1976

# The morphology and processes of the Virginia Chesapeake Bay shoreline

Peter Stuart Rosen
*College of William and Mary - Virginia Institute of Marine Science*

ROSEN, Peter Stuart, 1949-
THE MORPHOLOGY AND PROCESSES OF THE VIRGINIA CHESAPEAKE BAY SHORELINE.

The College of William and Mary in Virginia, Ph.D., 1976
Geology

# THE MORPHOLOGY AND PROCESSES OF THE VIRGINIA CHESAPEAKE BAY SHORELINE

A Dissertation

Presented to
The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Doctor of Philosophy

by
Peter S. Rosen
1976

APPROVAL SHEET

This dissertation is submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Author

Approved, August 1976

Robert J. Byrne, Chairman

John Jacobson

Victor Goldsmith

Gerald Johnson

John M. Zeigler

Gene Silberhorn

Ivar Strand

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D) Page

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Robert Byrne, Victor Goldsmith, and John Zeigler for their support on this project. The cooperation and enthusiasm of Ivar Strand, John Jacobson, Gerald Johnson, and Gene Silberhorn is greatly appreciated.

Valuable field and laboratory assistance was provided by Wray Evans, Rone Baldwin, Steven Shiver, and Michael Carron.

Kay Stubblefield, Michael Williams, William Jenkins, and Kenneth Thornberry assisted in graphics and photography.

Advice and assistance on computer applications were provided by William S. Richardson and Francis K. Degges.

## LIST OF TABLES

## LIST OF FIGURES

LIST OF FIGURES (CONT'D)

## ABSTRACT

There is a high degree of site-specificity to the coastal environments of the Virginia Chesapeake Bay. The variability is influenced by (1) the relict Pleistocene high order dendritic drainage system, resulting in a large diversity of shore orientations; (2) the moderate, but highly variable wave energy in the Bay system and highly variable submergence rates, resulting in a spectrum of shoreline transformation from primary to secondary types (Shepard, 1973); (3) eroding fastland exposures of sediments of widely varying composition and volume, and (4) diverse salt marsh development.

Eighty percent of the shore is beaches composed of three morphologically distinct beach environments, each reflecting different susceptibilities to erosion: (1) permeable beaches, composed entirely of sand-sized material, comprise 59% of the beaches (mean erosion = 0.85 m/yr) and have the largest vertical and horizontal dimensions. This provides the largest vertical buffer to the effects of storm surge and waves. (2) Impermeable beaches, composed of a veneer of sand overlying impermeable, pre-Holocene sediments, comprise 24% of the beaches. The combined influence of low swash infiltration, low beach elevation, and groundwater effects result in the highest mean erosion (1.14 m/yr). (3) Marsh barrier beaches, composed of a veneer of sand overlying peat contains a resistant rhizome framework, resulting in the least erodable beach environment (0.66 m/yr). Marsh margins, the remaining 20% of the shoreline, are the least erodable shore environment (0.54 m/yr).

Different areas in the Bay are in different stages of succession from primary to secondary types (Shepard, 1973). These rates are controlled by variations in shoreline submergence and wave energy.

There is a direct relationship between tide range, total beach elevation, and supratidal elevation. Tidal range is inversely related to shoreline erosion.

Wave refraction studies of the Virginia Chesapeake Bay show (1) wave energy is a direct factor controlling coastal succession, and (2) the bidirectional wave field resulting from the interaction of the wind field and the

fetch restrictions of this elongate basin are causing the initiation of shoreline reorientation forms on both shores of the Bay.

There is a large variability in the local subsidence rates along the shoreline. The subsidence highs correspond to areas of largest nearshore terraces, and the main concentrations of salt marsh development. An equilibrium situation exists as a result of salt marsh development: The marsh is resistant to shore erosion, yet it occurs at the areas of highest submergence where shoreline retreat should be highest.

Application of the Bruun model to the Virginia Chesapeake Bay shoreline demonstrates sea level rise accounts for the measured erosion rates. It is apparent, though, that sea level rise "...plays only a permissive role in coastal erosion, not a causitive one" (Davis, et al., 1973). The action of short-term processes (waves, tide, surge, ground water effects) can therefore be regarded as the smaller scale agents effecting the larger scale trend.

THE MORPHOLOGY AND PROCESSES

OF THE VIRGINIA CHESAPEAKE BAY SHORELINE

## INTRODUCTION

The Chesapeake Bay shoreline is characterized by a high variability in the morphology and processes of the shoreline over a relatively small area. This results in highly site-specific shore environments.

Investigations of coastal processes are typically designed to measure the effect of processes on the coastal form by monitoring the variation in that process and the concomitant shoreline response over time. In the Chesapeake Bay, the large variability of such processes as sea-level rise, tide range, and wave energy over a relatively small area offers the opportunity to investigate the shoreline response to areal variations in these processes. This study is designed to monitor these variations as a cross-sectional, stratified sampling of the shore environments of the Virginia Chesapeake Bay. The generalizations are reached by inductive logic and yield a conceptual model of the regional shoreline system.

Time-series process studies of the Chesapeake Bay shoreline are necessary to understand the system, but without a regional framework to work from, such results are myoptic.

The Chesapeake Bay is one of the largest estuaries in the world. The Bay is approximately 290 km long, with a mean width of 25 km (Wolman, 1968). This study examines the regional shoreline processes of the 115 by 40 km area of the Virginia Chesapeake Bay.

The Chesapeake Bay is the result of submergence of the high-order dendritic drainage system of the Susquehanna River. The basin is very shallow, with a mean depth of nine meters. The relict main channel of the Susquehanna River remains as a deep (40 m) channel running down the axis of the basin. The shorelines of the basin have a high variability in orientations, as the shore is a relict form of the highly dissected drainage system.

While fluvial sediments are an important input to the Upper Bay system, shore erosion is the most important sediment input into the Lower (Virginia) Bay. Four major rivers discharge into the western shore of the Virginia Chesapeake Bay (Potomac, Rappahannock, York, and James Rivers). Most of the fluvial sediments in these systems are deposited in their upper reaches and do not reach the main basin of the Bay (Schubel, 1972).

There is a high, and very variable rate of erosion along the Virginia Chesapeake Bay shoreline. Byrne and Anderson (1973) have estimated over 270,126,000 cubic yards of sediment in the last century were eroded and lost to the system. Erosion rates often exceed 18 acres per mile per century. It is estimated that the Chesapeake Bay has one of the highest rates of tidewater erosion in the United States (Slaughter, 1964). The processes effecting these shoreline changes are the major focus of this investigation.

# LITERATURE REVIEW

## MORPHOLOGY

An assessment of the shoreline erosion trends in the Virginia Chesapeake Bay was initiated by the Virginia Institute of Marine Science (Byrne, Anderson and Sallenger, 1972; Byrne and Anderson, 1973). Despite the fact that this is a moderate energy system affected only by locally generated seas, shoreline erosion is a critical problem. It was estimated that 270,126,000 cubic yards of sediment in the last century were eroded and lost to the system. Erosion rates were estimated to exceed 18 acres/mile/century. The magnitude of the erosion rates were delineated by counties. Further work (Athearn, Anderson, Byrne, Hobbs, and Zeigler, 1974, and successive volumes) provide an inventory of the shoreline erosion history, present status, and physiographic characteristics for each county in Tidewater, Virginia.

The Virginia Agricultural Experiment Station (1962) attempted to analyze the causal processes of riverbank erosion on the Potomac and Rappahannock Rivers. They concluded that regional factors were too complex to be delineated. The present study offers progress in this area.

A detailed inventory of shoreline erosion in the Maryland Chesapeake Bay was presented by Singewald and Slaughter (1949). This study detailed the magnitude and local variability of the erosion problem. As well, the use and effectiveness of various shore protection structures was considered. Clark, Murdock, and Palmer (1973) provided an analysis of shoreline erosion in the Chester River, Maryland to account for the riverine sedimentation. Slaughter (1964) and Schubel (1968) each discussed the shore erosion problem in the Maryland Chesapeake Bay using computations of volumes of sediment lost to the system. Slaughter concluded that the Chesapeake Bay region has one of the highest rates of tidewater erosion in the United States. Slaughter (1966, 1967a, 1967b) further outlined the magnitude of erosion in the Maryland Chesapeake Bay, showing that over 24,712 acres of land/century have been lost. The thrust of these investigations were to examine the effectiveness of different types of shore protection structures. Each report concluded that a clearer understanding of the total processes of the shoreline system were necessary to improve the attempts to control shore erosion.

Schubel, Carter, Schiemer and Whaley (1972) used long-term patterns in shoreline erosion to delineate prevailing littoral drift trends. This technique revealed local reversals in the drift system of the western shore of the Maryland Bay. These local reversals, resulting in convergences of drift systems, are similar to those delineated in this report by the use of wave refraction modelling.

Trident Engineering Associates (1968) submitted a planning analysis of the Chesapeake Bay shoreline. Wolman (1968) presented a thorough review of the geology and geography of the Maryland Chesapeake Bay shoreline.

Jordan (1961) and Hunter (1914) described local bathymetric changes at the mouth of the Choptank River, Maryland, and postulated as to the processes of nearshore terraces. O'Brien (1968) studied the distribution, origin, and sediment movement of the multiple nearshore bar systems which flank most of the Chesapeake Bay shoreline.

Ryan (1953) described the sedimentary framework of the Chesapeake Bay. This study shows that sands are confined to the margins of the Bay, while deeper portions of the Bay consist of finer silts and clay. This observation supports the assumptions of the application of the Bruun model in the present study.

Bond and Mead (1966) investigated the grain size distribution of suspended sediments in the Chesapeake Bay and offshore waters. They found no relationships between the Lower Bay and the Upper Bay or offshore waters. Briggs' (1962, 1967, 1970) studies of suspended and bottom sediments in the Maryland Chesapeake Bay resulted in an estimate of the sedimentation rate at 1.1 mm/year. Shideler (1975) concluded the bottom sediments of the

Lower Bay are the result of multiple sources, including shoreline erosion. Harrison, Lynch, and Altshaefl (1964) presented data on the bottom sediments of the Virginia Chesapeake Bay, with emphasis on mass properties. Palmer (1974) investigated the sources and distribution of bottom sediments in the Chester River Estuary, Maryland. Wolman (1968) 'hindcasted' the increase in sedimentation rates in the Chesapeake Bay with the advent of man.

The coastal plains geology of the Chesapeake Bay region is described by Stephenson, Cooke, and Mansfield (1933). Carter (1951) studied the soils and landforms of the Chesapeake Bay margins. Wolman (1968) outlined the geologic history of the Chesapeake Bay as a submerged dendritic drainage system.

## PROCESSES

Very few shoreline process studies have been undertaken in the Chesapeake Bay. Sallenger and Rosen (1974) investigated the accretional cycle on a permeable beach. Accretion occurs as both beach-face sedimentation and ridge-and-runnel migration. The occurrence of ridge-and-runnel systems on an adjacent impermeable beach is much less common. Palmer (1973) described the role of ground water in the erosion processes of impermeable beaches. Ground water runoff effects spalling of impermeable backbeach bluff, which augments erosion.

Bruun (1962) proposed a model relating sea-level change to shore erosion based on the onshore-nearshore sediment budget. Schwartz (1965, 1967, 1968) and DuBois (1975) have attempted to confirm the universality of the Bruun model.

Recent rates of relative sea-level rise were determined from mareograph records by Hicks (1972) and Hicks and Crosby (1974). Unpublished data from this study (Hicks, written communication, 1975) provides a detailed history of the varying rates of submergence in the Chesapeake Bay. Recent rates of subsidence were determined by Holdahl and Morrison (1974) for the Chesapeake Bay by comparisons of releveling data for tidal bench marks. These data provide a basis for the application of the Bruun model in the Chesapeake Bay.

Geologic evidence for vertical changes in sea level are discussed by Harrison, Malloy, Rusnak, and Terasme (1965) who suggested possible post-Pleistocene uplift in the Chesapeake Baymouth area. Various estimates of rates of shore submergence are offered by Newman and Rusnak (1965), Walcott (1975), Redfield (1967) and Kay and Barghoorn (1964).

The tides and currents in the Chesapeake Bay are outlined by Haight, Finnegan, and Anderson (1933). The magnitude of the tidal currents in the main basin of the Chesapeake Bay are small, due to the microtidal nature of the area. The tidal wave characteristics of the Bay are described by Hicks (1964), based on the 241 tide stations occupied by the U.S. Coast and Geodetic Survey. Pore (1960) described the nature of hurricane surges in the Chesapeake Bay. This work showed that the storm path affects the distribution of surge heights along the shoreline. Hurricanes passing to the west of the Bay result in higher surges in the northern portion of the Bay, while hurricanes passing to the east of the Bay result in higher surges to the south. Bretschneider (1959) presented a model for the prediction of hurricane surge heights in the Bay.

Both Bretschneider's model and Pore's analysis of Chesapeake Bay hurricane surge demonstrate that surges are event-specific, both in occurrence and regional variations in amplitude. As the design of the present investigation is site-specific, storm surge is addressed only in terms of backbeach elevation. This is a measure of susceptibility to erosion from storm surge. Warnke et al. (1966) showed that the rise in water elevation itself effects erosion. The superposition of waves on a surge increases the erosional potential, as the waves are acting on a zone above the normal shore buffer zone (beach).

The meteorological framework of the Chesapeake Bay area is described by the U.S. Weather Bureau (1956), and the U.S. Navy (1963, 1972).

## METHODOLOGY

The study area comprises the margins of the Virginia Chesapeake Bay (Figs. 1 and 2).

A large variability of shoreline types, and site-specificity of environments is dominant in the study area. In order to elicit the regional trends in the morphology and processes of the system, a stratified, cross-sectional sample of the morphology and processes was taken by dividing the 336 km of shoreline under consideration into 209 reaches of varying length. These reaches were determined to be approximately process-constant coastal environments. The boundaries of the reaches were determined initially through topographic map interpretation based primarily on shore orientations and evidence for similar shore environments and later refined by field reconnaissance (see Appendix A).

A long term erosion rate was determined by comparison of the 1860 and 1940 shoreline positions (U.S. Coast and Geodetic Survey triangulation sheets printed on stable-base acetate) and averaged over each reach to determine a mean retreat rate. The 1940 shoreline position was chosen as an endpoint because of the availability of the data, and, as well, the retreat rates in this period are assumed to be more purely a result of natural processes.

Figure 1: Counties surrounding the Virginia Chesapeake Bay.

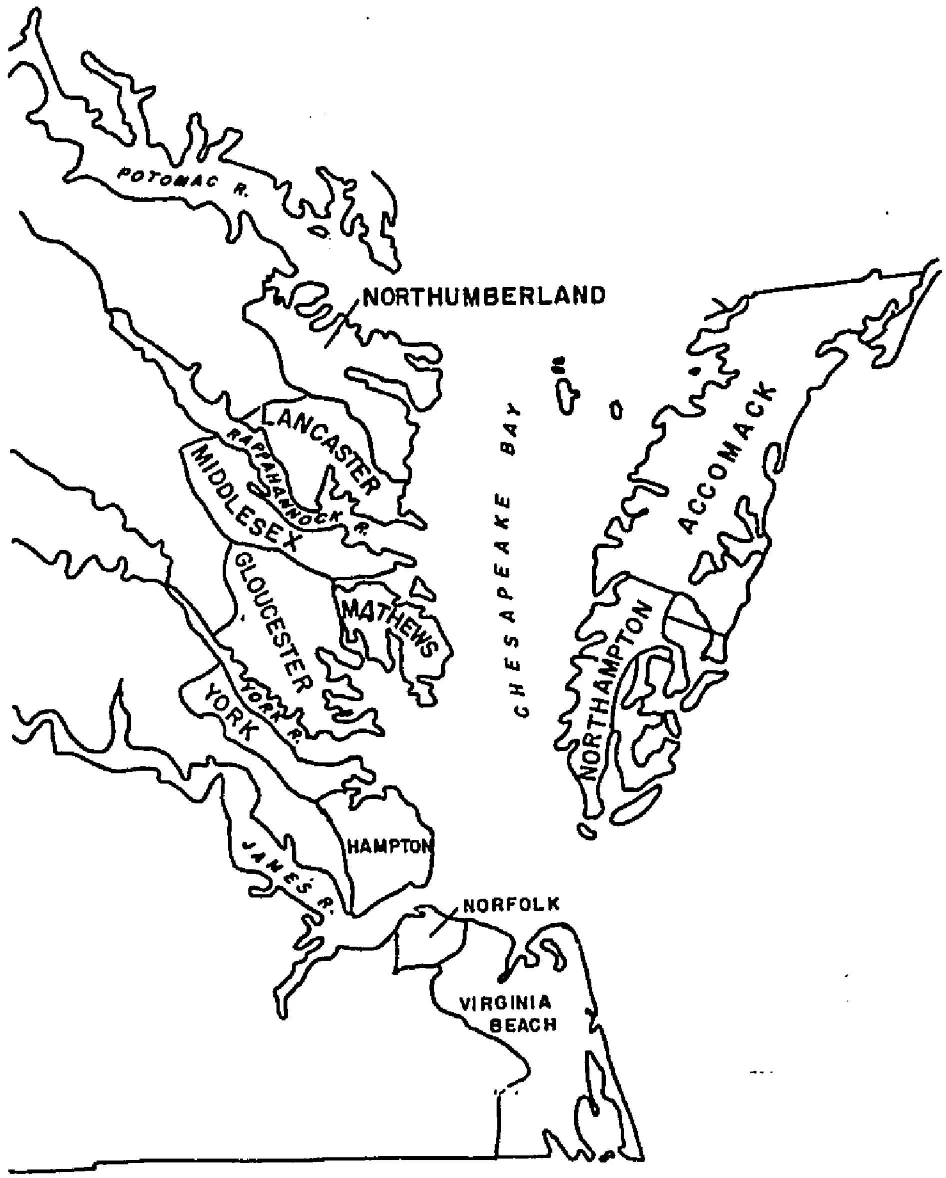
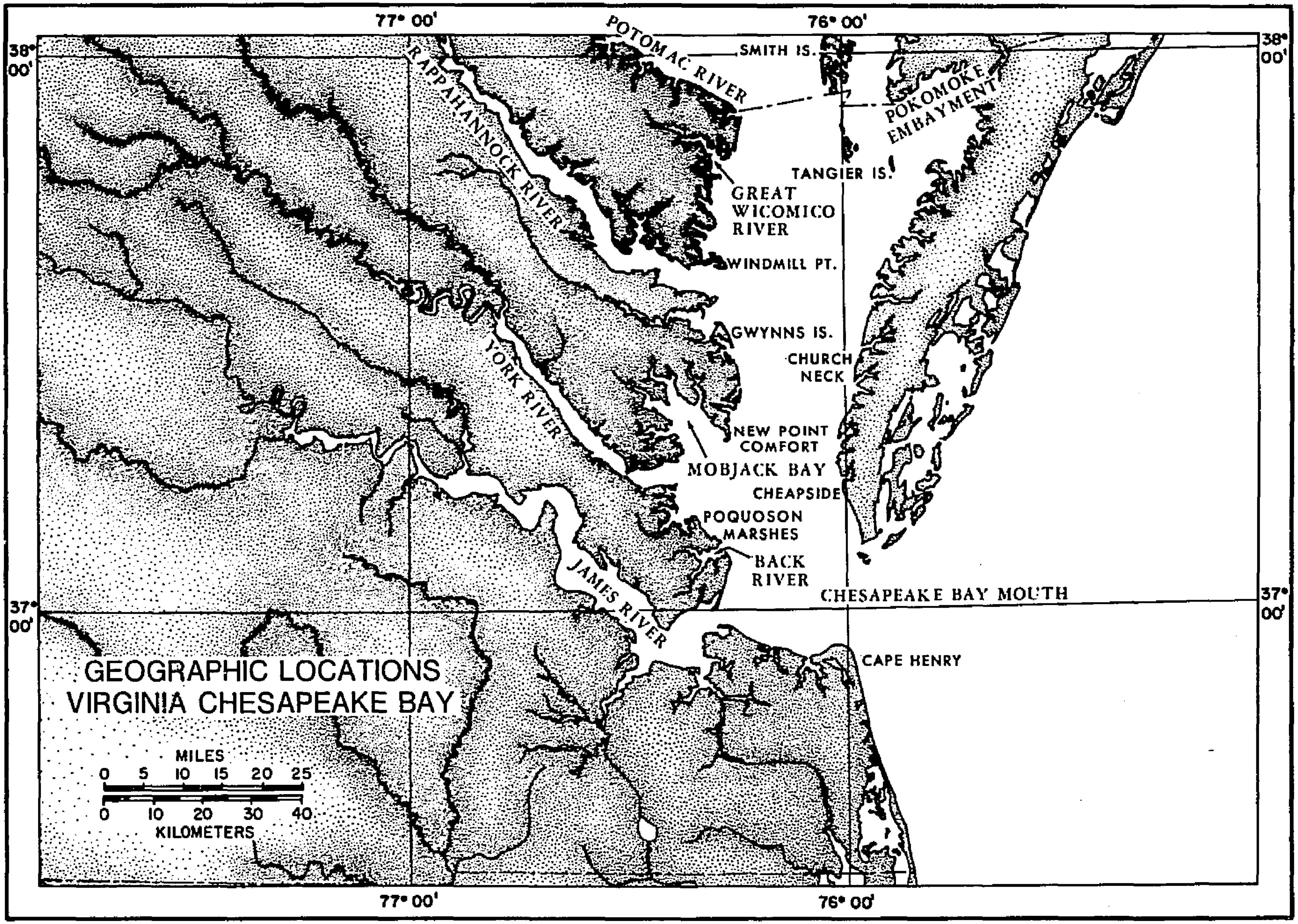

POTOMAC R.
NORTHUMBERLAND
LANCASTER
RAPPAHANNOCK R.
MIDDLESEX
MATHEWS
GLOUCESTER
YORK R.
YORK
HAMPTON
JAMES R.
NORFOLK
VIRGINIA BEACH
CHESAPEAKE BAY
ACCOMACK
NORTHAMPTON

Figure 2: Geographic locations cited in text, Virginia Chesapeake Bay.



77° 00'
76° 00'
38° 00'
37° 00'
POTOMAC RIVER
SMITH IS.
POKOMOKE EMBAYMENT
RAPPAHANNOCK RIVER
TANGIER IS.
GREAT WICOMICO RIVER
WINDMILL PT.
GWYNNS IS.
CHURCH NECK
YORK RIVER
NEW POINT COMFORT
MOBJACK BAY
CHEAPSIDE
POQUOSON MARSHES
BACK RIVER
JAMES RIVER
CHESAPEAKE BAY MOUTH
CAPE HENRY
GEOGRAPHIC LOCATIONS
VIRGINIA CHESAPEAKE BAY
MILES
0 5 10 15 20 25
0 10 20 30 40
KILOMETERS

The length of each reach was determined for use in the computation of weighted means, so the region can be described with minimal sampling bias.

The following variables, which represent morphologic characteristics (process-response), or a process, were chosen on the criteria that (a) the processes they represent have an effect on the erodability of the shoreline; (b) there is a regional variation in each, so the effect can be determined within the design of this experiment; and (c) the variable can be measured on the regional scale. Sampling and measurements were taken at the midpoint of each reach.

1. Orientation: An average shoreline orientation was measured for each reach. The azimuth direction (recorded to the nearest whole degree) was to the right of the shoreline, facing landward.

2. Re-orientation: If the orientation of a shoreline in any reach measurably varied between 1860 and 1940, the amount of rotation was recorded. A clockwise rotation is +, and counter clockwise is –.

3. Fetch: The fetch for each reach was measured at $30^{\circ}$ intervals at the center of each reach.

4. Nearshore terrace: The margin of the nearshore terrace was defined for measurement at the 3.6 m (12 ft.) contour. This distance was determined normal to the shore at each reach by measurements from charts.

5. Bluff height: The height of the bluff adjacent

to the beach was measured in the field.

6. Fastland type: Four major shoreline types, permeable (Holocene or pre-Holocene fastland), impermeable (beach underlain by clay), and marsh barrier and marsh margin were determined by field observations.

7. Backbeach type: Each reach was described in terms of dune, bluff or other.

8. Tide range: The tide range for each reach was determined from Hicks (1964). The data is based on the 241 tide stations occupied in the Chesapeake Bay by the U.S. Coast and Geodetic Survey.

9. Subsidence rates: Subsidence rates for each reach were determined from data by Holdahl and Morrison (1974). The interpolations of subsidence rates at each reach are based on the 51 tidal benchmarks releveled around the margins of the Chesapeake Bay.

10. Beach dimensions: At each reach a beach profile was taken using the method described by Emery (1961). From this a measurement of beach width, maximum elevation and foreshore slope was determined. The low water line was assumed to be at the break-in-slope at the lower limit of the beachface. A series of eight test profiles at Gloucester Point, Virginia showed a maximum error of 15 cm. vertically.

As well, the following list of descriptors was used as they applied to each reach:

1. Bayfront shoreline
2. Spit

3. Island
4. Marsh margin
5. Marsh barrier
6. Mobjack Bay
7. Offshore Bar present now
8. Creek shoreline
9. South of major creek
10. North of major creek
11. Extensive fringe marsh
12. Intermittant fringe marsh

A compilation of this information is shown in Appendix B.

Sediment sampling was performed as follows: At the midpoint of the foreshore of each reach, one or two samples of beach sediment were taken. When trenching revealed stratified sedimentation, each layer was sampled separately. On impermeable beaches, the material underlying the beach sand was sampled, and the thickness of beach sediments at the midpoint of the foreshore was measured. When an exposed bluff was on a beach, a mixed sample of this sediment was taken.

The sediments were analyzed as follows:

Clayey material was separated from sand by wet sieving to determine sand/mud ratios by the method described by Folk (1968, p. 21). Beach sand samples and sand residuals from clays were analyzed in the Rapid Sediment Analyzer at the Virginia Institute of Marine Science.

## ANALYSIS

The above basic shoreline variables were initially regressed on erosion rate using a stepwise multiple regression program. The purpose of this procedure was to screen the data for variables correlated with long-term erosion. This procedure also analyzed the noise level in both the data and the system.

The data was analyzed also by graphical means. The shoreline in the study area was straightened to form a U-shaped representation of the area. The variables were plotted on this format to help discern regional relationships.

The arguments presented are the result of the graphical and statistical evidence. The result is a conceptual model for the regional trends in the Virginia Chesapeake Bay shoreline erosion processes. As noted previously, the shoreline of the Virginia Chesapeake Bay is extremely variable. The only unifying factors in the region are a common geomorphic setting (submerged dendritic drainage system), and the restricted fetch environment. Since the region is a geographic entity, this study is designed to define the regionally unifying trends in the shoreline. This conceptual process-response model is meant to serve as a study of moderate energy beach processes, as a tool for regional shoreline planning and enhancement, and as an investigation of shoreline processes.

A study of beach processes is best designed as a time series sampling, so process-variations can be compared over time (i.e. Fox and Davis, 1971). This model results from cross-sectional sampling, so variations in process over time are not addressed while process and response variations over space can be defined.

Krumbein (1960) stated, "Most geological processes are very complex and involve (1) interaction of a large number of variables, and (2) simultaneous variation of all or most variables." The problems of applying statistics to geology "...revolve in part around at least three considerations: severe sampling restrictions in some geological studies, the multiplicity of variables in even the seemingly simplest geologic situation, and the high 'noise level' of some geologic data."

Krumbein and Sloss (1963, p. 501) suggested that in the search for "...generalizing principles it is a useful philosophical device to recognize models--actual or conceptual frameworks to which observations are referred as an aid in identification and a basis for prediction".

Whitten (1964) suggested an "initial hypothesis can be structured into a conceptual model process-response model. For example, the broad outlines of the interrelationships of process-factors (wind, waves, etc.) and the observed nature of a beach may be embraced in a single conceptual model." In this study, the empirical and statistical evidences are used to justify the nature of the conceptual model, but the noise level and geophysical complexity in the system prevents expressing the system purely statistically.

Krumbein (1960) stated, "Geological factors operate at more than one level temporally and geographically, so that many small-scale fluctuations are superimposed on broader large-scale effects, giving rise to a high degree of variability in some geological measurements." This study addresses the large scale effects, in both the dimensions of area and time. The noise level in this particularly diverse region makes a more rigorous statistical treatment of the data unrealistic. Statistical reasoning, whether formal or informal, is implicit in some aspects of virtually all geological studies.

The large variability in the Virginia Chesapeake Bay system presents some difficulty in relating process-variables over area. However, this same high variability presents an opportunity to define the rôle of such regional trends as tide range, subsidence rates, and nearshore terrace widths on shoreline morphology. Each has a large variation over a relatively small area in this system.

The effects of variations in wave energy along the Virginia Chesapeake Bay shoreline was investigated by adapting the Virginia Sea Wave Climate Model (Goldsmith, et al, 1974) for use in a restricted fetch area. The Chesapeake Bay Wave Refraction Model was used to predict wave patterns in a growing sea. The input wave rays in the model were designed to follow the upwind shore, and uniformly cover the entire study area, so any regional trends are evident. Histograms of predicted wave height, energy, period, and orthogonal density along the shoreline show graphically the effect of waves on the shoreline. Statistical comparison of wave-related variables with shore erosion under various data stratifications are used to attempt to measure the intensity of this relationship.

## COASTAL MORPHOLOGY OF THE VIRGINIA CHESAPEAKE BAY

The morphology of the shoreline of the Virginia Chesapeake Bay is dominated by a large variability in coastal environments. The major factors causing this rapid change in coastal types are:

(A) The relict Pleistocene high-order dendritic drainage system (Hack, 1957), which results in a large diversity of shoreline orientations.

(B) The moderate, but variable, energy in the Chesapeake Bay system and the small-scale variations in submergence rates results in a spectrum of shoreline transformation from primary to secondary types (Shepard, 1973).

(C) The erosional nature (Fig. 3) of most of the shoreline exposes fastland sediments (coastal plain) of highly variable composition which effects different coastal forms.

(D) The abundance of biologic activity (salt marsh) causes variations in coastal forms.

### BEACH ENVIRONMENTS

Table 1 summarizes the shoreline characteristics of all beach environments in the study area.

Eighty percent of the shoreline of the Virginia Chesapeake Bay is beaches. Figure 4 depicts the types,

Figure 3: Longterm erosion rates (1860-1940), Virginia Chesapeake Bay. The shoreline of the margins of Bay have been straightened to interpret the regional trends.

# VIRGINIA CHESAPEAKE BAY
# SHORELINE EROSION-ALL REACHES

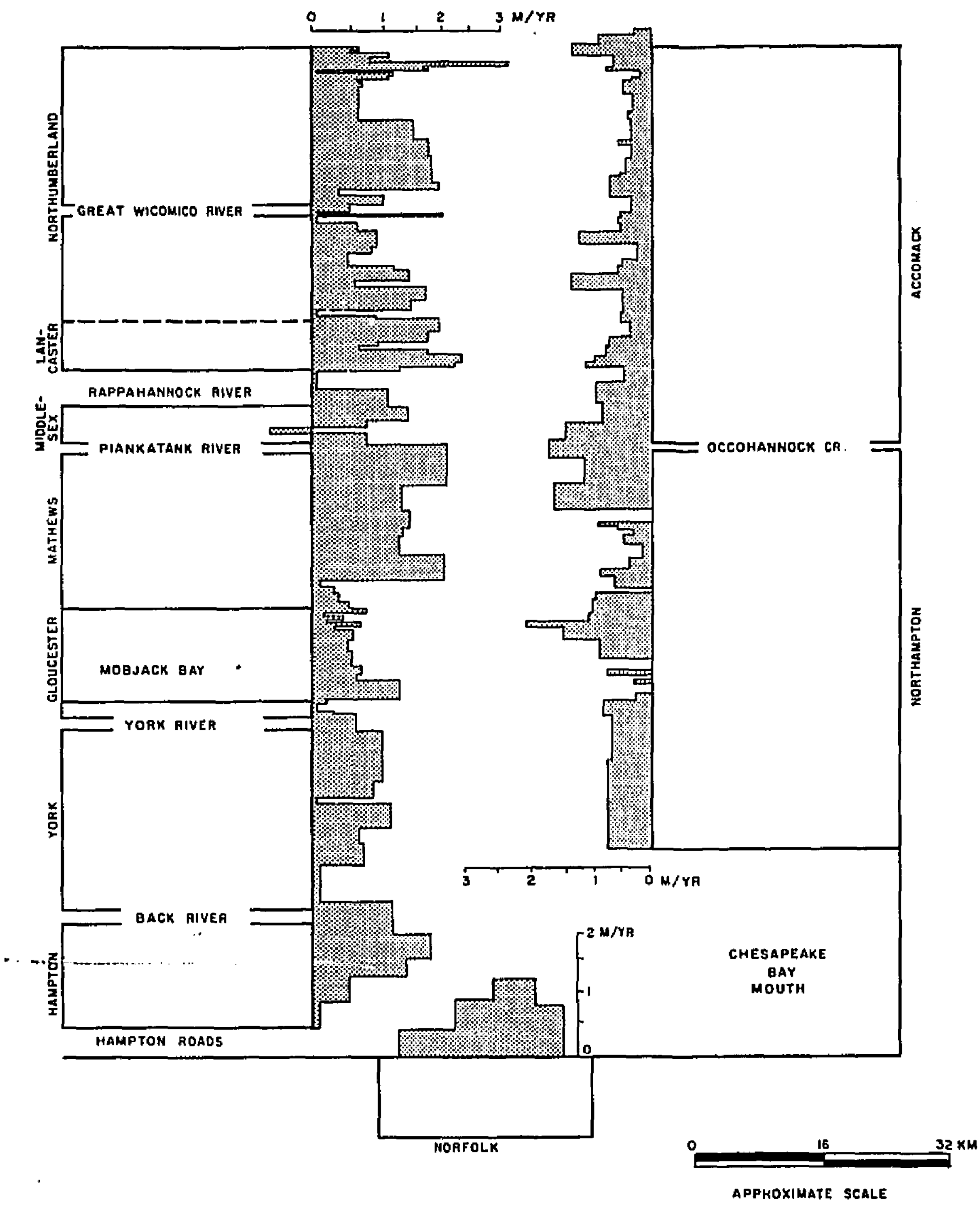


TABLE 1
SHORELINE MORPHOLOGY
VIRGINIA CHESAPEAKE BAY
ALL SHORE ENVIRONMENTS

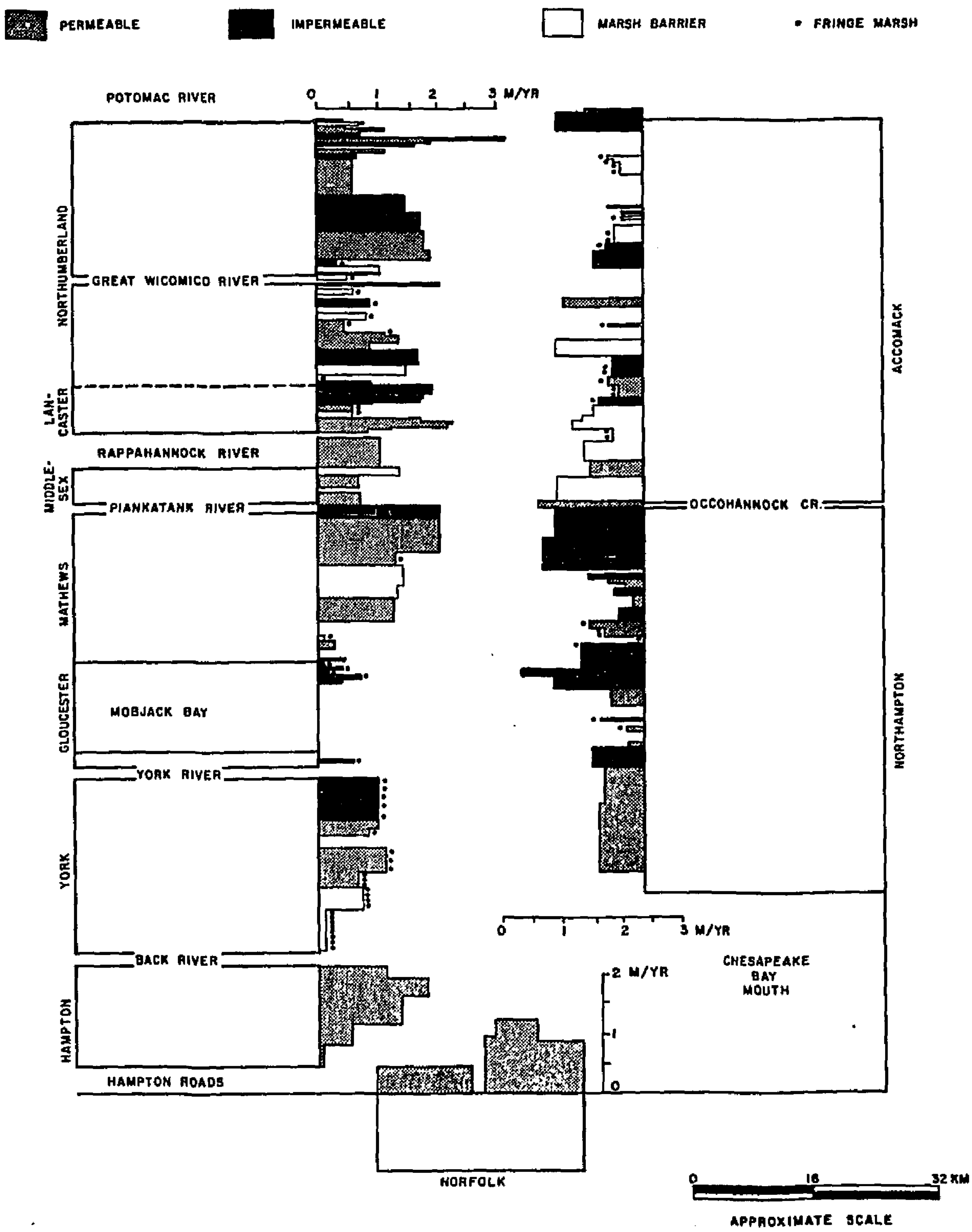
| | VIRGINIA CHESAPEAKE BAY | NORTHAMPTON COUNTY | ACCOMACK COUNTY | NORTHUMBERLAND COUNTY | LANCASTER COUNTY | MIDDLESEX COUNTY |
|---|---|---|---|---|---|---|
| SHORELINE LENGTH (km) | 336 | 57 | 79 | 56 | 19 | 10 |
| NUMBER OF REACHES | 209 | 41 | 50 | 45 | 13 | 6 |
| MEAN NEARSHORE TERRACE WIDTH (m) | 1777 | 1362 | 4019 | 1130 | 880 | 890 |
| STANDARD DEVIATION | 1073 | 623 | 1992 | 748 | 430 | 524 |
| MEAN BLUFF HEIGHT (m) | 1.2 | 2.7 | 0.5 | 1.6 | 0.4 | 1.4 |
| STANDARD DEVIATION | 2.3 | 3.5 | 0.9 | 2.3 | 0.5 | 1.8 |
| MEAN BEACH WIDTH (m) | 11.9 | 14.5 | 9.7 | 9.6 | 8.8 | 13.0 |
| STANDARD DEVIATION | 6.2 | 5.6 | 3.4 | 2.9 | 4.9 | 4.5 |
| MEAN BEACH ELEVATION (m) | 1.2 | 1.5 | 1.0 | 1.0 | 0.9 | 1.2 |
| STANDARD DEVIATION | 0.4 | 0.5 | 0.2 | 0.2 | 0.5 | 0.3 |
| MEAN BEACH SLOPE | 0.125 | 0.121 | 0.126 | 0.127 | 0.131 | 0.130 |
| STANDARD DEVIATION | 0.023 | 0.025 | 0.028 | 0.017 | 0.036 | 0.009 |
| MEAN EROSION (m/yr) | 0.85 | 0.82 | 0.73 | 1.0 | 1.31 | 0.74 |
| STANDARD DEVIATION | 1.25 | 2.12 | 0.74 | 0.85 | 1.03 | 0.82 |
| FRINGE MARSH (km) | 129 | 7 | 49 | 13 | 3 | 0 |
| BACKSHORE CHARACTERISTICS: | | | | | | |
| DUNE (km) | 123 | 13 | 33 | 23 | 7 | 3 |
| BLUFF (km) | 63 | 7 | 7 | 19 | 6 | 0 |
| OTHER (km) | 16 | 1 | 0 | 2 | 0 | 2 |

TABLE 1 (cont'd)
SHORELINE MORPHOLOGY
VIRGINIA CHESAPEAKE BAY
ALL SHORE ENVIRONMENTS

| | MATHEWS COUNTY | GLOUCESTER COUNTY | YORK COUNTY | HAMPTON | NORFOLK/ VIRGINIA BEACH | EASTERN SHORE | WESTERN SHORE |
|---|---|---|---|---|---|---|---|
| SHORELINE LENGTH (km) | 32 | 17 | 26 | 14 | 25 | 136 | 199 |
| NUMBER OF REACHES | 18 | 13 | 12 | 6 | 5 | 91 | 118 |
| MEAN NEARSHORE TERRACE WIDTH (m) | 978 | 978 | 1923 | 430 | 369 | 2898 | 1016 |
| STANDARD DEVIATION | 414 | 548 | 547 | 570 | 606 | 1351 | 862 |
| MEAN BLUFF HEIGHT (m) | 0.6 | - | 0.2 | 1.1 | 1.9 | 1.4 | 1.0 |
| STANDARD | 0.8 | - | 0.7 | 1.4 | 3.1 | 2.6 | 2.0 |
| MEAN BEACH WIDTH (m) | 11.3 | - | 9.0 | 28.5 | 29.3 | 12.2 | 11.6 |
| STANDARD DEVIATION | 3.6 | - | 3.6 | 19.0 | 2.8 | 5.2 | 6.9 |
| MEAN BEACH ELEVATION (m) | 1.1 | - | 0.9 | 1.6 | 2.2 | 1.3 | 1.1 |
| STANDARD DEVIATION | 0.3 | - | 0.2 | 0.9 | 0.3 | 0.5 | 0.4 |
| MEAN BEACH SLOPE | 0.128 | - | 0.116 | 0.126 | 0.133 | 0.124 | 0.127 |
| STANDARD DEVIATION | 0.022 | - | 0.011 | 0 | 0.009 | 0.026 | 0.020 |
| MEAN EROSION (m/yr) | 1.13 | 0.48 | 0.60 | 0.96 | 0.76 | 0.78 | 0.91 |
| STANDARD DEVIATION | 1.23 | 0.36 | 0.60 | 1.51 | 0.79 | 1.51 | 0.99 |
| FRINGE MARSH (km) | 15 | 16 | 26 | 0 | 0 | 56 | 73 |
| BACKSHORE CHARACTERISTICS: | | | | | | | |
| DUNE (km) | 18 | 0 | 11 | 1 | 13 | 47 | 77 |
| BLUFF (km) | 2 | 0 | 4 | 0 | 0 | 31 | 33 |
| OTHER (km) | 0 | 0 | 0 | 3 | 5 | 1 | 15 |

Figure 4: Distribution of beach environments and longterm erosion rates in the Virginia Chesapeake Bay.

# VIRGINIA CHESAPEAKE BAY
# BEACH EROSION



distribution and erosion rates of beach environments. There are three morphologically distinct beach environments; permeable, beach composed entirely of sand-sized material; impermeable, beach underlain by impermeable clay layer; and marsh barrier, beach underlain by salt marsh peat. The response of each to erosional processes results in differing susceptibilities to shoreline erosion.

A Bartletts' chi-square test of the erosion data showed a ($\log_{10}(x + 1)$) transformation of the data fulfilled the assumptions that the data was homogeneous and normally distributed. An analysis of variance indicated there are significant ($p < .01$) treatment effects; that is, there are significant differences among means of erosion rate for three beach environments:

ANALYSIS OF VARIANCE

| Treatment | Sum of Squares | Degrees of Freedom | Mean Square | F |
|---|---|---|---|---|
| Among groups | 0.1747 | 2 | 0.873 | 4.8075** |
| Within groups | 3.6536 | 201 | 0.0181 | |
| Total | 3.8284 | 203 | | |

** Significant at .01 level

A Student-Newman-Keuls Test was used to make an *a posteriori* multiple comparison among the three means. It was determined that all three means are significantly different ($p < .05$) from each other (Sokal and Rohlf, 1969).

Permeable Beaches

Permeable beaches are defined as beaches composed totally of sand-sized material in cross-section (Fig. 5). This is the most prevalent coastal environment in the Bay system. Permeable beaches comprise 59% of the beaches in the area, and 47% of the total shoreline. A permeable beach results from either (A) an accretional beach adjoining any fastland; (B) an accretional feature such as a spit; or (C) an erosional beach where the fastland is sandy. Twenty-five percent of the permeable beaches in the system are the result of erosion into a sandy, pre-Holocene fastland. Seventy-five percent of the permeable beaches are some sort of accretional coastal landform (although presently may be eroding).

Table 2 summarized the regional morphology and distribution of permeable beaches in the Virginia Chesapeake Bay. The mean erosion of these beaches is 0.85 m/yr. The large standard deviation ($\sigma = 1.52$) around this mean is typical of the variability of environments in the system. The erosion rate of this environment is about the mean rate for the whole system (0.86 m/yr). Seventy-three percent of the permeable beaches have some form of dune development in the back beach.

Permeable beaches have the largest beach dimensions (vertical and horizontal) of any environment in the system. The mean beach width is 14 meters. The broadest beaches are in the Hampton/Norfolk physiographic

Figure 5: Photograph showing a permeable beach (Plumtree Island, York County).

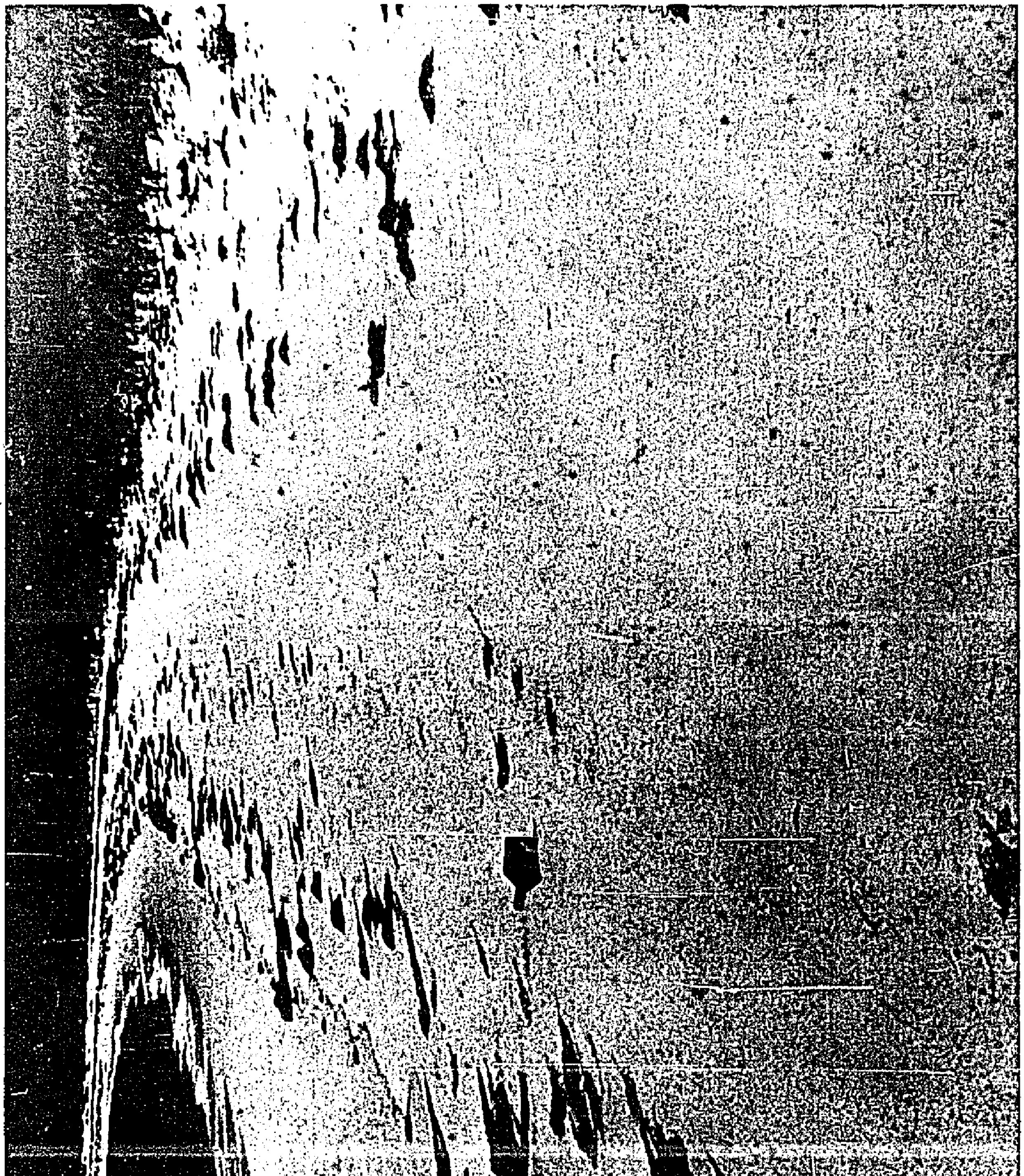


TABLE 2
SHORELINE MORPHOLOGY
VIRGINIA CHESAPEAKE BAY
PERMEABLE BEACH ENVIRONMENT

| | VIRGINIA CHESAPEAKE BAY | NORTHAMPTON COUNTY | ACCOMACK COUNTY | NORTHUMBERLAND COUNTY | LANCASTER COUNTY | MIDDLESEX COUNTY |
|---|---|---|---|---|---|---|
| SHORELINE LENGTH (km) | 160 | 40 | 11 | 24 | 12 | 9 |
| NUMBER OF REACHES | 102 | 28 | 13 | 22 | 8 | 5 |
| MEAN NEARSHORE TERRACE WIDTH (m) | 1029 | 1427 | 2524 | 965 | 837 | 806 |
| STANDARD DEVIATION | 787 | 874 | 897 | 606 | 537 | 546 |
| MEAN BLUFF HEIGHT (m) | 1.5 | 2.5 | 0.9 | 1.4 | 0.4 | 1.5 |
| STANDARD DEVIATION | 2.7 | 3.9 | 0.5 | 2.1 | 0.5 | 1.9 |
| MEAN BEACH WIDTH (m) | 14.0 | 15.3 | 8.7 | 10.4 | 11.5 | 13.0 |
| STANDARD DEVIATION | 7.2 | 5.5 | 2.2 | 3.5 | 3.5 | 4.5 |
| MEAN BEACH ELEVATION (m) | 1.3 | 1.7 | 1.2 | 1.1 | 1.2 | 1.3 |
| STANDARD DEVIATION | 0.5 | 0.5 | 2.1 | 0.3 | 0.4 | 0.3 |
| MEAN BEACH SLOPE | 0.136 | 0.127 | 0.151 | 0.137 | 0.150 | 0.130 |
| STANDARD DEVIATION | 0.020 | 0.023 | 0.023 | 0.014 | 0.025 | 0.009 |
| MEAN EROSION (m/yr) | 0.85 | 0.61 | 0.90 | 0.89 | 1.29 | 0.61 |
| STANDARD DEVIATION | 1.51 | 2.40 | 0.41 | 0.62 | 1.32 | 0.84 |
| EXTENSIVE FRINGE MARSH (km) | 16 | 5 | 2 | 0 | 0 | 0 |
| INTERMITTANT FRINGE MARSH (km) | 8 | 1 | 1 | 2 | 1 | 0 |

TABLE 2 (cont'd)
SHORELINE MORPHOLOGY
VIRGINIA CHESAPEAKE BAY
PERMEABLE BEACH ENVIRONMENT (cont'd)

| | MATHEWS COUNTY | GLOUCESTER COUNTY | YORK COUNTY | HAMPTON | NORFOLK/ VIRGINIA BEACH | EASTERN SHORE | WESTERN SHORE |
|---|---|---|---|---|---|---|---|
| SHORELINE LENGTH (km) | 15 | 0.5 | 10 | 14 | 25 | 51 | 109 |
| NUMBER OF REACHES | 6 | 1 | 8 | 6 | 5 | 41 | 61 |
| MEAN NEARSHORE TERRACE WIDTH (m) | 975 | 1066 | 976 | 430 | 368 | 1661 | 736 |
| STANDARD DEVIATION | 968 | 0 | 784 | 570 | 606 | 879 | 674 |
| MEAN BLUFF HEIGHT (m) | 0.9 | - | 0 | 3.7 | 6.1 | 7.2 | 3.8 |
| STANDARD DEVIATION | 1.0 | - | 0 | 4.5 | 10.2 | 10.9 | 7.3 |
| MEAN BEACH WIDTH (m) | 13.0 | - | 10.5 | 28.5 | 29.3 | 13.6 | 14.1 |
| STANDARD DEVIATION | 2.4 | - | 6.3 | 19.0 | 2.9 | 5.6 | 7.9 |
| MEAN BEACH ELEVATION (m) | 1.3 | - | 0.9 | 1.6 | 2.2 | 1.6 | 1.3 |
| STANDARD DEVIATION | 0.3 | - | 0.3 | 0.9 | 0.3 | 0.5 | 0.5 |
| MEAN BEACH SLOPE | 0.139 | - | 0.119 | 0.126 | 0.133 | 0.133 | 0.137 |
| STANDARD DEVIATION | 0.017 | - | 0.019 | 0 | 0.009 | 0.025 | 0.017 |
| MEAN EROSION (m/yr) | 1.23 | 0.61 | 0.73 | 0.96 | 0.76 | 0.68 | 0.92 |
| STANDARD DEVIATION | 1.35 | 0 | 0.46 | 1.51 | 0.79 | 1.98 | 1.07 |
| EXTENSIVE FRINGE MARSH (km) | 0 | 0 | 9 | 0 | 0 | 6 | 10 |
| INTERMITTANT FRINGE MARSH (km) | 2 | 0 | 1 | 0 | 0 | 2 | 6 |

subdivision (south end of the Bay) where the beaches have the dimensional characteristics of, and a source material from, ocean beaches. Their mean width is 29 meters, and elevation is 2.0 meters. On an average, beaches elsewhere in the Bay have smaller dimensions.

The mean elevation above mean low water of permeable beaches in the Bay is 1.3 meters ( $\sigma = 0.5$). These beaches generally provide the largest vertical buffer to changes in water elevation. Permeable beaches have the largest average supra-tidal elevations, (i.e. distance from mean high water to the maximum elevation of the backbeach) (Table 3). As well, the sand composition of these beaches results in the greatest potential for infiltration of the swash into the foreshore. This reduces the volume of backwash, which, in effect, inhibits erosion. Field reconnaissance and studies have shown accretion on these beaches result from ridge-and-runnel migration, as well as direct beach face sedimentation (Sallenger and Rosen, 1974).

