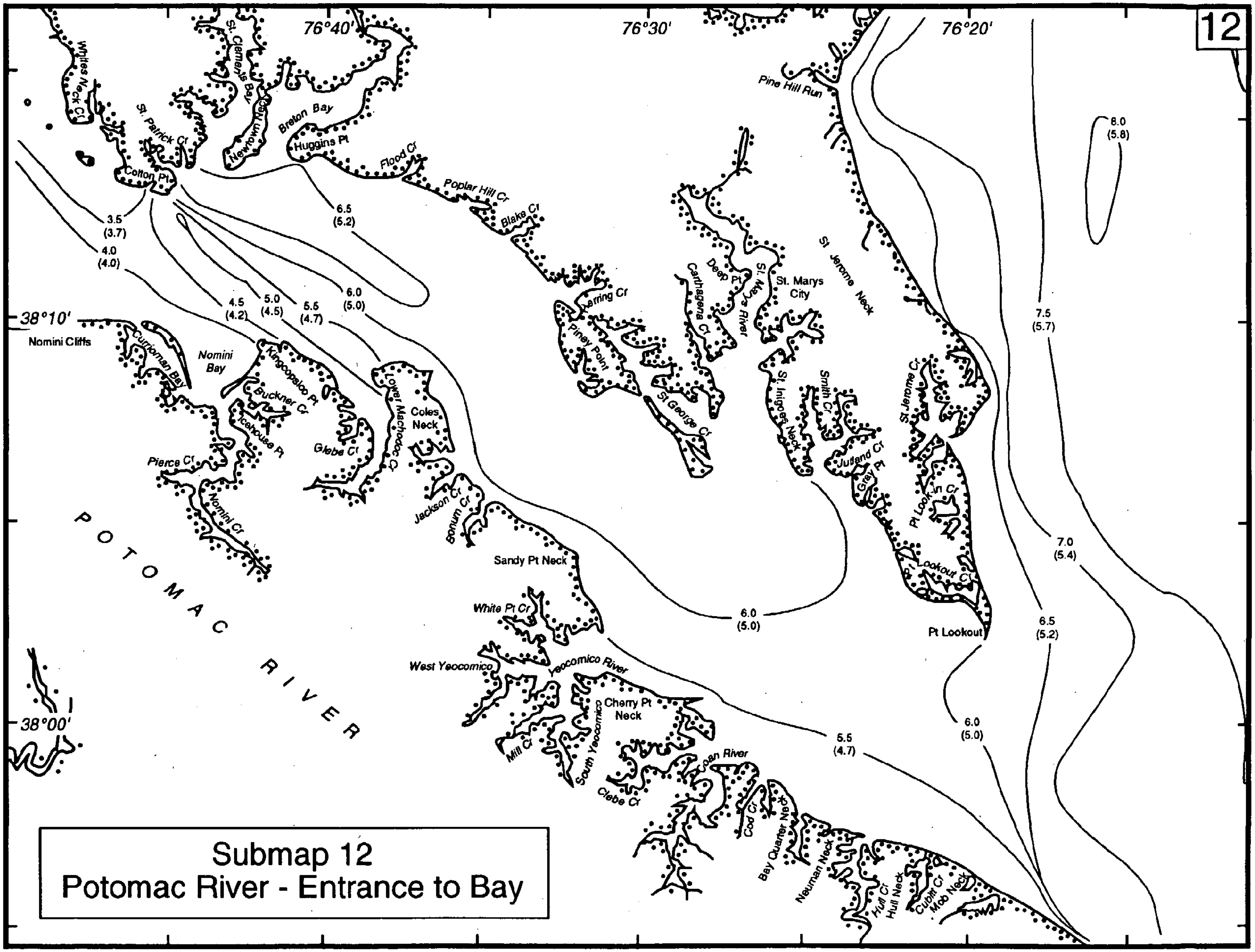


Submap 9
Bay Lower Reach and Eastern Shore





Submap 11
Bay Middle Reach
Tangier Island and Eastern Shore



Submap 12
Potomac River - Entrance to Bay