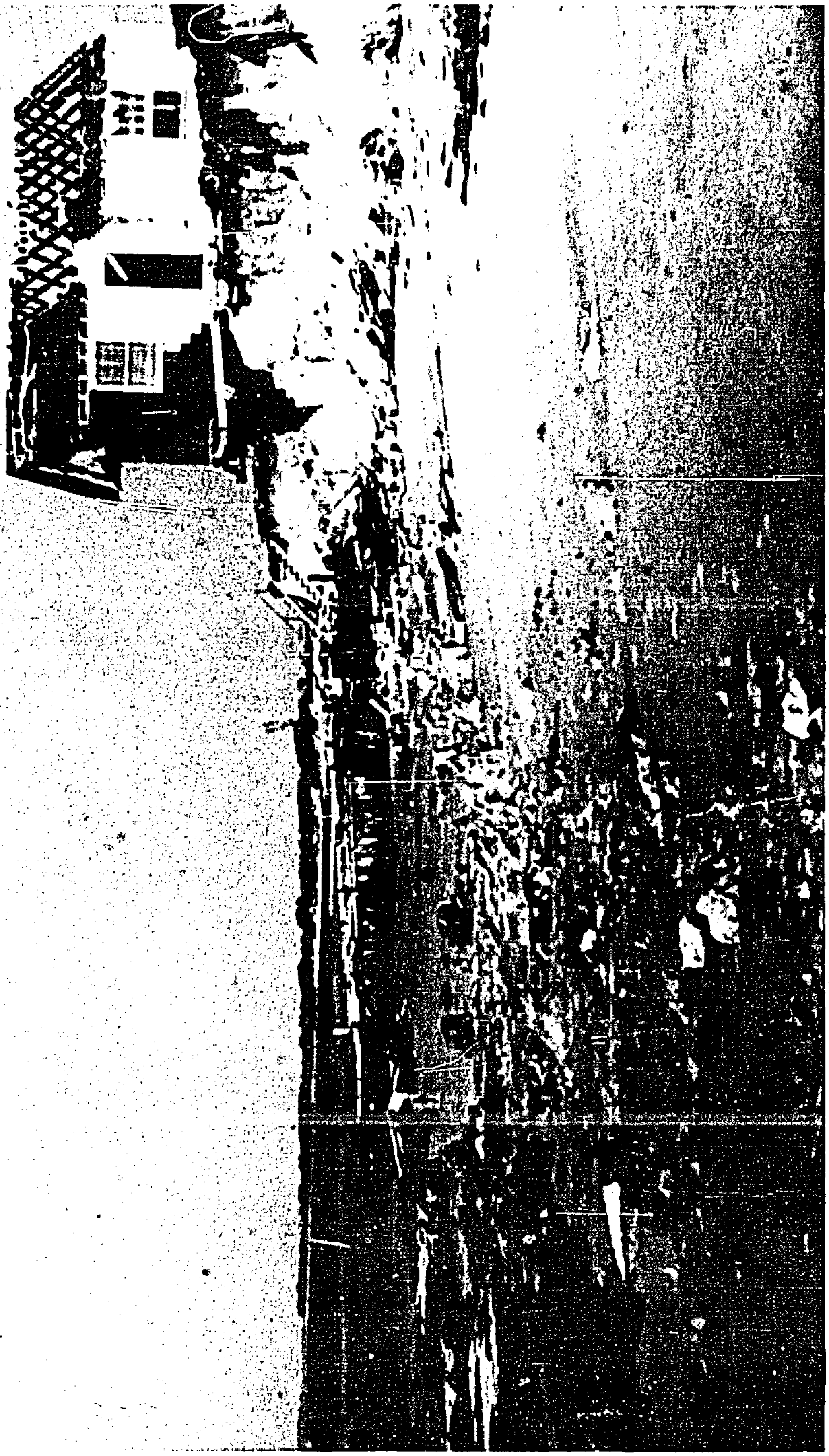
## Impermeable Beaches

Impermeable beaches are composed of a veneer of sand overlying impermeable, pre-Holocene sediments having a high clay content (Fig. 6). They are the result of erosion into clay-rich pre-Holocene sediments, and generally have an erosional bluff adjacent to the backbeach. The regional morphology of impermeable

TABLE 3
MEAN SUPRA-TIDAL BEACH ELEVATIONS
VIRGINIA CHESAPEAKE BAY

| | ALL BEACHES | IMPERMEABLE BEACHES | PERMEABLE BEACHES | MARSH BARRIER BEACHES |
|---|---|---|---|---|
| MEAN SUPRA-TIDAL ELEVATION (meters) | 0.64 | 0.44 | 0.82 | 0.51 |
| STANDARD DEVIATION | 0.41 | 0.34 | 0.42 | 0.19 |
| MEAN TIDE RANGE (meters) | 0.52 | 0.51 | 0.54 | 0.49 |

Figure 6: Photograph showing an impermeable beach (near Eastville, Northampton County).



beaches is summarized in Table 4. Impermeable beaches comprise 30% of the Virginia Chesapeake Bay shoreline, and 24% of the beaches.

The thickness of the veneer of sediment overlying the impermeable layer ranged, in this sampling, from 1 to 30 cm. No apparent relationship between this thickness and the longterm erosional history of the area, or with the composition of the underlying sediment was revealed by stepwise multiple linear regression analysis with regionally stratified samples.

The contact between clay and sand in all cases was sharp contact (Fig. 7). No impermeable beaches were observed having exposed clay without a lag of sand at least partially covering it. Clay is most typically exposed at the low water line.

Despite short-term variations in weather, during reconnaissance, 64% of the impermeable beaches sampled had perched water tables. The impermeable layer served to elevate the beach water table, so when trenched the water drained from the overlying sand. This perched water serves to make these beaches more susceptible to wave erosion. Grant (1948) and Emery and Foster (1948) showed that high beach water tables promotes erosion of the beach face. Isaacs and Bascom (1949) measured water tables on ten Pacific beaches and recognized the damping of the tidal wave as it passes through the sand body. Duncan (1964), Strahler (1966) and Geise (1966) showed that zones of

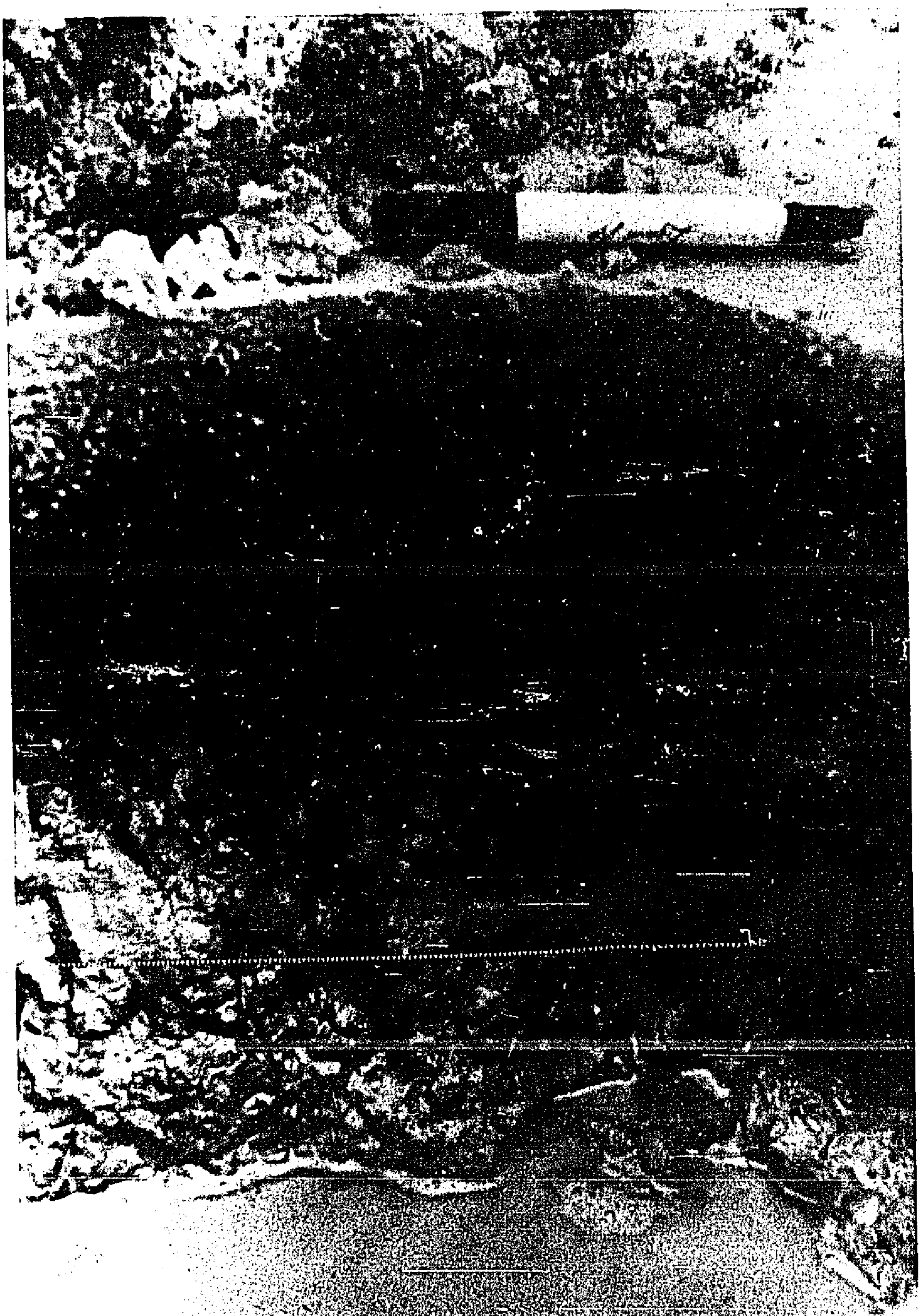
TABLE 4
SHORELINE MORPHOLOGY
VIRGINIA CHESAPEAKE BAY
IMPERMEABLE BEACH ENVIRONMENT

| | VIRGINIA CHESAPEAKE BAY | NORTHAMPTON COUNTY | ACCOMACK COUNTY | NORTHUMBERLAND COUNTY | LANCASTER COUNTY | MIDDLESEX COUNTY |
|---|---|---|---|---|---|---|
| SHORELINE LENGTH (km) | 77 | 18 | 16 | 21 | 5 | 0 |
| NUMBER OF REACHES | 48 | 13 | 9 | 13 | 4 | 0 |
| MEAN NEARSHORE TERRACE WIDTH (m) | 1659 | 1215 | 3895 | 1068 | 980 | - |
| STANDARD DEVIATION | 1157 | 797 | 1293 | 653 | 223 | - |
| MEAN BLUFF HEIGHT (m) | 1.7 | 3.1 | 0.8 | 2.5 | 0.6 | - |
| STANDARD DEVIATION | 2.2 | 2.4 | 0.8 | 2.9 | 0 | - |
| MEAN BEACH WIDTH (m) | 9.9 | 13.5 | 9.4 | 8.6 | 3.3 | - |
| STANDARD DEVIATION | 4.8 | 5.8 | 2.9 | 2.6 | 0.5 | - |
| MEAN BEACH ELEVATION (m) | 0.9 | 1.28 | 0.9 | 0.9 | 0.3 | - |
| STANDARD DEVIATION | 0.3 | 0.4 | 0.3 | 0.2 | 0.1 | - |
| MEAN BEACH SLOPE | 0.113 | 0.112 | 0.112 | 0.119 | 0.092 | - |
| STANDARD DEVIATION | 0.022 | 0.026 | 0.027 | 0.018 | 0.011 | - |
| MEAN EROSION (m/yr) | 1.13 | 1.30 | 0.83 | 1.28 | 1.64 | - |
| STANDARD DEVIATION | 1.09 | 1.36 | 0.85 | 1.22 | 0.41 | - |
| EXTENSIVE FRINGE MARSH (km) | 7.2 | 0 | 2.4 | 0 | 0 | 0 |
| INTERMITTANT FRINGE MARSH (km) | 15.1 | 1.3 | 3.8 | 1.4 | 0 | 0 |

TABLE 4 (cont'd)
SHORELINE MORPHOLOGY
VIRGINIA CHESAPEAKE BAY
IMPERMEABLE BEACH ENVIRONMENT

| | MATHEWS COUNTY | GLOUCESTER COUNTY | YORK COUNTY | HAMPTON | NORFOLK/ VIRGINIA BEACH | EASTERN SHORE | WESTERN SHORE |
|---|---|---|---|---|---|---|---|
| SHORELINE LENGTH (km) | 8 | 4 | 4 | 0 | 0 | 34 | 42 |
| NUMBER OF REACHES | 5 | 2 | 2 | 0 | 0 | 22 | 26 |
| MEAN NEARSHORE TERRACE WIDTH (m) | 888 | 1021 | 548 | - | - | 2511 | 967 |
| STANDARD DEVIATION | 370 | 35 | 0 | - | - | 1093 | 509 |
| MEAN BLUFF HEIGHT (m) | 0.5 | - | 0.9 | - | - | 2.0 | 1.5 |
| STANDARD DEVIATION | 0.7 | - | 1.8 | - | - | 2.0 | 2.4 |
| MEAN BEACH WIDTH (m) | 12.0 | - | 7.5 | - | - | 11.9 | 7.8 |
| STANDARD DEVIATION | 0 | - | 2.1 | - | - | 5.2 | 6.0 |
| MEAN BEACH ELEVATION (m) | 0.9 | - | 0.8 | - | - | 1.1 | 0.8 |
| STANDARD DEVIATION | 0 | - | 0.1 | - | - | 0.4 | 0.2 |
| MEAN BEACH SLOPE | 0.116 | - | 0.111 | - | - | 0.112 | 0.114 |
| STANDARD DEVIATION | 0 | - | 0 | - | - | 0.025 | 0.018 |
| MEAN EROSION (m/yr) | 1.01 | 0.57 | 1.07 | - | - | 1.07 | 1.19 |
| STANDARD DEVIATION | 1.40 | 0.19 | 0.57 | - | - | 1.16 | 1.05 |
| EXTENSIVE FRINGE MARSH (km) | 0 | 1.4 | 0 | 0 | 0 | 2.4 | 4.9 |
| INTERMITTANT FRINGE MARSH (km) | 0 | 0.4 | 4.2 | 0 | 0 | 5.3 | 9.8 |

Figure 7: Photograph showing trench in an impermeable beach. The thin veneer of sand overlays the impermeable Preholocene sediments. The beach groundwater table is often perched above this aquaclude.



erosion and deposition migrate up and down the foreshore in response to the relative positions of the water table. Harrison, et al. (1971) investigated the variations of the water table in a tidal beach and found a three hour lag-time in the passage of the tidal wave through the beach.

Bagnold demonstrated in model studies (1940) that an impermeable layer underlying a beach serves to decrease infiltration of the swash into the beach, hence increasing the force of the backwash, which augments erosion. This effect is demonstrated in the beachface sediment distribution. Regionally, impermeable beaches have a finer grain size ($\bar{x}$ = 1.64 Ø ) than permeable beaches ($\bar{x}$ = 1.32 Ø ). Presumably, the increased backwash in impermeable beaches winnows part of the fine sediments. Palmer (1974) discussed the tendency for impermeable bluffs in the Chesapeake Bay to readily spall as a result of ground water flow. This results in a relatively increased shore retreat.

The dimensions of impermeable beaches are the smallest of all beach environments in the system. This is another factor resulting in the increased erodability of this environment due to increased susceptibility to storm surge. The mean width and elevation of beaches on the eastern shore are greater than the western shore. An influencing factor in this is the larger bluff heights on the eastern shore ($\bar{x}$ = 2.2 m) as compared to the western shore ($\bar{x}$ = 1.3 m) as well as the sand composition of the highest bluffs (Northampton County) on the eastern shore is 11.9 meters, and is 7.8 meters on the western shore.

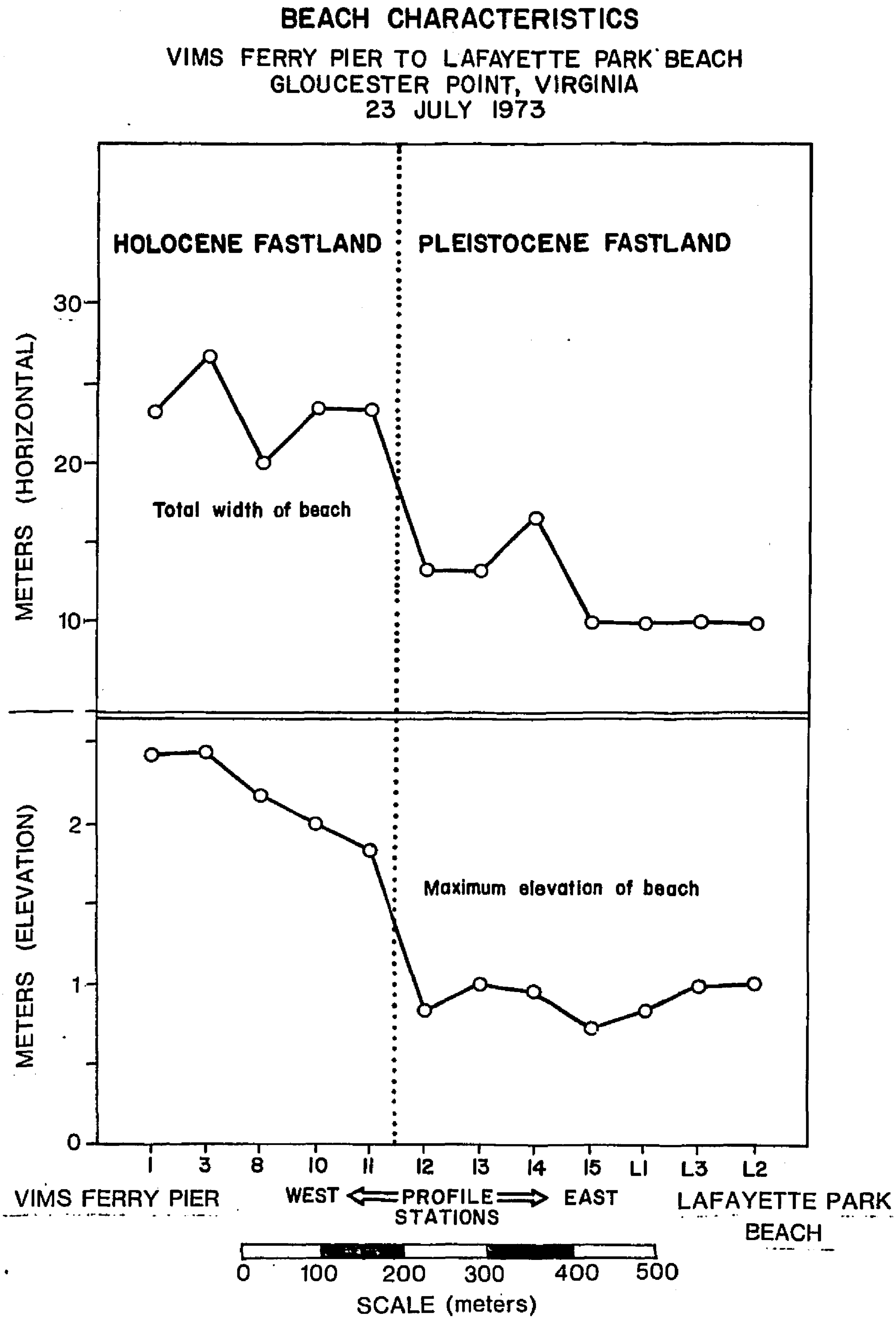
A major variable influencing a shoreline's erodability in the Bay is beach elevation, as observations show storm surge is a major factor in the erosion resulting from storms (Warnke et al., 1966). The mean elevation on the eastern shore for impermeable beaches is 1.1 meters ( $\sigma = 0.4$) and on the western shore, 0.8 meters ($\sigma = 0.2$). These variations in elevation are statistically correlated to the higher average tidal range on the eastern shore as compared to the western shore. Impermeable beaches are low, and many are totally covered at high tide, with the high water level at the base of the bluff. Hence, fastlands fronted by impermeable beaches are most susceptible to erosion caused by increases in water level by storm surge and wave activity.

As well, the bulk of the landform is not composed of sand, which is the only accretional beach material in the system. When fine material is eroded from the shore (over 80% by weight), it is not recovered by the beach system.

If a longterm accretional trend occurs on an impermeable beach, the beach will become a permeable environment. Thus, the environment is by definition an indicator on an erosional shoreline.

These changes in beach dimensions are demonstrated at Gloucester Point (Fig. 8). There, the contact

Figure 8: Variations in beach width and elevation, Gloucester Point, Virginia. Permeable beaches have formed adjacent to the Holocene fastland, and impermeable beaches adjacent to the Pleistocene fastland.


BEACH CHARACTERISTICS
VIMS FERRY PIER TO LAFAYETTE PARK BEACH
GLOUCESTER POINT, VIRGINIA
23 JULY 1973
HOLOCENE FASTLAND
PLEISTOCENE FASTLAND
METERS (HORIZONTAL)
30
20
10
Total width of beach
METERS (ELEVATION)
2
1
0
Maximum elevation of beach
1
3
8
10
11
12
13
14
15
L1
L3
L2
VIMS FERRY PIER
WEST ⟸ PROFILE STATIONS ⟹ EAST
LAFAYETTE PARK BEACH
0
100
200
300
400
500
SCALE (meters)

between the impermeable Norfolk Formation and permeable Holocene spit deposits intersects the present shoreline. The reach is essentially process-constant, except for the change from an impermeable to permeable environment. Both the width and elevation of the beach decreases in the impermeable environment. The slope of the impermeable beach is lower than the permeable beaches.

These factors result in the increased erodability of impermeable beaches. The regional means for this environment are significantly higher than all other environments in the system. The mean shoreline retreat rate for all impermeable beaches is 1.14 m/yr with a rate of 1.07 m/yr on the eastern shore, and 1.18 m/yr on the western shore.

### Marsh Barrier

Marsh barrier beaches are composed of a veneer of sand overlying salt marsh peat (Fig. 9). They result from the erosion and overwash of a marsh margin. Longshore sand input may increase the amount of sand on the beach. Figure 10 shows the distribution of marsh barrier beaches in the Virginia Chesapeake Bay. The main concentrations of this environment are in the northeast and southwest ends of the Bay, which corresponds with the higher subsidence rates on either side of the Bay (Morrison and Holdahl, 1974; see Fig. 31). These higher subsidence rates result in greater marsh development. All marsh barriers sampled have some forms of dune

Figure 9: Photograph showing a marsh barrier beach. Note exposed peat outcropping at base of foreshore (Simpson Bend, Accomac County).

vegetation in the backshore.

A set of 10 randomly selected peat samples from throughout the study area were analyzed for composition by the procedure described by McCormick (1968). This reconnaissance sampling showed the peat to be composed of about 50% sand, 40% silt and clay, and 10% organic material by weight. This material is less permeable than sand, but more permeable than the clay in impermeable beaches, as no perched water tables were observed. Permeability does not appear to be a controlling factor influencing the erodability of these beaches.

During the sampling, 65% of the beaches had peat exposed on the foreshore, with an eroding peat scarp about 30-50 cm in height. Peat is a highly resistant material, due to the extensive rhizome systems serving as a framework for the cohesive fine sediments. The integrity of the peat results in marsh barriers being the least erodable beach environment in the study area.

The regional beach characteristics for marsh barriers are summarized in Table 5. The mean width of marsh barrier beaches is 9.7 meters, and the mean elevation is 1.0 meters with little regional variation. These dimensions are similar to impermeable beaches.

There is little variation in these dimensions between the eastern and western shores of the Bay. This is probably due to the fact that the beach form is controlled by the physical characteristics of the salt marsh peat

TABLE 5
SHORELINE MORPHOLOGY
VIRGINIA CHESAPEAKE BAY
MARSH BARRIER BEACH ENVIRONMENT

| | VIRGINIA CHESAPEAKE BAY | NORTHAMPTON COUNTY | ACCOMACK COUNTY | NORTHUMBERLAND COUNTY | LANCASTER COUNTY | MIDDLESEX COUNTY |
|---|---|---|---|---|---|---|
| SHORELINE LENGTH (km) | 100 | 0 | 51 | 11 | 0 | 0 |
| NUMBER OF REACHES | 59 | 0 | 28 | 10 | 0 | 0 |
| MEAN NEARSHORE TERRACE WIDTH (m) | 3061 | - | 4373 | 1586 | - | - |
| STANDARD DEVIATION | 1320 | - | 1560 | 527 | - | - |
| MEAN BLUFF HEIGHT (m) | 0.2 | - | 0.3 | 0.1 | - | - |
| STANDARD DEVIATION | 0.8 | - | 1.0 | 0.1 | - | - |
| MEAN BEACH WIDTH (m) | 9.7 | - | 10.1 | 9.8 | - | - |
| STANDARD DEVIATION | 0.9 | - | 1.2 | 0.4 | - | - |
| MEAN BEACH ELEVATION (m) | 1.0 | - | 1.0 | 1.0 | - | - |
| STANDARD DEVIATION | 0.1 | - | 0.1 | 0 | - | - |
| MEAN BEACH SLOPE | 0.120 | - | 0.125 | 0.118 | - | - |
| STANDARD DEVIATION | 0.020 | - | 0.024 | 0.013 | - | - |
| MEAN EROSION (m/yr) | 0.66 | - | 0.61 | 0.75 | - | - |
| STANDARD DEVIATION | 0.44 | - | 0.31 | 0.40 | - | - |
| FRINGE MARSH (km) | 82.0 | 0 | 37.9 | 9.6 | 0 | 0 |

TABLE 5 (cont'd)
SHORELINE MORPHOLOGY
VIRGINIA CHESAPEAKE BAY
MARSH BARRIER BEACH ENVIRONMENT (cont'd)

| | MATHEWS COUNTY | GLOUCESTER COUNTY | YORK COUNTY | HAMPTON | NORFOLK/ VIRGINIA BEACH | EASTERN SHORE | WESTERN SHORE |
|---|---|---|---|---|---|---|---|
| SHORELINE L LENGTH (km) | 10 | 0 | 11 | 0 | 0 | 51 | 48 |
| NUMBER OF REACHES | 7 | 0 | 2 | 0 | 0 | 28 | 31 |
| MEAN NEARSHORE TERRACE WIDTH (m) | 1051 | - | 3299 | - | - | 4373 | 1681 |
| STANDARD DEVIATION | 592 | - | 1124 | - | - | 1560 | 1052 |
| MEAN BLUFF HEIGHT (m) | 0.3 | - | 0 | - | - | 0.3 | 0.2 |
| STANDARD DEVIATION | 0.4 | - | 0 | - | - | 1.0 | 0.3 |
| MEAN BEACH WIDTH (m) | 5.9 | - | 8.8 | - | - | 10.1 | 8.8 |
| STANDARD DEVIATION | 0.1 | - | 0.0 | - | - | 1.2 | 0.6 |
| MEAN BEACH ELEVATION (m) | 0.9 | - | 1.0 | - | - | 1.0 | 1.0 |
| STANDARD DEVIATION | 0 | - | 0 | - | - | 0.1 | 0 |
| MEAN BEACH SLOPE | 0.101 | - | 0.120 | - | - | 0.125 | 0.115 |
| STANDARD DEVIATION | 0.007 | - | 0 | - | - | 0.024 | 0.013 |
| MEAN EROSION (m/yr) | 0.91 | - | 0.42 | - | - | 0.61 | 0.67 |
| STANDARD DEVIATION | 0.76 | - | 0.47 | - | - | 0.31 | 0.53 |
| FRINGE MARSH (km) | 7.1 | 0 | 11.4 | 0 | 0 | 39.5 | 42.3 |

rather than the coastal processes.

Marsh barriers are the least erodable beach environment in the Virginia Chesapeake Bay. The mean erosion rate is 0.66 m/yr with 0.67 m/yr on the eastern shore and 0.65 m/yr on the western shore. The marsh barriers between Gwynns Island and New Point Comfort (Mathews County) have an unusually high erosion rate of 1.38 m/yr, but all beach environments in this area have a similarly high erosion rate. This high rate is probably related to the narrow nearshore terrace width in this area (856 m) and direct exposure to the Bay (see Appendix D).

## MARSH ENVIRONMENTS

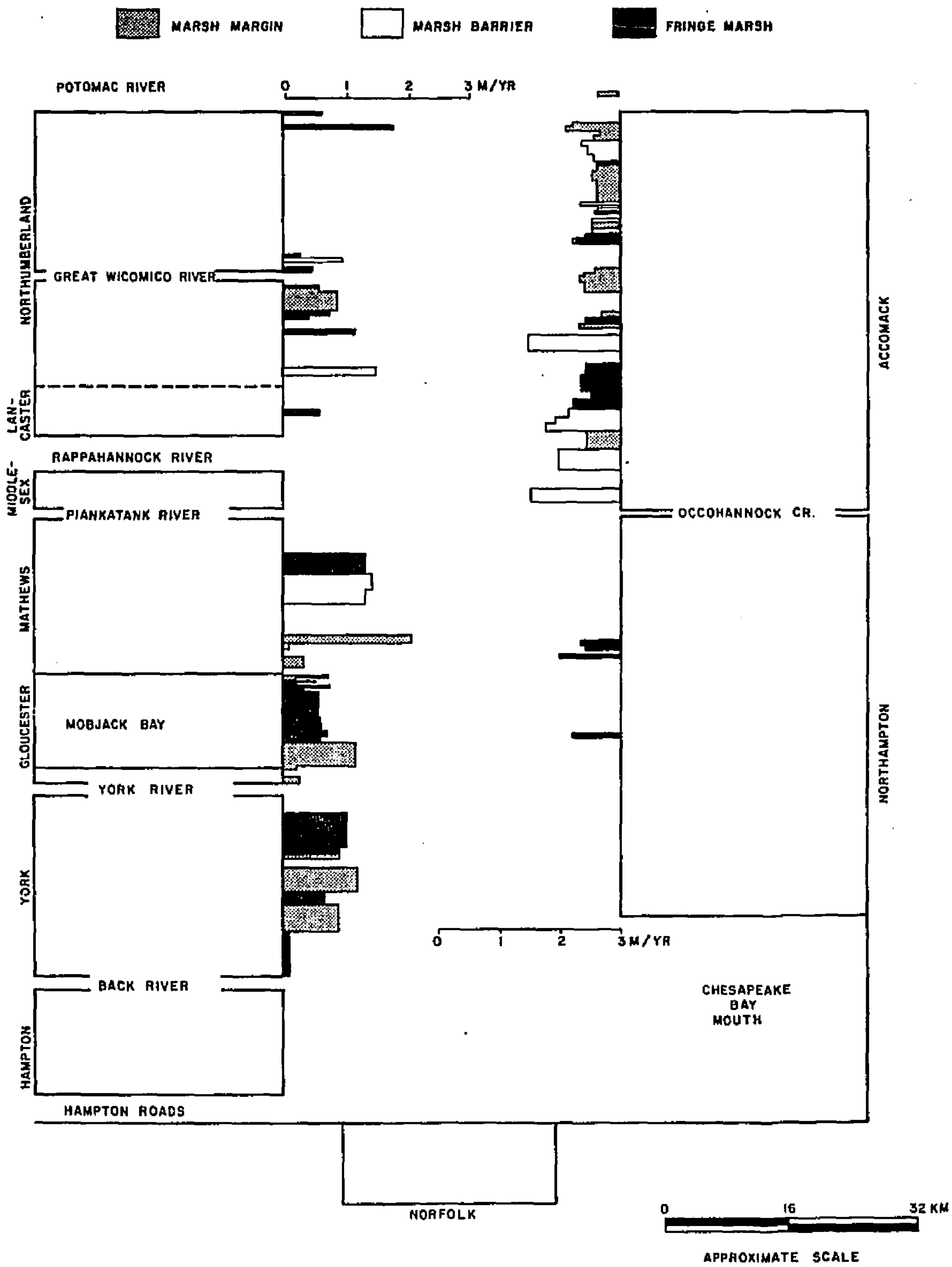
Marsh barrier beaches are also a form of marsh shoreline, and so they are included in Figure 10, which shows the distribution and erosion rates of marsh shorelines. The main concentration of marsh shorelines are in the northeast and southwest regions of the Virginia Chesapeake Bay. The presence of marsh concentrations correlates with the higher subsidence rates in the area, which provides broad, shallow terraces, as environment more conducive to marsh growth (Chapman, 1972).

### Marsh Margin Shorelines

Marsh margins compose 20% of the shoreline of the Bay, over half of which is in Accomack County. They are the least erodable coastal environment in the Virginia

Figure 10: Distribution of marsh environments and longterm erosion rates in the Virginia Chesapeake Bay.

# VIRGINIA CHESAPEAKE BAY
# EROSION IN MARSH ENVIRONMENT



Chesapeake Bay (Fig. 11). This is due, as in marsh barrier beaches to the extensive root systems serving as a framework for cohesive fine sediments. The distribution of extensive marsh development is not related to variations in tidal range. An eroding marsh margin could presumably become a marsh barrier, if sufficient sediment existed in the system. If the sand were derived from an authigenic source, a marsh barrier may be the resultant landform from a high marsh margin erosion rate. There is no direct evidence for this, however, as marsh barriers generally flank on the higher-energy exposures in extensive marsh systems. This also suggests that a higher wave energy is necessary to break down the peat and redistribute the sand on the eroding marsh margin.

Table 6 summarizes the distribution and erosional trends on marsh margin shorelines. The erosion rates are lower than in marsh barriers. This is partially due to the greater cohesiveness of living marsh exposed on the shoreline rather than exposed dead peat material. As well, marsh barriers often occur in areas of higher fetch.

The average marsh shoreline retreat for the study area is 0.54 m/yr. The eastern shore shows typically less erosion, with a mean retreat rate of 0.45 m/yr, as compared to 0.64 m/yr for the western shore. The anomalously high erosion rates in Mathews County (1.25 m/yr) is typical of the area. This discrepancy may in part be due to the relatively small nearshore terrace (856 m) as

Figure 11: Aerial oblique photograph showing marsh margin shoreline (Big Island, Guinea, Gloucester County, Virginia).

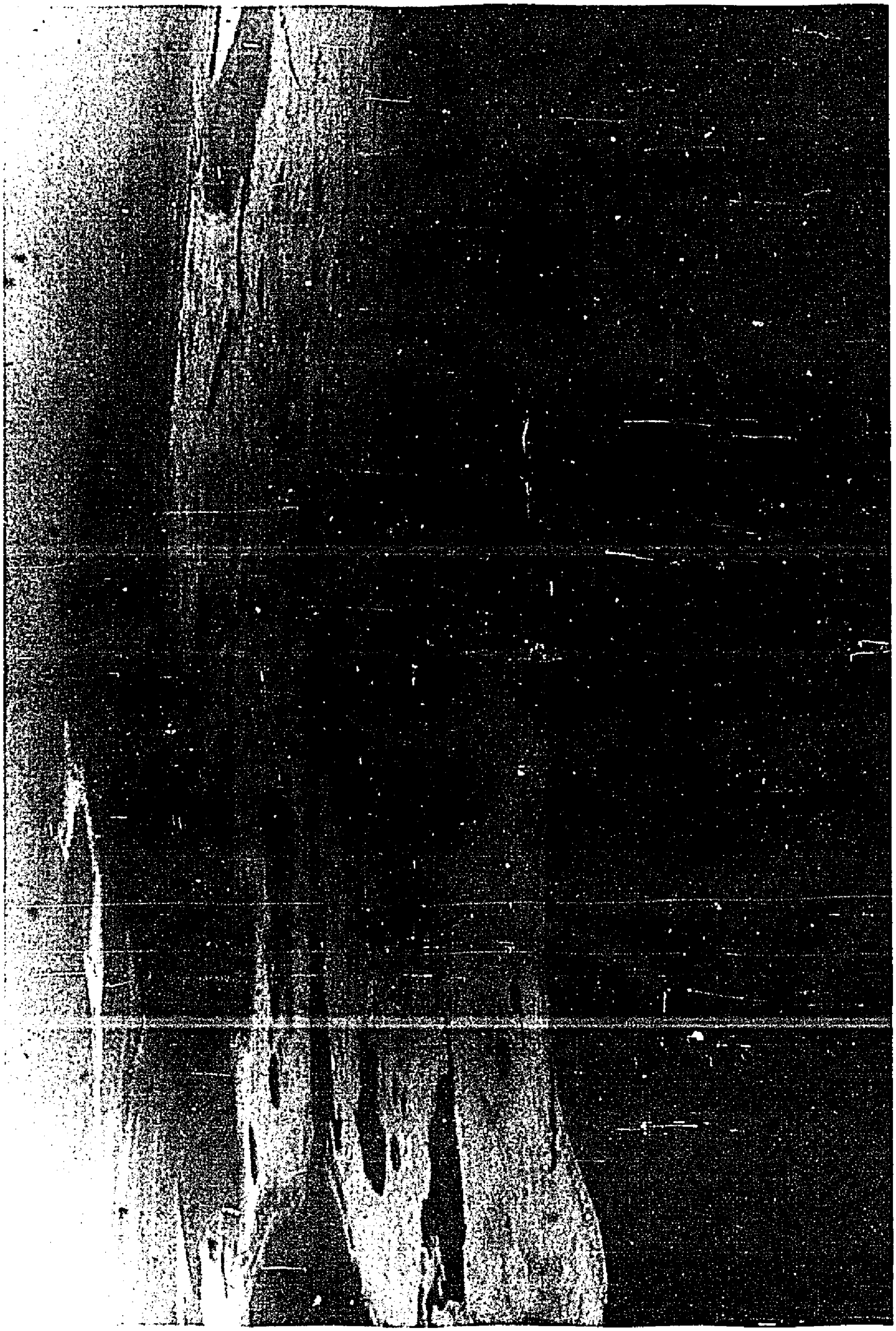


TABLE 6
SHORELINE MORPHOLOGY
VIRGINIA CHESAPEAKE BAY
MARSH MARGIN ENVIRONMENT

| | VIRGINIA CHESAPEAKE BAY | NORTHAMPTON COUNTY | ACCOMACK COUNTY | NORTHUMBERLAND COUNTY | LANCASTER COUNTY | MIDDLESEX COUNTY |
|---|---|---|---|---|---|---|
| SHORELINE LENGTH (km) | 65.9 | 2.5 | 34.1 | 5.9 | 0 | 0 |
| NUMBER OF REACHES | 39 | 1 | 19 | 4 | 0 | 0 |
| MEAN NEARSHORE TERRACE WIDTH (m) | 3050 | 2148 | 4713 | 2059 | - | - |
| STANDARD DEVIATION | 1956 | 0 | 1810 | 1319 | - | - |
| MEAN EROSION (m/yr) | 0.53 | 0 | 0.48 | 0.67 | - | - |
| STANDARD DEVIATION | 0.54 | 0 | 0.37 | 0.33 | - | - |

| | MATHEWS COUNTY | GLOUCESTER COUNTY | YORK COUNTY | HAMPTON | NORFOLK/ VIRGINIA BEACH | EASTERN SHORE | WESTERN SHORE |
|---|---|---|---|---|---|---|---|
| SHORELINE LENGTH (km) | 5.8 | 12.2 | 5.1 | 0 | 0 | 36.7 | 29.1 |
| NUMBER OF REACHES | 3 | 10 | 2 | 0 | 0 | 20 | 19 |
| MEAN NEARSHORE TERRACE WIDTH (m) | 856 | 961 | 1102 | - | - | 4530 | 1187 |
| STANDARD DEVIATION | 944 | 585 | 1070 | - | - | 1699 | 942 |
| MEAN EROSION (m/yr) | 1.18 | 0.45 | 0.45 | - | - | 0.45 | 0.64 |
| STANDARD DEVIATION | 1.22 | 0.38 | 1.02 | - | - | 0.38 | 0.68 |

compared to the nearshore of other marsh environments. As well, the extensive marsh in this area is fully exposed to the maximum fetches of the Bay (see Appendix D).

## Fringe Marsh

Fringe marsh (Fig. 12) in the Virginia Chesapeake Bay is composed of a narrow band of *Spartina alterniflora* that runs parallel to a beach along the intertidal zone. Figure 10 shows that the distribution of fringe marsh is much more extensive than other marsh forms, however, it also shows a concentration along the northeast and southwest margins of the Bay.

Fringe marsh is effective at dampening the shoreline wave energy. Wayne (1976) found *Spartina alterniflora* reduced wave heights by as much as 71%, and wave energy by 92%, measured over a 20 meter distance. This yields a wave height gradient of 3.6% per meter, and a wave energy gradient of 4.6% per meter. For this reason marsh grasses should be considered as an alternative in shore protection design. Table 7 shows the amount of fringe marsh shoreline in the Bay, and a comparison of beach environments with and without fringe marsh. In nearly every case, the long-term erosion rate is lower on beaches with fringe marsh. Over the study area, fringe marsh decreases erosion by 20% on permeable beaches, 38% on impermeable beaches, and 50% on marsh barriers. The higher stabilization rate on marsh barriers is due to

Figure 12: Photograph showing fringe marsh recolonizing outcropping peat on a marsh barrier beach.

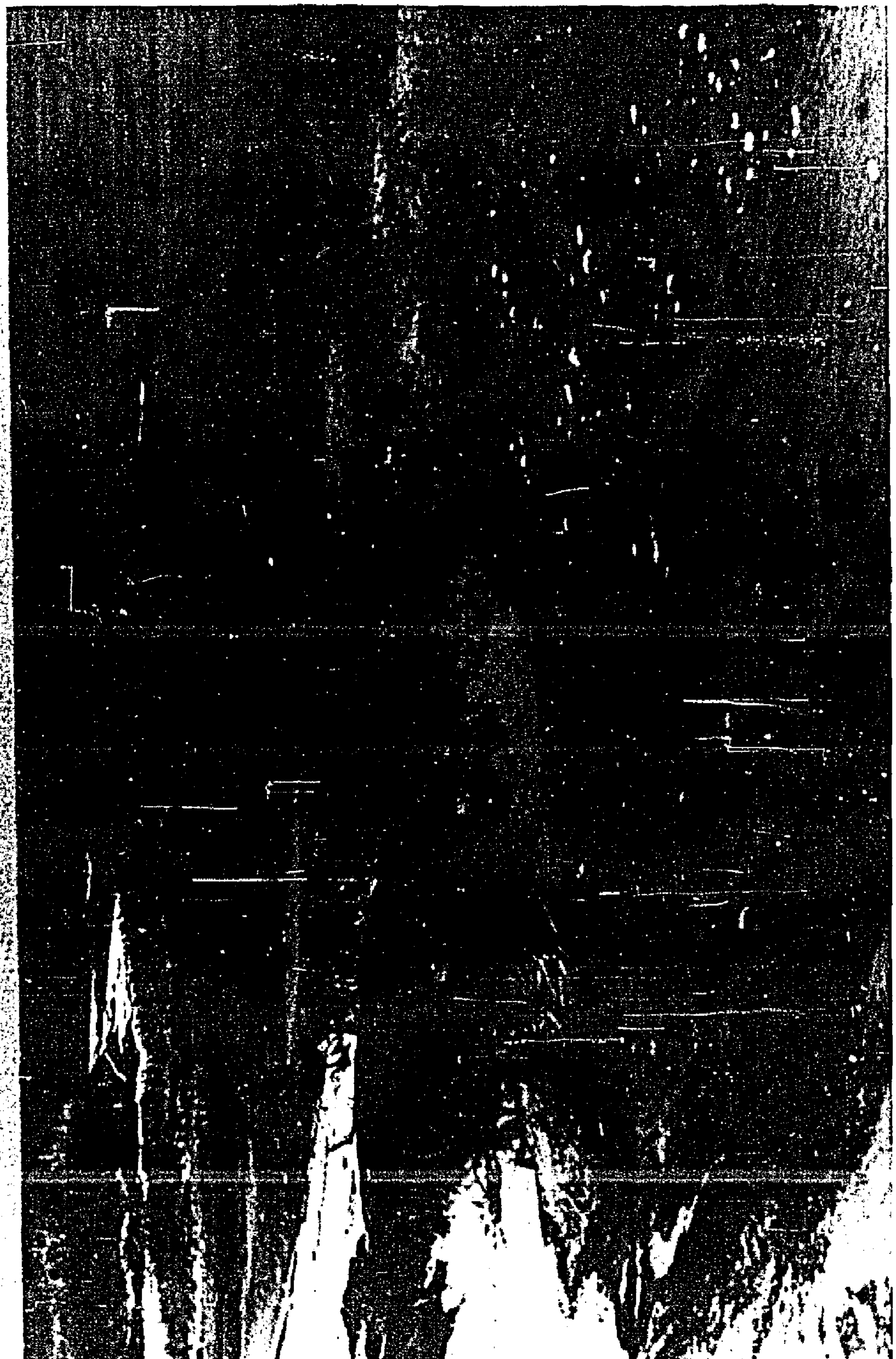


TABLE 7
CHARACTERISTICS OF FRINGE MARSH SHORELINES
VIRGINIA CHESAPEAKE BAY

| | LOWER CHESAPEAKE BAY | EASTERN SHORE | WESTERN SHORE | POTOMAC RIVER TO GREAT WICOMICO RIVER | GREAT WICOMICO RIVER TO RAPPAHANNOCK RIVER |
|---|---|---|---|---|---|
| IMPERMEABLE BEACHES WITH FRINGE MARSH (km) | 22.5 | 7.7 | 14.6 | 0.57 | 0.80 |
| PERMEABLE BEACHES WITH FRINGE MARSH (km) | 25.2 | 8.8 | 16.2 | 1.4 | 1.7 |
| MARSH BARRIER BEACHES WITH FRINGE MARSH (km) | 82.0 | 39.5 | 42.3 | 0.9 | 10.6 |
| EROSION RATES (m/yr): | | | | | |
| ALL FRINGE MARSH SHORELINE | 0.59 | 0.53 | 0.64 | 0.55 | 0.66 |
| PERMEABLE BEACHES WITH FRINGE MARSH | 0.70 | 0.50 | 0.81 | 0.62 | 0.50 |
| PERMEABLE BEACHES WITHOUT FRINGE MARSH | 0.87 | 0.71 | 0.94 | 1.03 | 0.94 |
| IMPERMEABLE BEACHES WITH FRINGE MARSH | 0.71 | 0.76 | 0.68 | 0.30 | 0.91 |
| IMPERMEABLE BEACHES WITHOUT FRINGE MARSH | 1.13 | 1.07 | 1.18 | 1.20 | 1.61 |
| MARSH BARRIER BEACHES WITH FRINGE MARSH | 0.53 | 0.49 | 0.56 | 0.60 | 0.67 |
| MARSH BARRIER BEACHES WITHOUT FRINGE MARSH | 1.04 | 1.14 | 0.83 | 1.03 | 0.40 |

TABLE 7 (cont'd)
CHARACTERISTICS OF FRINGE MARSH SHORELINES
VIRGINIA CHESAPEAKE BAY

| | RAPPAHANNOCK RIVER TO NEW POINT COMFORT | MOBJACK BAY AND YORK COUNTY | HAMPTON/ NORFOLK/ VIRGINIA BEACH | NORTHAMPTON COUNTY | ACCOMACK COUNTY |
|---|---|---|---|---|---|
| IMPERMEABLE BEACHES WITH FRINGE MARSH (km) | 0 | 13.3 | 0 | 1.3 | 6.4 |
| PERMEABLE BEACHES WITH FRINGE MARSH (km) | 2.7 | 10.2 | 0 | 5.4 | 3.4 |
| MARSH BARRIER BEACHES WITH FRINGE MARSH (km) | 2.7 | 28.0 | 0 | 0 | 39.5 |
| EROSION RATES (m/yr): | | | | | |
| ALL FRINGE MARSH SHORELINE | 1.41 | 0.56 | - | 0.59 | 0.52 |
| PERMEABLE BEACHES WITH FRINGE MARSH | 1.30 | 0.73 | - | 0.48 | 0.54 |
| PERMEABLE BEACHES WITHOUT FRINGE MARSH | 1.20 | 0.60 | 0.83 | 0.64 | 1.07 |
| IMPERMEABLE BEACHES WITH FRINGE MARSH | - | 0.76 | - | 1.03 | 0.71 |
| IMPERMEABLE BEACHES WITHOUT FRINGE MARSH | 2.1 | 0.68 | - | 1.32 | 0.83 |
| MARSH BARRIER BEACHES WITH FRINGE MARSH | 1.45 | 0.43 | - | - | 0.49 |
| MARSH BARRIER BEACHES WITHOUT FRINGE MARSH | 1.42 | - | - | - | 1.19 |

fringe marsh recolonizing the exposed peat outcrop on the foreshore, forming an environment similar to marsh margins seaward of the beach.

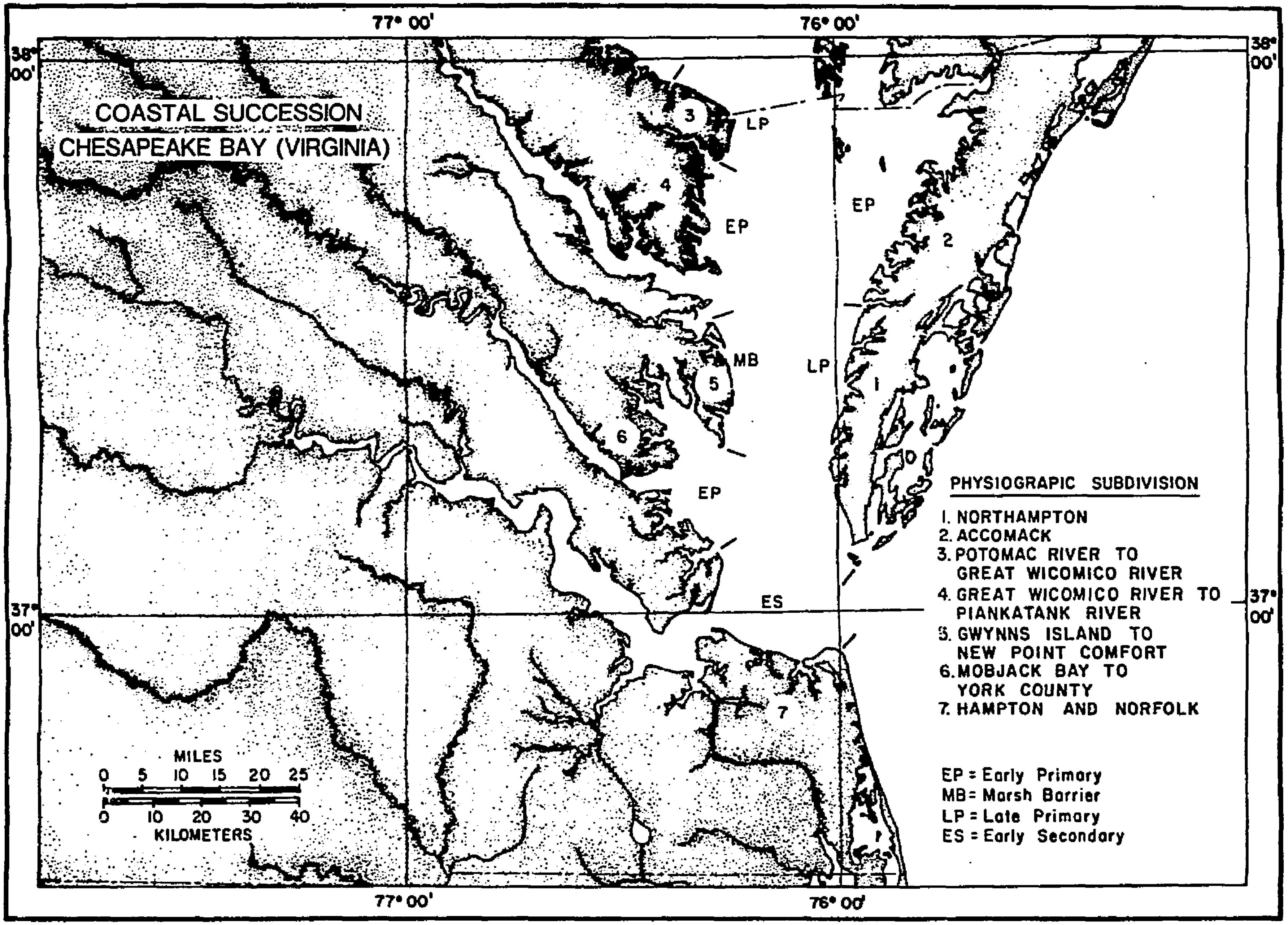
Forty-seven percent of the beaches in the study area showed the presence of either extensive or intermittant fringe marsh. Over 60% of the fringe marsh in the system occurs on marsh barriers, and most of these occur in Accomack County (eastern shore).

## COASTAL SUCCESSION

According to Shepard's (1973) classification of shoreline types, the Chesapeake Bay is classified as a primary shoreline--one whose form is dominated by terrestrial processes. By looking at the Bay on a smaller scale, it is evident that different areas are going through the succession from primary to secondary, or marine-dominated, characteristics at differing rates. These areas are shown in Figure 13, and form the only identifiable physiographic subdivisions of the Virginia Chesapeake Bay. The characteristics of these regions are summarized in Table 8.

The classification of the physiographic subdivisions of the Lower Bay into units representative of the degree of coastal succession is based on the following criteria: Early primary shorelines are characterized by a highly dissected shoreline, a complex array of shore orientations, and many breaks in the shore for stream drainage. Late primary coasts show a moderate degree of straightening of the shoreline by marine processes. All but major creeks have been closed by longshore drift. Secondary shorelines show the greatest straightening of the shoreline. Any drainage outlets along the shoreline have taken on the form of a coastal inlet.

Figure 13: Coastal succession of the Virginia Chesapeake Bay shoreline.



COASTAL SUCCESSION
CHESAPEAKE BAY (VIRGINIA)
77° 00'
76° 00'
38° 00'
37° 00'
LP
EP
MB
ES
1
2
3
4
5
6
7
PHYSIOGRAPIC SUBDIVISION
1. NORTHAMPTON
2. ACCOMACK
3. POTOMAC RIVER TO GREAT WICOMICO RIVER
4. GREAT WICOMICO RIVER TO PIANKATANK RIVER
5. GWYNNS ISLAND TO NEW POINT COMFORT
6. MOBJACK BAY TO YORK COUNTY
7. HAMPTON AND NORFOLK
EP = Early Primary
MB = Marsh Barrier
LP = Late Primary
ES = Early Secondary
MILES
0 5 10 15 20 25
0 10 20 30 40
KILOMETERS

TABLE 8
CHARACTERISTICS OF PHYSIOGRAPHIC SUB-DIVISIONS
VIRGINIA CHESAPEAKE BAY

| | Mean Nearshore Terrace Width (meters) | Mean Bluff Height (meters) | Mean Bluff Sand Content | Mean Erosion (meters/year) |
|---|---|---|---|---|
| EARLY SECONDARY: | | | | |
| HAMPTON AND NORFOLK/ VIRGINIA BEACH | 391. | 1.58 | 100% | 0.84 |
| LATE PRIMARY: | | | | |
| POTOMAC RIVER TO GREAT WICOMICO RIVER | 924. | 2.38 | 78% | 1.09 |
| NORTHAMPTON COUNTY | 1361. | 2.68 | 97% | 0.82 |
| MARSH BARRIER: | | | | |
| GWYNNS ISLAND TO NEW POINT COMFORT | 1000. | 0.79 | 100% | 1.37 |
| EARLY PRIMARY: | | | | |
| ACCOMACK COUNTY | 4018. | 0.52 | 24% | 0.73 |
| GREAT WICOMICO RIVER TO PIANKATANK RIVER | 1134. | 0.49 | 36% | 1.01 |
| MOBJACK BAY TO YORK COUNTY | 1438. | 0.12 | 43% | 0.56 |

The south shore of the Bay is most exposed to ocean wave activity through the Bay mouth, and is exposed to maximum fetch from the north. This shoreline has taken on the more mature secondary characteristics of adjacent ocean shorelines: The shoreline is straight, with few breaks from stream drainage. The beach is broad and high, similar to ocean beaches. This shore is considered to be in an early secondary stage of development. The secondary characteristics of this shore has resulted in the most economic development; hence the greatest concern about erosion, even though it has one of the lower measured beach erosion rates in the study area, 0.79 m/yr. The mean nearshore terrace width is 380 m, the smallest in the study area. The nearshore terrace in this region does not exist as a geomorphic entity. The nearshore has a gradual slope into deeper water, without evidence of an erosional-remnant bench at or near the 3.6 m (12 ft.) contour as in other areas. This is another secondary alteration of this shore, that is probably a function of the longshore sediment input from Cape Henry, at the Chesapeake Bay Mouth.

Two areas are classified as late primary in development: Northampton County, at the south end of the eastern shore, and the Potomac River to Great Wicomico River region on the western shore. The shoreline of each of these regions has been straightened, and is dominated by the highest bluffs on their respective sides of the

Bay. The mean bluff height in Northampton is 2.7 m, and 2.3 m in the Potomac River to Great Wicomico River region. All but major creeks have been closed in these areas by longshore drift.

The nearshore terraces in all areas considered to be in a primary stage of development, within the sampling interval of the field reconnaissance, appear to be flat erosional benches representing a base level of shoreline retreat, with modifications of nearshore bar development. The late primary shoreline regions are each located in the areas of lower submergence (Holdahl and Morrison, 1974) on their respective sides of the Bay, and, as a result, have the narrowest nearshore terrace widths, 924 m on the western shore, and 1361 m on the eastern shore.

According to Shepard's shoreline classification, biologic activity (i.e. salt marsh development) is a marine-dominated, or secondary characteristic. In the Chesapeake Bay, marsh development coincides with higher subsidence rates. The fastland drowning in these areas results in a highly dissected, more youthful, shoreline. So salt marsh development in the case of the Chesapeake Bay must be considered a primary shoreline feature.

In one region of the Bay, marsh barriers have straightened the highly dissected fastland shoreline. This is the Gwynns Island to New Point Comfort area on the western shore. This region is classified under the non-nominal category of marsh barrier.

The remaining areas on the western shore, Great Wicomico River to Piankatank River, and Mobjack Bay to York County, and Accomack County on the eastern shore, are classified as early primary, due to the highly dissected coastal form caused by submergence of the relict dendritic drainage system.

Many factors influence these differing degrees of coastal succession, including salt marsh development, and nature of the fastland form. However, the sediment supply is an important controlling factor.

The wide sandy beaches of the south shore of the Bay are fed by longshore currents from Cape Henry, a large stockpile of sand in turn fed sand by the ocean beaches to the south. The large sand supply in the longshore drift system has facilitated the straightening of the early secondary shoreline, and modification of the nearshore.

The late primary shorelines each have the highest bluffs on their respective sides of the Bay. This is probably influenced by the lower subsidence rates in these areas, which also results in narrower nearshore terraces. These narrower terraces would be expected to present less of a buffer to wave energy. As well, the sediment sampling has shown a higher sand content in the eroding fastland material in each of these regions.

The early primary shorelines are characterized by low bluffs, if any, and a higher clay content in the eroding sediments, resulting in sand-starved environments. This appears to dampen the succession rates.

Since the late primary shorelines occur in areas of lower subsidence, the rate of further shoreline dissection by submergence of the relict Pleistocene drainage system is diminished. On the early primary shorelines in the higher subsidence areas, sea level is encroaching on the coastal plain at a higher rate, forming new primary shoreline faster than the shore processes can progress in the succession towards shore simplification.

## WAVE REFRACTION

The distribution of wave energy throughout the Lower Bay is a significant variable affecting the changes in the morphology of the shoreline. The regional variations in wave energy were investigated by the application of a wave refraction model.

### MODEL DEVELOPMENT

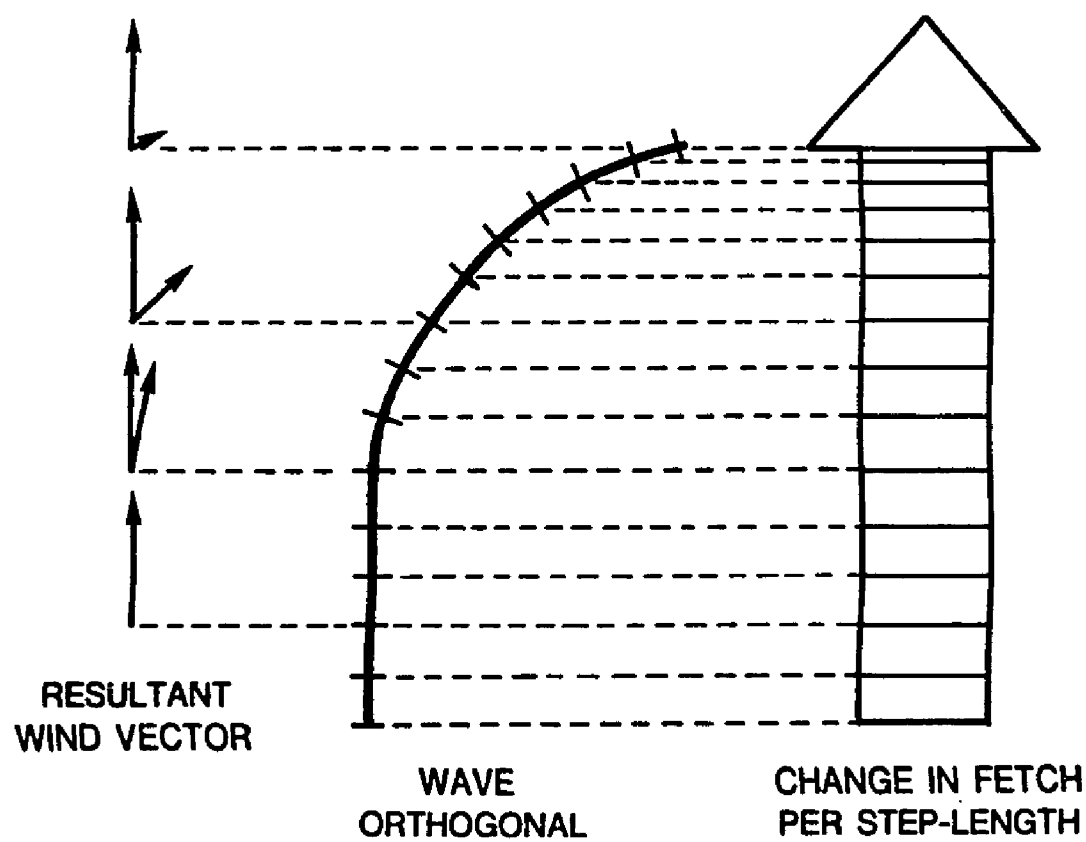
The Chesapeake Bay Wave Climate Model (Rosen, Goldsmith, Sutton and Richardson, 1976) is designed to simulate wave refraction in a growing sea situation. The model is a further development of the Virginian Sea Wave Climate Model (Goldsmith et al, 1974), which has the capability of simulating the refraction of swell. The wave (significant period and height) is continually re-forecasted at each step along each wave orthogonal using Wilson's (1965) forecast equation. Input for this equation is fetch and wind velocity. This technique was initially devised by Thrall (1973). The Chesapeake Bay model has several significant improvements, which include: 1) The wind input at each step interval is the resultant vector component of the wind parallel to the direction of wave propagation, and 2) the fetch input is the absolute fetch, or distance to land in the direction into the wind.

Figure 14 demonstrates how, as a wave refracts, the wind resultant vector will decrease, and the total fetch will increase, but in diminishing amounts. A point is reached where the increased fetch component is not sufficiently large to overcome the decreased wind component. At this point the wave is propagated as swell until such time that the reforecasted wave is larger than the previous forecast. This technique more accurately models a growing sea situation. The Chesapeake Bay Wave Climate Model also has the capability of simulating the effect of ocean swell (generated by the Virginian Sea Wave Climate Model) entering the Bay Mouth, and ocean swell entering the Bay and coming under the effect of the local wind regime.

The significant waves predicted from winds oblique to the long axis (N-S) of the basin, cross the basin, saturating the area and shoreline of the Bay with wave information. The significant waves predicted from winds parallel to the long axis of the basin tend to refract to the flanks of the basin. This effect is more pronounced as wind velocity increases (resulting from a larger significant wave which refracts more from the bathymetry). To overcome this effect, waves resulting from northerly winds were re-started at six positions in the Lower Bay, each with increasing input fetches. In this way, several components of the wave spectrum are simulated to create full coverage of the wave climate in the Bay for these wind conditions.

Figure 14: Diagram showing the effect of increased wave refraction on wave forecast input parameters; total fetch increases in diminishing amounts, wind resultant vector decreases.

## EFFECT OF WAVE REFRACTION ON WAVE FORCASTS



## MODEL INPUT

Wave input data for each selected wind direction (NE, N, NW, SW) was designed to fully cover the study area with wave orthogonals. The input for each direction is designed to follow the upwind shore, 1-2 km from shore to avoid the refraction effects of the shallow nearshore. An initial input fetch was determined for each orthogonal at each initial direction, to take into account the effects of irregular shorelines and river mouths (especially on the western shore). The input orthogonals are evenly spaced normal to the wind direction, with four orthogonals per nautical mile.

The Lower Chesapeake Bay depth input to the wave refraction model consists of data from National Ocean Survey original sounding sheets, on a 0.25 n. mile grid. The grid dimensions are 360 (N-S) x 94 (E-W), or 166 km (N-S) x 43 km (E-W). This results in 33,840 depths. The boundaries of the depth grid are:

| | NW | SW | SE | NE |
|---|---|---|---|---|
| Latitude | 38°23'N | 36°55'N | 36°55'N | 38°23'N |
| Longitude | 76°25'W | 76°25'W | 75°55'W | 75°55'W |

The major features of the Lower Chesapeake Bay bathymetry include the main channel of the Susquehanna River, running down the long axis of the basin with depths of over 40m. The mean depth of the Chesapeake Bay is about 9m. The submergent nearshore area is dominated by shallow ( $< 4$ m) flat terraces.

## WIND CLIMATE

There is considerable regional and annual variation in wind direction and speed in the Lower Chesapeake Bay. The prevailing wind has a steadiness of only sixteen percent on the average, and blows from the northwest during the winter months and southwest in the summer months. Gale winds, greater than 14 m/s, have been recorded approximately 15% of the time in winter, and approximately 1.5% of the time in summer.

In the winter, slow moving cold fronts tend to become stationary near the Gulf Stream. The resulting convergence may produce strong northeasterly winds. As well, the most extreme winter phenomenon is the Nor'easter, a subtropical storm which moves northeastward from the Gulf of Mexico and commonly passes offshore in the Cape Hatteras or Virginia Capes area. Increased winds occur while the storm is still several hundred miles away. As the low passes through the area, contact with the relatively warm coastal water may produce rapid intensification of winds. These high winds may persist for 12-24 hours during its passage. Winds in the spring are predominantly from two directions; northwest and south. The southerly winds are normally of moderate intensity. Northeast storm winds continue, although decreasing in number and intensity.

Summer winds are dominated by south to southwestern directions. Frontal-type thunderstorms most commonly approach from the west or northwest.

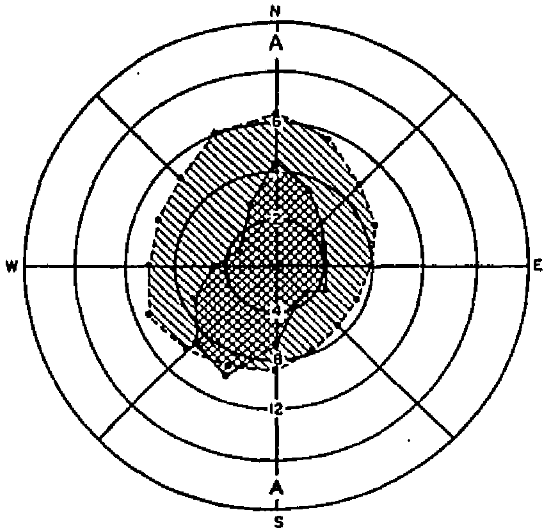
Fall winds are characterized by gusty northeasterly winds resulting from intense lows which form in Texas or the Gulf of Mexico, and move to the northeast. Hurricanes reach their maximum frequency in the fall. Resulting winds are highly variable, depending on the path of each hurricane (U.S. Navy, 1963).

Annual wind roses for four stations in the Virginia Chesapeake Bay area, Norfolk and Langley AFB, Virginia, at the south end; Patuxent River, Maryland and Fort Belvoir, Virginia, at the north end; are shown in Figs. 15-18. The data is presented as a total annual wind rose, frequency of winds greater than 5 m/s and 11 m/s, and annual peak-gust frequency. The variability of the winds in a small area is evident, due to the effects of the local geography.

Four wind directions were chosen for application of the Chesapeake Bay Wave Climate Model. It should be noted that a single wind is input in the wave model, while the wind records suggest such uniformity is rarely the case. However, for the initial application of this model for regional interpretation of shore morphology, this assumption is utilized. The northwest wind component dominates the peak gusts of the region (Fig. 18), as well as storm and moderate winds (Figs. 16 and 17). This is the winter prevalent wind. Southwest winds are the summer prevalent winds. Northeast and north wind

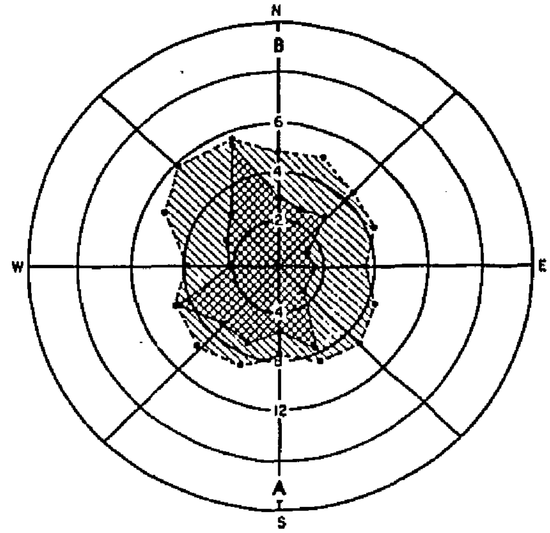
Figure 15: Total annual wind roses showing percent frequency and mean velocity at the following stations:

| Station | Years of Record |
|---|---|
| Langley AFB, VA | 1946-1970 |
| Norfolk, VA | 1946-1970 |
| Fort Belvoir, VA | 1957-1970 |
| Patuxent River, MD | 1945-1966 |



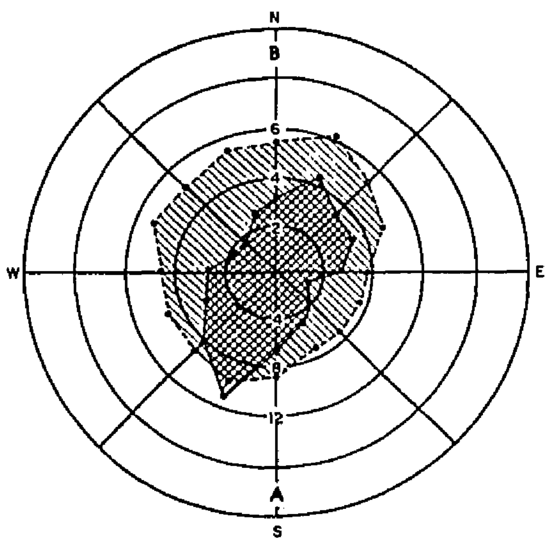

PERCENT FREQUENCY ( A )
MEAN VELOCITY m/s ( B )

LANGLEY AFB, VA.
ANNUAL WIND ROSE



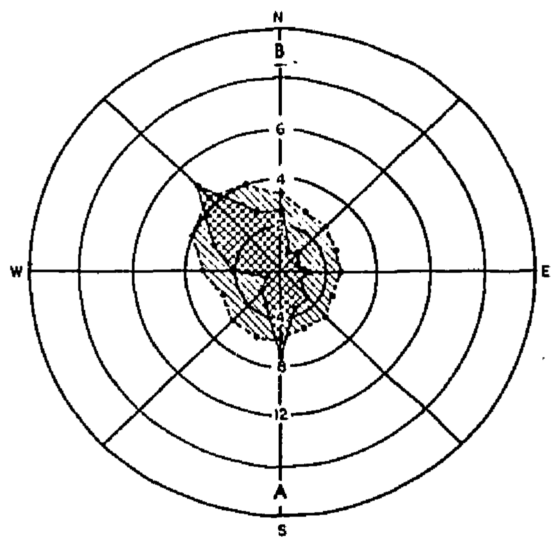

PERCENT FREQUENCY ( A )
MEAN VELOCITY m/s ( B )

PATUXENT RIVER, MD.
ANNUAL WIND ROSE




PERCENT FREQUENCY ( A )
MEAN VELOCITY m/s ( B )

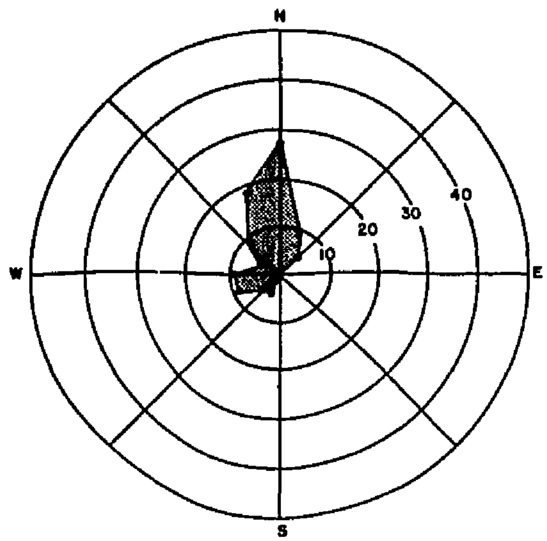
NORFOLK, VA.
ANNUAL WIND ROSE



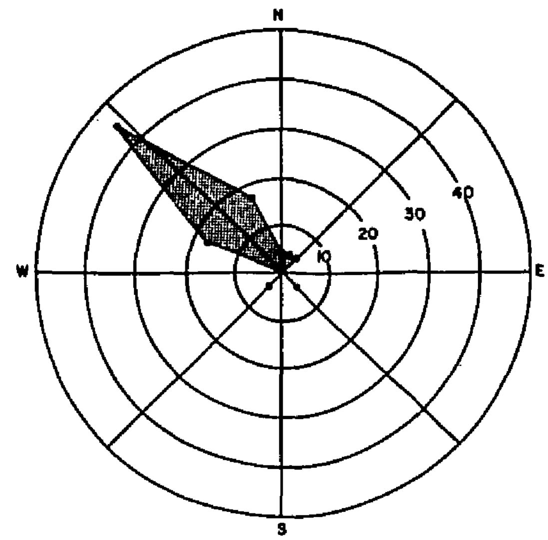

PERCENT FREQUENCY ( A )
MEAN VELOCITY m/s ( B )

FORT BELVOIR, VA.
ANNUAL WIND ROSE

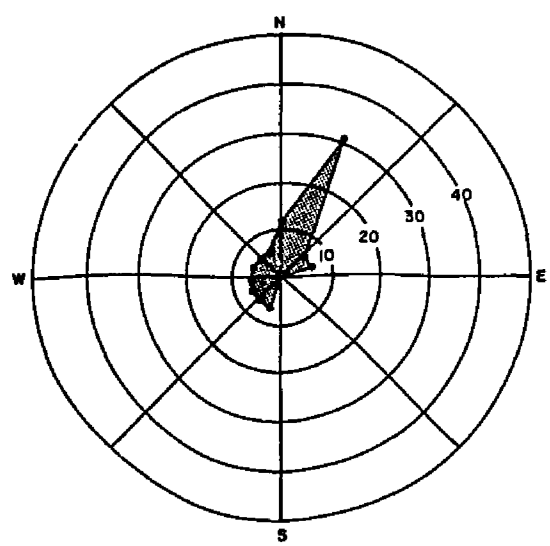
Figure 16: Frequency of winds greater than 11 m/s at Langley AFB, Norfolk, and Fort Belvoir, Virginia, and Patuxent River, MD.



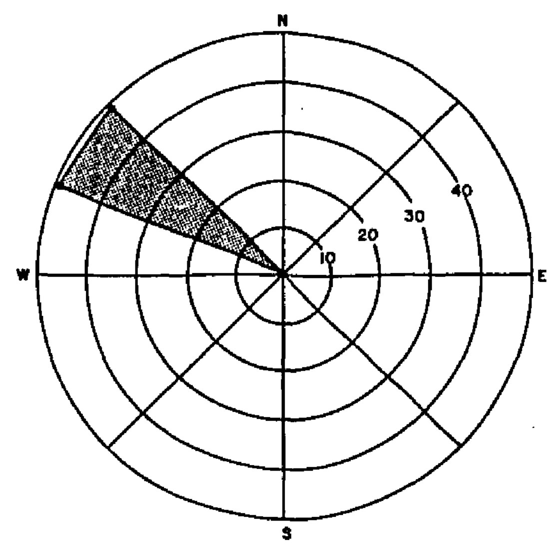

LANGLEY AFB, VA.
WINDS > 11 M/S
PERCENT FREQUENCY




PATUXENT RIVER, MD.
WINDS > 11 M/S
PERCENT FREQUENCY

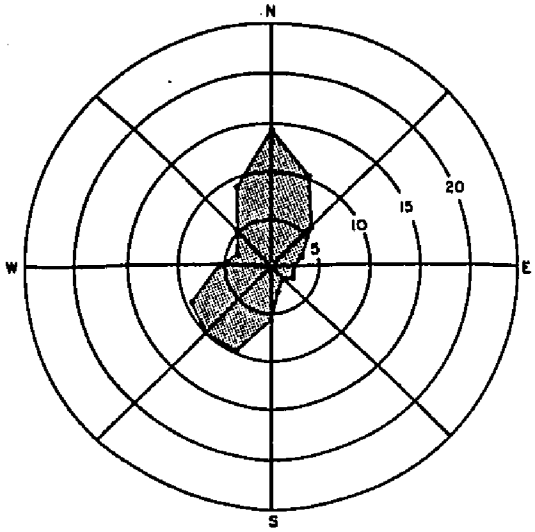



NORFOLK, VA.
WINDS > 11 M/S
PERCENT FREQUENCY

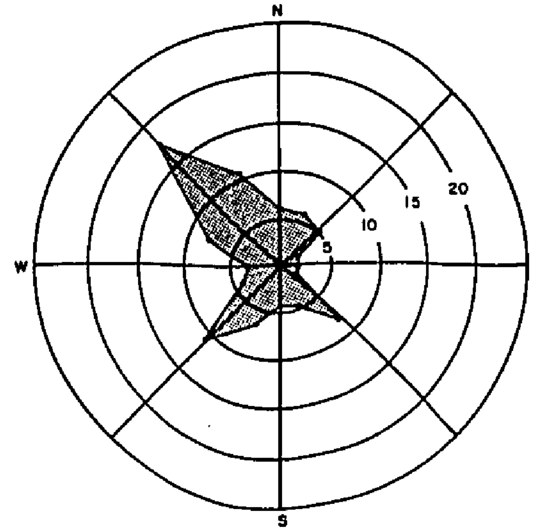



FORT BELVOIR, VA.
WINDS > 11 M/S
PERCENT FREQUENCY

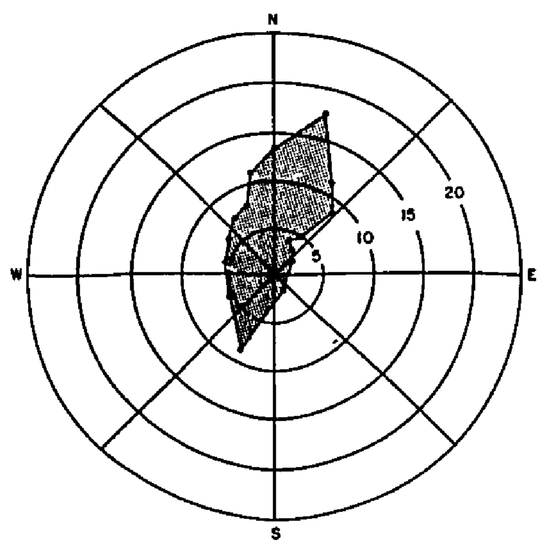
Figure 17: Frequency of winds greater than 5 m/s at Langley AFB, Norfolk, and Fort Belvoir, Virginia, and Patuxent River, Maryland.



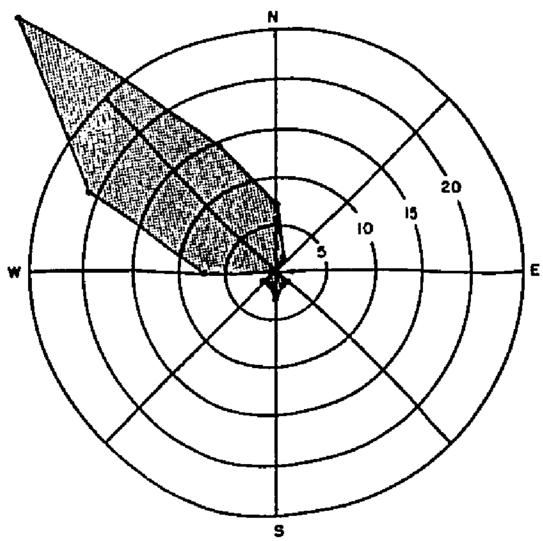

LANGLEY AFB, VA.
WINDS > 5 M/S
PERCENT FREQUENCY




PATUXENT RIVER, MD.
WINDS > 5 M/S
PERCENT FREQUENCY

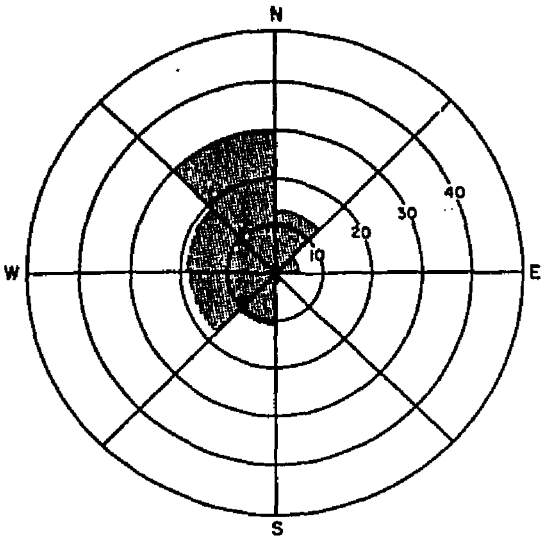



NORFOLK, VA.
WINDS > 5 M/S
PERCENT FREQUENCY

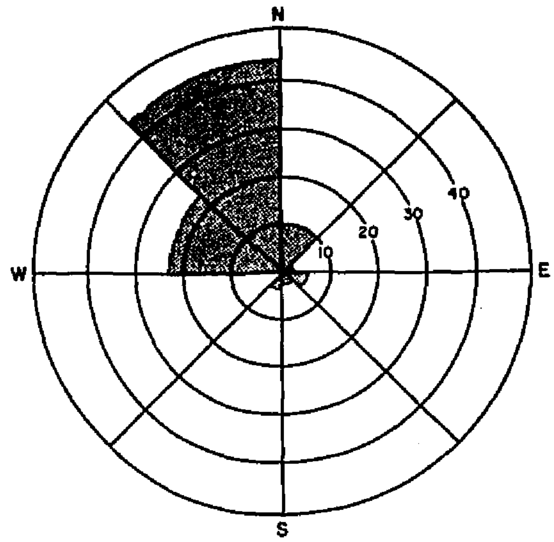



FORT BELVOIR, VA.
WINDS > 5 M/S
PERCENT FREQUENCY

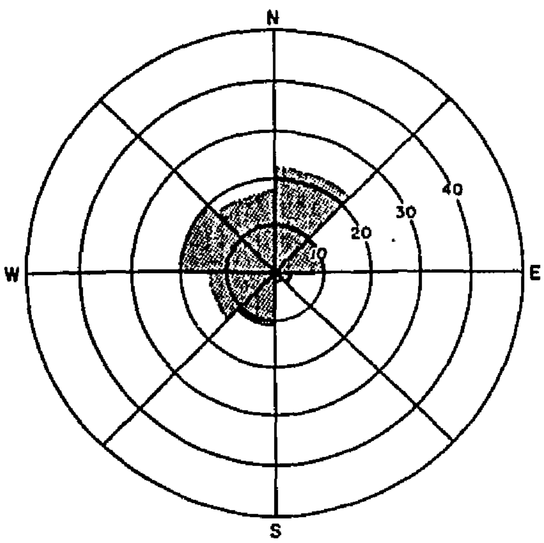
Figure 18: Frequency of highest monthly peak gusts at Langley AFB, Norfolk, and Fort Belvoir, Virginia, and Patuxent River, Maryland.



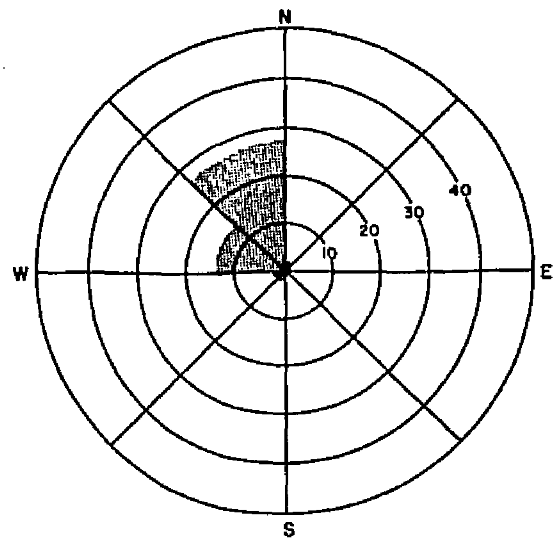

LANGLEY AFB, VA.
PEAK GUSTS
PERCENT FREQUENCY




PATUXENT RIVER, MD.
PEAK GUSTS
PERCENT FREQUENCY




NORFOLK, VA.
MONTHLY PEAK GUSTS
PERCENT FREQUENCY




FORT BELVOIR, VA.
MONTHLY PEAK GUSTS
PERCENT FREQUENCY

directions are each important higher wind components in the area.

## MODEL OUTPUT

Output from the model includes estimates of 19 wave parameters at each step on each orthogonal, a plot of wave orthogonal patterns, and punched output of wave parameters along the shoreline of the Lower Bay. The punched output is then plotted as histograms along the three (East, West, South) shorelines of the study area. Shoreline histograms of the significant wave period, height, and energy show the highest value in one nautical mile class intervals. Histograms of shoreline orthogonal density depict number of orthogonals approaching the shoreline per nautical mile.

The wave ray diagrams and shoreline histograms from this study are in Appendices C and D, respectively.

## DISCUSSION

The wave parameters (wave height, period, energy, and orthogonal density) along the shoreline of the Bay were regressed against the nearshore terrace widths and long-term erosion rates for each wave condition. A number of models, including multivariate ones, revealed no significant trends despite stratification by shore environment. It is suggested that multivariate nature of the wave processes precluded the statistical specification of the role of wave energy on the shoreline trends.

Winds from the north (parallel to the long axis of the basin) show an increasing deflection of wave orthogonals along the flanks of the basin with increasing wind velocities. Ten knot winds (Fig. C-1) produce waves whose main concentration is on the southern shore, reflecting only the geographic fetch, while 25 and 40 knot wind conditions (Figs. C-2, C-3) result in a more uniform distribution of wave energy throughout the basin.

Winds from the north produce a gradually increasing wave size (period) going to the south along the western shore of the Bay due to the increasing fetch (Figs. D-25, D-28, D-31). The growth rate increases with increasing wind velocities. Both northerly and northeasterly winds produce marked wave energy concentrations (orthogonal density) on the seawardmost headlands; the Potomac River to Great Wicomico River interfluve, Piankatank River to New Point Comfort, and Hampton-Norfolk (Figs. D-1, D-4, D-7). The largest period waves from north or northeast winds occur in the Potomac River area; these larger waves result from the waves travelling down the Upper Bay (Figs. D-34, D-36, D-38). On the northeasterly direction, the second largest fetch is from the Pokomoke River embayment. Waves generated in this area show no significant larger growth on the opposing western shore area.

The largest wave energy concentrations occur on all the areas that are not early-primary sections of shoreline. Wave energy is a controlling factor in the succession of the shore to a secondary, or marine-dominated form (Shepard, 1973).

Northerly winds on the eastern shore also demonstrate the gradual growth of wave period going to the south (Fig. D-26). However, the greatest concentration of wave energy (orthogonal density) occurs on the Northampton County shoreline. The 0°, 40 kt. case shows this concentration is limited to the area north of Cheapside (Fig. D-8) Northwest winds produce a more uniform distribution of wave periods along the eastern shore (Fig. D-43, D-45, D-47). The 315°, 25 and 40 kt. cases show a marked increase in wave period along the Smith Island area. Comparison of shoreline histograms with wave ray diagrams show this area is most affected by waves travelling south from the Upper Bay. A slight increase in wave period near the Tangier Island area is due to the increased upwind fetch due to the Potomac River. The waves from the Upper Bay show a distinct contact with locally generated waves, since this model does not evaluate the effects of wave diffraction, this area of larger waves is probably a broad gradation.

Both the southwest and northwest wave conditions (Figs. D-42, D-47) show that the increased fetch due to rivers on the western shore show no measurable increase in wave period on the eastern shore (with the exception of a slight effect from the Potomac River, the largest river emptying into the Lower Bay).

SHORELINE REORIENTATION

While north and northwest winds produce a divergence of wave energy (low orthogonal density) south of Cheapside (Northampton County) (Figs. D-5, D-21), the southwesterly winds (10, 25, 40 kts.) (Figs. D-16, D-17, D-18) produce a convergence of wave energy on this area. The section of shoreline south of Cheapside is oriented into the southwest wind. Lewis (1938) stated that a shoreline will tend to orient into dominant wave-approach directions as a result of net longshore transport. Wave orthogonals are approximately normal to the shoreline in this area, while striking the shoreline more obliquely to the north of this area. This is suggesting that the shoreline south of Cheapside has reoriented into this prevalent wave approach in comparison with the shore to the north.

The intersection of the shoreline with wave rays from the northeast wind condition (25 kts) demonstrates several shorelines re-oriented into this wave direction, including the south Potomac River shore, the Windmill Point area, Gwynns Island and south, and the Poquoson marsh area (Fig. C-5).

The Church Neck area of Northampton County shows shore reorientation through the formation of hooked spits

(Fig. 19), although this trend is not discernable from the wave ray diagrams. The lower Northampton County shore has reoriented into the southwest winds.

Each of these areas appears to be the initiation of a shoreline reorientation feature (Rosen, 1975). The initiation of these forms is either a function of present shoreline processes (i.e. Gwynns Island area), or remnants of the relict pre-submergence terrestrial processes (i.e. Potomac River shore, Windmill Point). In either event, the present wave regime is strongly polarized by the geographic restrictions of this elongate basin, and the shore is reorienting in response to these different wave components in different areas on both shores of the Lower Bay. The poorly defined form of some of these features is a function of the sand-starved nature of the shoreline.

Examination of aerial photographs shows several of these areas do show a convergence of longshore drift systems at the break-in-orientation of the shoreline, including Cheapside, Church Neck, Smith Point (Potomac River), and Poquoson marshes. Generally, the high rate of sea level rise in the Lower Bay results in submergent, dissected topography to be the dominating shoreline form. However, if an equilibrium shoreline condition is reached, the form will not be a straightened shore, but a series of reorientation features (similar to cuspate spits) in response to the local bi-directional wave system on each shore of the Bay.

Figure 19: Photograph showing the development of hooked spits on Church Neck, Northampton County, Virginia (looking north).

## SHORELINE SEDIMENTS

Analysis of the shoreline sediment samples has shown the regional trends in grain size distribution. The sampling grid consisted of one set of samples at a representative location at each reach (see Appendix A). Three environments were sampled, when present, at each locality. The beachface sediments commonly contained two distinct, interlayered modes of sedimentation. Representative samples of each mode were taken from a trench at the mid-point of the foreshore. In an impermeable beach, the trench was dug to the surface of the underlying, pre-Holocene sediments. This material was sampled, and the depth of the veneer of sand recorded. The backshore material (dune or bluff) was sampled at the same location. One hundred sixty five beachface samples were analyzed, 26 samples beneath impermeable beaches, and 29 bluff samples.

Samples containing mud were analyzed by the method described by Folk (1968) to determine sand/mud ratios.

The sand samples, and residual sands from the above analyses, were analyzed with the Virginia Institute of Marine Science rapid sediment analyzer, similar to one described by Zeigler, Whitney and Hayes (1960). The system measures pressure changes induced in a column of water by sediment settling through a measured distance. The readout of the rapid sediment analyzer is time vs. percent of sample passing the one meter fall line. This data was corrected for temperature changes, and converted to phi-equivilent units using the settling curves of Zeigler and Gill (1959). A shape factor of 0.7 was assumed. A conversion scale for settling time (one meter fall) and phi-equivilents is shown in Figure 20. This conversion was confirmed by visual comparison of seived sand and the samples.

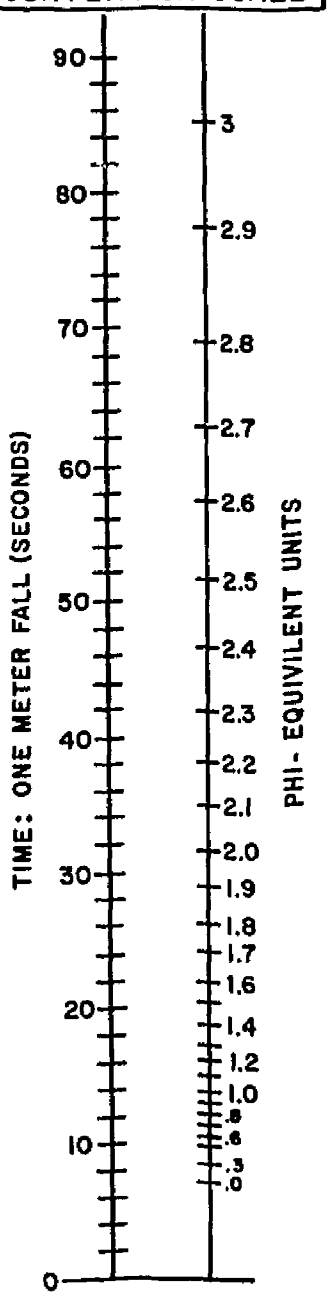
Figure 21 shows the distribution of coarse and fine mode sediment sizes of beachface samples along the margins cf the Virginia Chesapeake Bay. The results are summarized in Table 9. The coarse mode regional mean is 0.68 Ø, which does not deviate greatly throughout the flanks of the Bay. The regional mean grain size for the fine mode is 1.46 Ø, which is also fairly consistent.

Table 10 shows the summary of samples from bluffs. The regional mean is 1.52 Ø, which approximately corresponds to the regional mean of 1.63 Ø for samples beneath impermeable beaches (Table 11, Figure 22).

The beachface sediments along the flanks of the Virginia Chesapeake Bay showed a strikingly similar pattern of sedimentation. A fine mode and coarse mode of sand were typically interlayered, with a sharp contact between them (Figure 23). The sampling of bluffs, and material beneath impermeable beaches is an estimate of

Figure 20: Fall velocity - PHI equivilent conversion scale.

SETTLING TIME-PHI EQUIVILENT UNIT CONVERSION SCALE




WATER TEMPERATURE 20°C
SHAPE FACTOR 0.7

Figure 21: Mean grain size of beachface samples, Virginia Chesapeake Bay. Both the coarser and finer modes are shown on a shoreline that has been straightened to form a "U" for ease of data display. A summary of this data is shown in Table 9.

VIRGINIA CHESAPEAKE BAY

MEAN SIZE DISTRIBUTION - BEACHFACE SAMPLES

VALUES IN PHI EQUIVILENT UNITS

o FINE MODE

x COARSE MODE

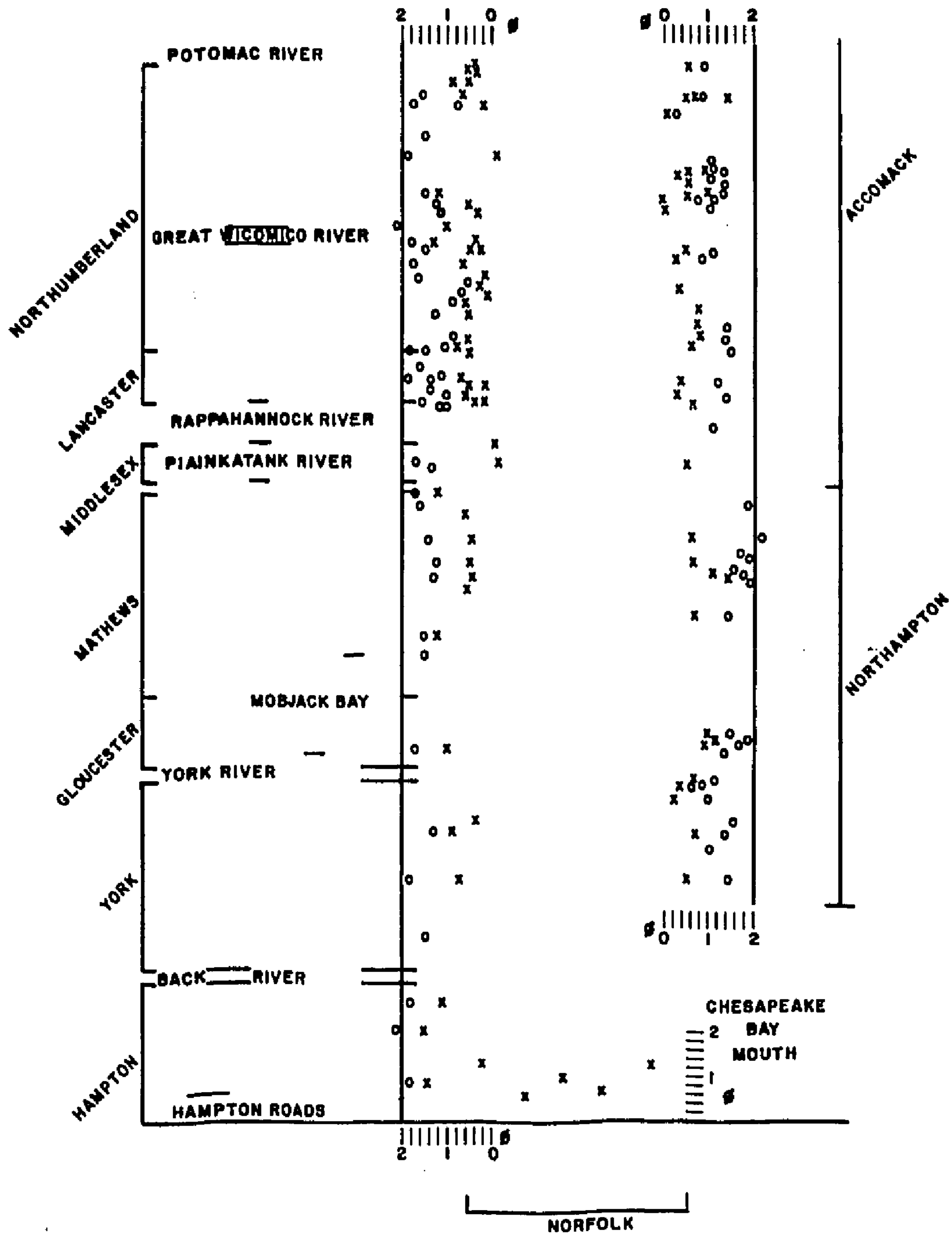


TABLE 9
SUMMARY OF SEDIMENT GRAIN SIZE
BEACHFACE SAMPLES
VALUES IN PHI UNITS

| | FINE MODE | | | | COARSE MODE | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean Ø | Median Ø | Standard Deviation | Number of Samples | Mean Ø | Median Ø | Standard Deviation | Number of Samples |
| VIRGINIA CHESAPEAKE BAY | | | | | | | | |
| Total Sample | 1.46 | 1.39 | 0.43 | 85 | 0.68 | 0.66 | 0.47 | 80 |
| Impermeable Beaches | 1.64 | 1.54 | 0.51 | 22 | 0.67 | 0.71 | 0.55 | 20 |
| Permeable Beaches | 1.32 | 1.28 | 0.39 | 36 | 0.58 | 0.56 | 0.39 | 45 |
| Marsh Barrier Beaches | 1.53 | 1.50 | 0.47 | 17 | 0.84 | 0.84 | 0.51 | 15 |
| EASTERN SHORE | | | | | | | | |
| Total Sample | 1.42 | 1.36 | 0.44 | 40 | 0.68 | 0.64 | 0.45 | 35 |
| Impermeable Beaches | 1.52 | 1.36 | 0.67 | 11 | 0.62 | 0.60 | 0.40 | 11 |
| Permeable Beaches | 1.28 | 1.22 | 0.34 | 20 | 0.63 | 0.55 | 0.44 | 18 |
| Marsh Barrier Beaches | 1.57 | 1.56 | 0.37 | 9 | 0.98 | 1.00 | 0.56 | 6 |
| WESTERN SHORE | | | | | | | | |
| Total Sample | 1.49 | 1.41 | 0.43 | 45 | 0.67 | 0.67 | 0.48 | 45 |
| Impermeable Beaches | 1.76 | 1.71 | 0.35 | 11 | 0.74 | 0.84 | 0.74 | 9 |
| Permeable Beaches | 1.41 | 1.28 | 0.41 | 26 | 0.60 | 0.52 | 0.38 | 28 |
| Marsh Barrier Beaches | 1.47 | 1.44 | 0.58 | 8 | 0.73 | 0.71 | 0.41 | 8 |
| NORTHAMPTON COUNTY | | | | | | | | |
| Total Sample | 1.34 | 1.25 | 0.50 | 22 | 0.59 | 0.54 | 0.40 | 23 |
| Impermeable Beaches | 1.53 | 1.32 | 0.81 | 8 | 0.62 | 0.59 | 0.38 | 9 |
| Permeable Beaches | 1.23 | 1.20 | 0.33 | 14 | 0.58 | 0.57 | 0.39 | 14 |
| Marsh Barrier Beaches | ---- | ---- | ---- | 0 | ---- | ---- | ---- | 0 |
| ACCOMAC COUNTY | | | | | | | | |
| Total Sample | 1.51 | 1.49 | 0.36 | 18 | 0.86 | 0.84 | 0.54 | 12 |
| Impermeable Beaches | 1.49 | 1.47 | 0.28 | 3 | 0.64 | 0.66 | 0.48 | 2 |
| Permeable Beaches | 1.44 | 1.41 | 0.38 | 6 | 0.77 | 0.69 | 0.55 | 4 |
| Marsh Barrier Beaches | 1.57 | 1.56 | 0.37 | 9 | 0.98 | 1.00 | 0.56 | 6 |

TABLE 9 (cont'd)
SUMMARY OF SEDIMENT
GRAIN SIZE

| | FINE MODE | | | | COARSE MODE | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean Ø | Median Ø | Standard Deviation | Number of Samples | Mean Ø | Median Ø | Standard Deviation | Number of Samples |
| NORTHUMBERLAND COUNTY | | | | | | | | |
| Total Sample | 1.41 | 1.37 | 0.48 | 23 | 0.62 | 0.63 | 0.47 | 28 |
| Impermeable Beaches | 1.73 | 1.69 | 0.37 | 6 | 0.72 | 0.83 | 0.78 | 6 |
| Permeable Beaches | 1.24 | 1.23 | 0.38 | 13 | 0.55 | 0.56 | 0.38 | 17 |
| Marsh Barrier Beaches | 1.47 | 1.45 | 0.86 | 4 | 0.64 | 0.59 | 0.39 | 5 |
| LANCASTER COUNTY | | | | | | | | |
| Total Sample | 1.46 | 1.43 | 0.30 | 7 | 0.69 | 0.64 | 0.31 | 3 |
| Impermeable Beaches | 1.89 | 1.85 | 0.30 | 3 | ---- | ---- | ---- | 0 |
| Permeable Beaches | 1.14 | 1.08 | 0.29 | 4 | 0.69 | 0.64 | 0.31 | 3 |
| Marsh Barrier Beaches | ---- | ---- | ---- | 0 | ---- | ---- | ---- | 0 |
| MIDDLESEX COUNTY | | | | | | | | |
| Total Sample | 1.59 | 1.55 | 0.27 | 2 | 0.38 | 0.30 | 0.36 | 2 |
| Impermeable Beaches | ---- | ---- | ---- | 0 | ---- | ---- | ---- | 0 |
| Permeable Beaches | 1.59 | 1.55 | 0.27 | 2 | 0.38 | 0.30 | 0.36 | 2 |
| Marsh Barrier Beaches | ---- | ---- | ---- | 0 | ---- | ---- | ---- | 0 |
| MATHEWS COUNTY | | | | | | | | |
| Total Sample | 1.57 | 1.52 | 0.29 | 7 | 0.80 | 0.78 | 0.48 | 8 |
| Impermeable Beaches | 1.93 | 1.80 | 0.46 | 1 | 0.77 | 0.86 | 0.58 | 2 |
| Permeable Beaches | 1.58 | 1.57 | 0.27 | 4 | 0.88 | 0.81 | 0.48 | 4 |
| Marsh Barrier Beaches | 1.38 | 1.33 | 0.23 | 2 | 0.67 | 0.61 | 0.37 | 2 |
| GLOUCESTER COUNTY | | | | | | | | |
| Total Sample | 1.36 | 1.33 | 0.30 | 1 | 0.78 | 0.80 | 0.75 | 1 |
| Impermeable Beaches | 1.36 | 1.33 | 0.30 | 1 | 0.78 | 0.80 | 0.75 | 1 |
| Permeable Beaches | ---- | ---- | ---- | 0 | ---- | ---- | ---- | 0 |
| Marsh Barrier Beaches | ---- | ---- | ---- | 0 | ---- | ---- | ---- | 0 |

TABLE 9 (cont'd)
SUMMARY OF SEDIMENT
GRAIN SIZE

| | FINE MODE | | | | COARSE MODE | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean Ø | Median Ø | Standard Deviation | Number of Samples | Mean Ø | Median Ø | Standard Deviation | Number of Samples |
| YORK COUNTY | | | | | | | | |
| Total Sample | 1.56 | 1.53 | 0.36 | 2 | 1.28 | 1.52 | 1.04 | 1 |
| Impermeable Beaches | ---- | ---- | ---- | 0 | ---- | ---- | ---- | 0 |
| Permeable Beaches | ---- | ---- | ---- | 0 | ---- | ---- | ---- | 0 |
| Marsh Barrier Beaches | 1.56 | 1.53 | 0.36 | 2 | 1.28 | 1.52 | 1.04 | 1 |
| HAMPTON* | | | | | | | | |
| Total Sample | 1.97 | 1.32 | 0.84 | 3 | | | | |
| Impermeable Beaches | ---- | ---- | ---- | 0 | | | | |
| Permeable Beaches | 1.94 | 1.44 | 0.92 | 3 | | | | |
| Marsh Barrier Beaches | ---- | ---- | ---- | 0 | | | | |
| NORFOLK/VIRGINIA BEACH* | | | | | | | | |
| Total Sample | 1.15 | 1.02 | 0.44 | 5 | | | | |
| Impermeable Beaches | ---- | ---- | ---- | 0 | | | | |
| Permeable Beaches | 1.15 | 1.02 | 0.44 | 5 | | | | |
| Marsh Barrier Beaches | ---- | ---- | ---- | 0 | | | | |

* The physiographic subdivision encompassing Hampton and Norfolk/Virginia Beach showed no differentiation of beachface sediments. A single representative sample was taken in these areas.

TABLE 10
SUMMARY OF SEDIMENT GRAIN SIZE
SAMPLES FROM BACKSHORE BLUFFS
VALUES IN PHI UNITS

| | Mean (Ø) | Median (Ø) | Standard Deviation | Number of Samples |
|---|---|---|---|---|
| VIRGINIA CHESAPEAKE BAY | | | | |
| Total Sample | 1.52 | 1.49 | 0.45 | 29 |
| Impermeable Beaches | 1.54 | 1.53 | 0.44 | 24 |
| Permeable Beaches | 1.26 | 1.23 | 0.52 | 2 |
| EASTERN SHORE | | | | |
| Total Sample | 1.55 | 1.51 | 0.48 | 11 |
| Impermeable Beaches | 1.62 | 1.58 | 0.47 | 9 |
| Permeable Beaches | 1.26 | 1.23 | 0.52 | 2 |
| WESTERN SHORE | | | | |
| Total Sample | 1.48 | 1.47 | 0.43 | 18 |
| Impermeable Beaches | 1.48 | 1.47 | 0.43 | 18 |
| Permeable Beaches | ---- | ---- | ---- | 2 |
| NORTHAMPTON COUNTY | | | | |
| Total Sample | 1.34 | 1.30 | 0.49 | 4 |
| Impermeable Beaches | 1.42 | 1.36 | 0.47 | 2 |
| Permeable Beaches | 1.26 | 1.23 | 0.52 | 2 |
| ACCOMAC COUNTY | | | | |
| Total Sample | 1.47 | 1.46 | 0.42 | 7 |
| Impermeable Beaches | 1.47 | 1.46 | 0.42 | 7 |
| Permeable Beaches | ---- | ---- | ---- | 0 |
| NORTHUMBERLAND COUNTY | | | | |
| Total Sample | 1.53 | 1.49 | 0.44 | 10 |
| Impermeable Beaches | 1.53 | 1.49 | 0.44 | 10 |
| Permeable Beaches | ---- | ---- | ---- | 0 |
| LANCASTER COUNTY | | | | |
| Total Sample | 1.85 | 1.75 | 0.46 | 3 |
| Impermeable Beaches | 1.85 | 1.75 | 0.46 | 3 |
| Permeable Beaches | ---- | ---- | ---- | 0 |
| MIDDLESEX COUNTY | | | | |
| Total Sample | 1.43 | 1.41 | 0.45 | 1 |
| Impermeable Beaches | 1.43 | 1.41 | 0.45 | 1 |
| Permeable Beaches | ---- | ---- | ---- | 0 |
| MATHEWS COUNTY | | | | |
| Total Sample | 1.84 | 1.83 | 0.49 | 2 |
| Impermeable Beaches | 1.84 | 1.83 | 0.49 | 2 |
| Permeable Beaches | ---- | ---- | ---- | 0 |

TABLE 10 (cont'd)
SUMMARY OF SEDIMENT
GRAIN SIZE
SAMPLES FROM BACKSHORE BLUFFS

| | Mean (Ø) | Median (Ø) | Standard Deviation | Number of Samples |
|---|---|---|---|---|
| GLOUCESTER COUNTY | | | | |
| Total Sample | 1.43 | 1.40 | 0.45 | 1 |
| Impermeable Beaches | ---- | ---- | ---- | 0 |
| Permeable Beaches | 1.43 | 1.40 | 0.45 | 1 |
| YORK COUNTY | | | | |
| Total Sample | 1.44 | 1.42 | 0.43 | 1 |
| Impermeable Beaches | 1.44 | 1.42 | 0.43 | 1 |
| Permeable Beaches | ---- | ---- | ---- | 0 |
| HAMPTON | | | | |
| Total Sample | ---- | ---- | ---- | 0 |
| Impermeable Beaches | ---- | ---- | ---- | 0 |
| Permeable Beaches | ---- | ---- | ---- | 0 |

TABLE 11
SUMMARY OF SEDIMENT GRAIN SIZE
SAMPLES BENEATH IMPERMEABLE BEACHES
VALUES IN PHI UNITS

| | Mean (Ø) | Median (Ø) | Standard Deviation | Number of Samples |
|---|---|---|---|---|
| VIRGINIA CHESAPEAKE BAY | 1.63 | 1.58 | 0.48 | 21 |
| EASTERN SHORE | 1.52 | 1.48 | 0.49 | 14 |
| WESTERN SHORE | 1.84 | 1.78 | 0.45 | 11 |
| NORTHAMPTON COUNTY | 1.46 | 1.41 | 0.45 | 5 |
| ACCOMACK COUNTY | 1.56 | 1.53 | 0.52 | 9 |
| NORTHUMBERLAND COUNTY | 1.95 | 1.86 | 0.46 | 4 |
| LANCASTER COUNTY | 1.69 | 1.67 | 0.44 | 3 |
| MIDDLESEX COUNTY | 1.74 | 1.74 | 0.43 | 1 |
| MATHEWS COUNTY | 1.75 | 1.74 | 0.41 | 1 |
| GLOUCESTER COUNTY | 1.80 | 1.72 | 0.49 | 1 |
| YORK COUNTY | 1.76 | 1.68 | 0.41 | 1 |
| HAMPTON | ---- | ---- | ---- | 0 |

Figure 22: Mean grain size of fastland samples, Virginia Chesapeake Bay. The plot shows samples from exposed backshore bluffs and from beneath impermeable beaches. A summary of this data is shown in Tables 10 and 11.

VIRGINIA CHESAPEAKE BAY

MEAN GRAIN SIZE- FASTLAND SAMPLES

VALUES IN PHI EQUIVILENT UNITS

° BACKSHORE BLUFF SAMPLES

x SAMPLES OF IMPERMEABLE LAYERS BENEATH PERMEABLE SANDS

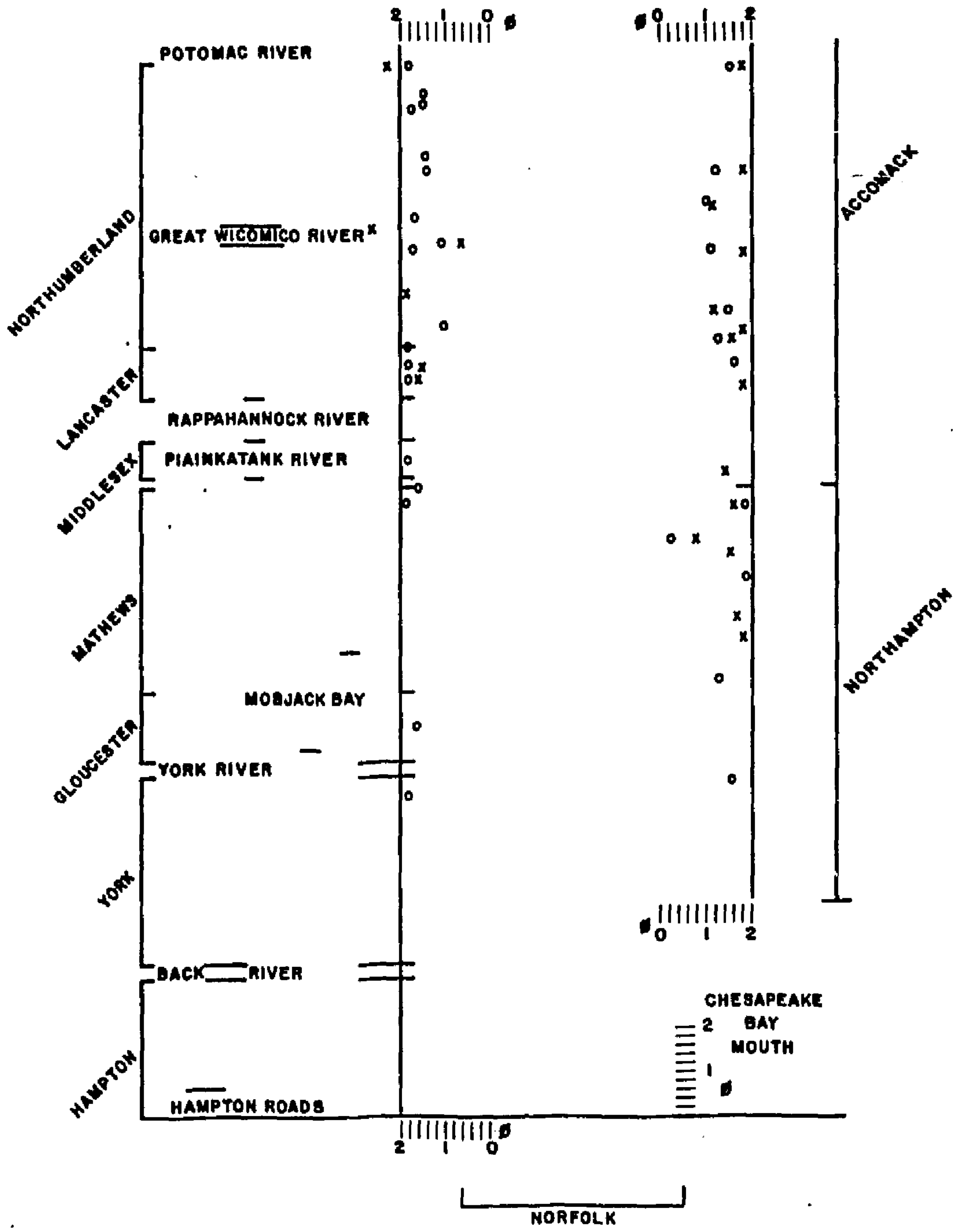


Figure 23: Photograph of beach trench in foreshore of a permeable beach showing typical interlayered fine and coarse modes. Seaward is to the left.

the regional sand input into the system. Correspondence of the fine-mode beachface mean (1.46 Ø) and the bluff mean (1.52 Ø) suggest a direct source for this mode. The coarse mode is probably a re-sorting of this material. The ends of accreting spits were typically composed entirely of the coarse mode of sediments. The mechanism for this sorting is beyond the scope of this investigation.

The coarse mode of beachface sediments showed no differentiation by beach environment. However, the fine mode generally was coarser on impermeable beaches than on permeable beaches (Table 9). This trend may be a function of the increased backwash on impermeable beaches resulting from decreased infiltration of the swash. This results in a winnowing of the finer tail of the sediment distribution. This is an equilibrium process, as the resulting coarser sediments can be expected to have a higher rate of infiltration.

The sand content of the bluff samples shows a correspondence to the physiographic sub-divisions (Table 8). Early primary shorelines have a source material of 24-43% sand, so erosion of the shoreline inputs relatively little sand into the system, despite the high rate of erosion. The late primary and early secondary shorelines all have high (78-100%) bluff sand content. As early primary shorelines also have the smallest bluff heights in the study area, these are the most sand-starved environments in the Bay.

In summary, the regional distribution of beachface sedimentation in the study area is characterized by two major modes of interlayered sediment. The finer mode corresponds in means to a sampling of source material, while the coarser mode is probably the result of re-working. Impermeable beach environments respond to the increased backwash by a slightly coarser trend of the sediments. The sand content and volume input into the beach system by bluff erosion corresponds to, and probably is a causitive factor of the succession of shorelines from primary to secondary forms.

## EFFECTS OF VARIATION IN TIDAL RANGE ON THE SHORELINE

The Virginia Chesapeake Bay has a 200% variation in tidal range (0.36 m to 1 m) over a 120 km shoreline distance.

Although the tides throughout the Bay are classified as microtidal, the effects of variations in tidal range on the shoreline can be examined over a relatively small area.

The tidal wave characteristics of the Chesapeake Bay are described in detail by Hicks (1964). An earlier compilation of tides and current data for the Bay was made by Haight et al (1930). Harris (1907) published an early co-tidal chart for the Chesapeake Bay. Systematic tide records were begun in the Chesapeake Bay in 1844 at Annapolis, Maryland and at Old Point Comfort, Virginia. Since then, 241 tide stations have been occupied by the Coast and Geodetic Survey in the Chesapeake Bay.

The tides in the Virginia Chesapeake Bay are classified as "semi-diurnal" in all areas except for the 74 km of shoreline from Gwynns Island to the Potomac River (western shore), where the tides are considered to be "mixed, semi-diurnal" (Courtier, 1938).

The tidal range in the Chesapeake Bay decreases from one meter at the Bay Mouth, to about 0.36 m off Annapolis, and finally rises to 0.70 m at the northern end of the Bay. The maximum range in the Chesapeake Bay is 1.2 m at Walkerton, on the upper Mattaponi River, which flows into the York River on the western shore.

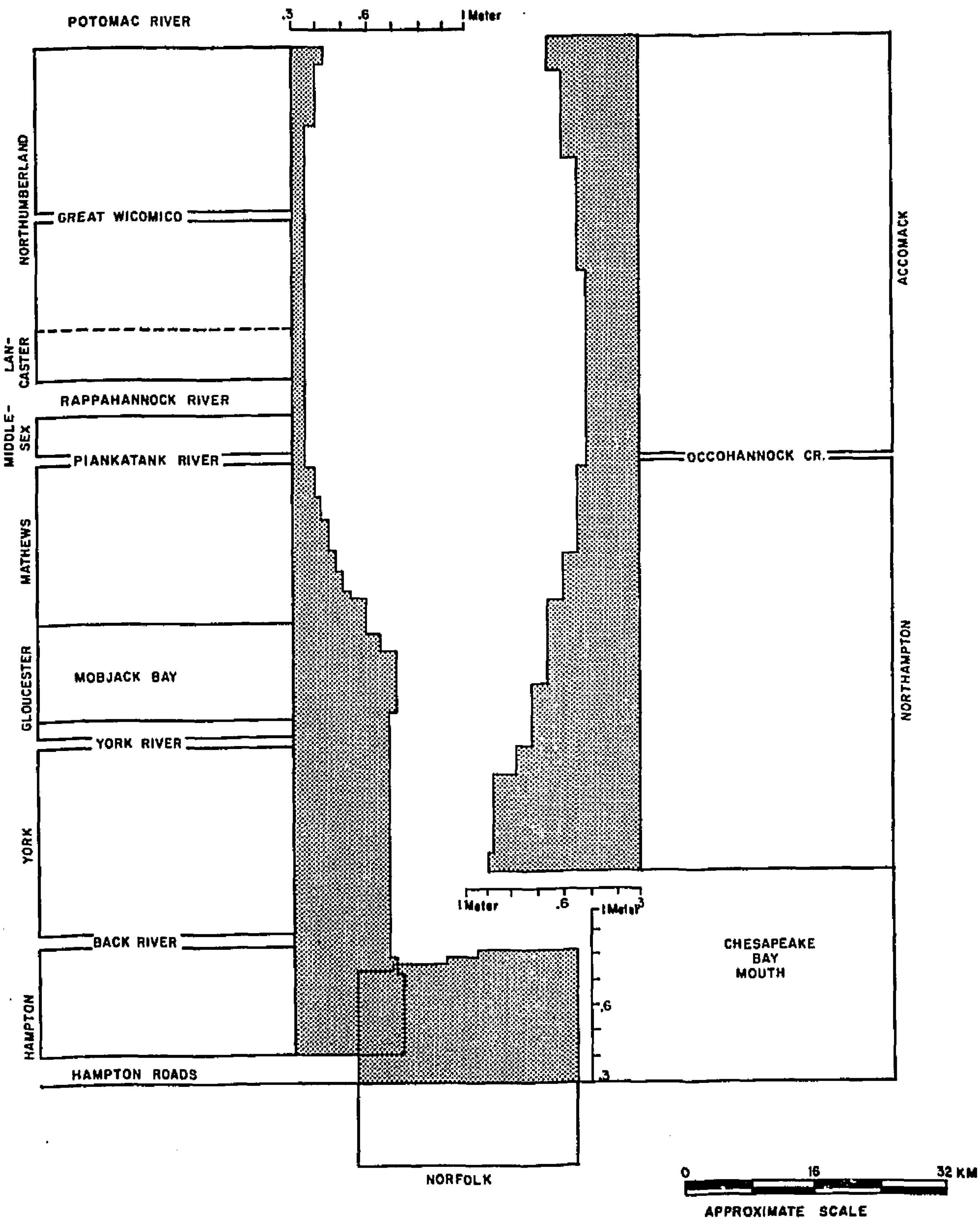
The tide range is significantly larger on the eastern shore of the Bay. This is due to the predominant progressive nature of the tidal wave. Since the strongest flood currents occur near high water, and strongest ebb currents near low water, the Coriolis effect augments the height of high water and decreases the height of low water on the eastern shore. This effect is most pronounced in the lower (Virginia) portion of the Chesapeake Bay (Hicks, 1964).

Figure 24 shows the variations in tidal range along the shore margins of the Virginia Chesapeake Bay. The general trend is a decrease in tidal range from the south to the north, with a slight increase in northern Accomack County (eastern shore). The distribution of the tidal ranges in the study area varies from one meter at the Bay mouth, to 0.3 meter off the Potomac River. The tide range is higher on the Eastern Shore at all points, compared to the corresponding point on the western shore. This disparity reaches a maximum of 0.3 meter at the northern end of the study area, but averages about 0.15 meter.

The elevation of the beach, measured from the low water line to the maximum elevation of the backbeach, is

Figure 24: Variation in mean tidal range along the Virginia Chesapeake Bay shoreline. The shoreline of the margins of the Bay have been straightened to interpret the regional trends.

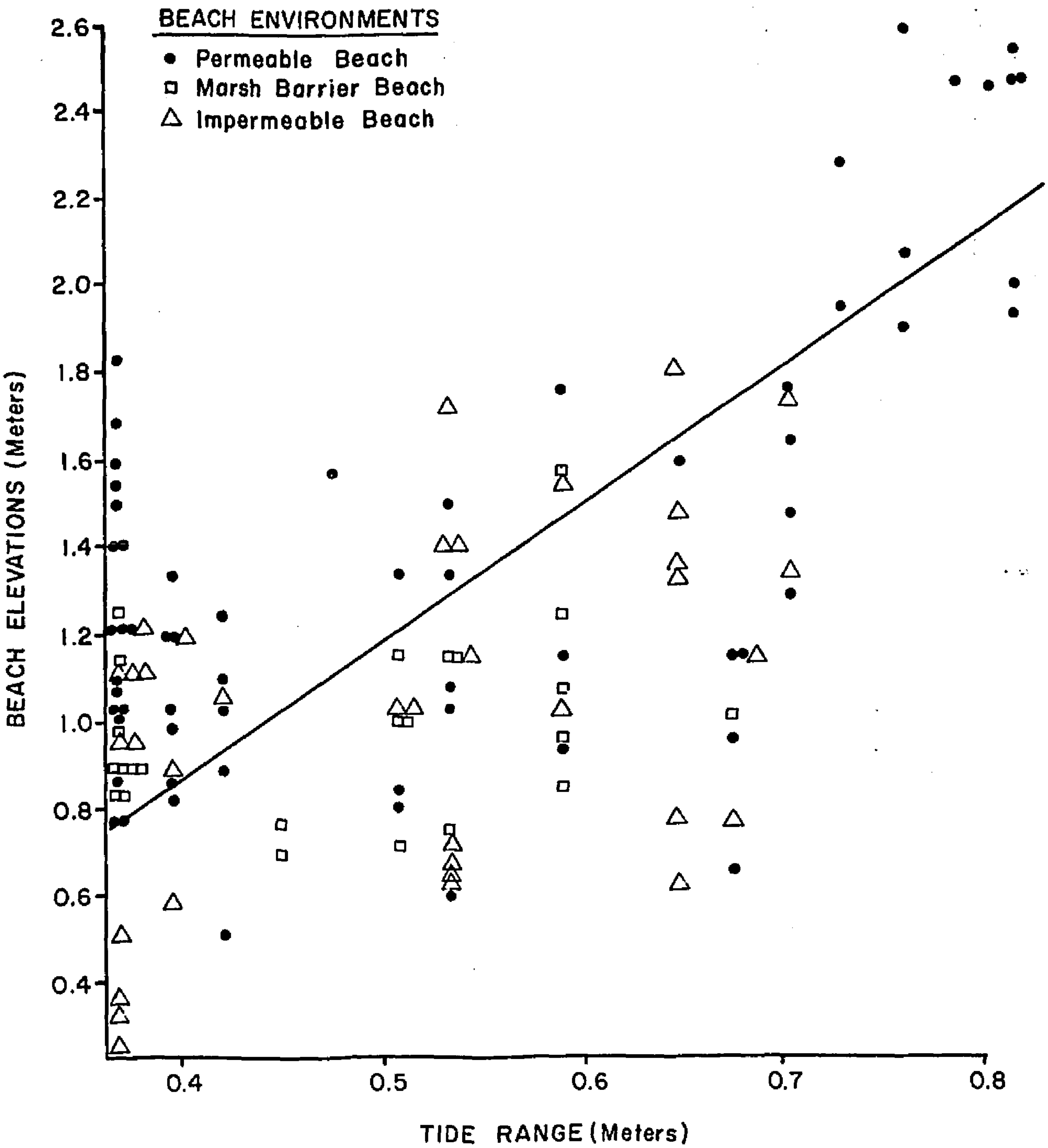
# VIRGINIA CHESAPEAKE BAY
# TIDE RANGE ALONG SHORELINE



correlated to the tidal range. Figure 25 shows the relationship between beach elevation and tidal range for each major coastal environment in the system. The coefficient of determination ($r^2$) for the sample of all beach environments is .33, and the tidal range coefficient is significant at the 1% level. Considering the noise level (Krumbein, 1960) of single variables extracted from a complex geologic interface (the shoreline) over a large area, this result is considered real. Each individual beach environment in the system (permeable, beach composed entirely of sand-sized material; impermeable, beach underlain by impermeable clay layer; marsh barrier, beach underlain by salt marsh peat) shows a similarly high coefficient of determination ($r^2$= .43, .21, .25, respectively) demonstrating the direct relationship between total beach elevation and tidal range.

By substracting the tidal range from the total elevation of the beach, a measure of the supra-tidal elevation of the beach is obtained. This is the elevation from the mean high water level to the maximum elevation of the back beach. As the supra-tidal elevation is a direct function of tide range and beach elevation, the previous statistical inferences also suggest higher tidal range beaches have a higher supra-tidal elevation. The magnitude of the supra-tidal elevation in permeable beaches is almost twice as large as the other environments. The permeable beaches comprise 47% of the shore

Figure 25: Variation in elevation of Virginia Chesapeake Bay beaches as a function of mean tidal range. The relationship is direct. Statistical results shown in Table 13.



BEACH ENVIRONMENTS
Permeable Beach
Marsh Barrier Beach
Impermeable Beach
BEACH ELEVATIONS (Meters)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.4
0.5
0.6
0.7
0.8
TIDE RANGE (Meters)

environments in the study area.

The inverse relationship between tidal range and erosion rates in the Virginia Chesapeake Bay can be demonstrated by comparing the areas of tidal range extremes in the system. Table 12 shows the average erosion rates of the highest tidal range areas in the Virginia Chesapeake Bay (Northampton County, Hampton and Norfolk, and Mobjack Bay to York County), which comprises the southern end of the Bay, and the lowest tidal range in the system (Potomac River to Rappahannock River). In each shoreline environment, the higher tidal range regions show a lower average erosion rate than the low tidal range area.

Figure 26 demonstrates the relationship between tidal range and long-term (80 years) erosion rates. The tidal range is inversely related to erosion, indicating that a higher tidal range results in lower expected erosion from a given set of conditions. This relationship is significant for the total beach system, and the total shoreline system at the 2.5% and 1% levels, respectively. The result in each beach environment supports the overall trend of the system, but the greater relative variation in the smaller number of samples result in a lack of statistical confirmation (Table 13).

A physical explanation for this relationship can be

TABLE 12
EROSION RATES COMPARED TO TIDAL RANGE
VIRGINIA CHESAPEAKE BAY

| | LARGE TIDAL RANGE | | | | | | SMALL TIDAL RANGE | |
|---|---|---|---|---|---|---|---|---|
| | Northampton County | | Mobjack Bay to York County | | Hampton and Norfolk | | Potomac River to Piankitank River | |
| Tide Range | 0.6 - 1.0 m | | 0.7 m | | 0.8 - 1.0 m | | 0.3 - 0.4 m | |
| | Length km | Erosion m/yr | Length km | Erosion m/yr | Length km | Erosion m/yr | Length km | Erosion m/yr |
| All Beach Environments | 57.5 | 0.82 | 52.3 | 0.57 | 38.9 | 0.84 | 75.8 | 1.09 |
| Permeable Beaches | 39.8 | 0.61 | 10.8 | 0.73 | 38.9 | 0.84 | 36.0 | 1.03 |
| Impermeable Beaches | 17.7 | 1.30 | 13.4 | 0.69 | 0 | -- | 26.3 | 1.35 |
| Marsh Barrier Beaches | 0 | -- | 28.0 | 0.43 | 0 | -- | 13.2 | 0.70 |
| Marsh Margins | 2.6 | 0.54 | 21.1 | 0.51 | 0 | -- | 5.9 | 0.67 |

Figure 26: Variation in long-term erosion rates of the Virginia Chesapeake Bay as a function of mean tidal range. The relationship is inverse. Statistical results shown in Table B.

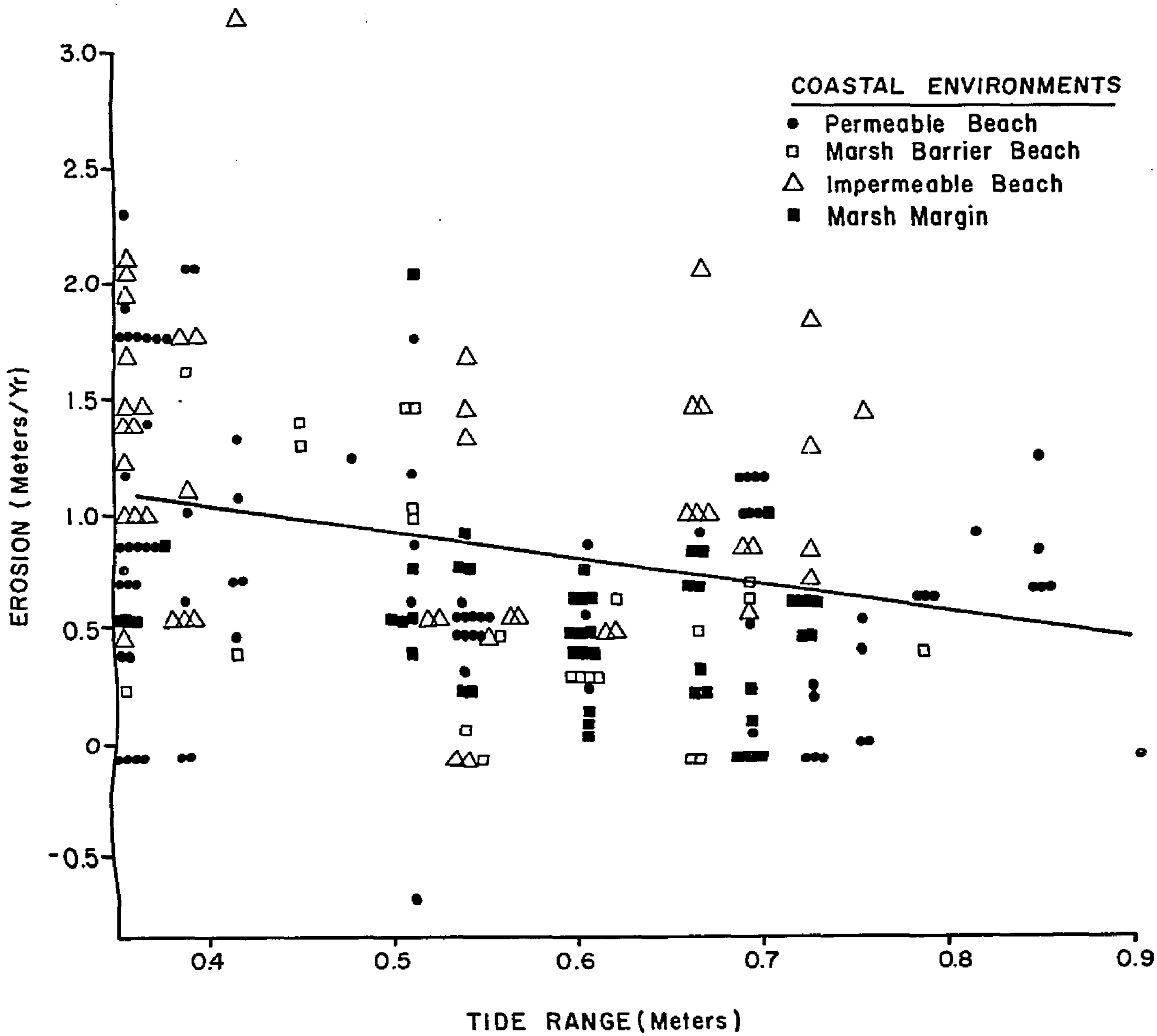

COASTAL ENVIRONMENTS
Permeable Beach
Marsh Barrier Beach
Impermeable Beach
Marsh Margin
EROSION (Meters/Yr)
3.0
2.5
2.0
1.5
1.0
0.5
0
-0.5
0.4
0.5
0.6
0.7
0.8
0.9
TIDE RANGE (Meters)

TABLE 13
STATISTICAL RESULTS

EQUATIONAL FORM: $y = \alpha + \beta x$

| DATA STRATIFICATION | VARIABLES- DEPENDENT (Y) INDEPENDENT (X) | $\alpha$ | t-STATISTIC | SIGNIFICANCE | $\beta$ | t-STATISTIC | SIGNIFICANCE | $r^2$ | OBSERVATIONS |
|---|---|---|---|---|---|---|---|---|---|
| All Beach Environments | eros/tide | 1.22 | 6.50 | < .001 | -0.65 | -2.103 | < .025 | .03 | 117 |
| | elev/tide | 0.75 | 1.69 | < .05 | 0.68 | +7.575 | < .001 | .33 | 117 |
| Total Shoreline | eros/tide | 1.17 | 8.70 | < .001 | -0.42 | -4.402 | < .001 | .07 | 206 |
| Permeable Beaches | eros/tide | 3.58 | 3.96 | < .001 | -0.56 | -1.169 | < .15 | .02 | 58 |
| | elev/tide | 0.31 | 1.83 | < .05 | 0.59 | +6.14 | < .001 | .43 | 58 |
| Impermeable Beaches | eros/tide | 4.31 | 6.76 | < .001 | -1.51 | -1.314 | < .100 | .05 | 38 |
| | elev/tide | 0.27 | 1.15 | < .15 | 0.41 | +3.053 | < .005 | .21 | 38 |
| Marsh Barrier Beaches | leros/tide | 2.55 | 4.01 | < .001 | -1.06 | -2.792 | < .010 | .29 | 21 |
| | elev/tide | 0.75 | 3.45 | < .005 | 0.16 | +1.226 | < .150 | .25 | 21 |
| Marsh Margins | eros/tide | 3.71 | 3.4 | < .01 | -0.95 | -1.832 | < .050 | .10 | 38 |

Variables:
eros - erosion rates
leros - In erosion rate
tide - tidal range
elev - beach elevation

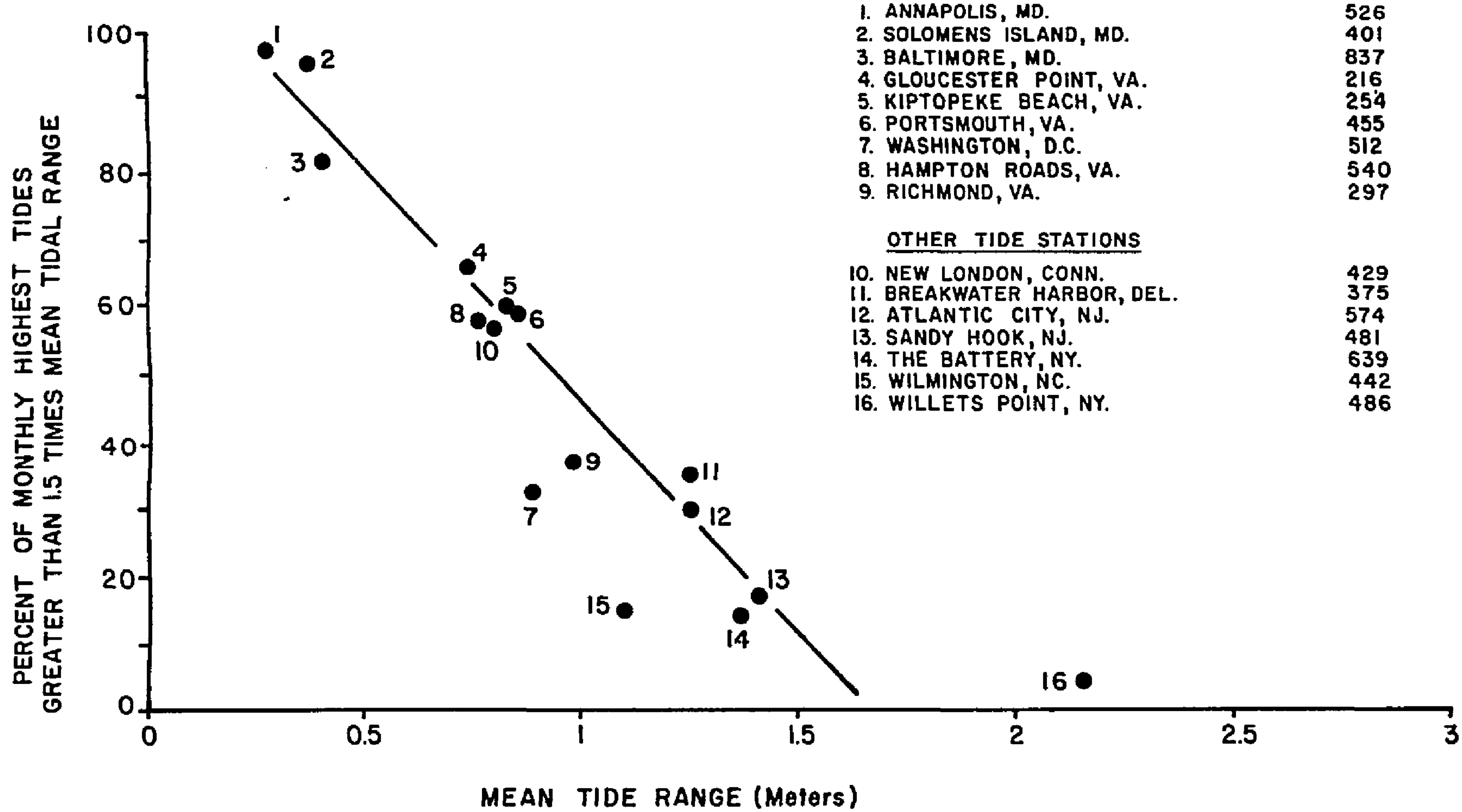
based on three factors:

1. In areas of lower tidal range, storm waves and surge have a greater probability of overtopping the beach, regardless of the stage of the tide (i.e., low or high) since the beach elevation is a function of tidal range. In areas of higher tidal range, the beach face serves as a buffer to raised water levels during lower tidal stages. This corresponds to a large percentage of the time during the occurrence of any storm surges. Any given meteorologic tide (surge) is a smaller percentage of the astronomic tide in areas of larger tidal range (Fig. 27). Thus, water levels increased by surges less often reach the elevation of the fastland (dune or bluff) material. This data documents the greater susceptibility of areas with low tidal ranges to flooding by storm surge. Warnke, et al. (1966) observed that shoreline erosion is controlled by the occurrence of storm surges raising water levels to the dune ridge behind the backbeach, not the size of the waves, in the low energy shore environment on the west coast of Florida. The same trend is evident in the Chesapeake Bay.

2. Since the supra-tidal elevation of the beach increases with higher tidal ranges, this increased elevation serves as an additional buffer to direct wave and surge effects on the backbeach and fastland areas, especially at high tide.

3. In areas of higher tidal range, the plunge point

Figure 27: Plot showing the percent of monthly highest tides greater than 1.5 times mean tidal range versus mean tidal range. This plot demonstrates that a given storm surge is a smaller percentage of the tide range with increasing tide range (Carl H. Hobbs, written communication, 1976).




| TIDE STATIONS IN CHESAPEAKE BAY | RECORD LENGTH (MONTHS) |
|---|---|
| 1. ANNAPOLIS, MD. | 526 |
| 2. SOLOMENS ISLAND, MD. | 401 |
| 3. BALTIMORE, MD. | 837 |
| 4. GLOUCESTER POINT, VA. | 216 |
| 5. KIPTOPEKE BEACH, VA. | 254 |
| 6. PORTSMOUTH, VA. | 455 |
| 7. WASHINGTON, D.C. | 512 |
| 8. HAMPTON ROADS, VA. | 540 |
| 9. RICHMOND, VA. | 297 |
| **OTHER TIDE STATIONS** | |
| 10. NEW LONDON, CONN. | 429 |
| 11. BREAKWATER HARBOR, DEL. | 375 |
| 12. ATLANTIC CITY, NJ. | 574 |
| 13. SANDY HOOK, NJ. | 481 |
| 14. THE BATTERY, NY. | 639 |
| 15. WILMINGTON, NC. | 442 |
| 16. WILLETS POINT, NY. | 486 |

of the breaking wave is distributed over a larger vertical distance during the time of the tide cycle. Also, the horizontal variation is quite large for the low gradient Chesapeake Bay beaches. Thus, the bulk of wave energy expended on the beach by the breaking waves is not concentrated on one point or a small area.

The inverse relationship between tidal range and erosion is also significant on the marsh margin shore environment. This is also probably a function of the wave energy being distributed over a larger area of the marsh margin through time, so any single point in the rhizome framework of the exposed marsh is not attacked and weakened, causing the eventual slumping of the peat, which results in retreat of the marsh shoreline.

In summary, it is apparent that a larger tidal range results in a more effective shoreline buffer for the erosional processes of the Chesapeake Bay shoreline, as indicated by decreased rates of long-term shore retreat. This relationship is explained by the observations that the larger tide range causes a higher beach to form than in areas of lower tidal range. Water levels increased by surges less often reach the fastland material, which is most susceptible to erosion by waves. This also results in a distribution of the wave energy over a larger vertical and horizontal area in the course of a tidal cycle.

This relationship is readily demonstrable in the

Chesapeake Bay since a large variation in tidal range occurs over a relatively short distance. It is proposed that this relationship is a general controlling factor on all tidal shorelines.

NEARSHORE TERRACES

The morphology of the nearshore in the Chesapeake Bay is dominated by a broad flat terrace, which extends from the low water line to about the 3.6 m contour (12 ft.). A break-in-slope delineates the seaward margin of the terrace, where the bottom then grades into deeper water. The seaward margin of the terrace is sometimes poorly defined, as the break-in-slope may be gradational; extending as deep as the 5.4 m (18 ft.) contour. For the regional compilation in this study, this margin is defined as the 3.6 m (12 ft.) depth. The mean slope of the terrace is .002, but ranges from .024 to nearly zero.

It is suggested by Athearn, et al. (1974) that the nearshore terrace is a wave base phenomena, since the 3.6 m contour is approximately wave base for a three second wave. This may be an influencing factor in the terrace processes, but the evidence to be presented suggest this structure is primarily a remnant erosional platform. Field reconnaissance shows that the terrace surfaces are often an erosional cut into the pre-Holocene sediments. However, it is often unclear whether the surface material of the nearshore is fine sediment deposition or autochthonous bioturbation. In either event, superimposed on the terrace in most exposed reaches are multiple offshore bar systems (O'Brien, 1968). The most extensive bar systems occur in Northampton County, which has the greatest fastland sediment supply, due to the large bluff heights and high sand content in the bluffs. Generally, the sand in the nearshore zone is not a continuous layer, due to the paucity of sand in the total system.

The nearshore terrace structure on the south shore of the Chesapeake Bay (Hampton and Norfolk) loses definition. The coastal environment in this physiographic subdivision is unique in the study area and is apparently due to the large sediment influx through the Chesapeake Bay Mouth. The nearshore is sandy, and the beaches are broad and high, similar to the adjacent ocean beaches. The nearshore morphology is best defined as a continuous, gradual slope. The wave climate in this area is an energy maximum. The south shore of the Bay is exposed to maximum fetch from the north, and maximum exposure to the Bay mouth. This suggests that the basic form of the nearshore terraces along the flanks of the Bay are a long-term erosional remnant, rather than a short-term wave-response process.

Textbook examples of wave refraction (e.g. Garner, 1974) show a convergence of orthogonals on headlands and divergence around embayments. This model assumes the nearshore bathymetry is an extension of the shoreline form. The nearshore terraces in the Virginia Chesapeake Bay are commonly a flat bench that in highly dissected areas do not reflect the shoreline form. A contributing factor is the lack of sand in the system. So waves reaching the shoreline in these areas do not necessarily converge on the headlands, within the small-scale variations in the shoreline, effecting straightening of the shoreline. This explains, at the sampling interval, that most shoreline retreat was parallel, rather than effecting a reorientation of the shore (see reorientation data in Appendix B).

Figure 28 shows the distribution of nearshore terrace widths in the Virginia Chesapeake Bay. The largest terraces in the system occur in Accomack County, with a mean width of 4018 m. The second largest regional terrace widths occur in York County, with a mean width of 1923 m. Both of these areas correspond to the highest submergence rates on their respective sides of the Bay. The nearshore terraces throughout the remainder of the Bay range from 600-1000 meters (Table 14).

The mean nearshore width (2897 m) on the eastern shore is considerably higher than the western shore mean width (1166 m). As well as a function of subsidence, an additional factor is the higher degree of dissection of the Western shore by river drainage. The many orders of drainage channels cutting through the terraces may decrease the regional averages.

The nearshore terraces of the Virginia Chesapeake Bay are an erosional remnant feature, bounded by the

Figure 28: Variation of nearshore terrace widths along the Virginia Chesapeake Bay shoreline. The shoreline of the margins of the Bay have been straightened to interpret the regional trends.

# VIRGINIA CHESAPEAKE BAY NEARSHORE TERRACE WIDTH

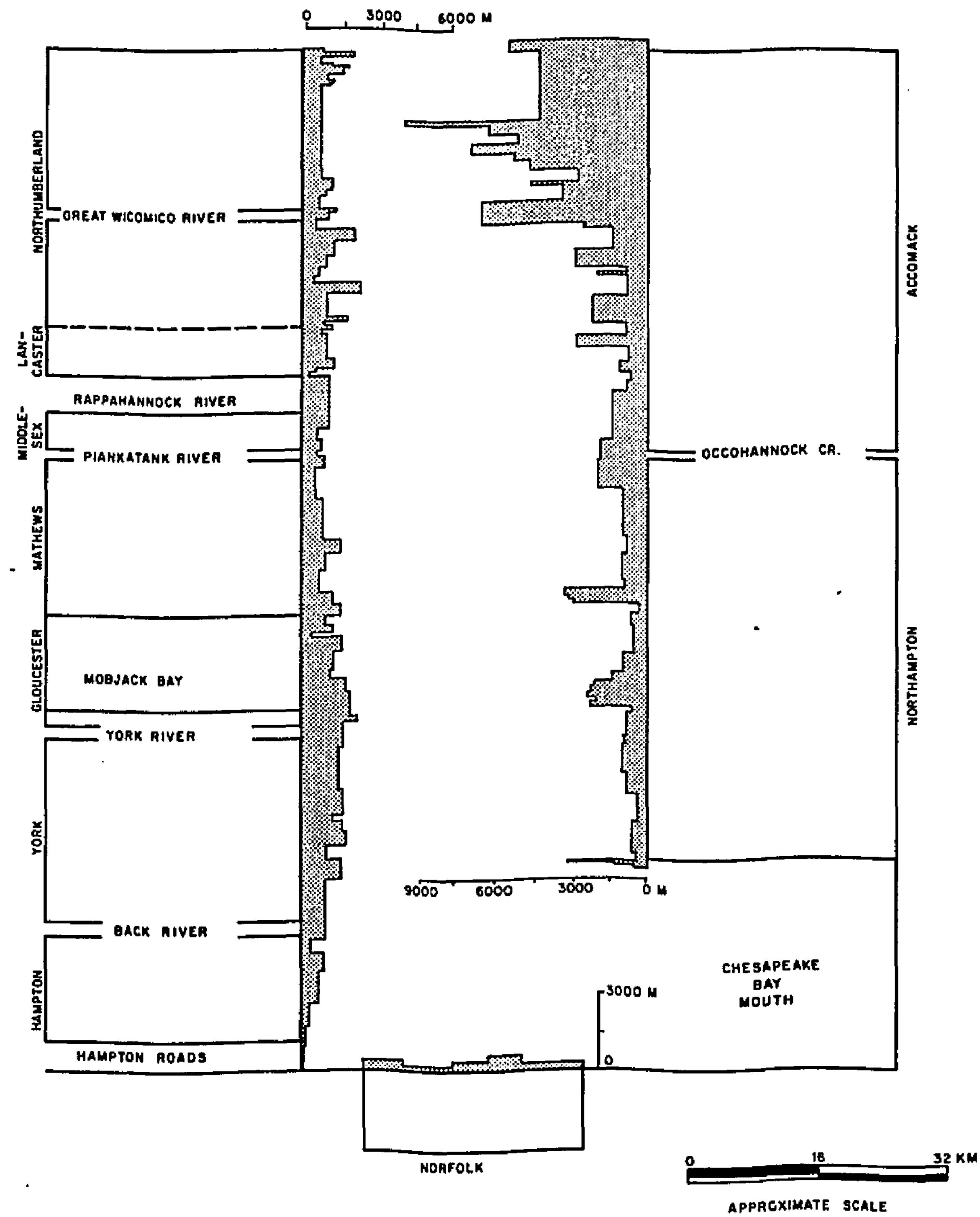


TABLE 14
NEARSHORE TERRACE WIDTHS
VIRGINIA CHESAPEAKE BAY

| | Mean Width (meters) | Standard Deviation | Weighted Mean Width (meters) | Standard Deviation |
|---|---|---|---|---|
| VIRGINIA CHESAPEAKE BAY | 1849 | 2068 | 1777 | 541 |
| EASTERN SHORE | 2942 | 2695 | 2897 | 3350 |
| WESTERN SHORE | 1006 | 605 | 1015 | 1862 |
| WESTERN SHORE (excluding Hampton/ Norfolk) | 1070 | 595 | 1166 | 1946 |
| COUNTIES: | | | | |
| NORTHAMPTON | 1393 | 907 | 1361 | 623 |
| ACCOMACK | 4212 | 3003 | 4018 | 1992 |
| NORTHUMBERLAND | 1154 | 585 | 1129 | 748 |
| LANCASTER | 890 | 266 | 880 | 430 |
| MIDDLESEX | 944 | 444 | 890 | 523 |
| MATHEWS | 1038 | 347 | 978 | 413 |
| GLOUCESTER | 989 | 706 | 978 | 548 |
| YORK | 1150 | 1023 | 1923 | 547 |
| HAMPTON | 383 | 310 | 430 | 570 |
| NORFOLK/VIRGINIA BEACH | 375 | 205 | 368 | 606 |
| INTERFLUVES: | | | | |
| POTOMAC RIVER TO RAPPAHANNOCK RIVER | 1096 | 540 | 1065 | 687 |
| RAPPAHANNOCK RIVER TO YORK RIVER | 1005 | 502 | 963 | 634 |

TABLE 14 (cont'd)
NEARSHORE TERRACE WIDTHS
VIRGINIA CHESAPEAKE BAY

| | Mean Width (meters) | Standard Deviation | Weighted Mean Width (meters) | Standard Deviation |
|---|---|---|---|---|
| YORK RIVER TO JAMES RIVER | 895 | 919 | 1395 | 451 |
| PHYSIOGRAPHIC SUBDIVISIONS: | | | | |
| POTOMAC RIVER TO GREAT WICOMICO RIVER | 1002 | 435 | 924 | 1134 |
| GREAT WICOMICO RIVER TO PIANKATANK RIVER | 1135 | 586 | 1134 | 690 |
| GWYNNS ISLAND TO NEW POINT COMFORT | 1053 | 368 | 1000 | 770 |
| MOBJACK BAY TO YORK COUNTY | 1055 | 779 | 1438 | 3453 |
| HAMPTON AND NORFOLK/ VIRGINIA BEACH | 379 | 268 | 391 | 614 |

present shoreline, and on the seaward side by a break-in-slope, where the bottoms grade more steeply into deeper water. On the assumption that this feature is not a wave-induced phenomenon, an explanation for the seaward break-in-slope must be proposed. Factors considered 'noise' in the data with regard to this question include varying rates of subsidence in the Bay, varying degrees of river drainage dissection of the landform, and varying local coastal environments. The nearshore terraces all terminate at approximately the same depth. This consistancy suggests that this regional slope change is due to a singular regional event.

An estimate of the age of the terrace margins can be made by extrapolating the measured shoreline erosion rates (80 year interval) seaward to the terrace margins for each reach, and averaging the results. Table 15 shows the estimates of the age of the terrace margins. The weighted means are a more representative regional sampling. The estimates of marsh reaches (including marsh margins and marsh barrier beaches) are further complicated by the effect of biologic activity on the shoreline position and process, so the means of beach reaches only are the best estimate. The age of the terrace margins, averaged Bay-wide, is 3147 years. The age of the Eastern shore terrace is 2938 years, and the Western shore is 3249 years.

The event that caused the change in nearshore slope

TABLE 15
CALCULATED AGE OF NEARSHORE TERRACE MARGINS
(Years)

| | Age From Calculated Erosion Marsh Reaches | Age From Measured Erosion Marsh Teaches | Age From Calculated Erosion Beach Reaches | Age From Measured Erosion Beach Reaches | Marsh Shoreline Length (km) | Beach Shoreline Length (km) |
|---|---|---|---|---|---|---|
| VIRGINIA CHESAPEAKE BAY | 1322 | 6288 | 2044 | 3147 | 98 | 237 |
| EASTERN SHORE | 1326 | 8955 | 2243 | 2938 | 58 | 77 |
| WESTERN SHORE | 1317 | 2488 | 1947 | 3249 | 40 | 159 |
| POTOMAC RIVER TO RAPPAHANNOCK RIVER | 1258 | 2352 | 1971 | 1185 | 14 | 61 |
| RAPPAHANNOCK RIVER TO YORK RIVER | 1343 | 2470 | 1806 | 1543 | 22 | 38 |
| YORK RIVER TO JAMES RIVER | 1361 | 2925 | 1783 | 10647 | 5 | 35 |
| NORFOLK/VIRGINIA BEACH | ---- | ---- | 2336 | 537 | 0 | 25 |
| NORTHAMPTON COUNTY | 1416 | 7250 | 2489 | 2079 | 3 | 54 |
| ACCOMACK COUNTY | 1321 | 9059 | 1690 | 4878 | 55 | 24 |

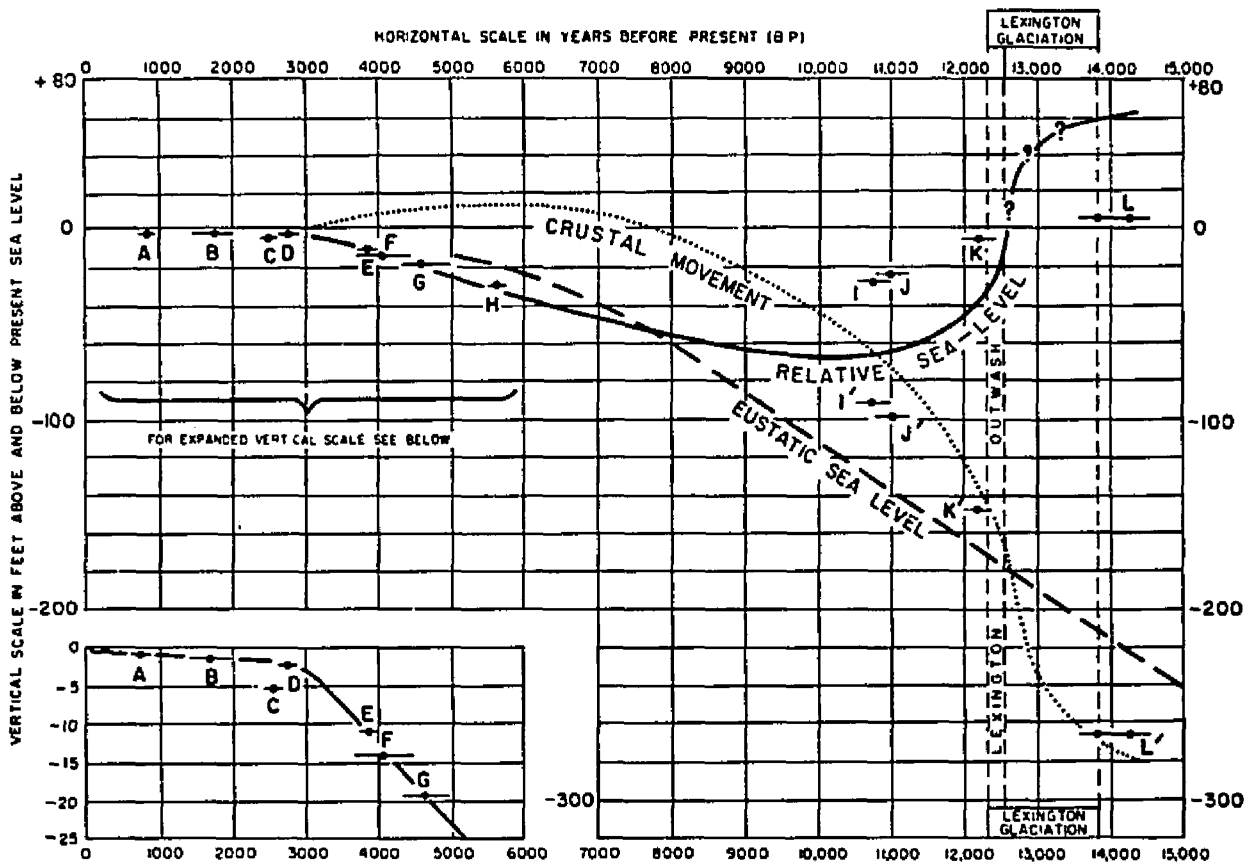
occurred about 3000 years ago. Figures 29 and 30 show sea-level rise curves by Kaye and Barghoorn (1964) and Redfield (1967) along the east coast the age of the change in rate of sea level rise is 3000 years, which corresponds to the initiation of terraces in the Bay.

The hypothesis that the rate of sea level rise has a causal relationship with the nearshore gradient is further substantiated by evidence of Bruun (1962), who investigated the role of sea level rise and shore erosion in Florida. Bruun found areas of steeper offshore slope corresponded to higher local rates of sea level rise, and the lower slopes to lower sea level rates.

An alternative hypothesis is that the shelf break at the seaward margin of the nearshore terraces represents the limits of the ancestral Susquehanna River flood plain. The terraces represent a sea level rise and wave induced phenomenon whose form is controlled by the previous, fluvial geomorphic agent.

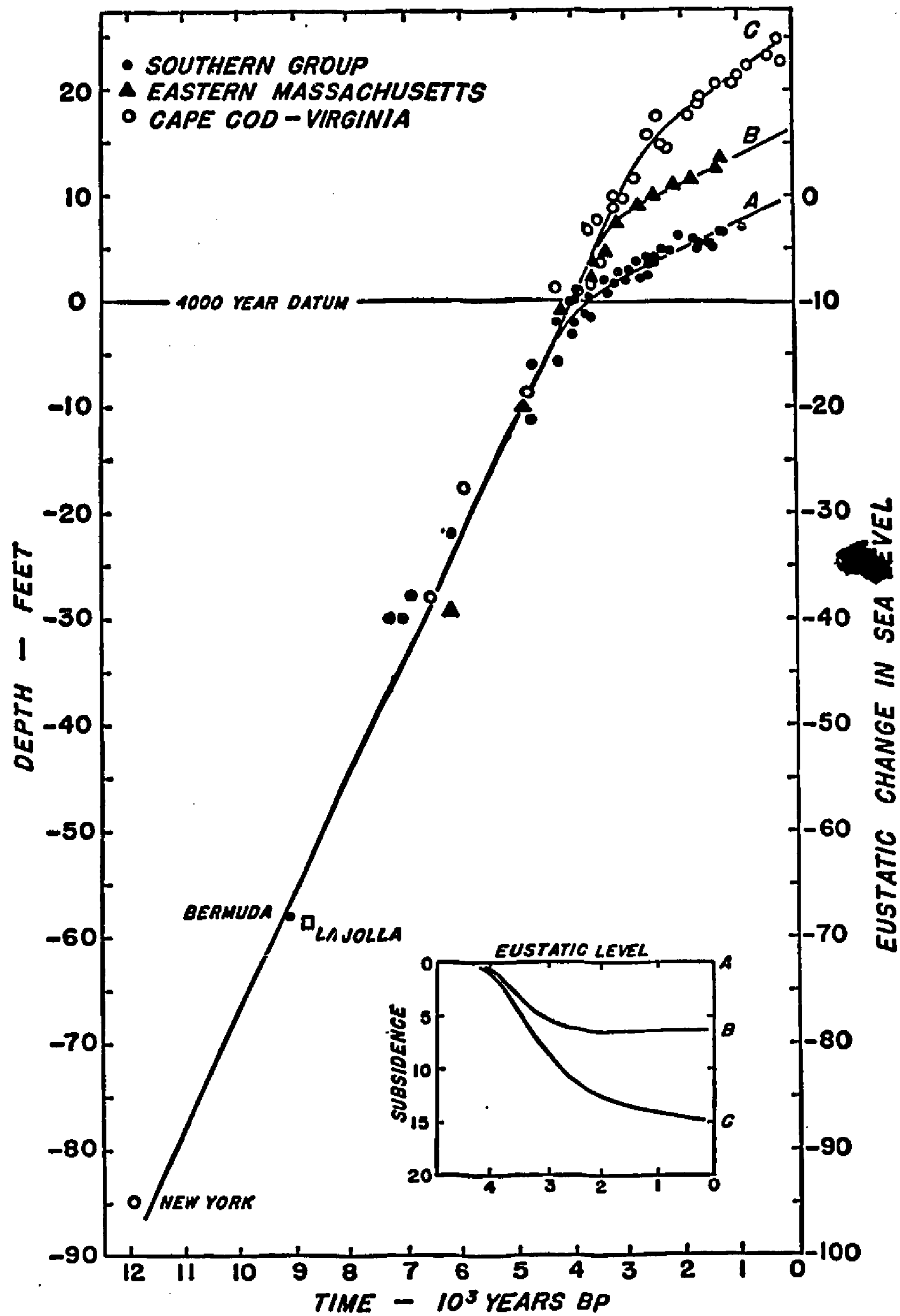
It is proposed that the nearshore terraces in the Chesapeake Bay were initiated at the change in rate of sea level rise about 3000 years ago. The steeper slopes seaward of the terraces correspond to the morphology resulting from a higher sea level rise rate, and the flat terraces are the wave-base erosional platform left by the transgression of the sea during the present, lower rate of sea level rise.

Figure 29: Sea level curve of Kaye and Barghoorn (1964). Note break in slope at 3000 years B.P.



HORIZONTAL SCALE IN YEARS BEFORE PRESENT (B P)
VERTICAL SCALE IN FEET ABOVE AND BELOW PRESENT SEA LEVEL
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10,000
11,000
12,000
13,000
14,000
15,000
+80
0
-100
-200
-300
LEXINGTON GLACIATION
CRUSTAL MOVEMENT
RELATIVE SEA-LEVEL
EUSTATIC SEA LEVEL
OUTWASH
LEXINGTON
FOR EXPANDED VERTICAL SCALE SEE BELOW
A
B
C
D
E
F
G
H
I
J
K
L
I'
J'
K'
L'
?
-5
-10
-15
-20
-25

Figure 30: Sea level curve of Redfield (1969).
Note break in slope at 3000 years B.P.


SOUTHERN GROUP
EASTERN MASSACHUSETTS
CAPE COD – VIRGINIA
C
B
A
4000 YEAR DATUM
BERMUDA
LA JOLLA
NEW YORK
EUSTATIC LEVEL
SUBSIDENCE
DEPTH – FEET
EUSTATIC CHANGE IN SEA
TIME – 10³ YEARS BP

## SEA LEVEL RISE

The best local estimates for relative sea level rise rates is obtained by long term compilation of mareograph data. Hicks and Crosby (1974) present estimates for many stations on the Atlantic shore. With mareograph data provided by Stacey Hicks (personal communication, 1974), estimates of sea level rise rates were computed for 10 stations in the Chesapeake Bay (Table 16). Although the different time-spans associated with the samples vary the reliability of estimates, the data demonstrates the high degree of local variation in sea level rise in the Chesapeake Bay area. The rates vary from 5.43 mm/yr at Old Point Comfort (Hampton County) to -0.46 mm/yr in Richmond, Virginia.

Relative sea level rise is the result of two components; the eustatic sea-level rise and crustal movements. As the eustatic rate is assumed to be constant worldwide at about 1.2 mm/yr (Wolcott, 1975), variations in sea level rise rates are a function of crustal movements. Figure 31 shows the regional distribution of subsidence rates along the shoreline of the Virgnia Chesapeake Bay. There is a large variability in a small area. The average subsidence rate is about 2 mm/yr. The subsidence increases going to the north on the eastern shore, and

## SEA LEVEL RISE

The best local estimates for relative sea level rise rates is obtained by long term compilation of mareograph data. Hicks and Crosby (1974) present estimates for many stations on the Atlantic shore. With mareograph data provided by Stacey Hicks (personal communication, 1974), estimates of sea level rise rates were computed for 10 stations in the Chesapeake Bay (Table 16). Although the different time-spans associated with the samples vary the reliability of estimates, the data demonstrates the high degree of local variation in sea level rise in the Chesapeake Bay area. The rates vary from 5.43 mm/yr at Old Point Comfort (Hampton County) to -0.46 mm/yr in Richmond, Virginia.

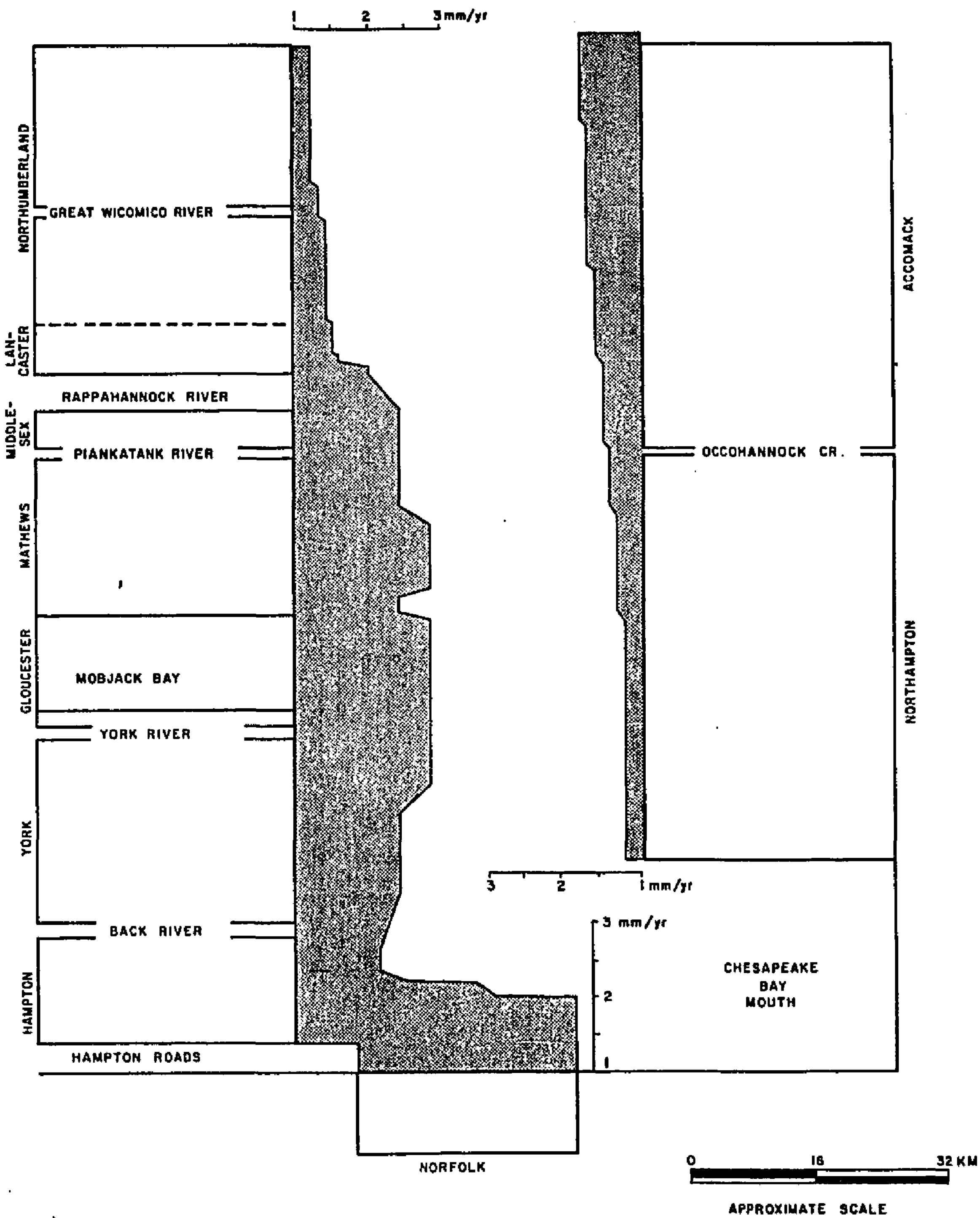
Relative sea level rise is the result of two components; the eustatic sea-level rise and crustal movements. As the eustatic rate is assumed to be constant worldwide at about 1.2 mm/yr (Wolcott, 1975), variations in sea level rise rates are a function of crustal movements. Figure 31 shows the regional distribution of subsidence rates along the shoreline of the Virgnia Chesapeake Bay. There is a large variability in a small area. The average subsidence rate is about 2 mm/yr. The subsidence increases going to the north on the eastern shore, and

TABLE 16
ESTIMATED RATES OF SEA LEVEL RISE
FROM MAREOGRAPH DATA

| LOCATION | RECORD LENGTH (years) | TREND (mm/yr) | STANDARD ERROR | VARIABILITY |
|---|---|---|---|---|
| Gloucester Point, Va. | 17. | 2.09 | 1.130 | 22.85 |
| Old Point Comfort, Va. | 15. | 5.43 | 1.280 | 26.01 |
| Kiptopeke, Va. | 22. | 3.93 | 0.877 | 26.08 |
| Richmond, Va. | 25. | -0.46 | 2.120 | 76.46 |
| Portsmouth, Va. | 38. | 3.93 | 0.396 | 26.87 |
| Hampton Roads, Va. | 47. | 4.68 | 0.323 | 29.95 |
| Solomons Island, Md. | 34. | 3.86 | 0.430 | 24.87 |
| Washington, D.C. | 43. | 3.40 | 0.430 | 33.20 |
| Baltimore, Md. | 71. | 3.42 | 0.152 | 26.35 |
| Annapolis, Md. | 44. | 4.26 | 0.287 | 24.36 |

Figure 31: Distribution of subsidence rates along the Virginia Chesapeake Bay shoreline (adapted from Holdahl and Morrison, 1974).

# VIRGINIA CHESAPEAKE BAY
# LOCAL SUBSIDENCE ALONG SHORELINE



increases to the south on the western shore. These subsidence rates are determined by comparisons of leveling data of the Vertical Network Branch of the National Geodetic Survey. The first set of leveling was performed between 1920 and 1942, and the last leveling was accomplished during 1971 and 1972 (Holdahl and Morrison, 1974).

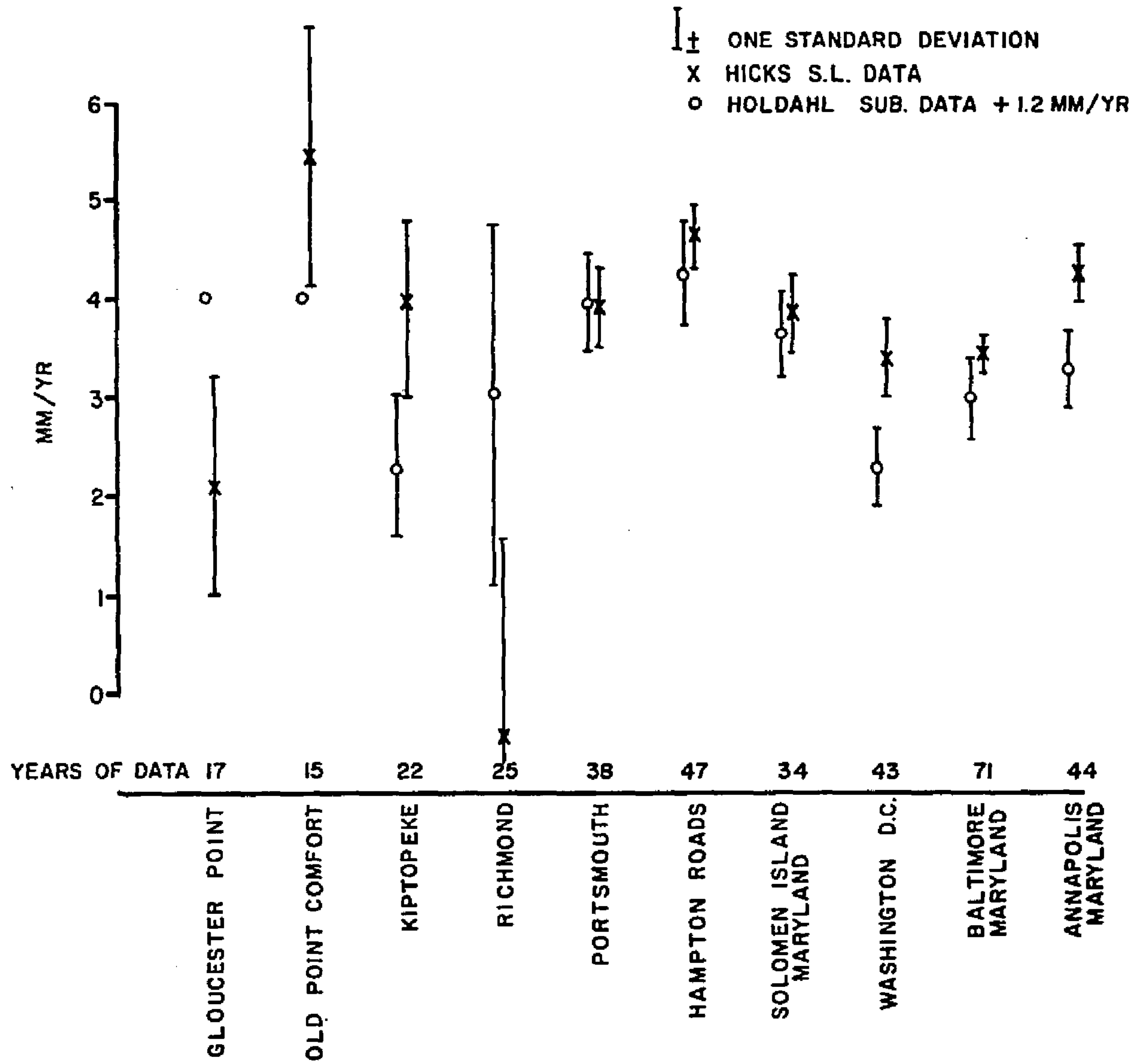
Figure 32 shows a comparison of mareograph records and releveling data for the 10 stations in the Chesapeake Bay. Although the inaccuracy in the releveling process is greater than mareograph data, this process affords comparison of local changes in relative sea level.

## THE EFFECT OF VARIATIONS IN SUBSIDENCE ON SHORELINE MORPHOLOGY

The regions of highest subsidence in the Virginia Chesapeake Bay are the northeast (1.6 mm/yr) and southwest (2.4 mm/yr) margins. These areas correspondingly have the largest nearshore terrace widths in the system. The mean width in Accomack County is 4010 m, and the mean in York County is 1923 m. This correspondence demonstrates that the nearshore terraces are a remnant feature, with the larger terraces resulting from increased shore retreat from higher submergence of the fastland. Conversely, this relationship serves as a geomorphic verification of the subsidence data.

Comparison of the distribution of subsidence rates along the shoreline (Fig. 31) with the distribution of marsh

Figure 32: Subsidence rates of Holdahl and Morrison (1974) compared to mareograph data of Hicks (written communication, 1975) for ten localities in the Chesapeake Bay. Six out of eight complete data sets fall within one standard deviation of each other.


ONE STANDARD DEVIATION
X HICKS S.L. DATA
O HOLDAHL SUB. DATA + 1.2 MM/YR
MM/YR
0
1
2
3
4
5
6
YEARS OF DATA
17
15
22
25
38
47
34
43
71
44
GLOUCESTER POINT
OLD POINT COMFORT
KIPTOPEKE
RICHMOND
PORTSMOUTH
HAMPTON ROADS
SOLOMEN ISLAND MARYLAND
WASHINGTON D.C.
BALTIMORE MARYLAND
ANNAPOLIS MARYLAND

environments (Fig. 9) demonstrates that the concentrations of marsh corresponds to the subsidence highs: at the southern end of the western shore and northern end of the eastern shore. This suggests that an increasingly submergent setting is conducive to the propagation of marsh in the Virginia Chesapeake Bay. The subsidence is a controlling factor in the distribution of salt marsh.

Shaler (1886) and Mudge (1858), and later Redfield (1958) discussed salt marsh growth as a function of the interaction of the accumulation of sediment and a rising sea level. Chapman (1964) states that salt marshes can occur on coasts that are stable, sinking or rising. On a sinking coast, the rate of sedimentation must be greater than the rate of subsidence for salt marsh development. Chapman also states that salt marsh development is also controlled by nearshore slope. A gently sloping nearshore is more conducive to salt marsh development. This criterion is met in the distribution of salt marshes in the Virginia Chesapeake Bay. A gently sloping nearshore (1) serves to decrease wave energy on the marsh shoreline, and (2) increases the concentration of locally derived suspended sediments in the water column and hence increases the amount of source material for vertical marsh growth. Thus, the broad nearshore terraces in the higher subsidence areas is the intermediary factor in the direct relationship between subsidence and salt marsh formation in the Virginia Chesapeake Bay.

## APPLICATION OF THE BRUUN MODEL IN THE VIRGINIA CHESAPEAKE BAY

Bruun (1962) proposed a model relating shoreline erosion and sea level rise. The model is based on the assumptions: (1) there is a shoreward displacement of the beach profile as the upper beach is eroded; (2) the material eroded from the upper beach is equal in volume to the material deposited on the nearshore bottom; and (3) the rise of the nearshore bottom as a result of this deposition is equal to the rise in sea level, thus maintaining a constant depth of water in that area. Figure 33 shows the relationship:

$$X (B + D) = AB'$$

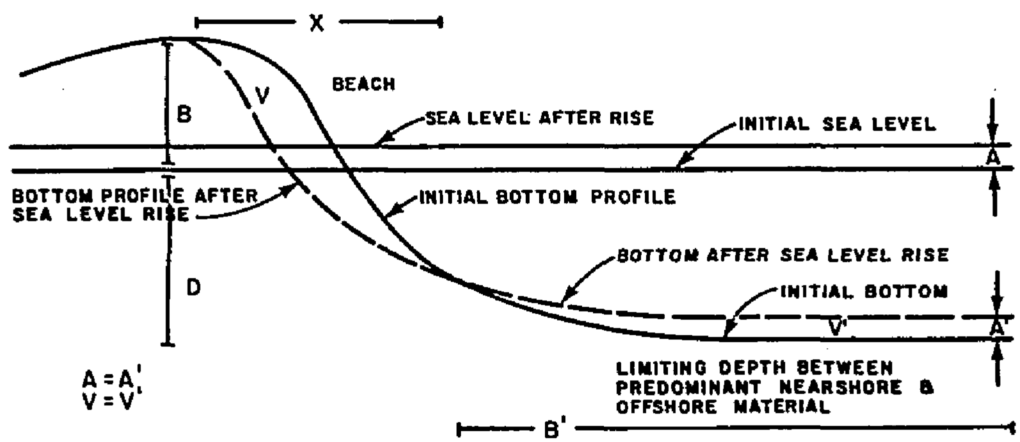
Where

$X$ = shore retreat
$B$ = fastland elevation
$D$ = limiting depth between predominant nearshore and offshore material
$A$ = rate of sea level rise
$B'$ = distance to limiting depth

In applying the model on ocean beaches, Bruun assumed that the 60 ft. depth contour as the limiting depth between predominant nearshore processes and offshore processes (the limit of offshore transport of sediment).

Bruun applied the model at several sites in Florida with successful results. Schwartz (1966) attempted to verify the model by using the variation between spring and neap tides to simulate sea level rise, and in a model wave basin. Dubois (1975) applied the Bruun model to seasonal lake-level changes on Lake Michigan. No large

Figure 33: Diagram illustrating the Bruun model relating sea level rise to shore erosion in the relationship. $x(B+D) = AB'$ (Bruun, 1962).


X
BEACH
B
V
SEA LEVEL AFTER RISE
INITIAL SEA LEVEL
A
BOTTOM PROFILE AFTER SEA LEVEL RISE
INITIAL BOTTOM PROFILE
BOTTOM AFTER SEA LEVEL RISE
INITIAL BOTTOM
D
V'
A'
A = A'
V = V'
LIMITING DEPTH BETWEEN PREDOMINANT NEARSHORE & OFFSHORE MATERIAL
B'

scale verification of the Bruun model exists in the literature applying it directly to the case it was intended for, shoreline changes as the result of long term sea level rise.

The Bruun model suggests that an area with higher bluffs will erode slower than an area with lower bluffs. When observationally applied to the Virginia Chesapeake Bay, the physiographic sub-divisions having the highest bluff heights on their respective sides of the Bay (Northampton County and Potomac River to Great Wicomico River) each have the narrowest nearshore terraces. As well, the areas with lowest bluff heights, Accomack County and Mobjack Bay to York County, have the correspondingly largest nearshore terraces. As the seaward margin of the nearshore terraces are proposed as a time constant shoreline location, these regional trends substantiate the Bruun model.

The Bruun model was applied to the Chesapeake Bay in an effort to account for the regional shoreline erosion in the system, and, conversely, as a large-scale verification of the Bruun model. The model was applied with the following additional assumptions:

(1) The calculations were performed on each reach in the study area, and averaged over various regions. As the model assumes longshore equilibrium by applying it over the whole region, longshore dis-equilibrium at individual reaches will be averaged out.

(2) Calculations for beach reaches were separated

from marsh reaches (including marsh margins and marsh barriers). The model loses physical meaning on marsh reaches. The beach calculations were further stratified by (A) whole area, (B) permeable beaches only, and (C) impermeable beaches only.

(3) The limit of the nearshore zone was defined at the 3.6 m (12 ft.) contour. A regional break-in-slope in the bathymetry occurs at this depth, and 3.6 m is approximately wave base for a three second wave. Ryan (1953) showed that sand deposition on the bottom is confined to this area.

(4) The total vertical distance cut by erosion is 3.6 m + beach elevation + bluff height. If the beach elevation was less than the tidal range, then the tidal range was assumed to be the beach elevation. The minimum bluff height is assumed to be three feet, as this parameter is intended to describe the fastland elevation.

(5) The local rate of relative sea level rise was computed for each reach using the subsidence data from Holdahl and Morrison (1974), adding 1.2 mm/yr for eustatic sea level rise (Wolcott, 1975). Weighted means were used to take regional averages of erosion rates, to model more precisely the Bay System.

Table 17 shows the results of calculations for all beach reaches in the Virginia Chesapeake Bay. The calculated mean erosion rate for the study area is 0.98 m/yr, which fits the long term measured rates with only

TABLE 17
APPLICATION OF THE BRUUN MODEL TO THE VIRGINIA CHESAPEAKE BAY
ALL BEACH ENVIRONMENTS

| | Weighted Measured Erosion (m/yr) | Weighted Predicted Erosion (m/yr) | Error (%) | Mean Measured Erosion (m/yr) | Mean Predicted Erosion (m/yr) | Error (%) | Number of Reaches |
|---|---|---|---|---|---|---|---|
| VIRGINIA CHESAPEAKE BAY | 0.94 | 0.98 | + 3 | 0.93 | 1.01 | + 8 | 146 |
| EASTERN SHORE | 0.87 | 1.38 | + 58 | 0.81 | 1.41 | + 72 | 57 |
| WESTERN SHORE | 1.03 | 0.95 | - 7 | 1.02 | 0.82 | - 19 | 78 |
| COUNTIES: | | | | | | | |
| NORTHAMPTON | 0.88 | 0.76 | - 13 | 0.86 | 0.79 | - 8 | 39 |
| ACCOMACK | 0.85 | 2.77 | + 224 | 0.73 | 2.74 | + 275 | 18 |
| NORTHUMBERLAND | 1.08 | 0.63 | - 41 | 1.03 | 0.70 | - 31 | 35 |
| LANCASTER | 1.49 | 0.76 | - 48 | 1.42 | 0.77 | - 46 | 12 |
| MIDDLESEX | 0.74 | 0.76 | - 2 | 0.68 | 0.85 | + 26 | 6 |
| MATHEWS | 1.13 | 0.88 | - 22 | 0.98 | 0.91 | - 7 | 12 |
| GLOUCESTER | 0.57 | 1.06 | + 85 | 0.58 | 1.09 | + 88 | 3 |
| YORK | 0.64 | 1.92 | + 199 | 0.92 | 1.08 | + 17 | 10 |
| HAMPTON | 0.97 | 0.35 | - 64 | 0.89 | 0.31 | - 64 | 6 |
| NORFOLK/VIRGINIA BEACH | 0.76 | 0.24 | - 68 | 0.82 | 0.24 | - 70 | 5 |

TABLE 17 (cont'd)
APPLICATION OF THE BRUUN MODEL TO THE
VIRGINIA CHESAPEAKE BAY
ALL BEACH ENVIRONMENTS

| | Weighted Measured Erosion (m/yr) | Weighted Predicted Erosion (m/yr) | Error (%) | Mean Measured Erosion (m/yr) | Mean Predicted Erosion (m/yr) | Error (%) | Number of Reaches |
|---|---|---|---|---|---|---|---|
| INTERFLUVES: | | | | | | | |
| POTOMAC RIVER TO RAPPAHANNOCK RIVER | 1.20 | 0.67 | - 44 | 1.13 | 0.72 | - 36 | 47 |
| RAPPAHANNOCK RIVER TO YORK RIVER | 0.96 | 0.87 | - 10 | 0.84 | 0.92 | + 10 | 21 |
| YORK RIVER TO JAMES RIVER | 0.77 | 1.28 | + 65 | 0.91 | 0.80 | - 12 | 16 |
| PHYSIOGRAPHIC SUBDIVISIONS: | | | | | | | |
| POTOMAC RIVER TO GREAT WICOMICO RIVER | 1.12 | 0.53 | - 52 | 1.10 | 0.63 | - 42 | 23 |
| GREAT WICOMICO RIVER TO PIANKATANK RIVER | 1.15 | 0.82 | - 28 | 1.06 | 0.82 | - 23 | 30 |
| GWYNNS ISLAND TO NEW POINT COMFORT | 1.37 | 0.84 | - 38 | 1.42 | 0.81 | - 43 | 7 |
| MOBJACK BAY TO YORK COUNTY | 0.59 | 1.62 | + 174 | 0.71 | 1.08 | + 53 | 18 |
| HAMPTON AND NORFOLK/ VIRGINIA BEACH | 0.84 | 0.28 | - 67 | 0.86 | 0.28 | - 64 | 11 |

a 3% error. The western shore (excluding Hampton and Norfolk) predicted mean erosion within 7% error. The large error observed (58%) on the eastern shore is the result of the influence of Accomack County, which is dominated by an overwhelming majority of marsh shoreline, so the beach processes are a minor influence. A truer picture of the eastern shore beaches is obtained by considering Northampton County, which is primarily beach. The predicted erosion in Northampton County is 0.76 m/yr, resulting in an error of 13% compared to measured erosion rates.

The largest errors are encountered in the regions dominated by marshes. Accomack County showed a 224% error, York County showed 199% error, and Gloucester County, 85% error. The fit was poor in Hampton and Norfolk (67% error), which is enigmatic, since the measured erosion rates (0.84 m/yr) was much higher than calculated (0.28 m/yr), despite the external influences of the large sediment input from Cape Henry, and the most extensive shore protection projects in the study area.

By applying the Bruun model to impermeable and permeable beach environments only, the overall fit is good (9% error in impermeable beaches only, and 24% error for permeable beaches only). The trends of the regional fits are similar to the total beach environment. In the permeable beaches, sand is the material in the model. Ryan (1953) demonstrated that sand on the

Chesapeake Bay bottom is confined to the margins of the basin, and is derived from erosion of the fastland, rather than by transport by rivers. However, in the impermeable environments, part of the eroded materials are silts and clays (see sedimentology section). This suggests that mud is deposited on the nearshore from a local source, although field reconnaissance provided no evidence supporting this.

The fit of the Bruun model on the shoreline of the Virginia Chesapeake Bay demonstrates that sea level rise could account for all the shoreline erosion in the system. It is apparent though, that sea level rise "...plays only a permissive role in coastal erosion, not a causitive one." (Davis, et al., 1973). The action of the short term processes (waves, tide, surge, groundwater flow) can therefore be regarded as the agents effecting the larger scale trend.

## SUMMARY AND CONCLUSIONS

There is a high degree of site-specificity in the coastal environments of the Virginia Chesapeake Bay. The variability is influenced by (1) the relict Pleistocene high-order dendritic drainage system, resulting in a large diversity of shore orientations, (2) the moderate but highly variable wave energy in the Bay system and highly variable submergence rates, resulting in a spectrum of shoreline transformation from primary to secondary types (Shepard, 1973), (3) eroding fastland exposures of sediments of widely varying composition and volume, and (4) salt marsh development.

Erosion as a Function of Beach Type: Eighty percent of the shore is beaches composed of three morphologically distinct beach environments, each reflecting different susceptibilities to erosion: (1) Permeable beaches, composed entirely of sand-sized material, comprise 59% of the beaches (mean erosion = 0.85 m/yr) and have the largest vertical and horizontal dimensions. This provides the largest vertical buffer to the effects of storm surge and waves and greatest potential for infiltration of swash into the foreshore. (2) Impermeable beaches, composed of a veneer of sand overlying impermeable, pre-Holocene sediments, comprise 24% of the beaches. The combined influence of low swash infiltration, low beach elevation; and ground water effects result in the highest mean erosion (1.14 m/yr). (3) Marsh Barrier beaches, composed of a veneer of sand overlying peat contains a resistant rhizome framework, resulting in the least erodably beach environment (0.66 m/yr). Marsh margins, the remaining 20% of the shoreline, are the least erodable shore environment (0.54 m/yr).

Succession of Shoreline Types: The Virginia Chesapeake Bay shoreline, although classified as a primary shoreline by Shepard (1973), is composed of a succession of shoreline types. Different areas are succeeding at different rates from primary to secondary, or marine dominated, characteristics. These variations are controlled regionally by the variations in shoreline submergence rates and variations in shoreline wave energy. The volume of sand in the shoreline system is a direct controlling factor in shoreline simplification.

Influence of Tide Range on Erosion Rate: The Virginia Chesapeake Bay has a 200% variation in tidal range (0.36 m to 1 m) over a 120 km shoreline distance. Tidal range increases going to the south on both shores of the Lower Bay, and is slightly greater on the eastern shore, due to the Coreolis deflection of the prograding tidal wave.

There is a direct relationship between tide range, total beach elevation, and supra-tidal elevation (elevation from the mean high water line to maximum elevation of the backbeach). Tidal range is inversely related to shoreline erosion. The physical basis for this relationship appears to lie in the fact that areas of lower tidal range have a greater probability of overtopping the beach during storm waves or surge than on a higher elevation, higher tidal range beach. Any given meteorologic tide (surge) is a smaller percentage of the astronomic tide in areas of larger tidal range. Since supra-tidal elevation of the beach increases with higher tidal ranges, this increased elevation serves as an additional buffer to raised water levels, especially at high tide. Thus, water levels increased by surges less often reach the elevation of the fastland (dune or bluff) material.

It is proposed that the inverse relationship between tide range and shore retreat is a general controlling factor on tidal shorelines.

Wave Refraction in Chesapeake Bay: Wave refraction studies of the Virginia Chesapeake Bay demonstrate a convergence of wave energy on the seaward-most headlands of the western shore and a divergence of wave energy away from early primary shorelines on both shores of the Bay. These data suggest that wave energy, as affected by the regional morphology of the basin, is one of the direct processes affecting the succession from primary to secondary shoreline types (Shepard, 1973).

Thus, the elongate nature of the Chesapeake Bay causes geographic limitations on the fetch, resulting in a bidirectional wave field. The regional wave climate is effecting a series of shoreline reorientation features on both shores of the Bay. The initiation of these forms is both due to the previous geologic framework and present wave climate. The poorly defined development of the shore reorientation forms is a function of the sediment-starved nature of the shoreline.

Beachface Sedimentation: The regional distribution of beachface sediments in the Virginia Chesapeake Bay is characterized by two major modes of interlayered sedimentation. The mean of the finer mode corresponds to the mean of a sampling of source material, while the coarser mode is suggested to be the result of reworking. Impermeable beach environments respond to the increased backwash by winnowing the fines, resulting in a slightly coarser trend of the sediments. The sand content and volume of bluff erosion input into the beach system corresponds to, and is probably a contributing factor of the succession of shorelines from primary to secondary forms.

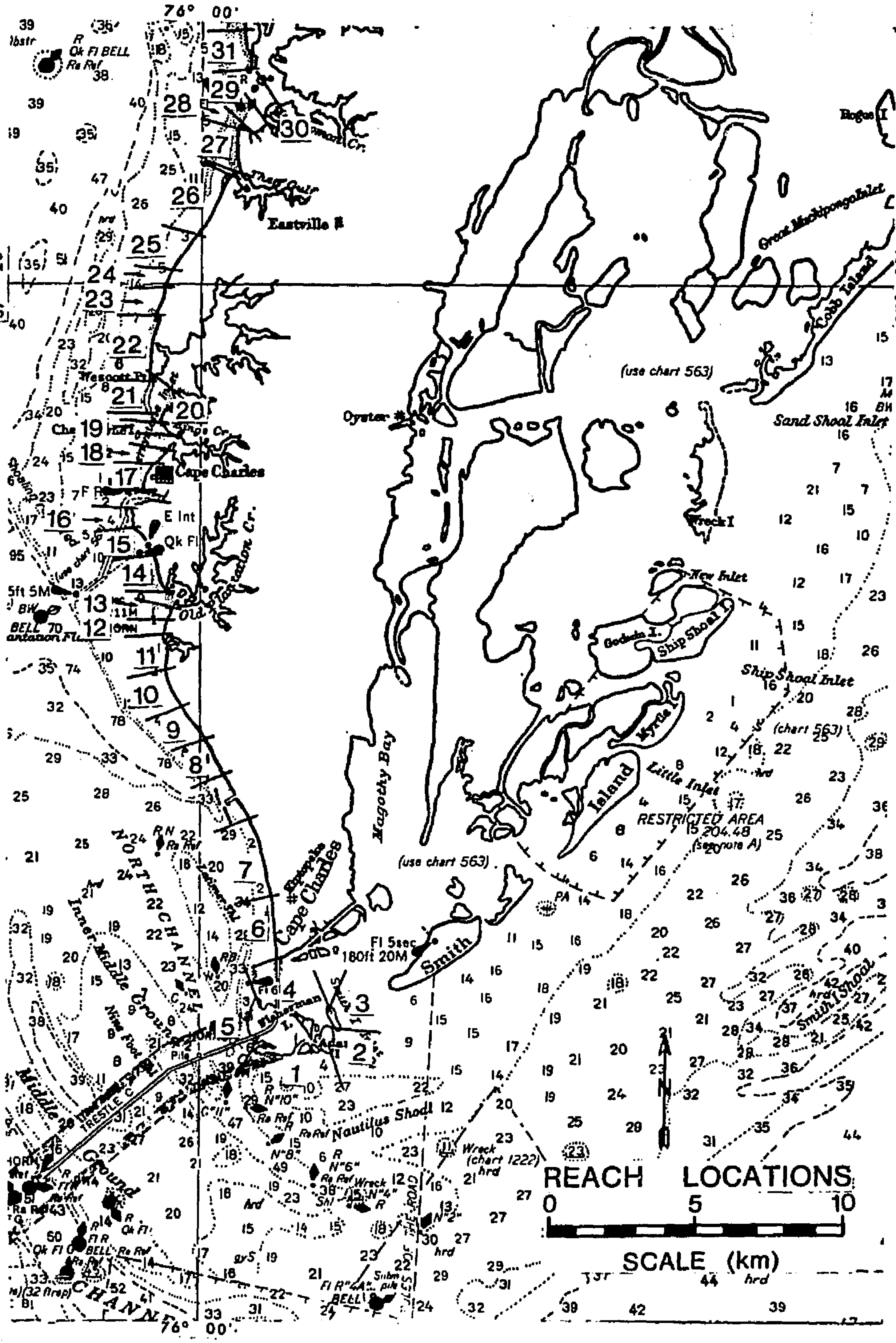
Influence of Sea Level Rise on Erosion Processes: There is a large variability in the local subsidence rates (and hence, submergence rates) along the Virginia Chesapeake Bay shoreline. Subsidence highs occur at the northeast and southwest ends of the basin. These areas correspondingly have the largest nearshore terrace widths in the system, with mean widths of 4010 m and 1923 m respectively. This correspondence suggests that the nearshore terraces are a remnant feature, with larger terraces resulting from increased submergence of the fastland.

The concentrations of salt marsh in the Lower Bay also correspond to the subsidence highs. The gently sloping nearshore in these areas (Chapman, 1964) is conducive to salt marsh development. An equilibrium situation exists as a result of the salt marsh development. By the nature of its structure, this shoreform is more resistant to shoreline retreat, while it occurs in areas of highest submergence where shore retreat would be expected to be the highest.

The Bruun model which relates sea level rise to shore erosion has been applied to the beaches of the Lower Chesapeake Bay. The results are a predicted longterm erosion rate (0.98 m/yr) within 3% of measured rates. Within the assumptions of the Bruun model, sea level rise accounts for all the shore erosion in the system. It is apparent, though, that sea level rise "...plays only a permissive role in coastal erosion, not a causitive one" (Davis et al., 1973). The action of short-term processes (waves, tide, surge, groundwater effects) can therefore be regarded as the smaller scale agents effecting the larger scale trend.

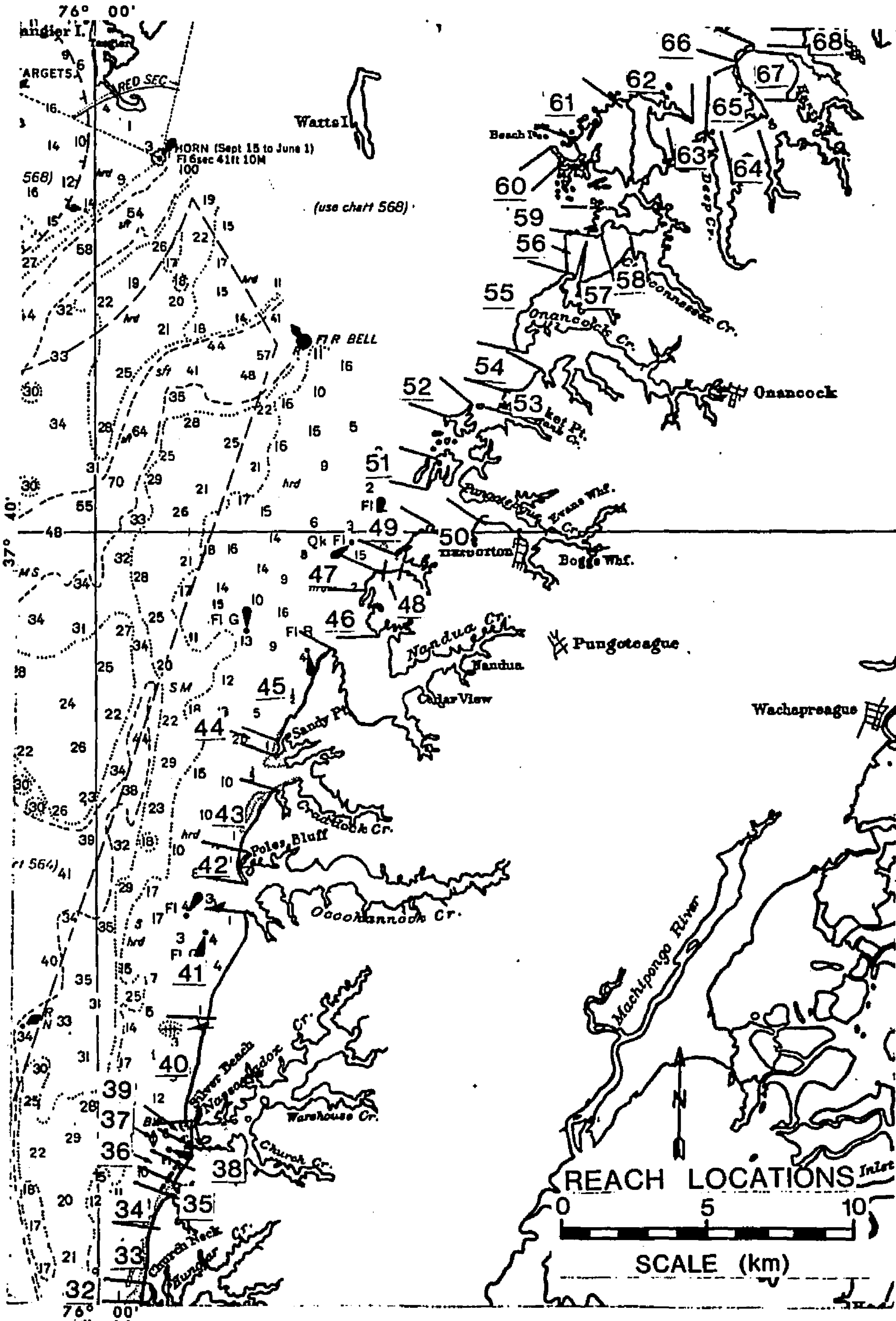
# APPENDIX A

## REACH LOCATIONS



REACH LOCATIONS
0 5 10
SCALE (km)
76° 00'
37° 20'
Cape Charles
Eastville
Oyster
Magothy Bay
Smith
Ship Shoal Inlet
Sand Shoal Inlet
New Inlet
Little Inlet
Great Machipongo Inlet
Cobb Island
Wreck I
RESTRICTED AREA
(use chart 563)
Nautilus Shoal
NORTH CHANNEL
Inner Middle Ground
Fisherman I.
Old Plantation Cr.
Smith Shoal


FIGURE A-1



76° 00'
Watts I.
HORN (Sept 15 to June 1)
Fl 6sec 41ft 10M
(use chart 568)
Fl R BELL
Onancock Cr.
Onancock
Pungoteague Cr.
Evans Whf.
Boggs Whf.
Harborton
Deep Cr.
Nandua Cr.
Nandua
Pungoteague
Cedar View
Wachapreague
Sandy Pt.
Poles Bluff
Occohannock Cr.
Machipongo River
Nassawadox Cr.
Warehouse Cr.
Church Cr.
Church Neck Cr.
Hungars Cr.
37° 40'
66
68
62
67
61
65
63
64
60
59
56
58
57
55
54
52
53
51
49
50
47
48
46
45
44
43
42
41
40
39
37
36
38
34
35
33
32
N
REACH LOCATIONS
0
5
10
SCALE (km)


FIGURE A22

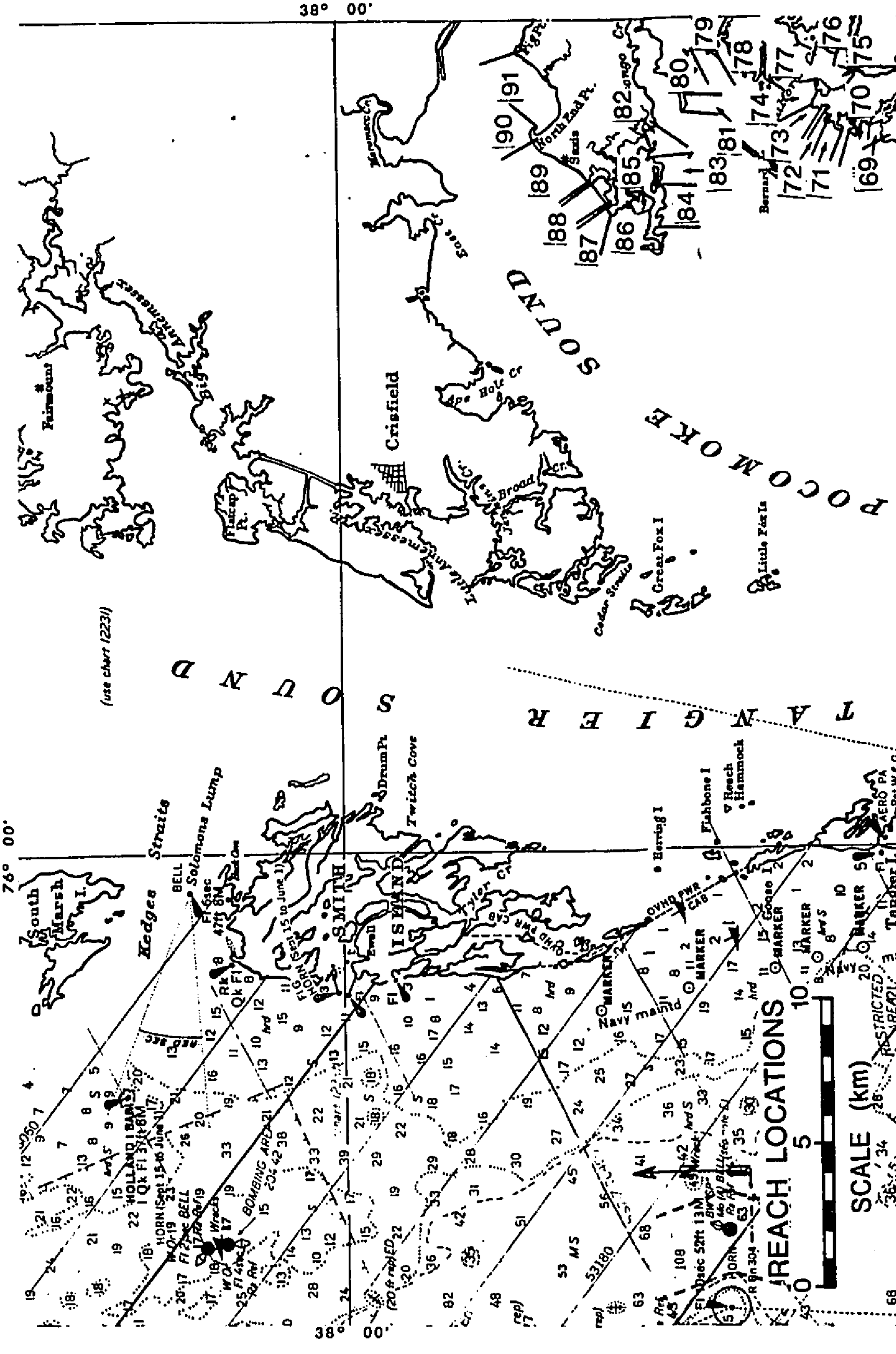
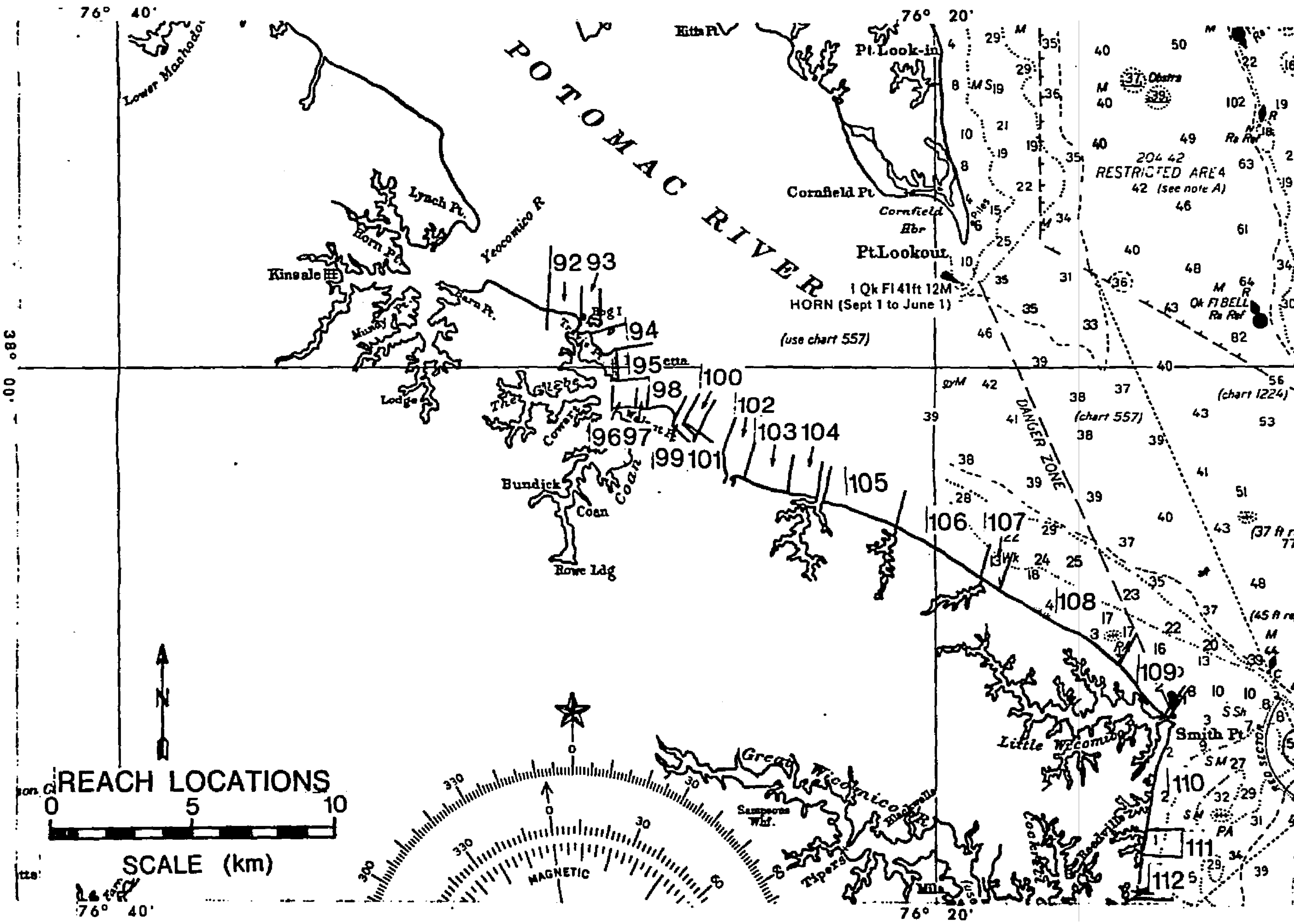

REACH LOCATIONS
SCALE (km)
POCOMOKE SOUND
TANGIER SOUND
Crisfield
SMITH ISLAND
Kedges Straits
South Marsh I.
38° 00'
76° 00'

FIGURE A-3



POTOMAC RIVER
76° 40'
76° 20'
38° 00'
Lower Machodoc
Lynch Pt.
Yeocomico R
Horn Pt.
Kinsale
Lodge
Bundick
Coan
Rowe Ldg
Pt. Lookout
Cornfield Pt
Cornfield Hbr
Pt. Look-in
1 Qk Fl 41ft 12M
HORN (Sept 1 to June 1)
(use chart 557)
(chart 557)
(chart 1224)
RESTRICTED AREA
(see note A)
DANGER ZONE
Smith Pt
Little Wicomico
Great Wicomico R
Sampsons Wharf
MAGNETIC
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
REACH LOCATIONS
0
5
10
SCALE (km)
N


FIGURE AA44

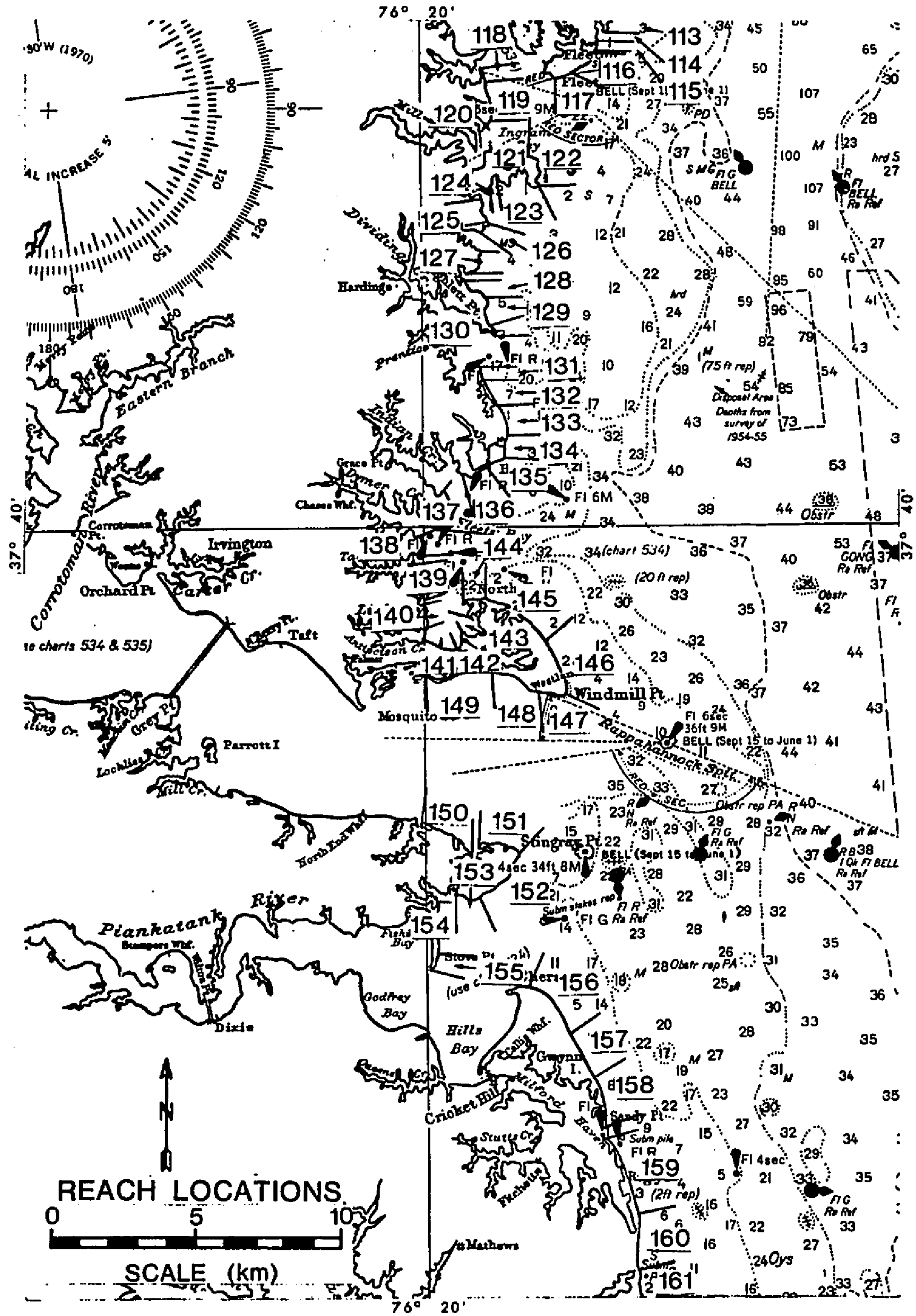
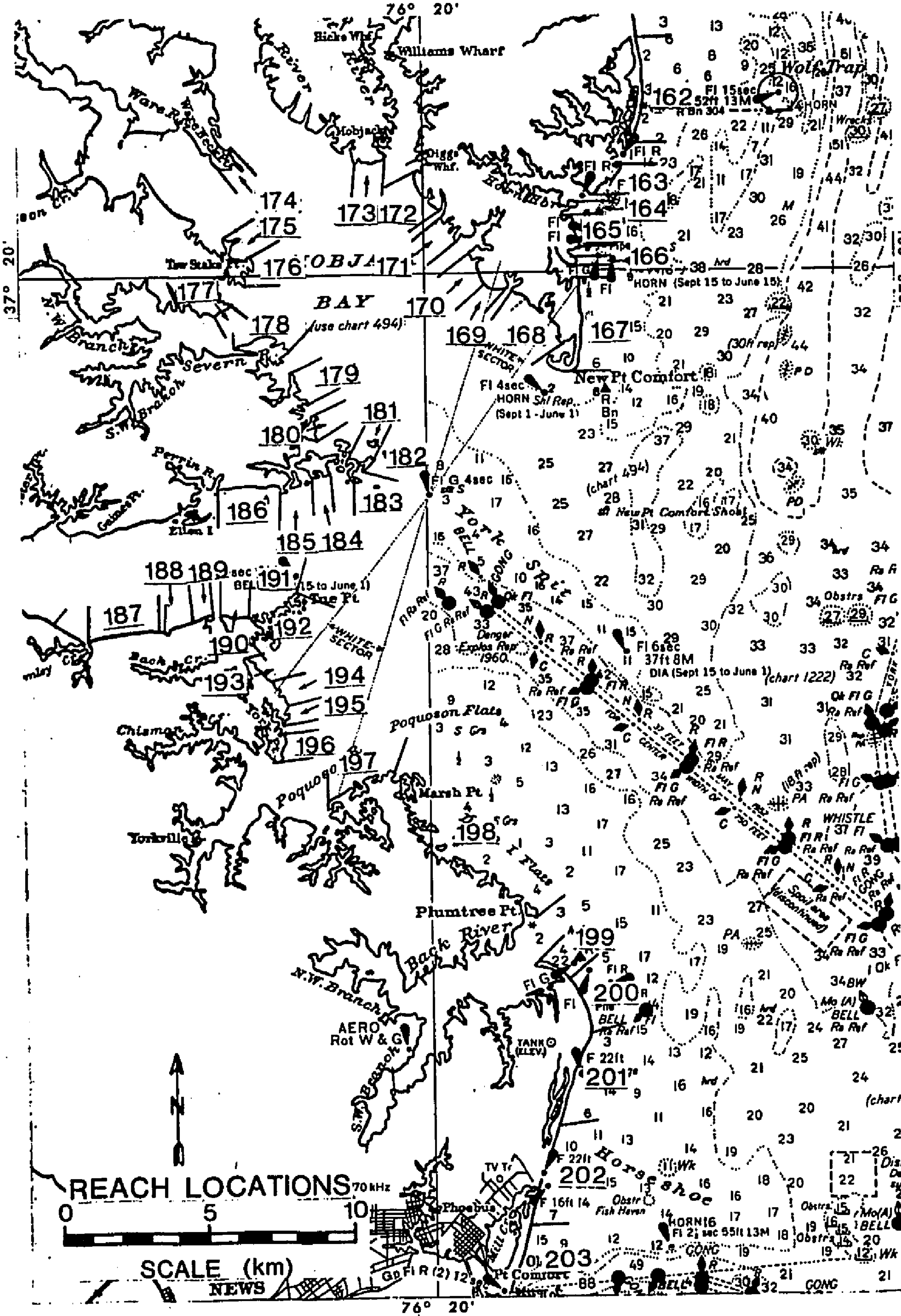
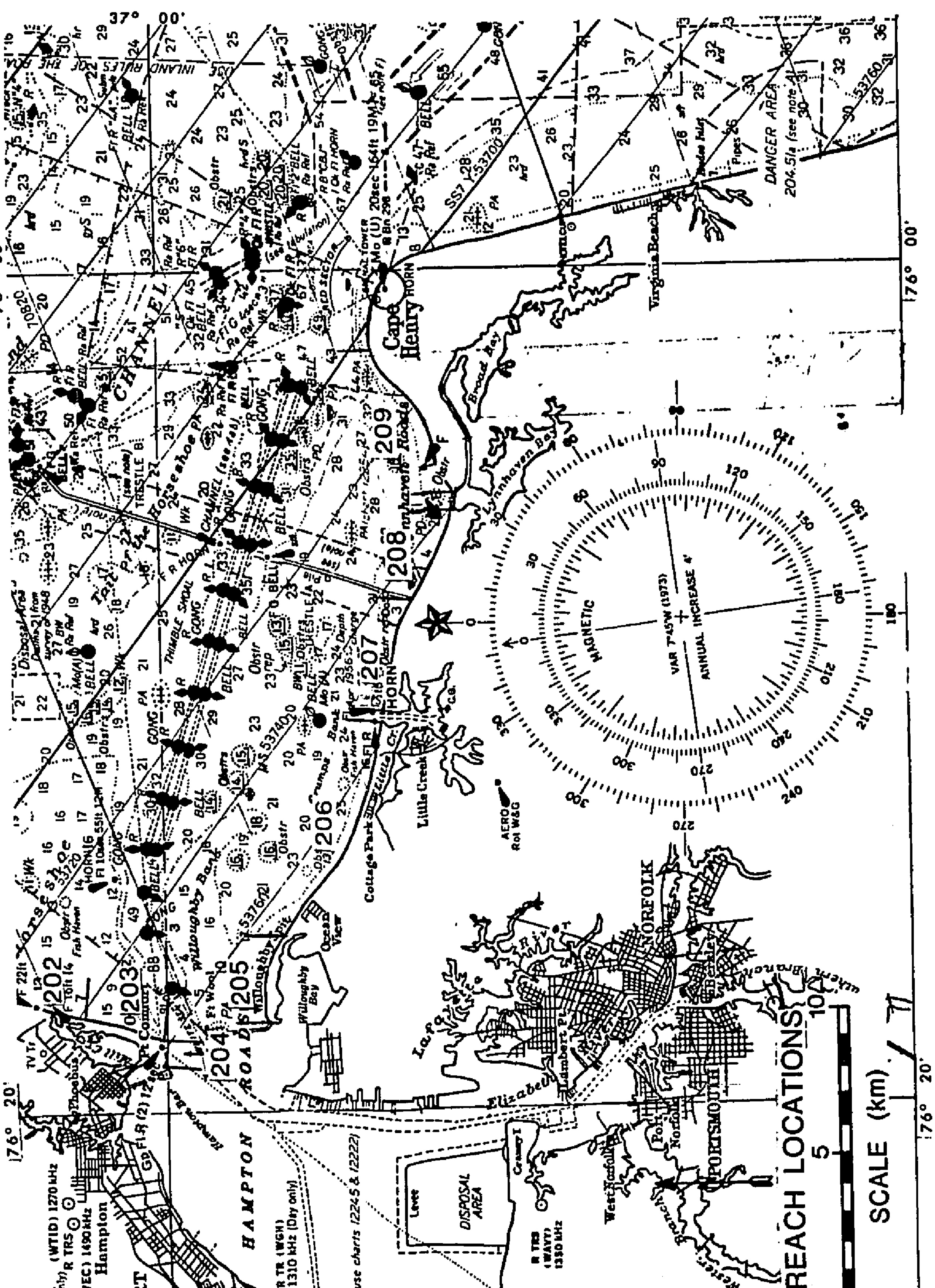

REACH LOCATIONS
0
5
10
SCALE (km)
76° 20'
37° 40'
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
Irvington
Orchard Pt.
Taft
Mosquito
Windmill Pt.
Parrott I
Hardinge
Piankatank
River
Godfrey Bay
Hills Bay
Cricket Hill
Milford Haven
Gwynn I.
Sandy Pt.
Dixie
Mathews
Eastern Branch
Corrotoman River
Rappahannock Spit
Stingray Pt.
Disposal Area
Depths from survey of 1954-55

FIGURE A-5



76° 20'
Williams Wharf
Wolf Trap
Mobjack
Ware River
North River
Ware Neck Pt.
Diggs Wharf
New Pt Comfort
MOBJACK BAY (use chart 494)
Severn R.
N.W. Branch
S.W. Branch
Perrin R.
Sarah Cr.
Gaines R.
Back Cr.
York River
Poquoson Flats
Poquoson River
Chisman Cr.
Yorktown
Marsh Pt
Plumtree Pt
Back River
N.W. Branch
S.W. Branch
AERO Rot W & G
Phoebus
Mill Cr
Pt Comfort
NEWS
Horse Shoe
York Spit
37° 20'
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
REACH LOCATIONS
0
5
10
SCALE (km)


FIGURE A-6



REACH LOCATIONS
SCALE (km)
0
5
10
202
203
204
205
206
207
208
209
NORFOLK
PORTSMOUTH
HAMPTON
Hampton
Cape Henry
Virginia Beach
Willoughby Bay
Little Creek
Lynnhaven Bay
Broad Bay
THIMBLE SHOAL
CHANNEL
DISPOSAL AREA
DANGER AREA
MAGNETIC
VAR 7°45'W (1973)
ANNUAL INCREASE 4'
37° 00'
76° 00'
76° 20'


FIGURE A-7

# APPENDIX B

## SHORELINE REACH CHARACTERISTICS

| VARIABLE | TABLE |
|---|---|
| Tide Range | B-1 |
| Subsidence Rate | B-1 |
| Beach Width | B-2 |
| Beach Elevation | B-2 |
| Foreshore Slope | B-2 |
| Backshore Type | B-2 |
| Reach Length | B-3 |
| Erosion Rate | B-3 |
| Nearshore Terrace Width | B-3 |
| Shoreline Orientation | B-3 |
| Shoreline Reprientation | B-3 |
| Bluff Height | B-3 |
| Fastland Type | B-3 |

TABLE B-1: EXPLANATION OF VARIABLES MEASURED SHORELINE REACH CHARACTERISTICS VIRGINIA CHESAPEAKE BAY

COUNTY:

1. Northampton
2. Accomack
3. Northumberland
4. Lancaster
5. Middlesex
6. Mathews
7. Gloucester
8. York
9. Hampton
10. Norfolk/Virginia Beach

See Location Map, Figure 1.

REACH NUMBER:

See Appendix A for reach locations.

TIDE RANGE:

Mean tide range in meters. See Figure 24.

SUBSIDENCE RATE:

Mean subsidence rate in mm/yr. See Figure 31.

## SHORELINE REACH CHARACTERISTICS
## VIRGINIA CHESAPEAKE BAY

| COUNTY | REACH NUMBER | TIDE RANGE (m) | SUBSIDENCE RATE (mm/yr) |
|---|---|---|---|
| 1 | 1 | 0.91 | 1.2 |
| 1 | 2 | 0.91 | 1.2 |
| 1 | 3 | 0.91 | 1.2 |
| 1 | 4 | 0.91 | 1.2 |
| 1 | 5 | 0.91 | 1.2 |
| 1 | 6 | 0.85 | 1.2 |
| 1 | 7 | 0.85 | 1.2 |
| 1 | 8 | 0.85 | 1.2 |
| 1 | 9 | 0.79 | 1.2 |
| 1 | 10 | 0.79 | 1.2 |
| 1 | 11 | 0.79 | 1.2 |
| 1 | 12 | 0.73 | 1.2 |
| 1 | 13 | 0.73 | 1.2 |
| 1 | 14 | 0.73 | 1.2 |
| 1 | 15 | 0.73 | 1.2 |
| 1 | 16 | 0.73 | 1.2 |
| 1 | 17 | 0.73 | 1.2 |
| 1 | 18 | 0.73 | 1.2 |
| 1 | 19 | 0.73 | 1.2 |
| 1 | 20 | 0.73 | 1.2 |
| 1 | 21 | 0.67 | 1.2 |
| 1 | 22 | 0.67 | 1.2 |
| 1 | 23 | 0.67 | 1.2 |
| 1 | 24 | 0.67 | 1.2 |
| 1 | 25 | 0.67 | 1.2 |
| 1 | 26 | 0.67 | 1.3 |
| 1 | 27 | 0.67 | 1.3 |
| 1 | 28 | 0.67 | 1.3 |
| 1 | 29 | 0.61 | 1.3 |
| 1 | 30 | 0.61 | 1.3 |
| 1 | 31 | 0.61 | 1.3 |
| 1 | 32 | 0.61 | 1.3 |
| 1 | 33 | 0.61 | 1.3 |
| 1 | 34 | 0.55 | 1.3 |
| 1 | 35 | 0.55 | 1.3 |
| 1 | 36 | 0.55 | 1.3 |
| 1 | 37 | 0.55 | 1.3 |
| 1 | 38 | 0.55 | 1.3 |
| 1 | 39 | 0.55 | 1.3 |
| 1 | 40 | 0.55 | 1.4 |
| 1 | 41 | 0.55 | 1.4 |
| 2 | 42 | 0.52 | 1.4 |
| 2 | 43 | 0.52 | 1.5 |

TABLE B-1

# SHORELINE REACH CHARACTERISTICS
## VIRGINIA CHESAPEAKE BAY

| COUNTY | REACH NUMBER | TIDE RANGE (m) | SUBSIDENCE RATE (mm/yr) |
|---|---|---|---|
| 2 | 44 | 0.52 | 1.5 |
| 2 | 45 | 0.52 | 1.5 |
| 2 | 46 | 0.52 | 1.5 |
| 2 | 47 | 0.52 | 1.5 |
| 2 | 48 | 0.52 | 1.5 |
| 2 | 49 | 0.52 | 1.6 |
| 2 | 50 | 0.52 | 1.6 |
| 2 | 51 | 0.52 | 1.6 |
| 2 | 52 | 0.52 | 1.6 |
| 2 | 53 | 0.52 | 1.6 |
| 2 | 54 | 0.52 | 1.6 |
| 2 | 55 | 0.52 | 1.6 |
| 2 | 56 | 0.52 | 1.6 |
| 2 | 57 | 0.52 | 1.6 |
| 2 | 58 | 0.55 | 1.7 |
| 2 | 59 | 0.55 | 1.7 |
| 2 | 60 | 0.55 | 1.7 |
| 2 | 61 | 0.55 | 1.7 |
| 2 | 62 | 0.55 | 1.7 |
| 2 | 63 | 0.55 | 1.7 |
| 2 | 64 | 0.55 | 1.7 |
| 2 | 65 | 0.55 | 1.7 |
| 2 | 66 | 0.55 | 1.7 |
| 2 | 67 | 0.55 | 1.7 |
| 2 | 68 | 0.55 | 1.7 |
| 2 | 69 | 0.55 | 1.7 |
| 2 | 70 | 0.55 | 1.7 |
| 2 | 71 | 0.61 | 1.7 |
| 2 | 72 | 0.61 | 1.7 |
| 2 | 73 | 0.61 | 1.7 |
| 2 | 74 | 0.61 | 1.7 |
| 2 | 75 | 0.61 | 1.7 |
| 2 | 76 | 0.61 | 1.7 |
| 2 | 77 | 0.61 | 1.7 |
| 2 | 78 | 0.61 | 1.7 |
| 2 | 79 | 0.61 | 1.8 |
| 2 | 80 | 0.61 | 1.8 |
| 2 | 81 | 0.61 | 1.8 |
| 2 | 82 | 0.61 | 1.8 |
| 2 | 83 | 0.61 | 1.8 |
| 2 | 84 | 0.61 | 1.8 |
| 2 | 85 | 0.61 | 1.8 |

TABLE B-1 continued

# SHORELINE REACH CHARACTERISTICS VIRGINA CHESAPEAKE BAY

| COUNTY | REACH NUMBER | TIDE RANGE (m) | SUBSIDENCE RATE (mm/yr) |
|---|---|---|---|
| 2 | 86 | 0.67 | 1.8 |
| 2 | 87 | 0.67 | 1.8 |
| 2 | 88 | 0.67 | 1.8 |
| 2 | 89 | 0.67 | 1.8 |
| 2 | 90 | 0.67 | 1.8 |
| 2 | 91 | 0.67 | 1.8 |
| 3 | 92 | 0.43 | 1.2 |
| 3 | 93 | 0.43 | 1.2 |
| 3 | 94 | 0.43 | 1.2 |
| 3 | 95 | 0.43 | 1.2 |
| 3 | 96 | 0.43 | 1.2 |
| 3 | 97 | 0.43 | 1.2 |
| 3 | 98 | 0.43 | 1.2 |
| 3 | 99 | 0.40 | 1.2 |
| 3 | 100 | 0.40 | 1.2 |
| 3 | 101 | 0.40 | 1.2 |
| 3 | 102 | 0.40 | 1.2 |
| 3 | 103 | 0.40 | 1.2 |
| 3 | 104 | 0.40 | 1.2 |
| 3 | 105 | 0.40 | 1.2 |
| 3 | 106 | 0.40 | 1.2 |
| 3 | 107 | 0.40 | 1.2 |
| 3 | 108 | 0.40 | 1.2 |
| 3 | 109 | 0.37 | 1.2 |
| 3 | 110 | 0.37 | 1.2 |
| 3 | 111 | 0.37 | 1.2 |
| 3 | 112 | 0.37 | 1.2 |
| 3 | 113 | 0.37 | 1.3 |
| 3 | 114 | 0.37 | 1.3 |
| 3 | 115 | 0.37 | 1.3 |
| 3 | 116 | 0.37 | 1.3 |
| 3 | 117 | 0.37 | 1.3 |
| 3 | 118 | 0.37 | 1.3 |
| 3 | 119 | 0.37 | 1.3 |
| 3 | 120 | 0.37 | 1.4 |
| 3 | 121 | 0.37 | 1.4 |
| 3 | 122 | 0.37 | 1.4 |
| 3 | 123 | 0.37 | 1.4 |
| 3 | 124 | 0.37 | 1.4 |
| 3 | 125 | 0.37 | 1.4 |
| 3 | 126 | 0.37 | 1.4 |
| 3 | 127 | 0.37 | 1.4 |

TABLE B-1 continued

# SHORELINE REACH CHARACTERISTICS VIRGINIA CHESAPEAKE BAY

| COUNTY | REACH NUMBER | TIDE RANGE (m) | SUBSIDENCE RATE (mm/yr) |
|---|---|---|---|
| 3 | 128 | 0.37 | 1.4 |
| 3 | 129 | 0.37 | 1.4 |
| 3 | 130 | 0.37 | 1.4 |
| 3 | 131 | 0.37 | 1.4 |
| 3 | 132 | 0.37 | 1.4 |
| 3 | 133 | 0.37 | 1.4 |
| 3 | 134 | 0.37 | 1.4 |
| 3 | 135 | 0.37 | 1.4 |
| 3 | 136 | 0.37 | 1.4 |
| 4 | 137 | 0.37 | 1.5 |
| 4 | 138 | 0.37 | 1.5 |
| 4 | 139 | 0.37 | 1.5 |
| 4 | 140 | 0.37 | 1.5 |
| 4 | 141 | 0.37 | 1.5 |
| 4 | 142 | 0.37 | 1.5 |
| 4 | 143 | 0.37 | 1.6 |
| 4 | 144 | 0.37 | 1.6 |
| 4 | 145 | 0.37 | 1.6 |
| 4 | 146 | 0.37 | 1.6 |
| 4 | 147 | 0.37 | 2.0 |
| 4 | 148 | 0.37 | 2.0 |
| 4 | 149 | 0.37 | 2.0 |
| 5 | 150 | 0.37 | 2.4 |
| 5 | 151 | 0.37 | 2.4 |
| 5 | 152 | 0.37 | 2.4 |
| 5 | 153 | 0.37 | 2.4 |
| 5 | 154 | 0.37 | 2.4 |
| 5 | 155 | 0.37 | 2.4 |
| 6 | 156 | 0.37 | 2.4 |
| 6 | 157 | 0.40 | 2.4 |
| 6 | 158 | 0.40 | 2.4 |
| 6 | 159 | 0.43 | 2.4 |
| 6 | 160 | 0.46 | 2.8 |
| 6 | 161 | 0.46 | 2.8 |
| 6 | 162 | 0.49 | 2.8 |
| 6 | 163 | 0.52 | 2.8 |
| 6 | 164 | 0.55 | 2.8 |
| 6 | 165 | 0.61 | 2.4 |
| 6 | 166 | 0.61 | 2.4 |
| 6 | 167 | 0.61 | 2.4 |
| 6 | 168 | 0.61 | 2.8 |
| 6 | 169 | 0.61 | 2.8 |

TABLE B-1 continued

# SHORELINE REACH CHARACTERISTICS
# VIRGINIA CHESAPEAKE BAY

| COUNTY | REACH NUMBER | TIDE RANGE (m) | SUBSIDENCE RATE (mm/yr) |
|---|---|---|---|
| 6 | 170 | 0.61 | 2.8 |
| 6 | 171 | 0.61 | 2.8 |
| 6 | 172 | 0.67 | 2.8 |
| 6 | 173 | 0.67 | 2.8 |
| 7 | 174 | 0.67 | 2.8 |
| 7 | 175 | 0.73 | 2.8 |
| 7 | 176 | 0.73 | 2.8 |
| 7 | 177 | 0.73 | 2.8 |
| 7 | 178 | 0.73 | 2.8 |
| 7 | 179 | 0.73 | 2.8 |
| 7 | 180 | 0.70 | 2.8 |
| 7 | 181 | 0.70 | 2.8 |
| 7 | 182 | 0.70 | 2.8 |
| 7 | 183 | 0.70 | 2.8 |
| 7 | 184 | 0.70 | 2.8 |
| 7 | 185 | 0.70 | 2.8 |
| 7 | 186 | 0.70 | 2.8 |
| 8 | 187 | 0.70 | 2.8 |
| 8 | 188 | 0.70 | 2.8 |
| 8 | 189 | 0.70 | 2.8 |
| 8 | 190 | 0.70 | 2.6 |
| 8 | 191 | 0.70 | 2.6 |
| 8 | 192 | 0.70 | 2.4 |
| 8 | 193 | 0.70 | 2.4 |
| 8 | 194 | 0.70 | 2.4 |
| 8 | 195 | 0.70 | 2.4 |
| 8 | 196 | 0.70 | 2.4 |
| 8 | 197 | 0.70 | 2.4 |
| 8 | 198 | 0.70 | 2.4 |
| 9 | 199 | 0.70 | 2.2 |
| 9 | 200 | 0.73 | 2.2 |
| 9 | 201 | 0.76 | 2.2 |
| 9 | 202 | 0.76 | 2.2 |
| 9 | 203 | 0.76 | 2.2 |
| 9 | 204 | 0.76 | 2.4 |
| 10 | 205 | 0.76 | 2.4 |
| 10 | 206 | 0.79 | 2.2 |
| 10 | 207 | 0.82 | 2.2 |
| 10 | 208 | 0.85 | 2.0 |
| 10 | 209 | 0.85 | 2.0 |

TABLE B-1 continued

TABLE B-2: EXPLANATION OF VARIABLES MEASURED SHORELINE REACH CHARACTERISTICS VIRGINIA CHESAPEAKE BAY

COUNTY:

1. Northampton
2. Accomack
3. Northumberland
4. Lancaster
5. Middlesex
6. Mathews
7. Gloucester
8. York
9. Hampton
10. Norfolk/Virginia Beach

See Location Map, Figure 1.

REACH NUMBER:

See Appendix A for reach locations.

BEACH WIDTH:

Distance in meters from low water line to backbeach.

BEACH ELEVATION:

Elevation in meters from low water line to maximum elevation of backbeach.

FORESHORE SLOPE:

Average beach slope seaward of high water line.

BACKSHORE TYPE:

1. Dune
2. Bluff
3. Other

## SHORELINE REACH CHARACTERISTICS VIRGINIA CHESAPEAKE BAY

| COUNTY | REACH NUMBER | BEACH WIDTH (m) | BEACH ELEVATION (m) | FORESHORE SLOPE | BACKSHORE TYPE |
|---|---|---|---|---|---|
| 1 | 6 | 21.0 | 2.45 | .103 | 1 |
| 1 | 7 | 22.5 | 2.45 | .130 | 2 |
| 1 | 8 | 18.0 | 1.92 | .130 | 2 |
| 1 | 9 | 21.0 | 2.59 | .130 | 1 |
| 1 | 10 | 24.0 | 2.06 | .113 | 2 |
| 1 | 11 | 21.0 | 1.90 | .133 | 1 |
| 1 | 12 | 12.0 | 1.72 | .140 | 2 |
| 1 | 14 | 12.0 | 1.32 | .106 | 2 |
| 1 | 15 | 15.0 | 1.74 | .106 | 1 |
| 1 | 16 | 15.0 | 1.62 | .130 | 1 |
| 1 | 17 | 9.0 | 1.27 | .145 | 3 |
| 1 | 18 | 12.0 | 1.46 | .126 | 1 |
| 1 | 22 | 12.0 | 1.59 | .146 | 1 |
| 1 | 23 | 6.0 | 0.74 | .126 | 2 |
| 1 | 24 | 24.0 | 1.34 | .073 | 2 |
| 1 | 25 | 21.0 | 1.47 | .073 | 2 |
| 1 | 26 | 15.0 | 1.79 | .130 | 2 |
| 1 | 27 | 7.5 | 1.32 | .160 | 2 |
| 1 | 31 | 9.0 | 0.93 | .083 | 2 |
| 1 | 34 | 14.0 | 1.40 | .126 | 1 |
| 1 | 35 | 9.0 | 1.12 | .120 | 2 |
| 1 | 36 | 12.0 | 1.38 | .133 | 1 |
| 1 | 37 | 18.0 | 1.33 | .113 | 2 |
| 1 | 38 | 9.0 | 0.60 | .106 | 2 |
| 1 | 39 | 9.0 | 0.58 | .186 | 1 |
| 1 | 40 | 18.0 | 1.69 | .102 | 2 |
| 1 | 41 | 6.0 | 0.65 | .100 | 2 |
| 2 | 42 | 6.0 | 0.98 | .193 | 1 |
| 2 | 43 | 9.0 | 1.02 | .120 | 1 |
| 2 | 45 | 12.0 | 0.83 | .140 | 1 |
| 2 | 47 | 9.0 | 1.31 | .140 | 1 |
| 2 | 49 | 9.0 | 1.12 | .130 | 1 |
| 2 | 52 | 7.5 | 1.00 | .146 | 1 |
| 2 | 53 | 6.0 | 0.78 | .130 | 1 |
| 2 | 54 | 12.0 | 0.67 | .093 | 2 |
| 2 | 55 | 3.0 | 0.98 | .173 | 1 |
| 2 | 58 | 9.0 | 1.14 | .140 | 1 |
| 2 | 61 | 6.0 | 0.71 | .106 | 1 |
| 2 | 65 | 9.0 | 0.64 | .123 | 1 |
| 2 | 66 | 6.0 | 0.72 | .120 | 1 |
| 2 | 67 | 12.0 | 1.06 | .106 | 1 |
| 2 | 68 | 9.0 | 1.02 | .116 | 1 |
| 2 | 70 | 12.0 | 1.48 | .140 | 1 |

TABLE B-2

# SHORELINE REACH CHARACTERISTICS
## VIRGINIA CHESAPEAKE BAY

| COUNTY | REACH NUMBER | BEACH WIDTH (m) | BEACH ELEVATION (m) | FORESHORE SLOPE | BACKSHORE TYPE |
|---|---|---|---|---|---|
| 2 | 71 | 12.0 | 1.54 | .156 | 2 |
| 2 | 72 | 15.0 | 1.56 | .146 | 1 |
| 2 | 74 | 12.0 | 1.01 | .100 | 1 |
| 2 | 75 | 12.0 | 0.83 | .066 | 2 |
| 2 | 82 | 12.0 | 0.92 | .083 | 1 |
| 2 | 84 | 9.0 | 1.12 | .133 | 1 |
| 2 | 85 | 18.0 | 1.22 | .133 | 1 |
| 2 | 89 | 6.0 | 0.60 | .106 | 2 |
| 3 | 92 | 12.0 | 1.04 | .116 | 2 |
| 3 | 93 | 12.0 | 1.22 | .123 | 1 |
| 3 | 94 | 9.0 | 0.87 | .133 | 1 |
| 3 | 95 | 9.0 | 1.01 | .150 | 1 |
| 3 | 96 | 9.0 | 0.50 | .113 | 1 |
| 3 | 99 | 6.0 | 0.84 | .140 | 1 |
| 3 | 102 | 6.0 | 0.79 | .131 | 1 |
| 3 | 103 | 6.0 | 0.57 | .096 | 2 |
| 3 | 104 | 9.0 | 1.18 | .143 | 1 |
| 3 | 106 | 9.0 | 0.86 | .101 | 2 |
| 3 | 107 | 9.0 | 1.17 | .120 | 2 |
| 3 | 108 | 9.0 | 1.02 | .150 | 1 |
| 3 | 109 | 9.0 | 0.84 | .120 | 2 |
| 3 | 110 | 12.0 | 1.10 | .120 | 2 |
| 3 | 111 | 9.0 | 1.20 | .143 | 1 |
| 3 | 112 | 18.0 | 1.83 | .146 | 3 |
| 3 | 113 | 18.0 | 1.53 | .153 | 3 |
| 3 | 114 | 12.0 | 1.14 | .130 | 2 |
| 3 | 116 | 9.0 | 0.82 | .100 | 2 |
| 3 | 118 | 12.0 | 1.20 | .153 | 1 |
| 3 | 119 | 6.0 | 0.88 | .126 | 2 |
| 3 | 120 | 12.0 | 0.96 | .126 | 1 |
| 3 | 121 | 9.0 | 0.94 | .100 | 1 |
| 3 | 125 | 6.0 | 0.87 | .163 | 1 |
| 3 | 126 | 9.0 | 0.86 | .120 | 1 |
| 3 | 127 | 12.0 | 0.99 | .113 | 1 |
| 3 | 128 | 9.0 | 1.05 | .133 | 1 |
| 3 | 129 | 12.0 | 1.38 | .143 | 1 |
| 3 | 130 | 9.0 | 1.10 | .136 | 1 |
| 3 | 132 | 9.0 | 0.83 | .106 | 1 |
| 3 | 133 | 9.0 | 1.11 | .130 | 2 |
| 3 | 134 | 9.0 | 0.86 | .106 | 1 |
| 3 | 135 | 9.0 | 1.20 | .130 | 1 |
| 3 | 136 | 4.0 | 0.48 | .116 | 2 |

TABLE B-2 continued

## SHORELINE REACH CHARACTERISTICS VIRGINIA CHESAPEAKE BAY

| COUNTY | REACH NUMBER | BEACH WIDTH (m) | BEACH ELEVATION (m) | FORESHORE SLOPE | BACKSHORE TYPE |
|---|---|---|---|---|---|
| 4 | 137 | 4.0 | 0.35 | .096 | 2 |
| 4 | 138 | 3.0 | 0.24 | .080 | 2 |
| 4 | 140 | 3.0 | 0.30 | .100 | 2 |
| 4 | 141 | 6.0 | 0.75 | .146 | 1 |
| 4 | 142 | 12.0 | 1.01 | .113 | 1 |
| 4 | 144 | 12.0 | 1.48 | .133 | 1 |
| 4 | 145 | 15.0 | 1.59 | .160 | 2 |
| 4 | 148 | 9.0 | 0.76 | .180 | 1 |
| 4 | 149 | 15.0 | 1.38 | .173 | 1 |
| 5 | 150 | 12.0 | 1.08 | .140 | 3 |
| 5 | 152 | 18.0 | 1.68 | .123 | 1 |
| 5 | 153 | 9.0 | 1.02 | .128 | 1 |
| 6 | 156 | 12.0 | 0.94 | .116 | 2 |
| 6 | 157 | 15.0 | 1.32 | .146 | 1 |
| 6 | 158 | 12.0 | 0.96 | .113 | 1 |
| 6 | 159 | 12.0 | 1.09 | .133 | 1 |
| 6 | 160 | 6.0 | 0.74 | .106 | 1 |
| 6 | 161 | 6.0 | 0.68 | .096 | 1 |
| 6 | 162 | 15.0 | 1.56 | .136 | 1 |
| 6 | 165 | 9.0 | 1.07 | .166 | 1 |
| 6 | 167 | 15.0 | 1.75 | .140 | 1 |
| 8 | 187 | 6.0 | 0.93 | .106 | 2 |
| 8 | 188 | 9.0 | 0.76 | .116 | 2 |
| 8 | 192 | 15.0 | 1.13 | .133 | 1 |
| 8 | 195 | 6.0 | 0.64 | .106 | 1 |
| 8 | 198 | 9.0 | 1.12 | .120 | 1 |
| 9 | 199 | 15.0 | 0.98 | .126 | 1 |
| 9 | 202 | 42.0 | 2.27 | .126 | 3 |
| 10 | 205 | 27.0 | 1.94 | .146 | 3 |
| 10 | 207 | 30.0 | 2.46 | .132 | 1 |
| 10 | 208 | 33.0 | 2.53 | .130 | 1 |
| 10 | 209 | 27.0 | 1.99 | .126 | 1 |

TABLE B-2 continued

TABLE B-3: EXPLANATION OF VARIABLES MEASURED
SHORELINE REACH CHARACTERISTICS
VIRGINIA CHESAPEAKE BAY

**COUNTY:**

1. Northampton
2. Accomack
3. Northumberland
4. Lancaster
5. Middlesex
6. Mathews
7. Gloucester
8. York
9. Hampton
10. Norfolk/Virginia Beach

See Location Map, Figure 1.

**REACH NUMBER:**

See Appendix A for reach locations.

**REACH LENGTH:**

Length of shoreline in meters characterized by this sampling.

**EROSION RATE:**

Mean shoreline retreat over length of reach, 1860-1940.

**NEARSHORE TERRACE WIDTH:**

Distance from shore to 3.6 m (12 ft) contour line.

**SHORELINE ORIENTATION:**

Azimuth. Orientation of shore; bearing to the right, facing landward.

**SHORELINE REORIENTATION:**

Change in orientation in degrees over 1860-1940 period. + is clockwise change, - is counter-clockwise change.

**BLUFF HEIGHT:**

Mean bluff height in meters over reach length.

**FASTLAND TYPE:**

1. Impermeable Beach
2. Permeable Beach
3. Marsh Barrier Beach

# SHORELINE REACH CHARACTERISTICS VIRGINIA CHESPEAKE BAY

| COUNTY | REACH NUMBER | REACH LENGTH (m) | EROSION RATE (m/yr) | NEARSHORE TERRACE WIDTH | SHORELINE ORIENTATION | SHORELINE REORIENTATION | BLUFF HEIGHT (m) | FASTLAND TYPE |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 2438. | -6.0 | 548. | 281. | 0. | 0. | 2 |
| 1 | 2 | 1463. | 6.0 | 1371. | 227. | 0. | 1. | 2 |
| 1 | 3 | 1402. | 6.0 | 3261. | 155. | 0. | 0. | 2 |
| 1 | 4 | 2621. | 0.0 | 2148. | 102. | 0. | 0. | 2 |
| 1 | 5 | 1524. | 3.0 | 335. | 10. | 10. | 0. | 2 |
| 1 | 6 | 2865. | 0.7 | 670. | 355. | 0. | 1. | 2 |
| 1 | 7 | 3048. | 0.7 | 457. | 346. | 0. | 7. | 2 |
| 1 | 8 | 2164. | 0.7 | 914. | 331. | 0. | 2. | 2 |
| 1 | 9 | 2316. | 0.7 | 1097. | 328. | 0. | 3. | 2 |
| 1 | 10 | 1036. | 0.7 | 1066. | 3. | 0. | 3. | 2 |
| 1 | 11 | 426. | 0.7 | 1127. | 3. | 0. | 1. | 2 |
| 1 | 12 | 1005. | 0.7 | 1005. | 11. | 0. | 1. | 1 |
| 1 | 13 | 335. | 0.7 | 1097. | 20. | 0. | 1. | 2 |
| 1 | 14 | 792. | 0.8 | 853. | 335. | 0. | 1. | 1 |
| 1 | 15 | 701. | 0.2 | 640. | 340. | 0. | 1. | 2 |
| 1 | 16 | 640. | 0.0 | 2438. | 24. | 0. | 3. | 2 |
| 1 | 17 | 944. | 0.0 | 2072. | 23. | 0. | 1. | 2 |
| 1 | 18 | 914. | 0.3 | 2621. | 45. | 0. | 1. | 2 |
| 1 | 19 | 701. | 0.0 | 2438. | 350. | 0. | 1. | 2 |
| 1 | 20 | 1219. | 0.7 | 2286. | 30. | 0. | 1. | 2 |
| 1 | 21 | 914. | 0.0 | 1524. | 8. | 0. | 1. | 2 |
| 1 | 22 | 2987. | 0.9 | 975. | 11. | 0. | 2. | 2 |
| 1 | 23 | 1066. | 1.5 | 609. | 32. | 0. | 3. | 1 |
| 1 | 24 | 883. | 2.1 | 609. | 35. | 5. | 3. | 1 |
| 1 | 25 | 914. | 1.0 | 609. | 29. | 0. | 3. | 1 |
| 1 | 26 | 1554. | 1.0 | 762. | 25. | 0. | 4. | 1 |
| 1 | 27 | 1371. | 1.0 | 420. | 352. | 0. | 6. | 1 |
| 1 | 28 | 1219. | 0.0 | 3200. | 277. | 0. | 0. | 2 |
| 1 | 29 | 1005. | 0.6 | 3596. | 76. | 0. | 1. | 2 |
| 1 | 30 | 1158. | 0.6 | 3779. | 330. | 0. | 2. | 2 |
| 1 | 31 | 1676. | 0.9 | 975. | 353. | 0. | 2. | 2 |
| 1 | 32 | 548. | 0.4 | 1036. | 10. | 0. | 1. | 1 |
| 1 | 33 | 2499. | 0.1 | 1097. | 10. | 0. | 1. | 2 |
| 1 | 34 | 1097. | 0.5 | 944. | 34. | 0. | 3. | 1 |
| 1 | 35 | 304. | 0.3 | 944. | 347. | 0. | 1. | 2 |
| 1 | 36 | 1066. | 0.6 | 914. | 33. | 0. | 3. | 2 |
| 1 | 37 | 457. | 0.9 | 1158. | 22. | 6. | 3. | 1 |
| 1 | 38 | 45. | 0.0 | 1127. | 297. | 0. | 3. | 1 |
| 1 | 39 | 152. | 0.0 | 1127. | 297. | 0. | 1. | 2 |
| 1 | 40 | 2926. | 1.7 | 1097. | 8. | 0. | 4. | 1 |
| 1 | 41 | 5059. | 1.5 | 2164. | 25. | 6. | 1. | 1 |
| 2 | 42 | 1219. | 1.8 | 2072. | 341. | 3. | 0. | 2 |
| 2 | 43 | 2743. | 1.5 | 1158. | 34. | 0. | 0. | 3 |

TABLE B-3

## SHORELINE REACH CHARACTERISTICS VIRGINIA CHESAPEAKE BAY

| COUNTY | REACH NUMBER | REACH LENGTH (m) | EROSION RATE (m/yr) | NEARSHORE TERRACE WIDTH | SHORLINE ORIENTATION | SHORELINE REORIENTATION | BLUFF HEIGHT (m) | FASTLAND TYPE |
|---|---|---|---|---|---|---|---|---|
| 2 | 44 | 548. | 0.9 | 1341. | 30. | 0. | 0. | 2 |
| 2 | 45 | 3672. | 1.0 | 1615. | 30. | 0. | 0. | 3 |
| 2 | 46 | 2438. | 0.5 | 914. | 348. | 0. | 0. | 3 |
| 2 | 47 | 1097. | 1.2 | 701. | 37. | 0. | 1. | 2 |
| 2 | 48 | 914. | 1.0 | 1249. | 88. | 0. | 0. | 2 |
| 2 | 49 | 1554. | 0.8 | 853. | 40. | 0. | 0. | 3 |
| 2 | 50 | 2453. | 0.7 | 853. | 92. | 0. | 0. | 1 |
| 2 | 51 | 914. | 0.4 | 3139. | 30. | 0. | 0. | 2 |
| 2 | 52 | 1158. | 0.6 | 944. | 64. | 0. | 1. | 2 |
| 2 | 53 | 1219. | 0.5 | 2407. | 9. | 0. | 0. | 1 |
| 2 | 54 | 1798. | 0.5 | 2438. | 64. | 0. | 0. | 1 |
| 2 | 55 | 3657. | 1.5 | 1066. | 39. | 0. | 1. | 3 |
| 2 | 56 | 365. | -0.6 | 1066. | 290. | 0. | 0. | 2 |
| 2 | 57 | 1188. | 0.6 | 2194. | 67. | 0. | 0. | 3 |
| 2 | 58 | 929. | 0.6 | 914. | 32. | 0. | 0. | 2 |
| 2 | 59 | 1463. | 0.3 | 3413. | 11. | 0. | 0. | 3 |
| 2 | 60 | 1249. | 1.3 | 1798. | 322. | 0. | 2. | 2 |
| 2 | 61 | 2743. | 0.6 | 1645. | 62. | 0. | 0. | 3 |
| 2 | 62 | 3688. | 0.6 | 1676. | 108. | 0. | 0. | 3 |
| 2 | 63 | 1584. | 0.6 | 2804. | 60. | 0. | 0. | 3 |
| 2 | 64 | 2743. | 0.3 | 6705. | 64. | 0. | 0. | 3 |
| 2 | 65 | 3048. | 0.8 | 5181. | 334. | 0. | 1. | 1 |
| 2 | 66 | 944. | 0.8 | 3352. | 52. | 0. | 1. | 1 |
| 2 | 67 | 1828. | 0.6 | 4876. | 355. | 0. | 0. | 1 |
| 2 | 68 | 670. | 0.5 | 3139. | 0. | 0. | 0. | 3 |
| 2 | 69 | 304. | 0.5 | 3139. | 74. | 0. | 0. | 3 |
| 2 | 70 | 701. | 0.5 | 3078. | 330. | 0. | 1. | 2 |
| 2 | 71 | 670. | 0.4 | 4876. | 25. | 0. | 1. | 1 |
| 2 | 72 | 609. | 0.4 | 5486. | 88. | 0. | 0. | 3 |
| 2 | 73 | 304. | 0.4 | 5486. | 12. | 0. | 0. | 3 |
| 2 | 74 | 883. | 0.4 | 5638. | 100. | 0. | 0. | 3 |
| 2 | 75 | 1524. | 0.4 | 5974. | 140. | 0. | 0. | 1 |
| 2 | 76 | 701. | 0.6 | 7315. | 43. | 0. | 0. | 2 |
| 2 | 77 | 2438. | 0.4 | 5181. | 315. | 0. | 0. | 3 |
| 2 | 78 | 3048. | 0.3 | 6400. | 48. | 0. | 0. | 3 |
| 2 | 79 | 1249. | 0.5 | 10668. | 11. | 0. | 0. | 3 |
| 2 | 80 | 2438. | 0.3 | 10515. | 280. | 0. | 0. | 3 |
| 2 | 81 | 365. | 0.3 | 10362. | 280. | 0. | 0. | 2 |
| 2 | 82 | 609. | 0.4 | 10515. | 328. | 0. | 0. | 3 |
| 2 | 83 | 1188. | 0.5 | 10972. | 245. | 0. | 0. | 3 |
| 2 | 84 | 2164. | 0.6 | 10393. | 270. | 0. | 1. | 3 |
| 2 | 85 | 2072. | 0.4 | 4663. | 54. | 0. | 0. | 3 |

TABLE B-3 continued

# SHORELINE REACH CHARACTERISTICS VIRGINIA CHESAPEAKE BAY

| COUNTY | REACH NUMBER | REACH LENGTH (m) | EROION RATE (m/yr) | NEARSHORE TERRACE WIDTH | SHORELINE ORIENTATION | SHORELINE REORIENTATION | BLUFF HEIGHT (m) | FASTLAND TYPE |
|---|---|---|---|---|---|---|---|---|
| 2 | 86 | 670. | 0.2 | 4937. | 332. | 0. | 0. | 3 |
| 2 | 87 | 243. | 0.9 | 4815. | 41. | 0. | 0. | 3 |
| 2 | 88 | 975. | 0.7 | 4815. | 48. | 0. | 0. | 3 |
| 2 | 89 | 3108. | 1.4 | 4815. | 38. | 0. | 0. | 1 |
| 2 | 90 | 3962. | 0.3 | 5486. | 56. | 0. | 1. | 3 |
| 2 | 91 | 640. | 0.9 | 5577. | 121. | 0. | 1. | 2 |
| 3 | 92 | 914. | 0.4 | 883. | 102. | 0. | 3. | 1 |
| 3 | 93 | 975. | 0.6 | 883. | 104. | 0. | 0. | 3 |
| 3 | 94 | 1219. | 0.4 | 2011. | 124. | 0. | 0. | 2 |
| 3 | 95 | 975. | 1.1 | 640. | 180. | 0. | 0. | 2 |
| 3 | 96 | 1341. | 0.7 | 579. | 95. | 0. | 0. | 2 |
| 3 | 97 | 243. | 0.7 | 182. | 88. | 0. | 0. | 2 |
| 3 | 98 | 1097. | 3.2 | 1219. | 125. | 0. | 1. | 2 |
| 3 | 99 | 243. | 0.0 | 1828. | 176. | 0. | 0. | 2 |
| 3 | 100 | 228. | 1.8 | 1524. | 125. | 0. | 0. | 2 |
| 3 | 101 | 1219. | 1.7 | 1584. | 133. | 0. | 1. | 1 |
| 3 | 102 | 853. | 0.0 | 1402. | 133. | 0. | 0. | 2 |
| 3 | 103 | 2804. | 1.1 | 975. | 110. | 0. | 3. | 1 |
| 3 | 104 | 60. | 1.0 | 883. | 110. | 0. | 1. | 2 |
| 3 | 105 | 2560. | 0.5 | 1341. | 108. | 0. | 3. | 2 |
| 3 | 106 | 3657. | 0.6 | 1036. | 122. | 0. | 4. | 1 |
| 3 | 107 | 243. | 0.6 | 670. | 121. | 0. | 1. | 1 |
| 3 | 108 | 4937. | 0.6 | 518. | 121. | 0. | 3. | 2 |
| 3 | 109 | 2560. | 1.4 | 701. | 134. | 0. | 3. | 1 |
| 3 | 110 | 4023. | 1.7 | 670. | 190. | 0. | 1. | 1 |
| 3 | 111 | 1219. | 1.8 | 640. | 190. | 0. | 0. | 2 |
| 3 | 112 | 1158. | 1.8 | 792. | 190. | 0. | 3. | 2 |
| 3 | 113 | 914. | 1.9 | 1188. | 212. | 0. | 2. | 2 |
| 3 | 114 | 579. | 0.3 | 1341. | 183. | 0. | 3. | 1 |
| 3 | 115 | 335. | 1.0 | 944. | 208. | -3. | 0. | 2 |
| 3 | 116 | 1188. | 1.0 | 1066. | 231. | -5. | 3. | 1 |
| 3 | 117 | 914. | 0.4 | 548. | 272. | 0. | 0. | 2 |
| 3 | 118 | 304. | 0.0 | 518. | 154. | 0. | 0. | 2 |
| 3 | 119 | 1402. | 2.1 | 1371. | 182. | 0. | 1. | 1 |
| 3 | 120 | 579. | 0.0 | 396. | 212. | 0. | 0. | 2 |
| 3 | 121 | 1645. | 0.6 | 701. | 98. | 0. | 0. | 3 |
| 3 | 122 | 1280. | 0.6 | 2255. | 161. | 0. | 0. | 3 |
| 3 | 123 | 2773. | 0.6 | 2194. | 270. | 0. | 0. | 3 |
| 3 | 124 | 670. | 0.6 | 2072. | 185. | 0. | 0. | 3 |
| 3 | 125 | 792. | 0.9 | 1950. | 180. | 0. | 0. | 1 |
| 3 | 126 | 1188. | 0.9 | 1524. | 185. | 0. | 0. | 3 |
| 3 | 127 | 944. | 0.8 | 1341. | 180. | 0. | 0. | 3 |

TABLE B-3 continued

# SHORELINE REACH CHARACTERISTICS
## VIRGINIA CHESAPEAKE BAY

| COUNTY | REACH NUMBER | REACH LENGTH (m) | EROSION RATE (m/yr) | NEARSHORE TERRACE WIDTH | SHORELINE ORIENTATION | SHORELINE REORIENTATION | BLUFF HEIGHT (m) | FASTLAND TY |
|---|---|---|---|---|---|---|---|---|
| 3 | 128 | 1188. | 0.4 | 883. | 162. | 0. | 0. | 2 |
| 3 | 129 | 1524. | 0.4 | 883. | 165. | 0. | 0. | 2 |
| 3 | 130 | 243. | 1.2 | 731. | 145. | 0. | 0. | 3 |
| 3 | 131 | 609. | 1.4 | 487. | 140. | 0. | 0. | 2 |
| 3 | 132 | 1280. | 0.6 | 2346. | 154. | 0. | 0. | 2 |
| 3 | 133 | 1158. | 1.7 | 2346. | 154. | 0. | 0. | 1 |
| 3 | 134 | 1036. | 1.5 | 1097. | 191. | 0. | 0. | 3 |
| 3 | 135 | 640. | 0.0 | 2042. | 211. | 0. | 0. | 3 |
| 3 | 136 | 640. | 0.9 | 762. | 280. | -3. | 0. | 1 |
| 4 | 137 | 1280. | 2.0 | 1341. | 193. | 0. | 0. | 1 |
| 4 | 138 | 1310. | 1.8 | 640. | 192. | 0. | 0. | 1 |
| 4 | 139 | 1341. | 1.7 | 975. | 146. | 0. | 0. | 1 |
| 4 | 140 | 1280. | 0.9 | 975. | 170. | 0. | 0. | 1 |
| 4 | 141 | 1310. | 0.6 | 883. | 108. | 0. | 0. | 2 |
| 4 | 142 | 640. | 0.6 | 883. | 13. | 0. | 0. | 2 |
| 4 | 143 | 1889. | 0.6 | 883. | 45. | 0. | 0. | 3 |
| 4 | 144 | 1554. | 1.8 | 914. | 84. | 0. | 0. | 2 |
| 4 | 145 | 2804. | 2.4 | 1188. | 157. | 0. | 0. | 2 |
| 4 | 146 | 914. | 2.2 | 1219. | 157. | 0. | 0. | 2 |
| 4 | 147 | 1280. | 1.2 | 731. | 281. | 5. | 0. | 2 |
| 4 | 148 | 1615. | 0.8 | 457. | 296. | 0. | 0. | 2 |
| 4 | 149 | 2255. | 0.0 | 487. | 252. | 0. | 0. | 2 |
| 5 | 150 | 2164. | 1.0 | 1097. | 118. | 0. | 1. | 2 |
| 5 | 151 | 1584. | 1.4 | 1341. | 100. | 0. | 0. | 3 |
| 5 | 152 | 2164. | 0.7 | 883. | 226. | -5. | 0. | 2 |
| 5 | 153 | 1280. | -0.7 | 243. | 280. | 0. | 0. | 2 |
| 5 | 154 | 2499. | 0.7 | 670. | 184. | 0. | 3. | 2 |
| 5 | 155 | 426. | 0.7 | 1432. | 212. | 0. | 0. | 2 |
| 6 | 156 | 2560. | 2.2 | 914. | 198. | 0. | 1. | 1 |
| 6 | 157 | 929. | 2.1 | 426. | 156. | 0. | 0. | 2 |
| 6 | 158 | 1950. | 2.1 | 640. | 155. | 0. | 0. | 2 |
| 6 | 159 | 2743. | 1.3 | 1127. | 165. | 0. | 0. | 2 |
| 6 | 160 | 1859. | 1.4 | 1127. | 175. | 0. | 0. | 3 |
| 6 | 161 | 944. | 1.3 | 1615. | 173. | 0. | 0. | 3 |
| 6 | 162 | 4846. | 1.3 | 1005. | 180. | 0. | 0. | 2 |
| 6 | 163 | 1828. | 2.1 | 609. | 212. | 0. | 0. | 3 |
| 6 | 164 | 914. | 0.0 | 1310. | 218. | 0. | 0. | 3 |
| 6 | 165 | 1554. | 0.3 | 1310. | 170. | 0. | 0. | 2 |
| 6 | 166 | 335. | 0.3 | 1554. | 170. | 0. | 0. | 3 |
| 6 | 167 | 2651. | 0.4 | 1005. | 190. | 0. | 1. | 2 |
| 6 | 168 | 3718. | 0.7 | 914. | 312. | 0. | 0. | 3 |
| 6 | 169 | 929. | 0.1 | 883. | 288. | 0. | 0. | 1 |

TABLE B-3 continued

# SHORELINE REACH CHARACTERISTICS
# VIRGINIA CHESAPEAKE BAY

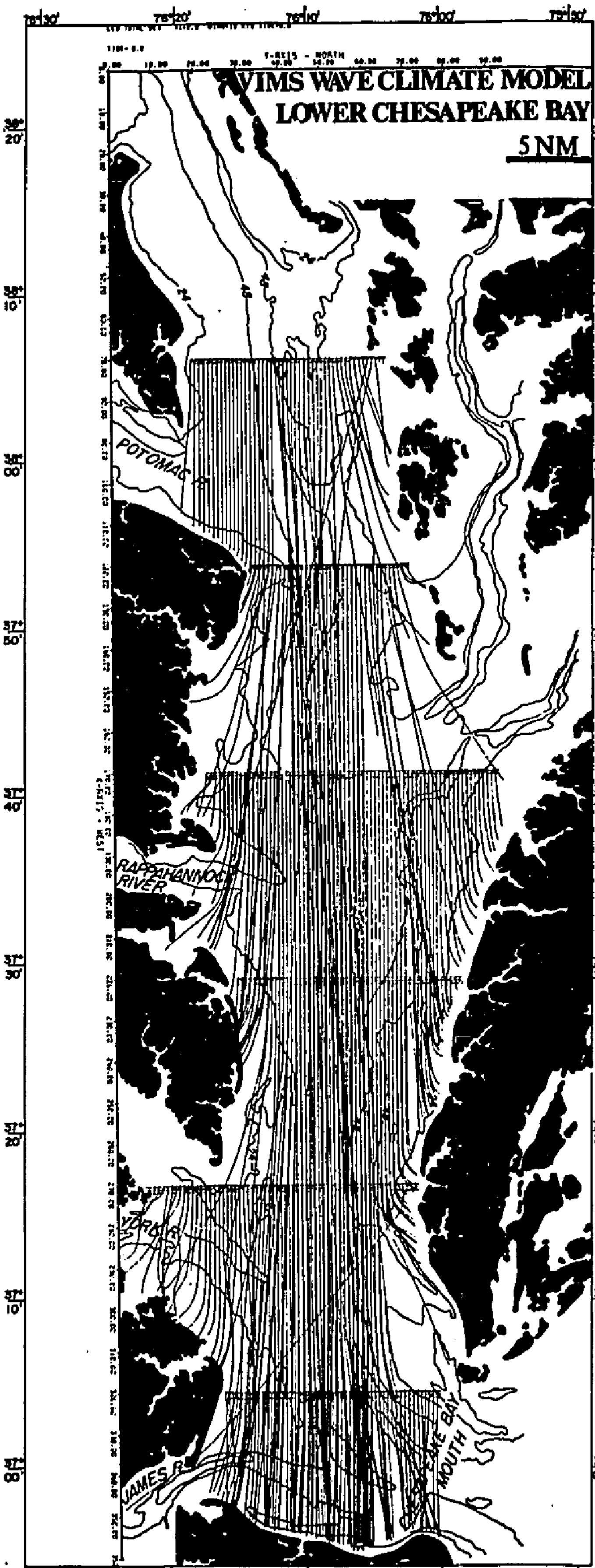
| COUNTY | REACH NUMBER | REACH LENGTH (m) | EROSION RATE (m/yr) | NEARSHORE TERRACE WIDTH | SHORELINE ORIENTATION | SHORELINE REORIENTATION | BLUFF HEIGHT (m) | FASTLAND TY |
|---|---|---|---|---|---|---|---|---|
| 6 | 170 | 1310. | 0.4 | 1219. | 336. | 0. | 0. | 1 |
| 6 | 171 | 670. | 0.1 | 1402. | 345. | 0. | 0. | 3 |
| 6 | 172 | 1920. | 0.7 | 457. | 325. | 0. | 0. | 1 |
| 6 | 173 | 1219. | 0.2 | 1158. | 270. | 0. | 0. | 1 |
| 7 | 174 | 1524. | 0.5 | 1219. | 220. | 0. | 0. | 1 |
| 7 | 175 | 1767. | 0.5 | 914. | 133. | 0. | 0. | 3 |
| 7 | 176 | 975. | 0.5 | 609. | 196. | 0. | 0. | 3 |
| 7 | 177 | 731. | 0.7 | 213. | 232. | 0. | 0. | 3 |
| 7 | 178 | 2804. | 0.6 | 762. | 90. | 0. | 0. | 3 |
| 7 | 179 | 975. | 1.3 | 853. | 148. | 0. | 0. | 3 |
| 7 | 180 | 853. | 0.1 | 914. | 170. | -3. | 0. | 3 |
| 7 | 181 | 1219. | 0.0 | 853. | 105. | 0. | 0. | 3 |
| 7 | 182 | 1036. | 0.0 | 3200. | 200. | 0. | 0. | 3 |
| 7 | 183 | 670. | 0.0 | 670. | 260. | 0. | 0. | 3 |
| 7 | 184 | 1219. | 0.3 | 701. | 253. | 3. | 0. | 3 |
| 7 | 185 | 2194. | 0.5 | 883. | 270. | 0. | 0. | 1 |
| 7 | 186 | 548. | 0.6 | 1066. | 270. | 3. | 0. | 2 |
| 8 | 187 | 2743. | 1.0 | 548. | 83. | 0. | 1. | 1 |
| 8 | 188 | 1524. | 1.0 | 548. | 75. | 0. | 0. | 1 |
| 8 | 189 | 274. | 1.0 | 487. | 73. | 0. | 0. | 2 |
| 8 | 190 | 609. | 0.9 | 609. | 98. | 0. | 0. | 2 |
| 8 | 191 | 2560. | 0.9 | 640. | 71. | 0. | 0. | 2 |
| 8 | 192 | 2621. | 0.0 | 1554. | 232. | 0. | 0. | 2 |
| 8 | 193 | 1036. | 1.1 | 365. | 135. | 0. | 0. | 2 |
| 8 | 194 | 1371. | 1.1 | 1066. | 142. | 0. | 0. | 2 |
| 8 | 195 | 640. | 1.1 | 1249. | 190. | 0. | 0. | 2 |
| 8 | 196 | 1249. | 0.6 | 1005. | 195. | 0. | 0. | 2 |
| 8 | 197 | 3718. | 0.7 | 1615. | 75. | 0. | 0. | 3 |
| 8 | 198 | 7680. | 0.0 | 4114. | 132. | 0. | 0. | 3 |
| 9 | 199 | 1097. | 1.2 | 304. | 128. | 0. | 0. | 2 |
| 9 | 200 | 2164. | 1.9 | 914. | 152. | 0. | 1. | 2 |
| 9 | 201 | 4145. | 1.4 | 548. | 200. | 0. | 1. | 2 |
| 9 | 202 | 3169. | 0.5 | 320. | 200. | 0. | 0. | 2 |
| 9 | 203 | 2712. | 0.0 | 182. | 195. | -4. | 0. | 2 |
| 9 | 204 | 944. | 0.0 | 30. | 270. | 0. | 0. | 2 |
| 10 | 205 | 7924. | 0.4 | 396. | 115. | 0. | 1. | 2 |
| 10 | 206 | 3566. | 0.4 | 182. | 115. | -3. | 1. | 2 |
| 10 | 207 | 4267. | 0.9 | 304. | 108. | 7. | 1. | 2 |
| 10 | 208 | 3474. | 1.3 | 701. | 110. | 0. | 1. | 2 |
| 10 | 209 | 5486. | 0.8 | 289. | 65. | 0. | 3. | 2 |

TABLE B-3 continued

# APPENDIX C

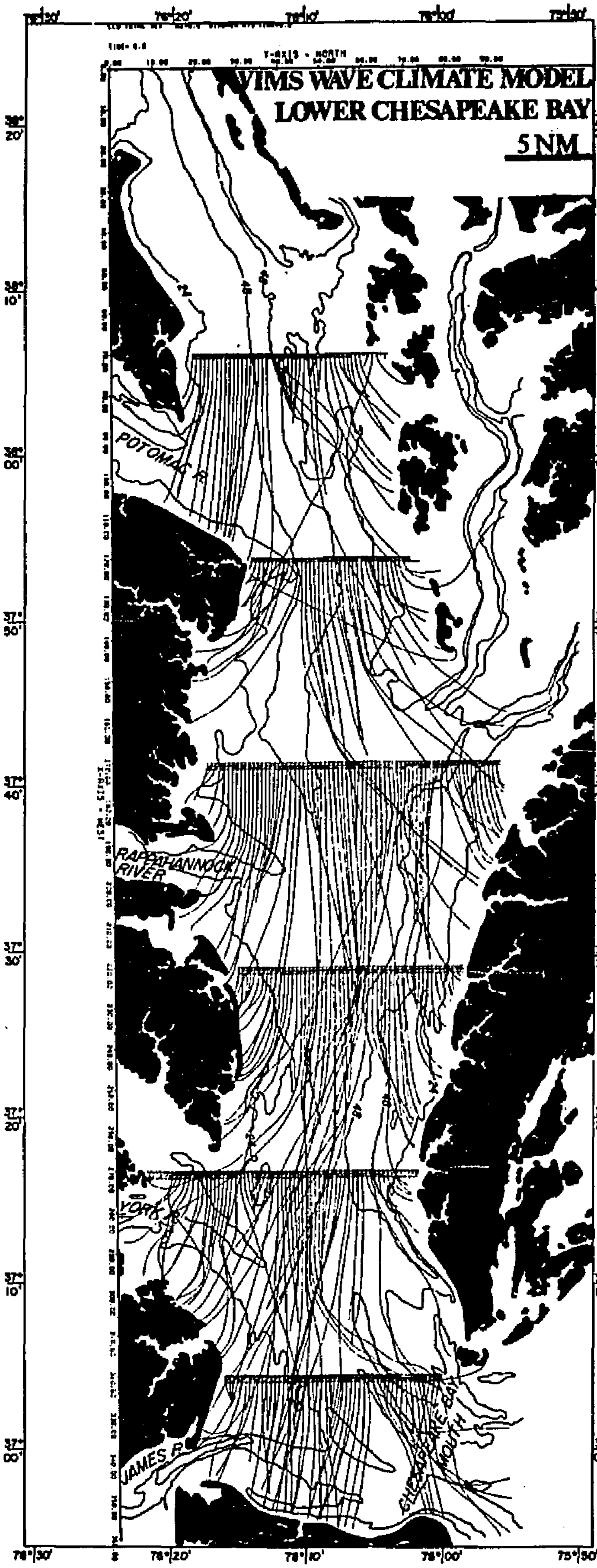
## WAVE REFRACTION DIAGRAMS

| Input Wind Direction (azimuth) | Input Wind Velocity (knots) | Figure Number |
|---|---|---|
| 0° | 10 | C - 1 |
| 0° | 25 | C - 2 |
| 0° | 40 | C - 3 |
| 45° | 10 | C - 4 |
| 45° | 25 | C - 5 |
| 45° | 40 | C - 6 |
| 225° | 10 | C - 7 |
| 225° | 25 | C - 8 |
| 225° | 40 | C - 9 |
| 315° | 10 | C - 10 |
| 315° | 25 | C - 11 |
| 315° | 40 | C - 12 |



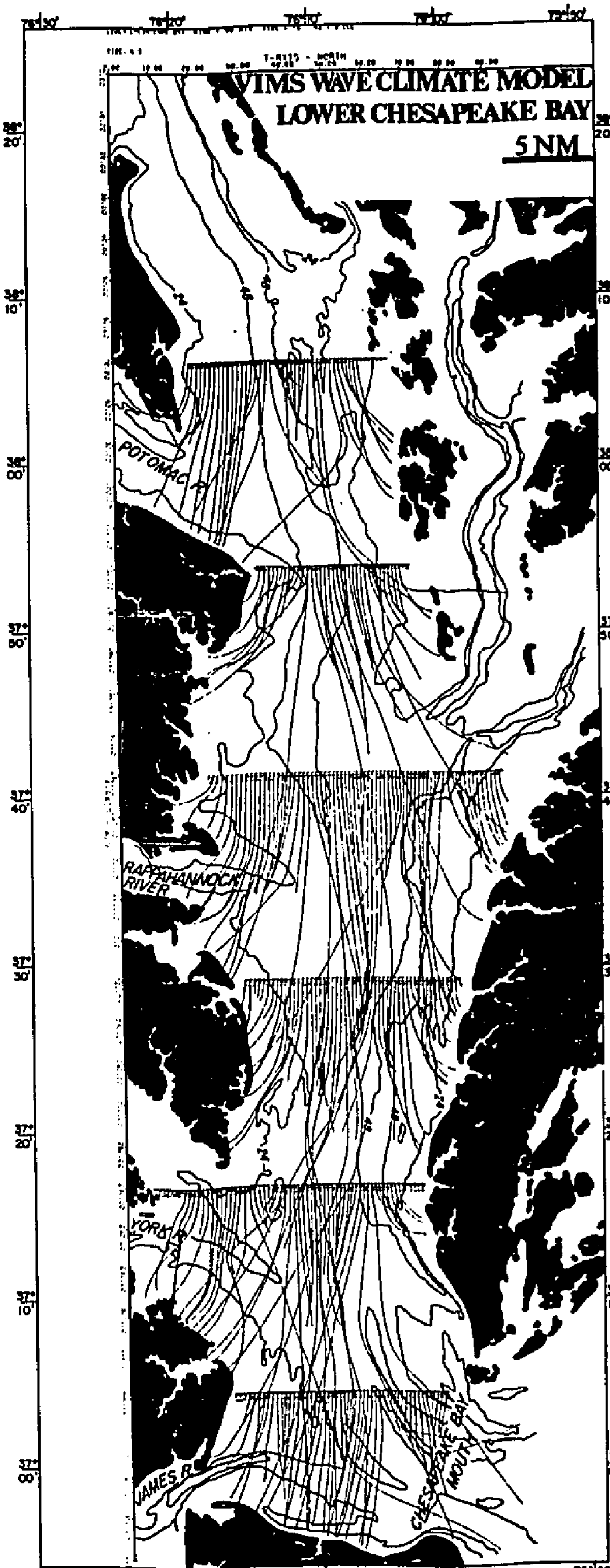

INPUT WIND: AZ=0°, VELOCITY=10 KTS

FIGURE C-1



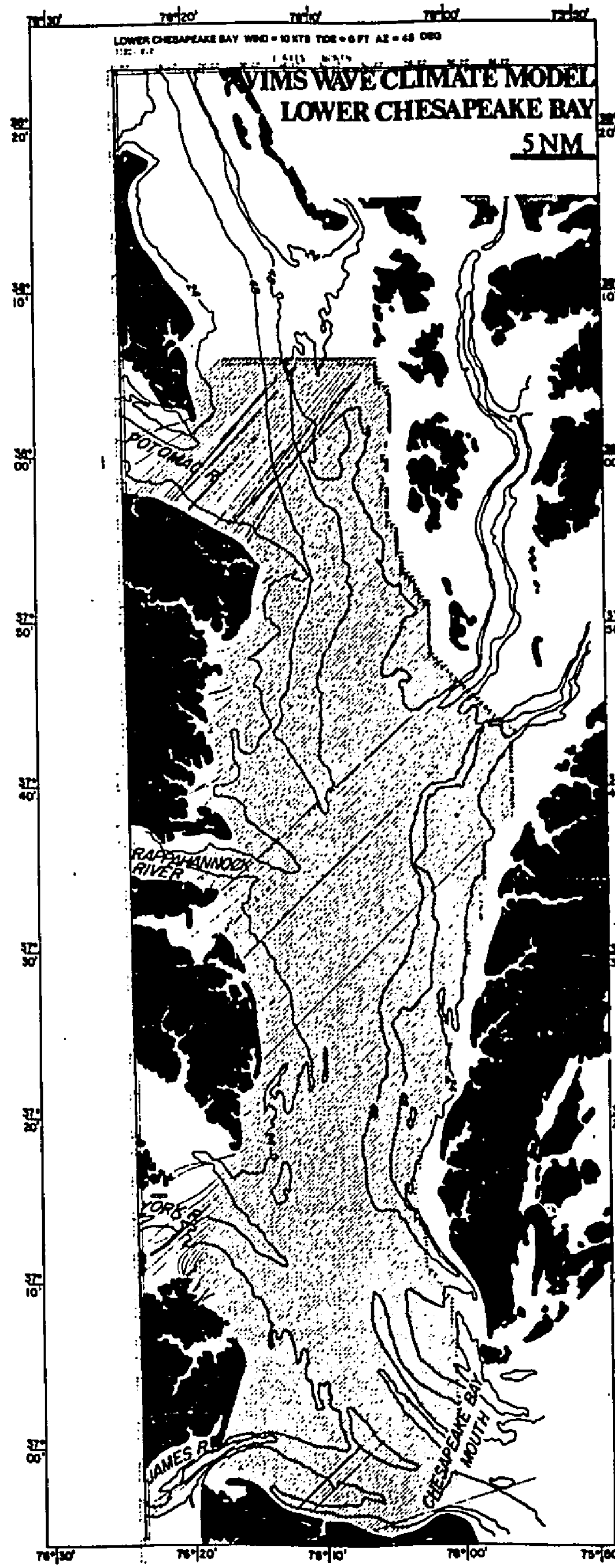

INPUT WIND: AZ=0°, VELOCITY=25 KTS

FIGURE C-2



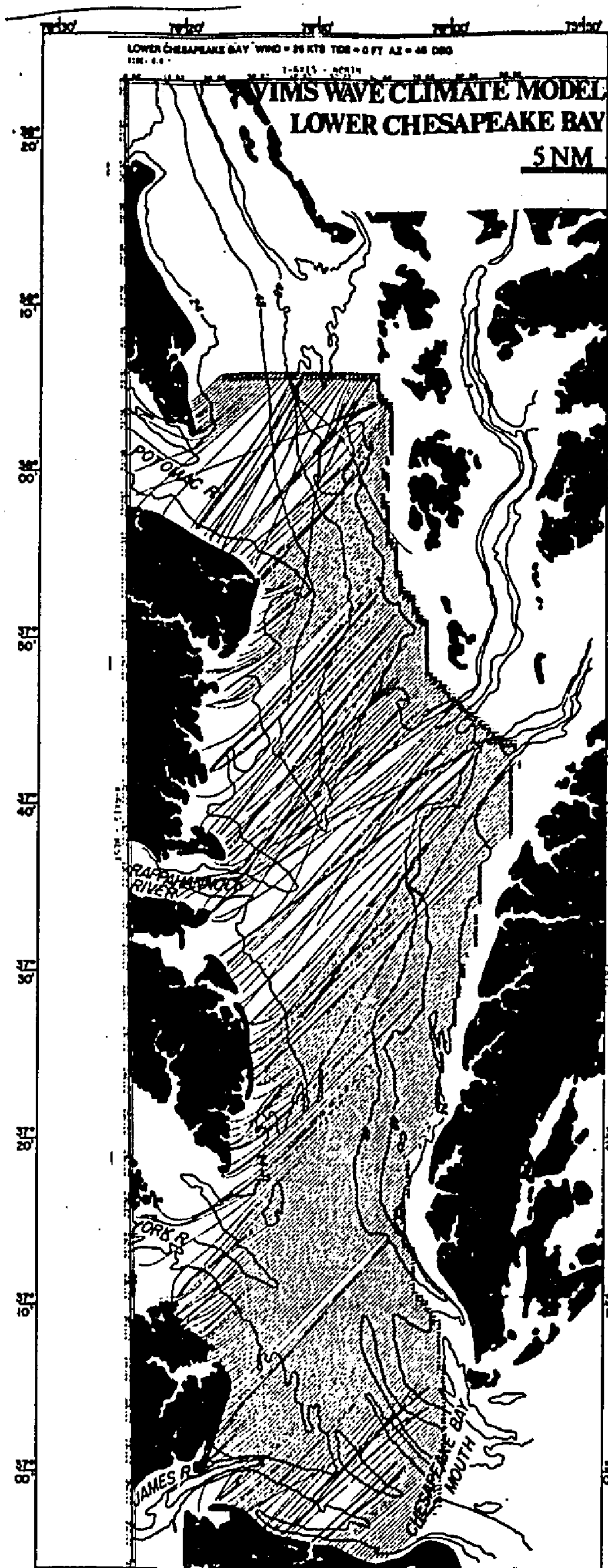

INPUT WIND: AZ=0°, VELOCITY=40 KTS

FIGURE C-3



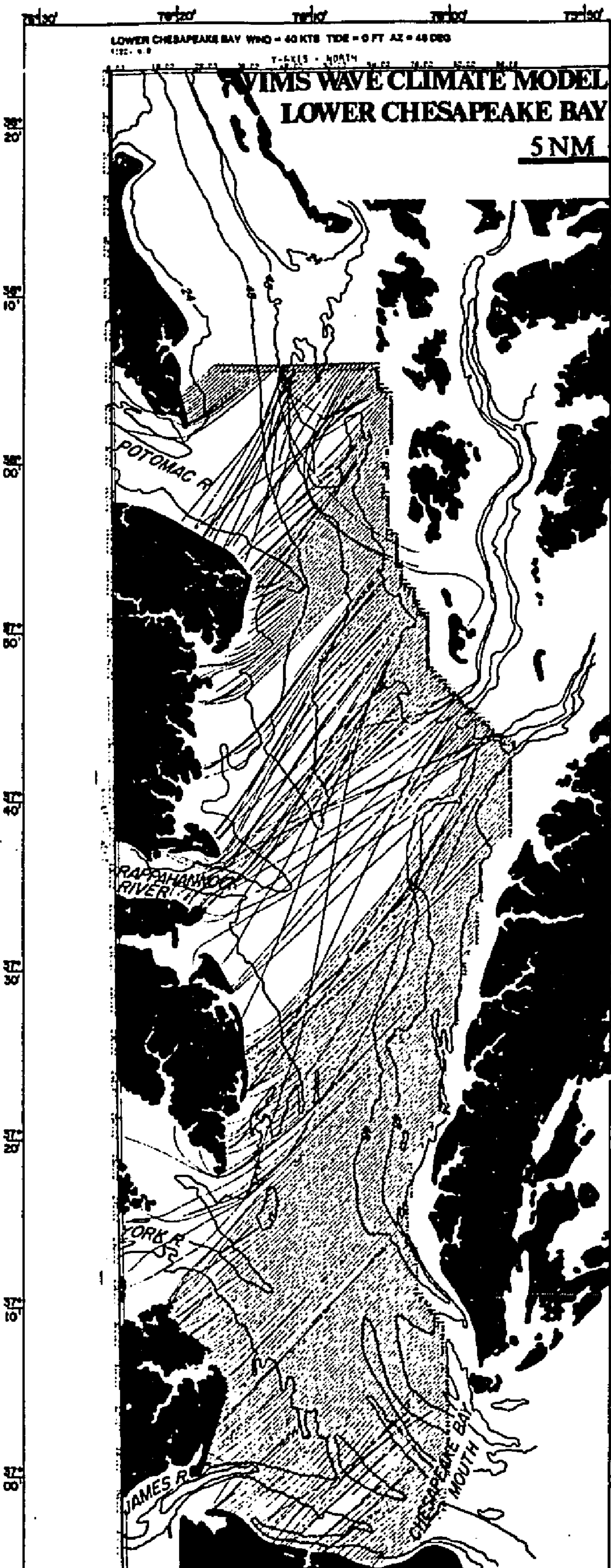

INPUT WIND: AZ=45°, VELOCITY=10 KTS

FIGURE C-4



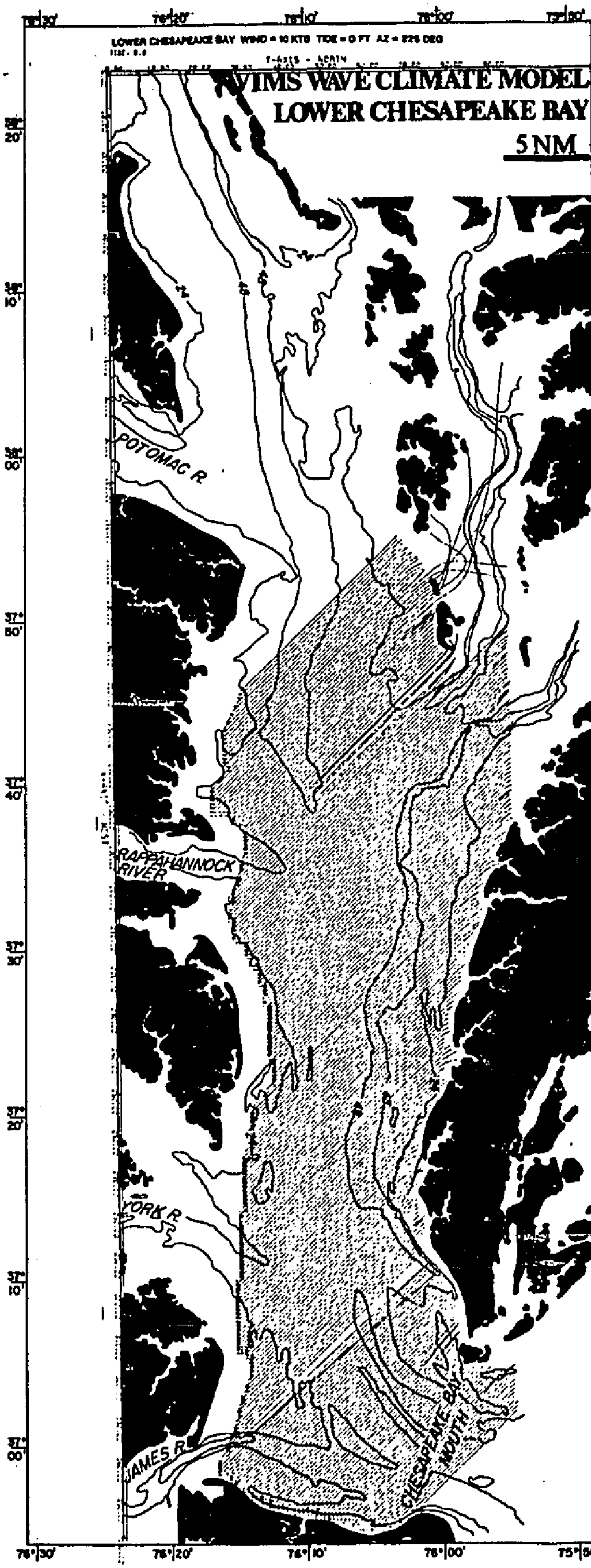

INPUT WIND: AZ=45°, VELOCITY=25 KTS

FIGURE C-5



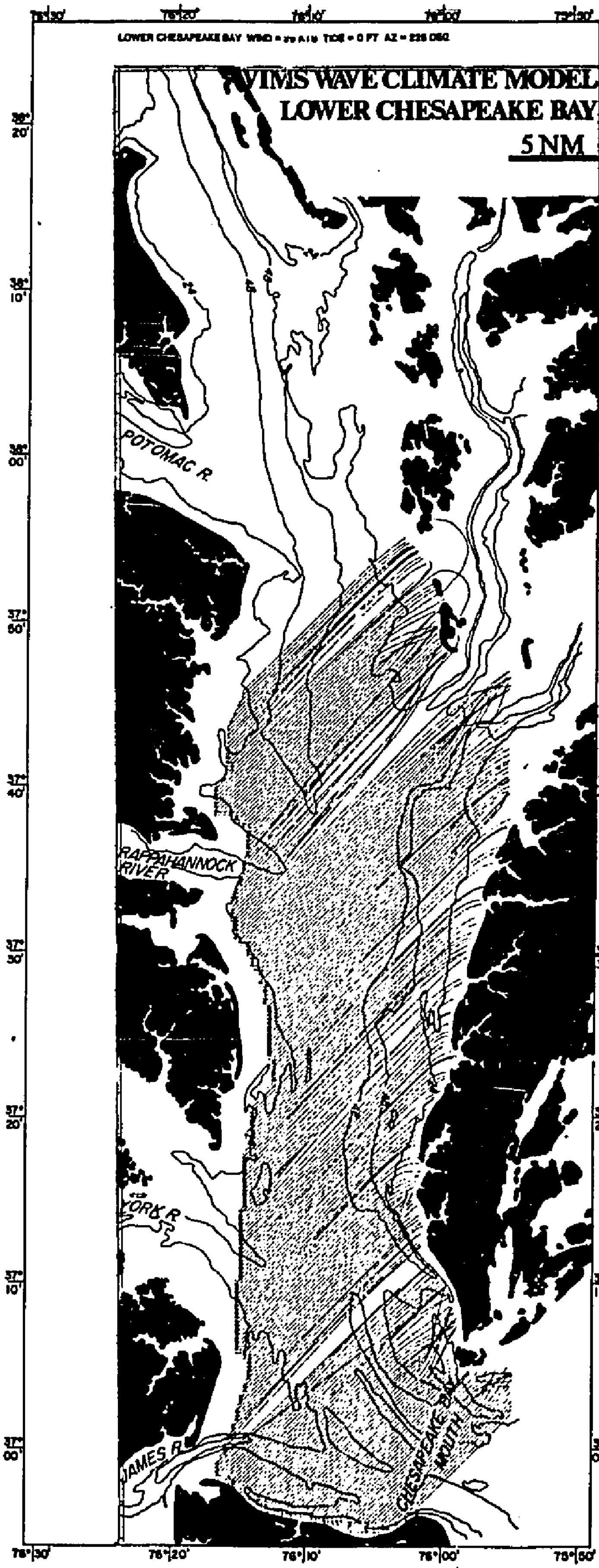

INPUT WIND: AZ=45°, VELOCITY=40 KTS

FIGURE C-6



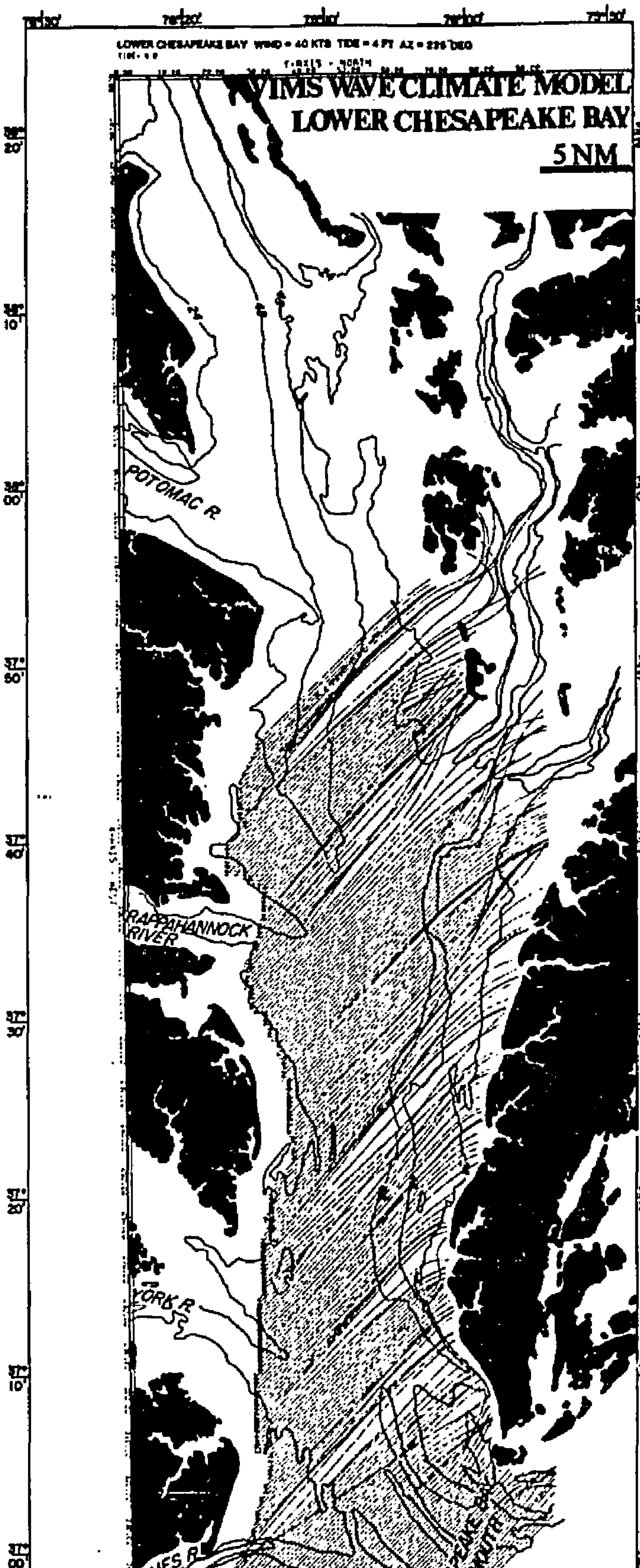

INPUT WIND: AZ=225°, VELOCITY=10 KTS

FIGURE C-7



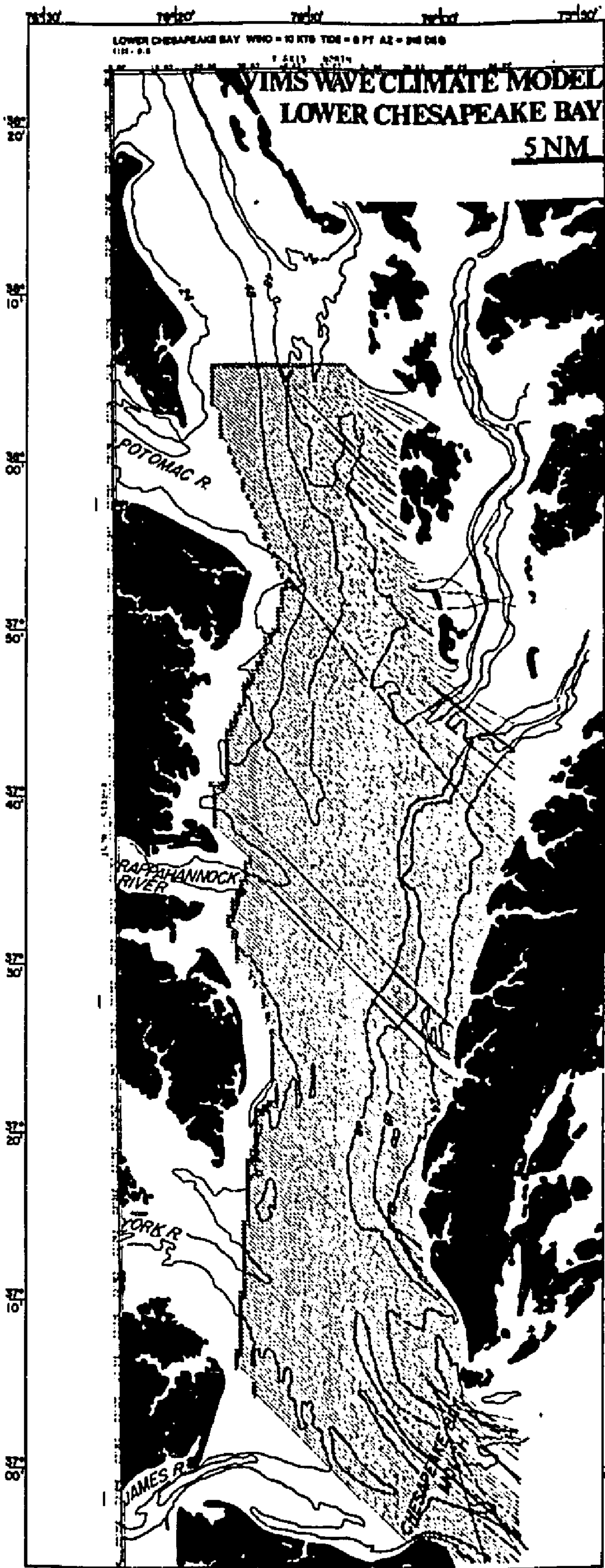

INPUT WIND: AZ =225°, VELOCITY=25 KTS

FIGURE C-8



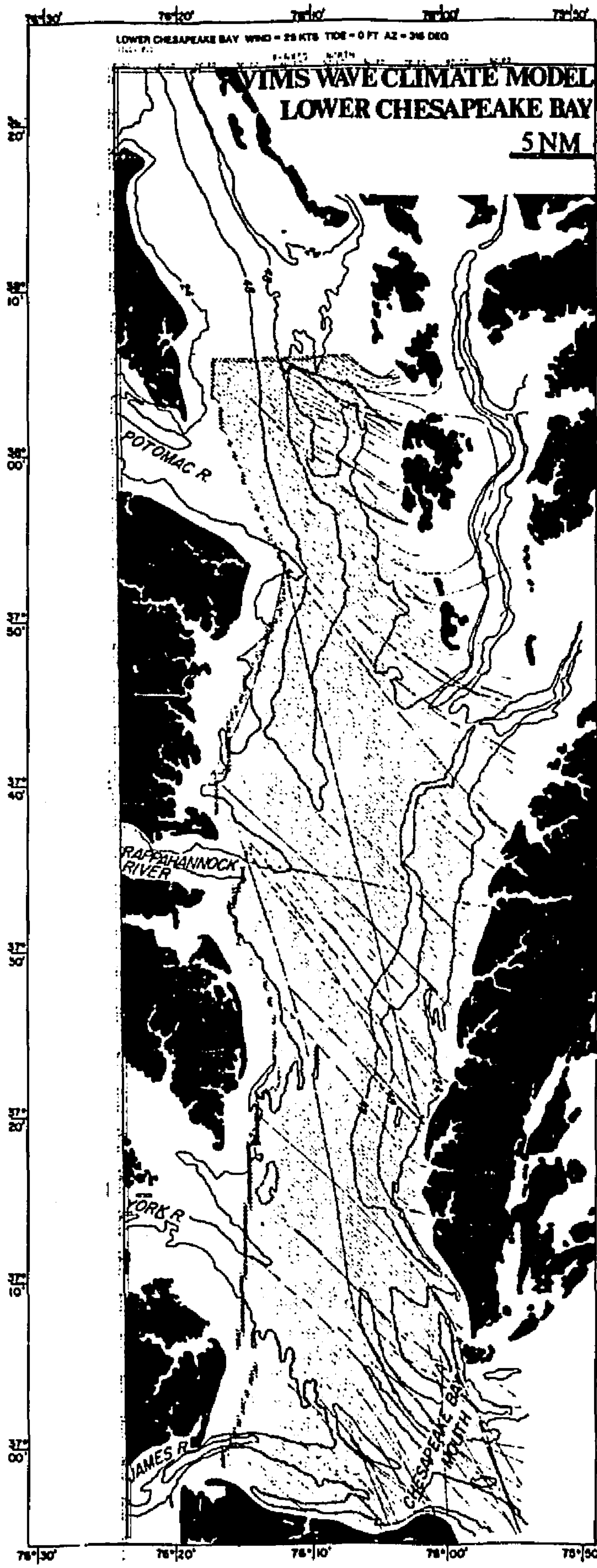

INPUT WIND: AZ=225°, VELOCITY=40 KTS

FIGURE C-9



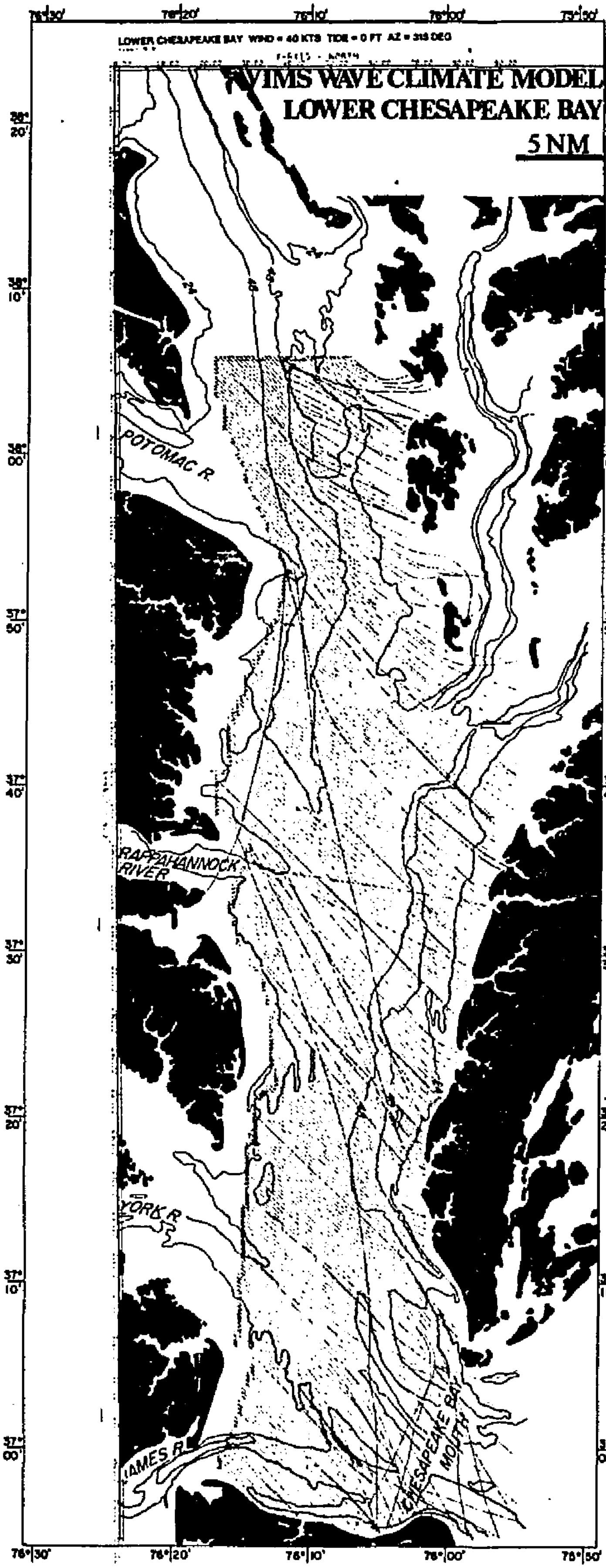

INPUT WIND: AZ=315°, VELOCITY=10 KTS

FIGURE C-10




INPUT WIND: AZ=315°, VELOCITY=25 KTS

FIGURE C-111




INPUT WIND: AZ=315°, VELOCITY=40 KTS

FIGURE C-12

# APPENDIX D

## SHORELINE HISTOGRAMS

The shoreline histograms presented show the variation in four wave parameters, orthogonal density, period, wave height, and wave energy along the three shorelines of the Virginia Chesapeake Bay (western, eastern, and southern) predicted from varying input wind conditions.

The plots of wave period, height, and energy represent the highest value in each one nautical mile class interval. The orthogonal density plots show the number of orthogonals reaching the shore in each one nautical mile class interval. This plot demonstrates the redistribution of wave energy due to refraction. The waves are input at the uniform spacing of four orthogonals per nautical mile normal to each input wind condition.

Table D-1 shows the input wind conditions and corresponding histograms.

TABLE D-1. Shoreline Histograms Figure Numbers

| Input Wind | | Figure Number | | |
|---|---|---|---|---|
| Direction (azimuth) | Velocity (knots) | Western Shore | Eastern Shore | Southern Shore |
| | | ORTHOGONAL DENSITY | | |
| $0^{o}$ | 10 | D-1 | D-2 | D-3 |
| $0^{o}$ | 25 | D-4 | D-5 | D-6 |
| $0^{o}$ | 40 | D-7 | D-8 | D-9 |
| $45^{o}$ | 10 | D-10 | | D-11 |
| $45^{o}$ | 25 | D-12 | | D-13 |
| $45^{o}$ | 40 | D-14 | | D-15 |
| $225^{o}$ | 10 | | D-16 | |
| $225^{o}$ | 25 | | D-17 | |
| $225^{o}$ | 40 | | D-18 | |
| $315^{o}$ | 10 | | D-19 | D-20 |
| $315^{o}$ | 25 | | D-21 | D-22 |
| $315^{o}$ | 40 | | D-23 | D-24 |
| | | PERIOD (seconds) | | |
| $0^{o}$ | 10 | D-25 | D-26 | D-27 |
| $0^{o}$ | 25 | D-28 | D-29 | D-30 |
| $0^{o}$ | 40 | D-31 | D-32 | D-33 |
| $45^{o}$ | 10 | D-34 | | D-35 |
| $45^{o}$ | 25 | D-36 | | D-37 |
| $45^{o}$ | 40 | D-38 | | D-39 |
| $225^{o}$ | 10 | | D-40 | |
| $225^{o}$ | 25 | | D-41 | |
| $225^{o}$ | 40 | | D-42 | |
| $315^{o}$ | 10 | | D-43 | D-44 |
| $315^{o}$ | 25 | | D-45 | D-46 |
| $315^{o}$ | 40 | | D-47 | D-48 |
| | | WAVE HEIGHT (meters) | | |
| $0^{o}$ | 10 | D-49 | D-50 | D-51 |
| $0^{o}$ | 25 | D-52 | D-53 | D-54 |
| $0^{o}$ | 40 | D-55 | D-56 | D-57 |
| $45^{o}$ | 10 | D-58 | | D-59 |
| $45^{o}$ | 25 | D-60 | | D-61 |
| $45^{o}$ | 40 | D-62 | | D-63 |
| $225^{o}$ | 10 | | D-64 | |
| $225^{o}$ | 25 | | D-65 | |
| $225^{o}$ | 40 | | D-66 | |
| $315^{o}$ | 10 | | D-67 | D-68 |
| $315^{o}$ | 25 | | D-69 | D-70 |
| $315^{o}$ | 40 | | D-71 | D-72 |

TABLE D-1, Cont'd

WAVE ENERGY (joules)

| Input Wind | | Figure Number | | |
|---|---|---|---|---|
| Direction (azimuth) | Velocity (knots) | Western Shore | Eastern Shore | Southern Shore |
| 0° | 10 | D-73 | D-74 | D-75 |
| 0° | 25 | D-76 | D-77 | D-78 |
| 0° | 40 | D-79 | D-80 | D-81 |
| 45° | 10 | D-82 | | D-83 |
| 45° | 25 | D-84 | | D-85 |
| 45° | 40 | D-86 | | D-87 |
| 225° | 10 | | D-88 | |
| 225° | 25 | | D-89 | |
| 225° | 40 | | D-90 | |
| 315° | 10 | | D-91 | D-92 |
| 315° | 25 | | D-93 | D-94 |
| 315° | 40 | | D-95 | D-96 |

WESTERN SHORE
LOWER CHES BAY WIND- 10 KTS
TIDE- 0 AZ- 0 DEG
X AXIS IN NAUTICAL MILES
SHORELINE ORTHOGONAL DENSITY

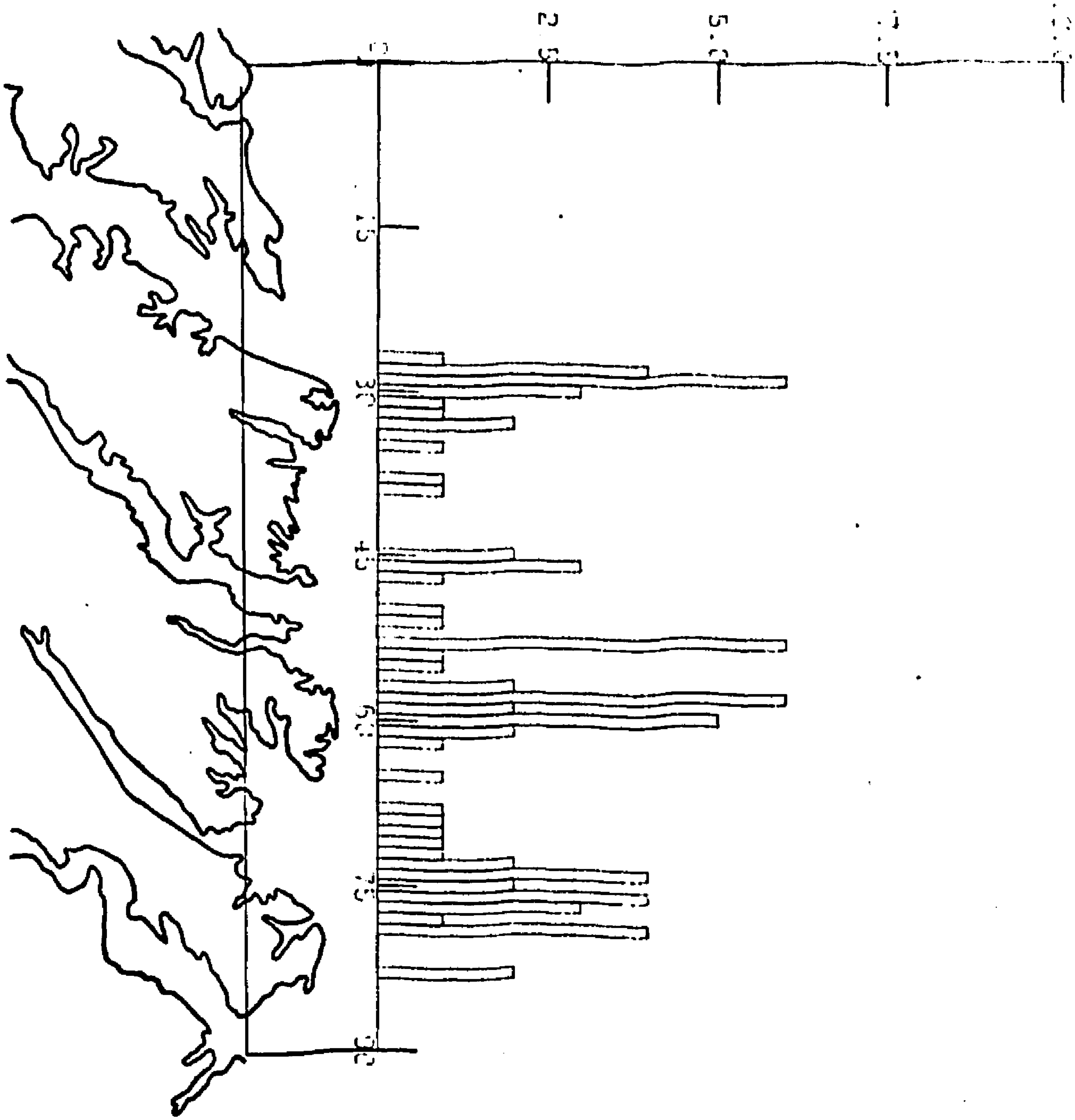
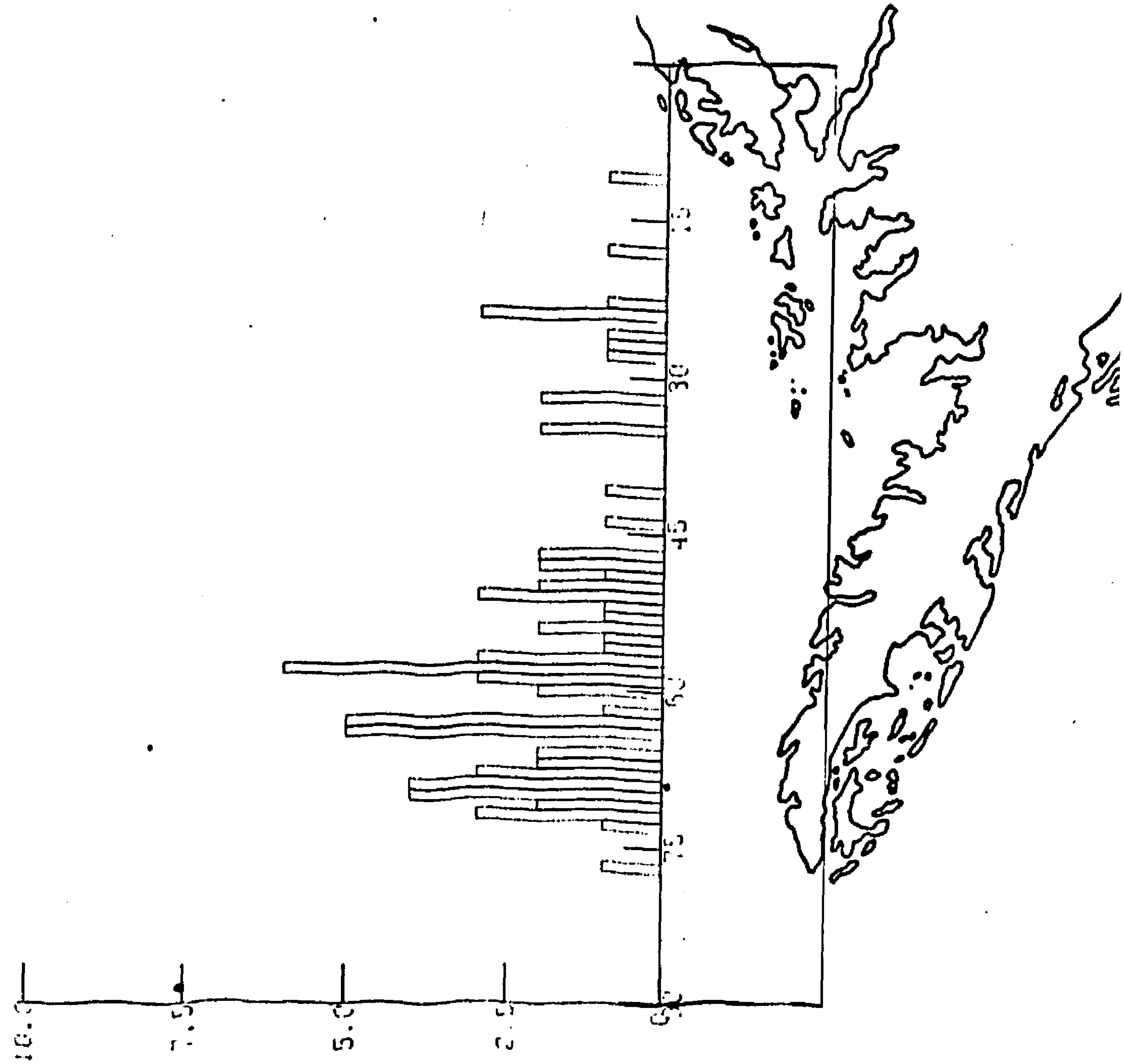


FIGURE D-1




SHORELINE ORTHOGONAL DENSITY
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 0 DEG
LOWER CHES BAY WIND= 10 KTS
EASTERN SHORE

**FIGURE D-2**

SOUTHERN SHORE
LOWER CHES BAY WIND- 10 KTS
TIDE- 0 AZ- 0 DEG
X AXIS IN NAUTICAL MILES.
SHORELINE ORTHOGONAL DENSITY

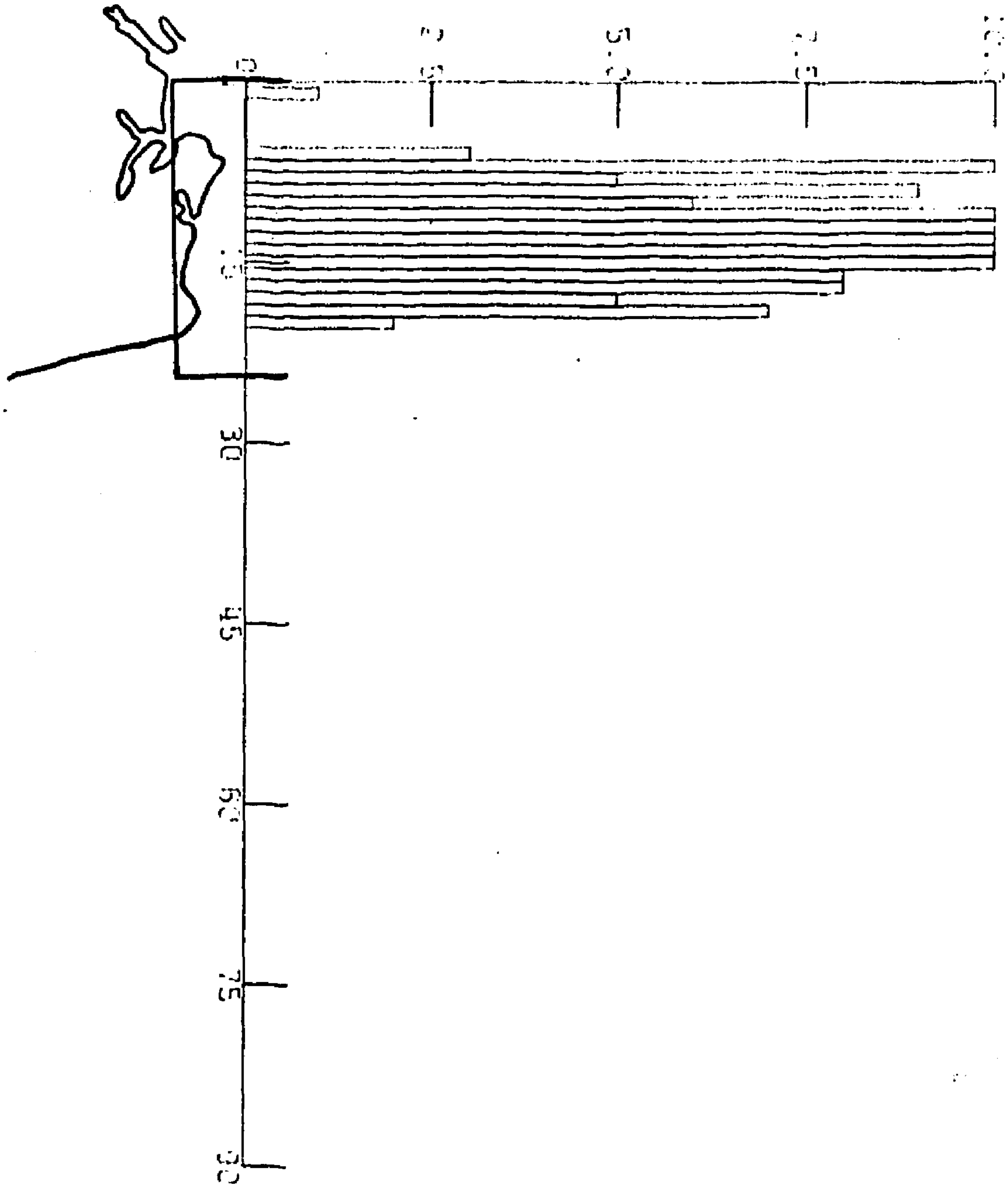



**FIGURE D-3**

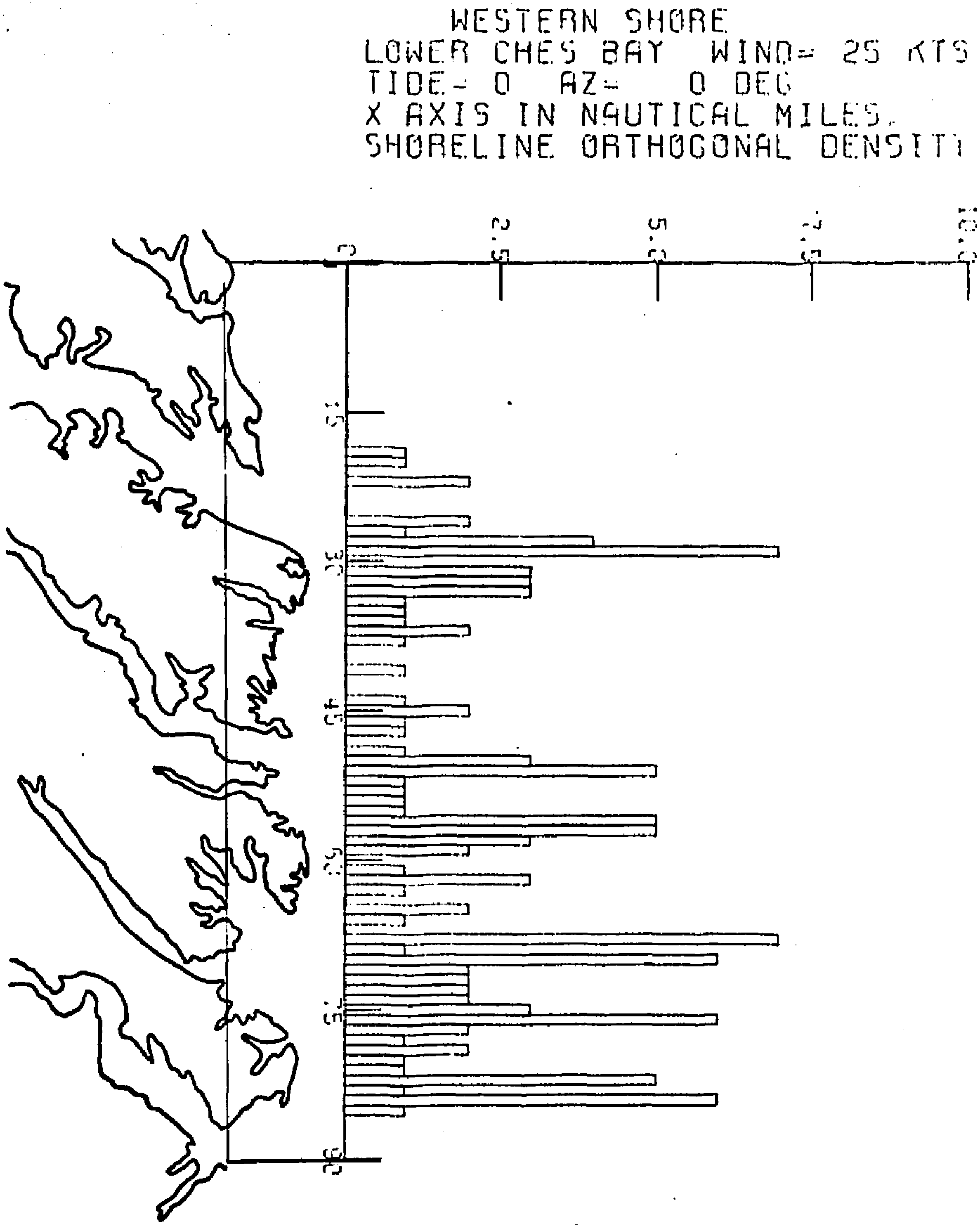
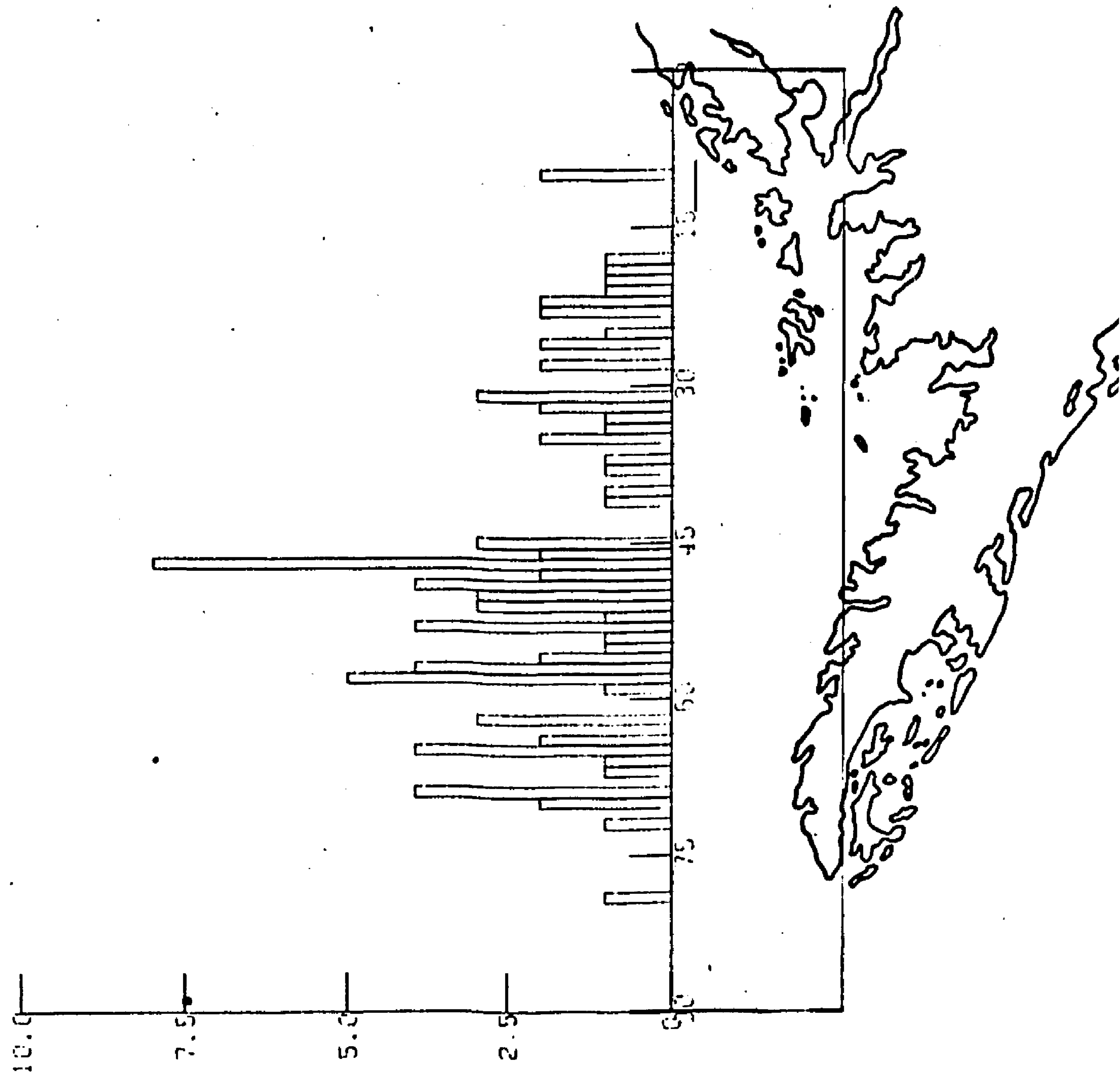

WESTERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
SHORELINE ORTHOGONAL DENSITY
0
2.5
5.0
7.5
10.0
15
30
45
60
75
90

**FIGURE D-4**




SHORELINE ORTHOGONAL DENSITY
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 0 DEG
LOWER CHES BAY WIND= 25 KTS
EASTERN SHORE

**FIGURE D-5**

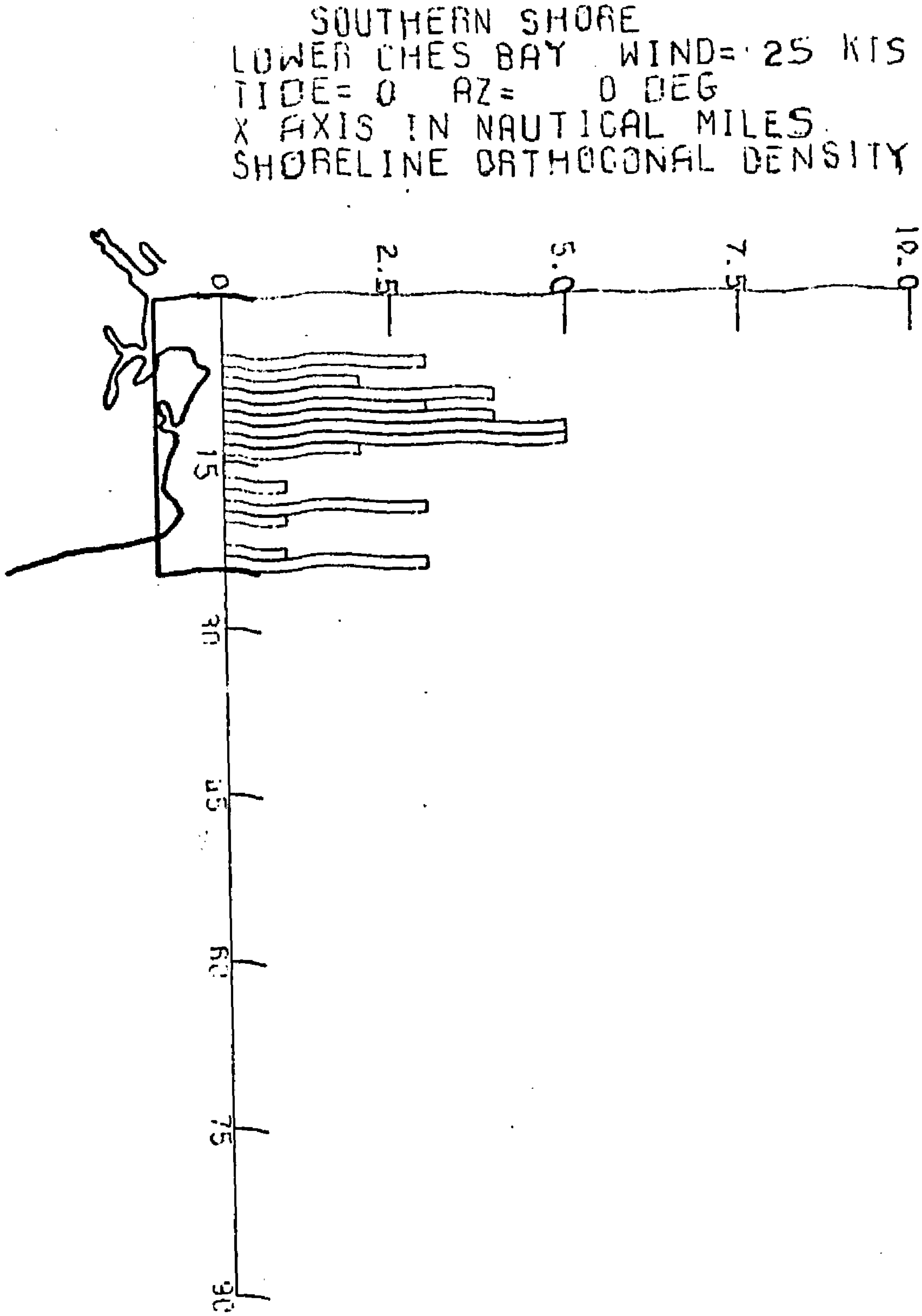

SOUTHERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 0 DEG
X AXIS IN NAUTICAL MILES
SHORELINE ORTHOGONAL DENSITY
0
2.5
5.0
7.5
10.0
15
30
75

FIGURE D-6

WESTERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= +4 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
SHORELINE ORTHOGONAL DENSITY

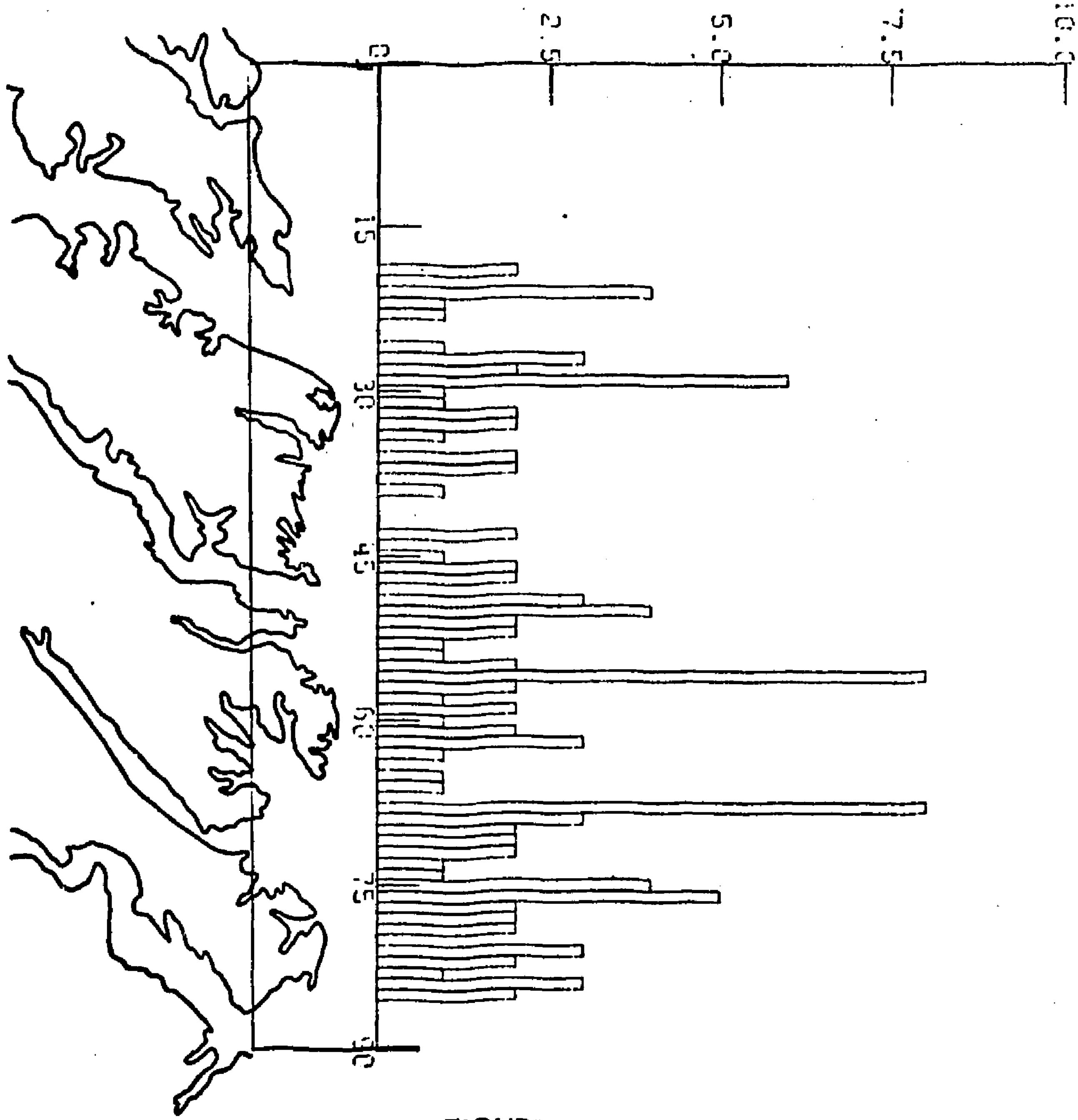
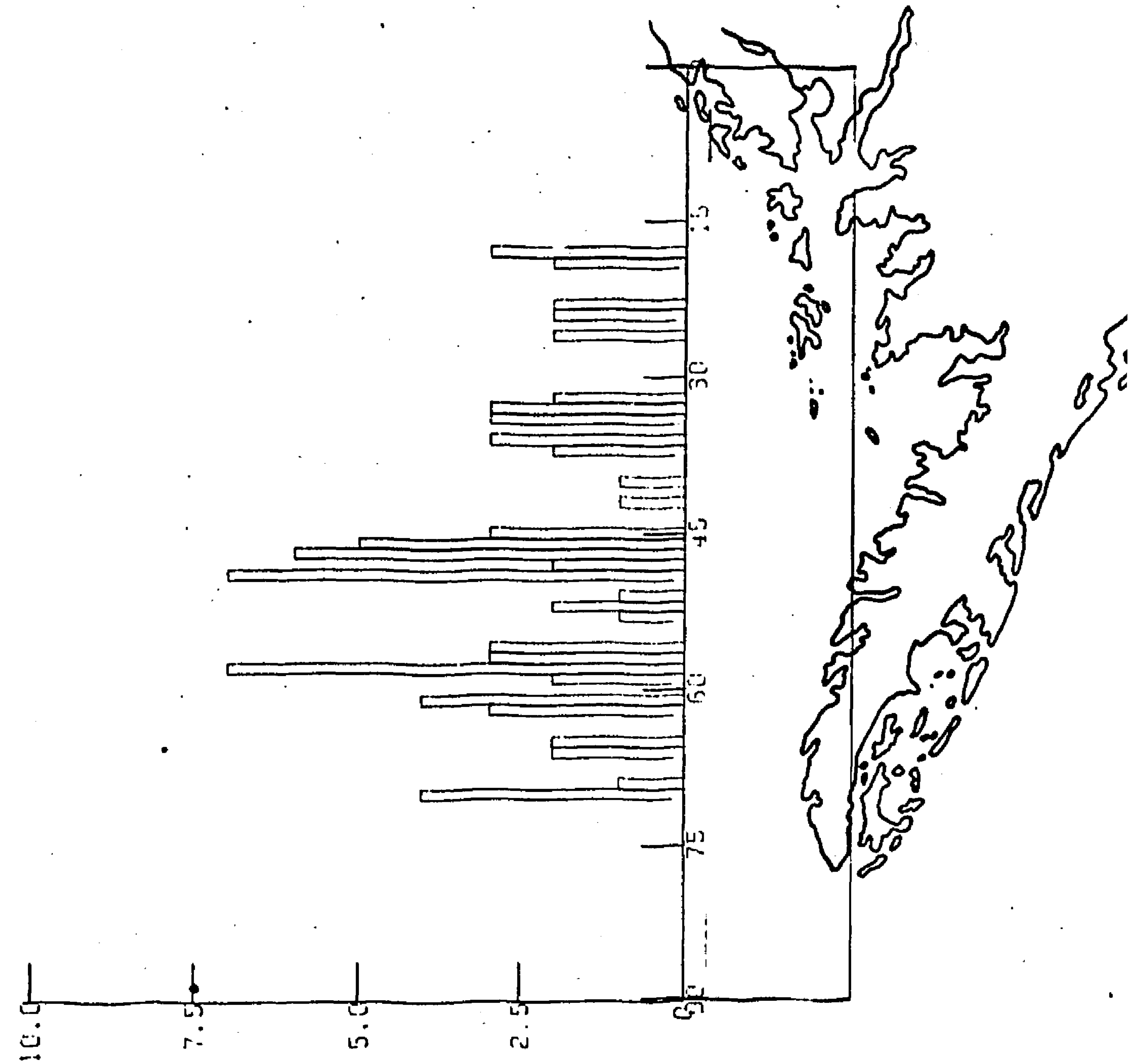



FIGURE D-7




SHORELINE ORTHOGONAL DENSITY
X AXIS IN NAUTICAL MILES.
TIDE= +4 AZ= 0 DEG
LOWER CHES BAY WIND= 40 KTS
EASTERN SHORE

**FIGURE D-8**

SOUTHERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= +4 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
SHORELINE ORTHOGONAL DENSITY

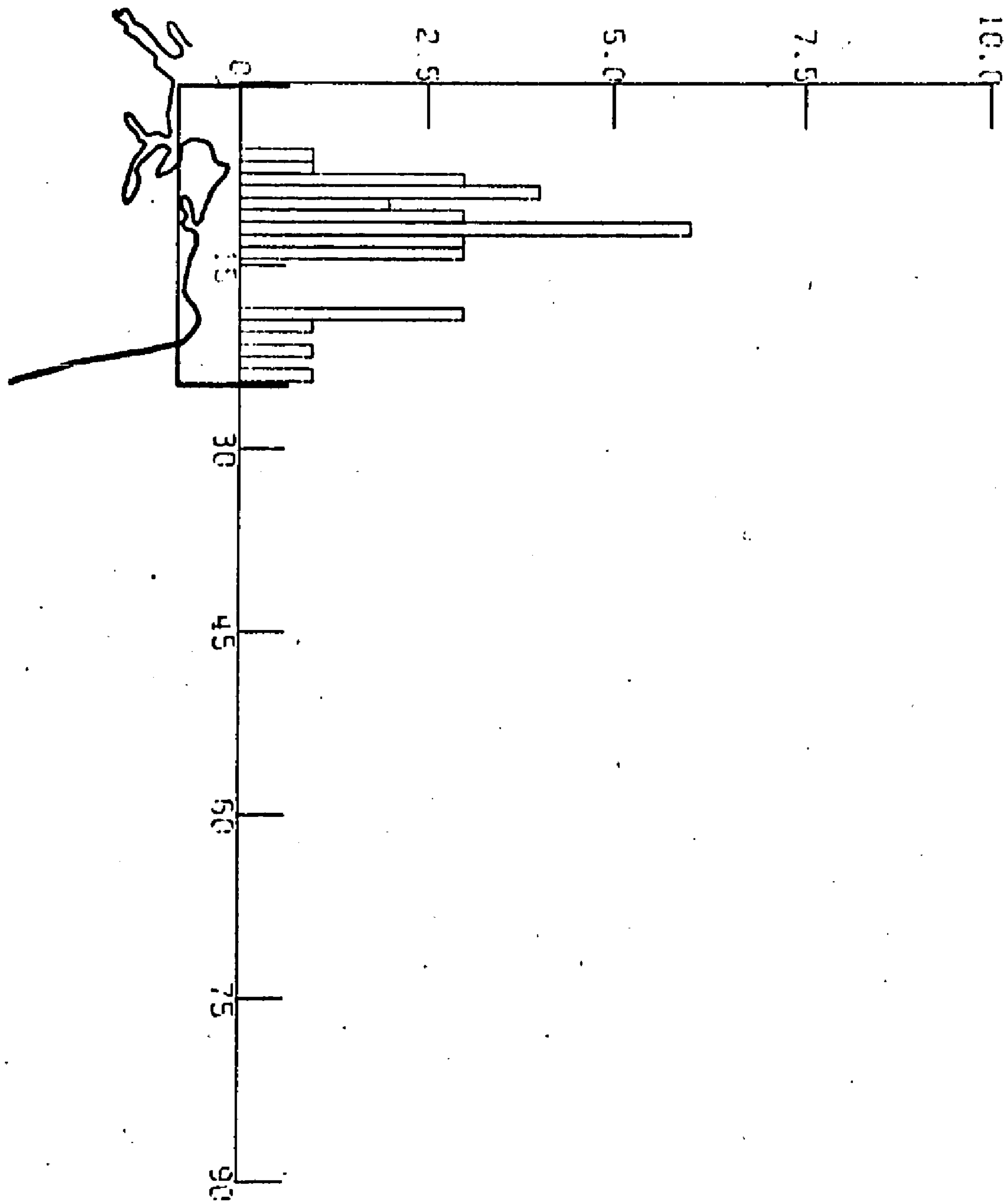



**FIGURE D-9**

WESTERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
SHORELINE ORTHOGONAL DENSITY

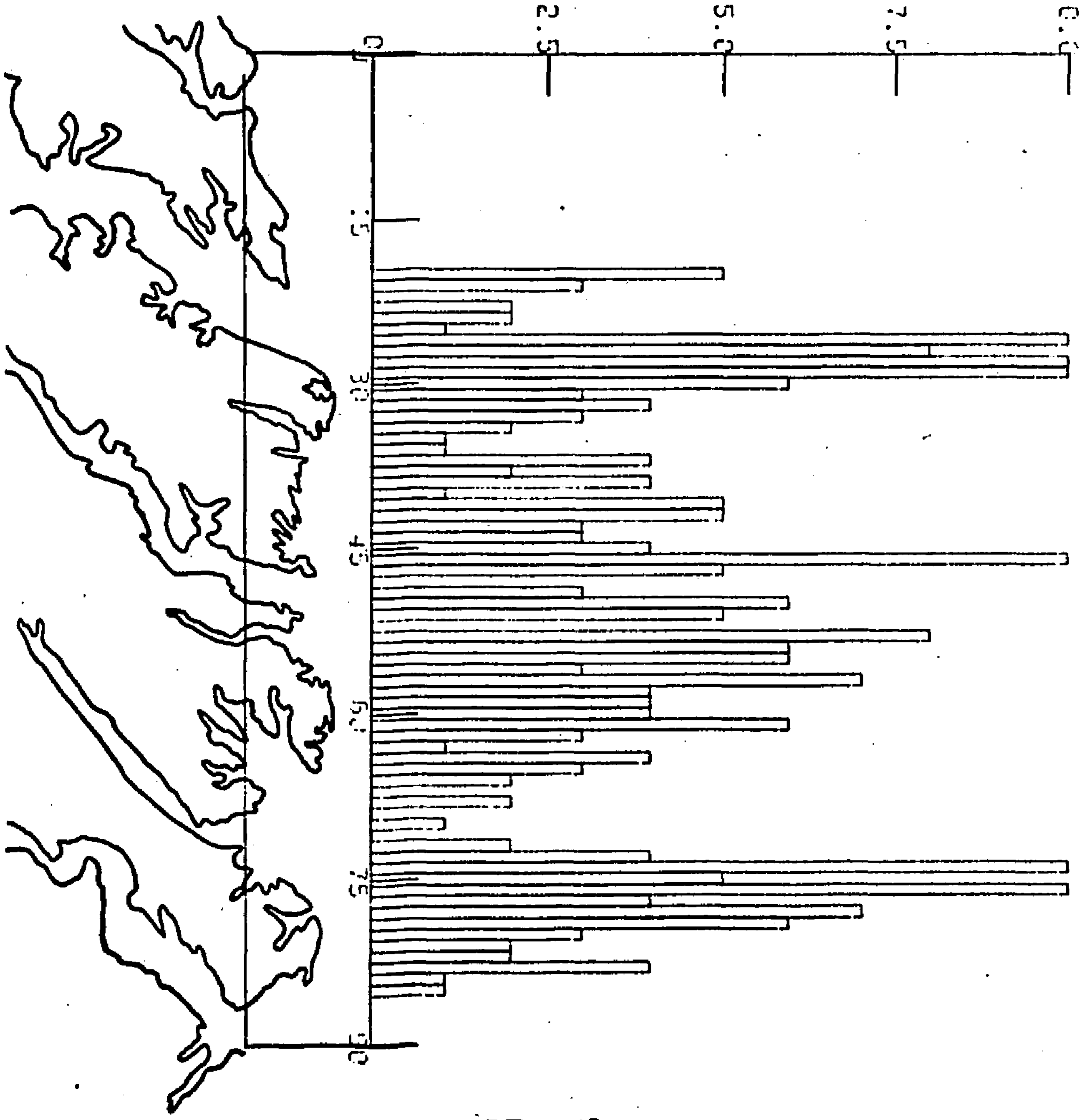



**FIGURE D-10**

SOUTHERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
SHORELINE ORTHOGONAL DENSITY

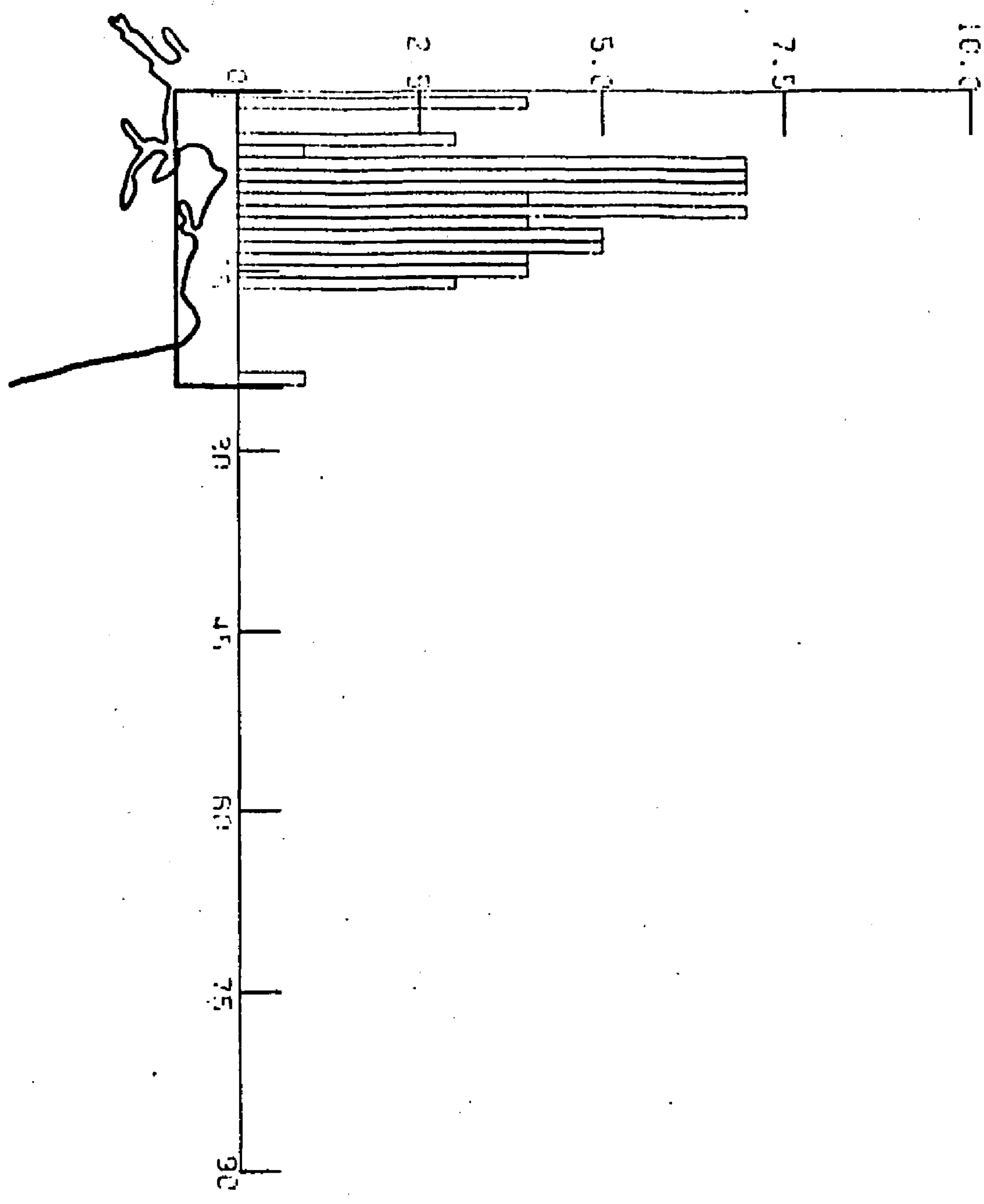



FIGURE D-11

WESTERN SHORE
LOWER CHES BAY  WIND= 25 KTS
TIDE= 0  AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
SHORELINE ORTHOGONAL DENSITY

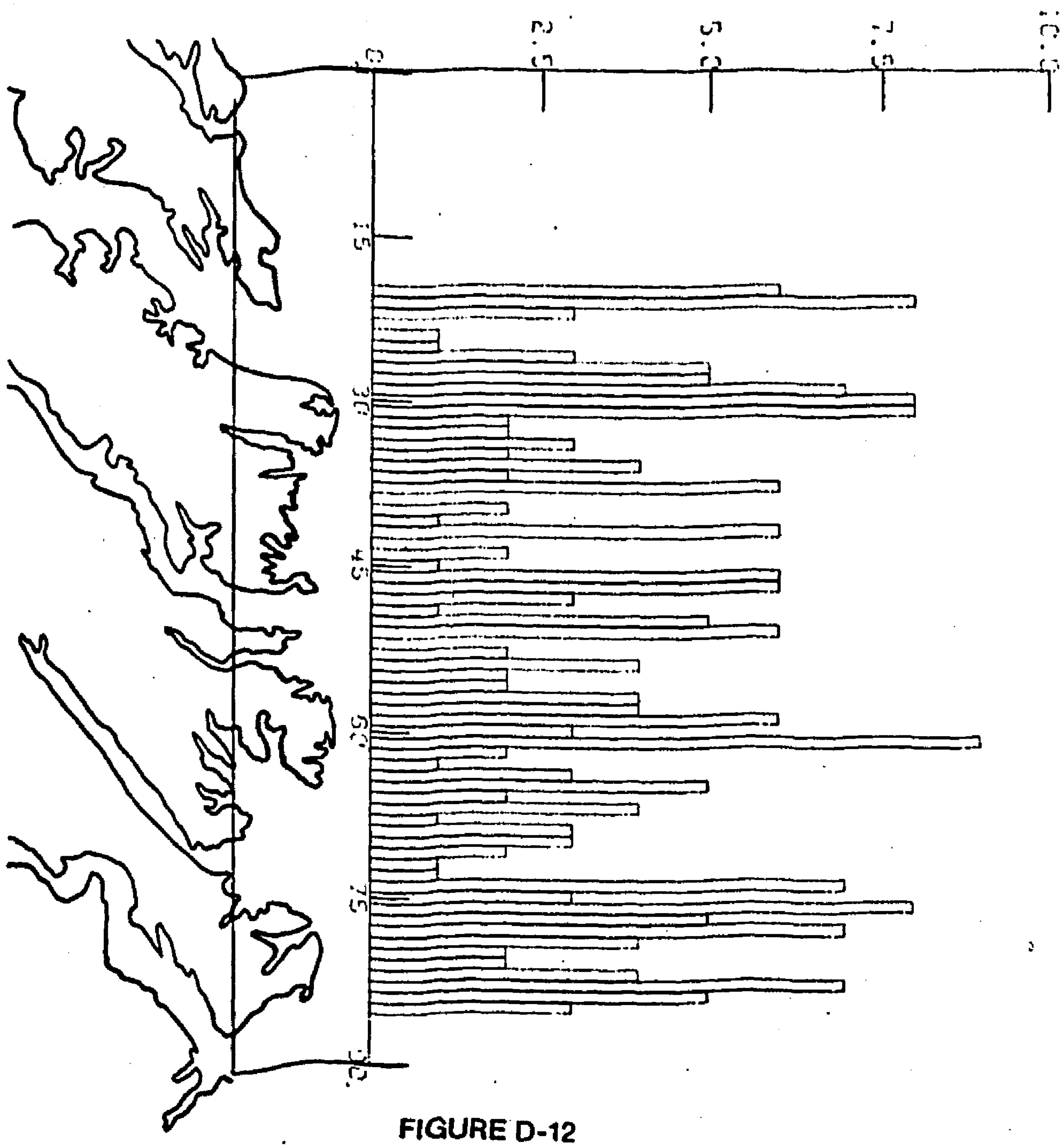



FIGURE D-12

SOUTHERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE- 0 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
SHORELINE ORTHOGONAL DENSITY

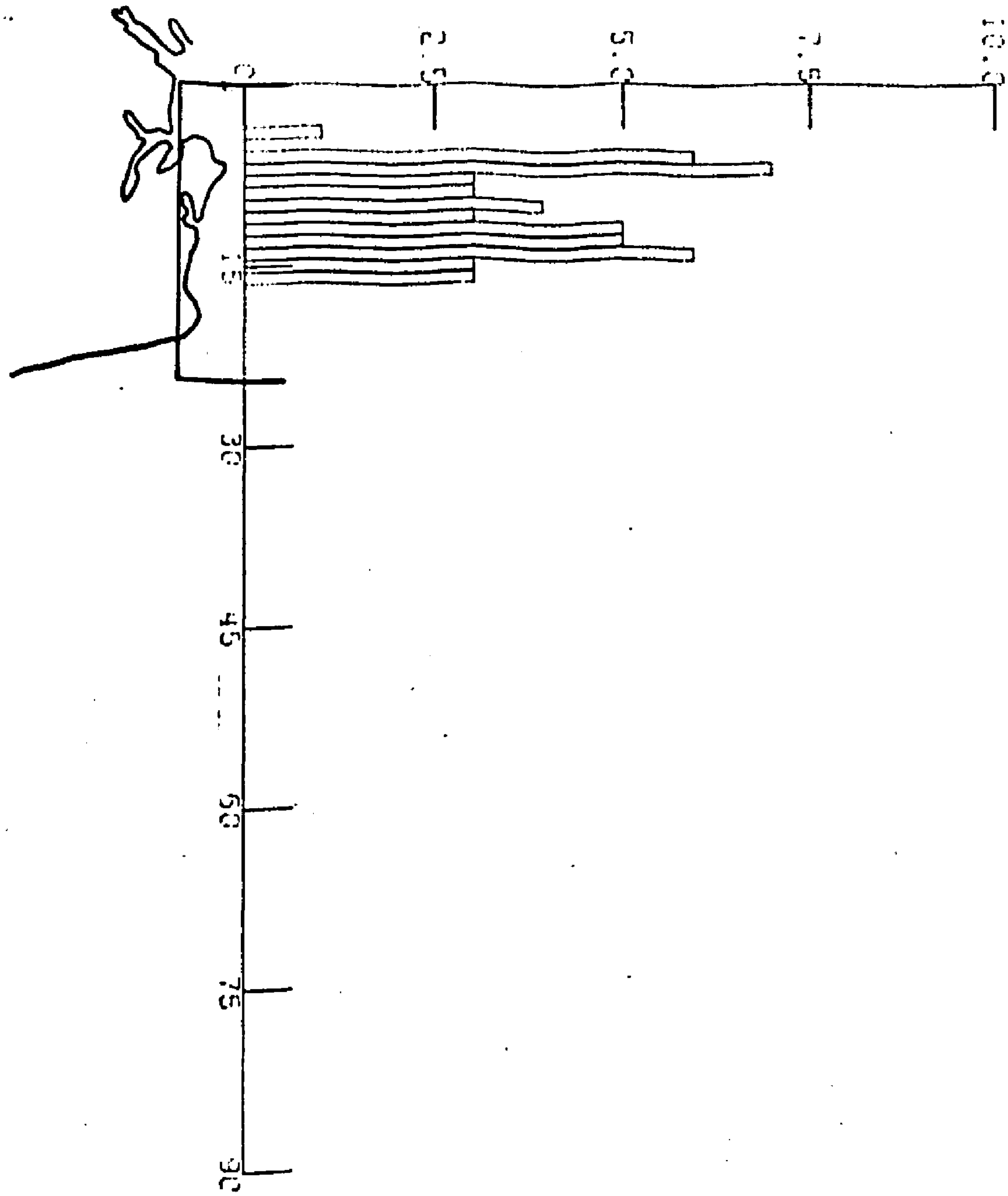



FIGURE D-13

WESTERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= 4 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
SHORELINE ORTHOGONAL DENSITY

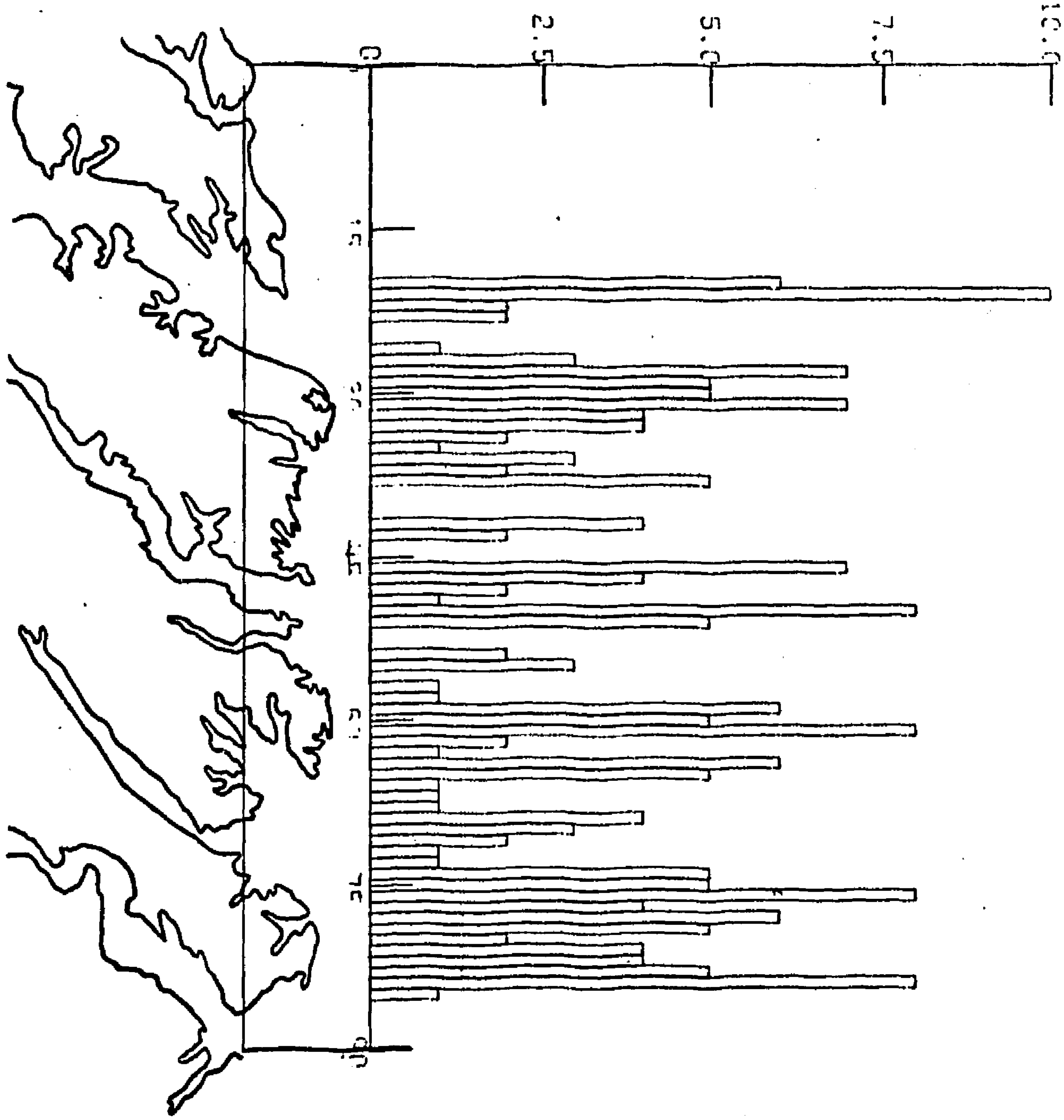



**FIGURE D-14**

SOUTHERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= 4 AZ= 45 DEG
X AXIS IN NAUTICAL MILES
SHORELINE ORTHOGONAL DENSITY

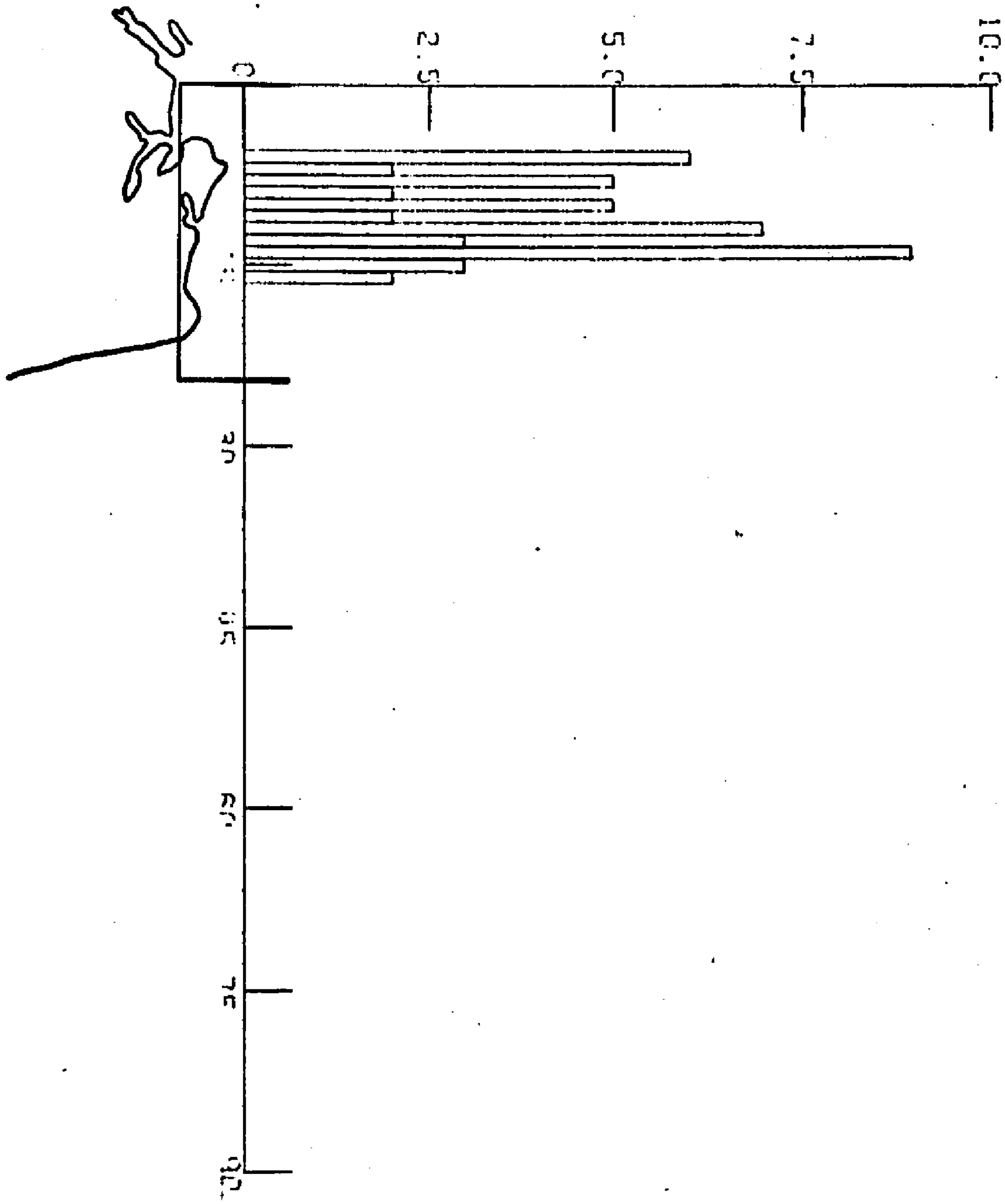
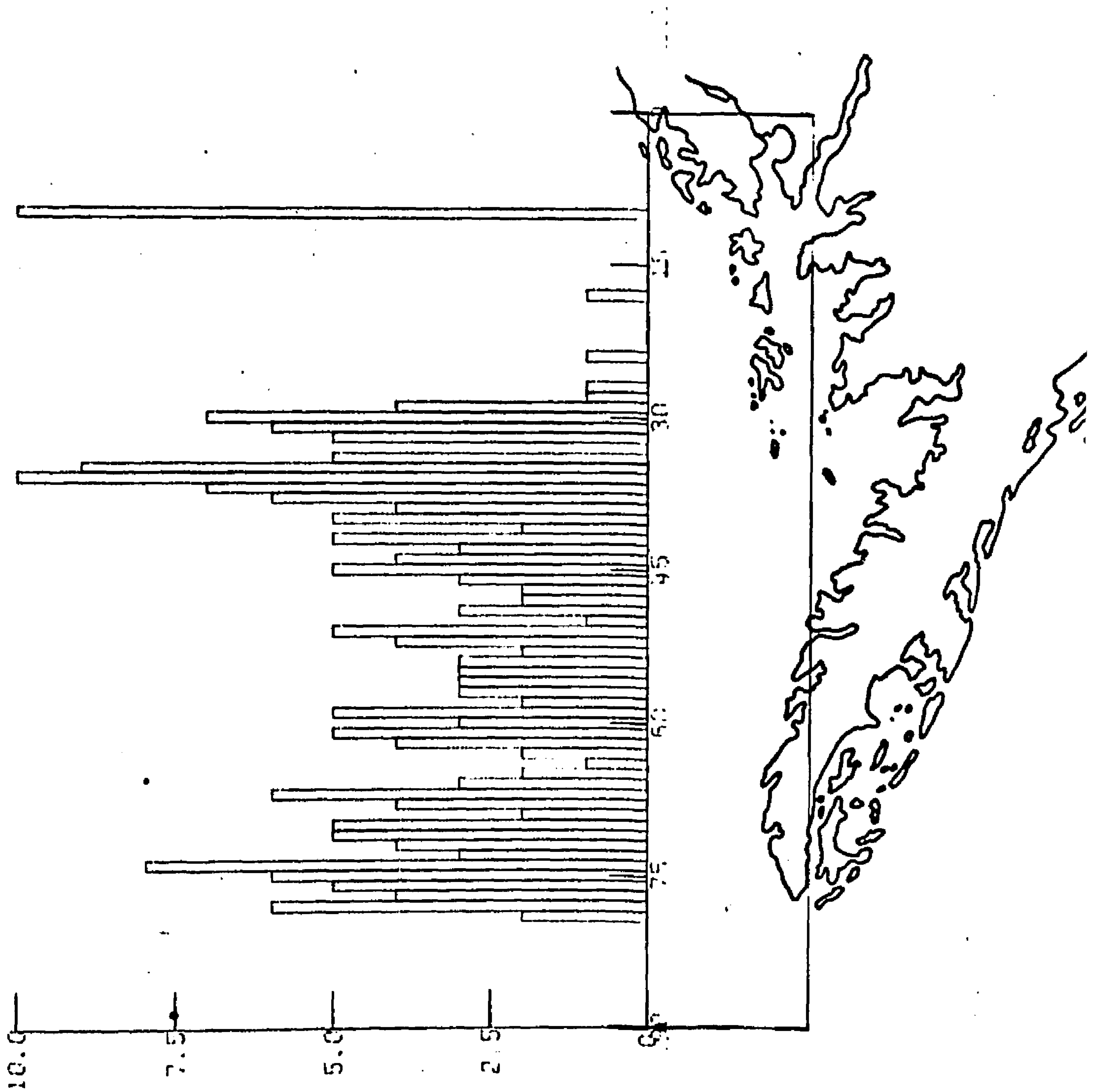
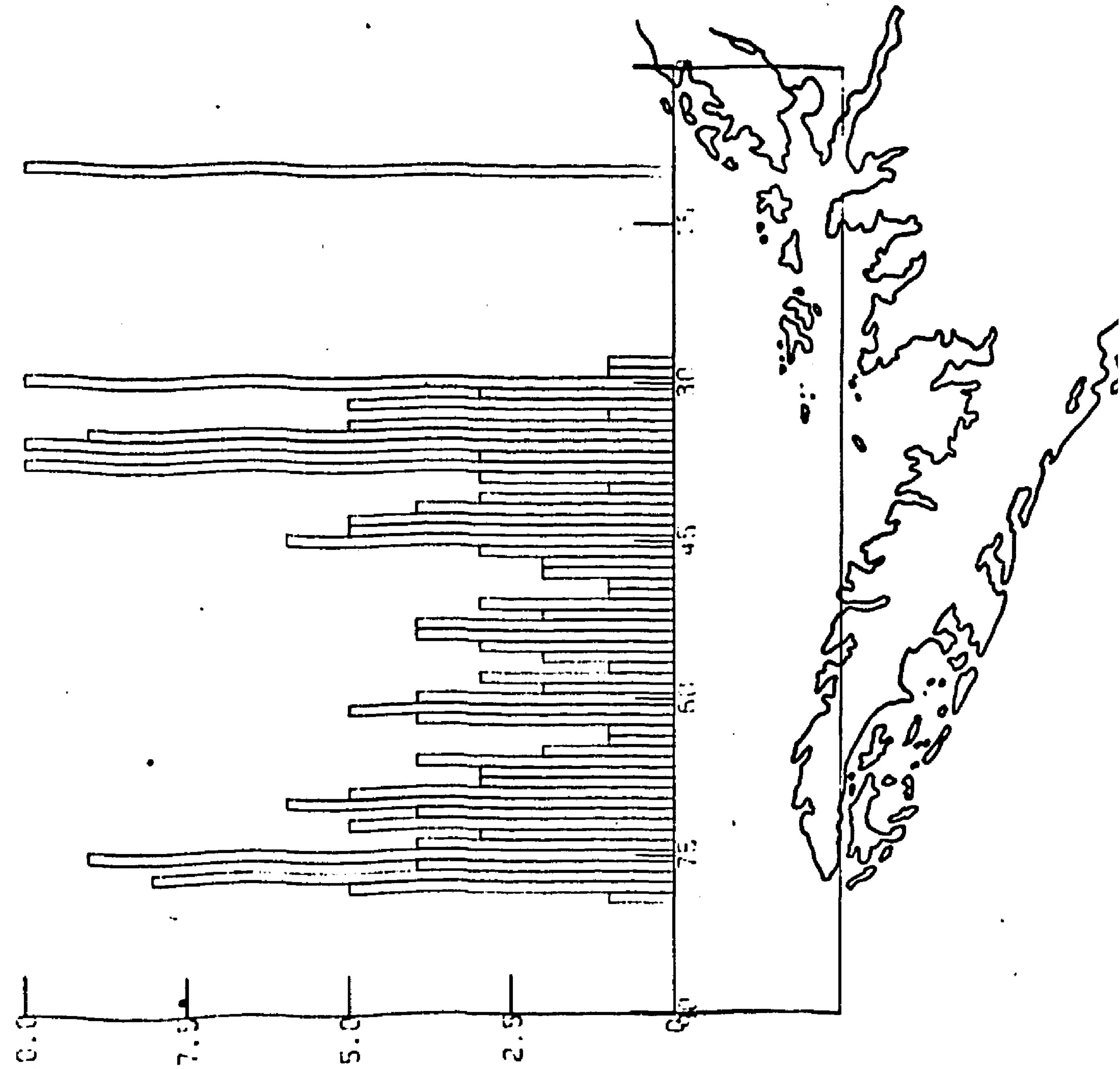



FIGURE D-15



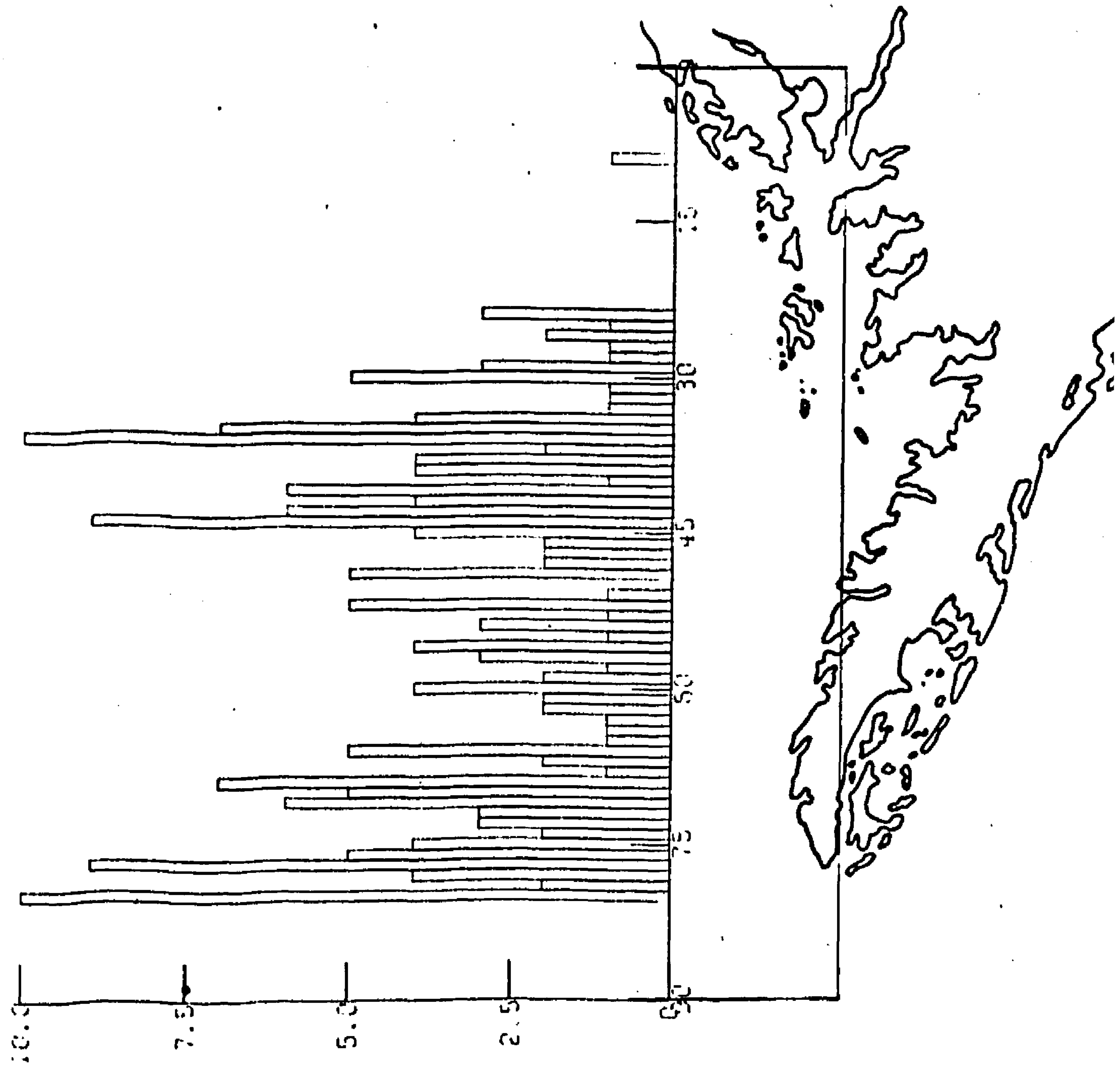

SHORELINE ORTHOGONAL DENSITY
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 225 DEG
LOWER CHES BAY WIND= 10 KTS
EASTERN SHORE

**FIGURE D-16**



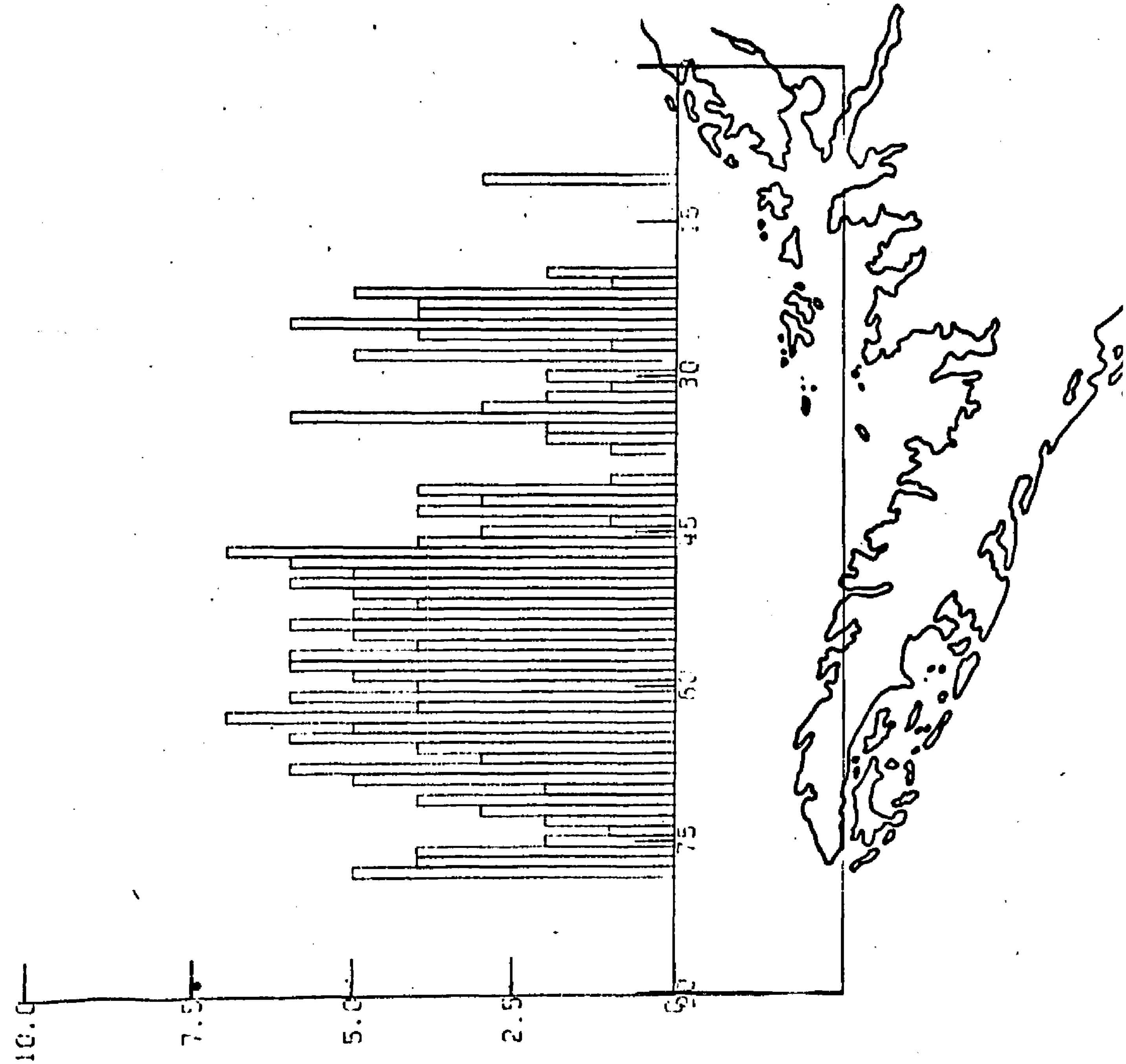

SHORELINE ORTHOGONAL DENSITY
X AXIS IN NAUTICAL MILES.
TIDE= 0  AZ= 225 DEG
LOWER CHES BAY  WIND= 25 KTS
EASTERN SHORE

FIGURE D-17




SHORELINE ORTHOGONAL DENSITY
X AXIS IN NAUTICAL MILES.
TIDE= 4 AZ= 225 DEG
LOWER CHES BAY WIND= 40 KTS
EASTERN SHORE

**FIGURE D-18**




SHORELINE ORTHOGONAL DENSITY
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 315 DEG
LOWER CHES BAY WIND= 10 KTS
EASTERN SHORE

FIGURE D-19

SOUTHERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 315 DEG
X AXIS IN NAUTICAL MILES
SHORELINE ORTHOGONAL DENSITY

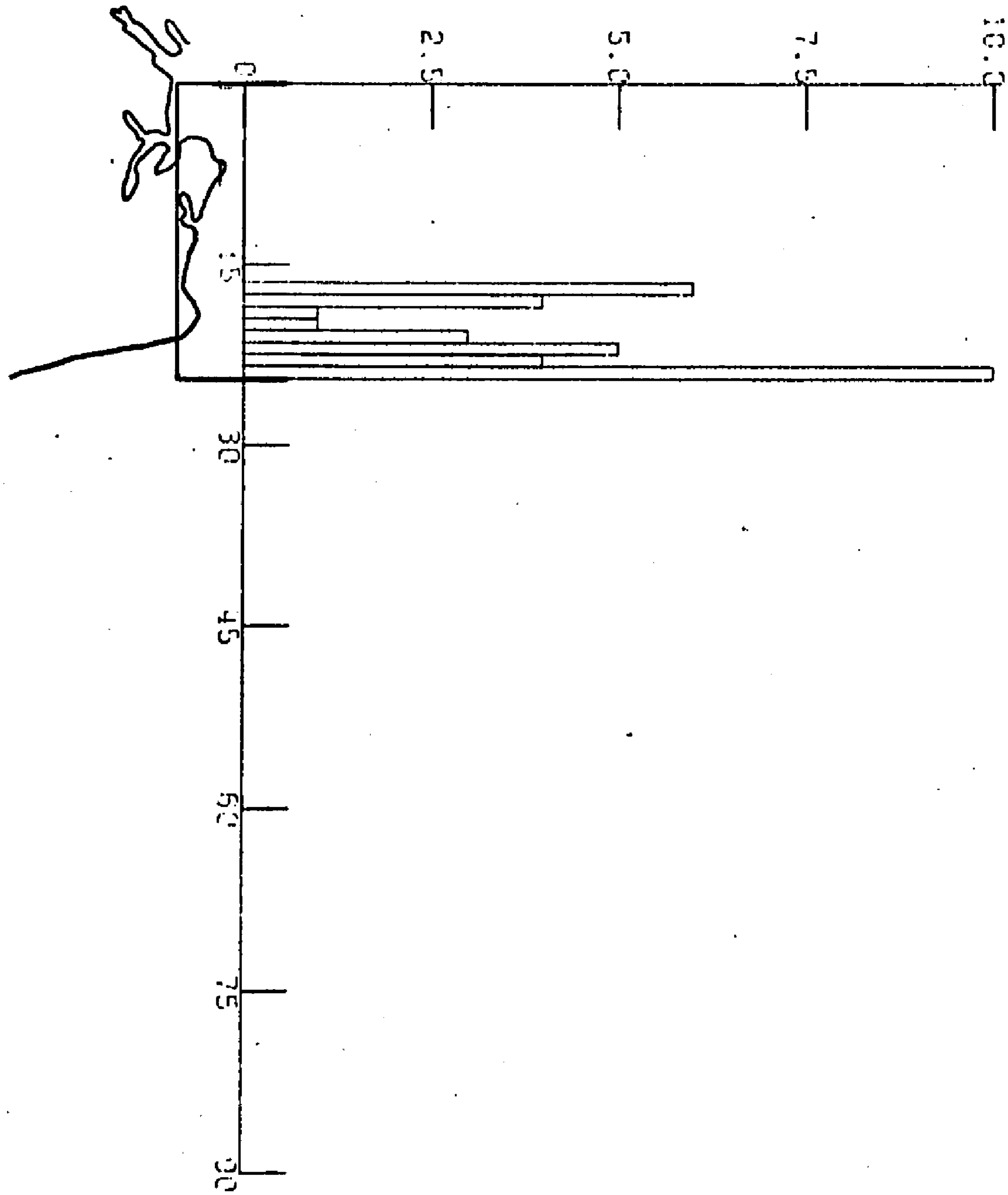
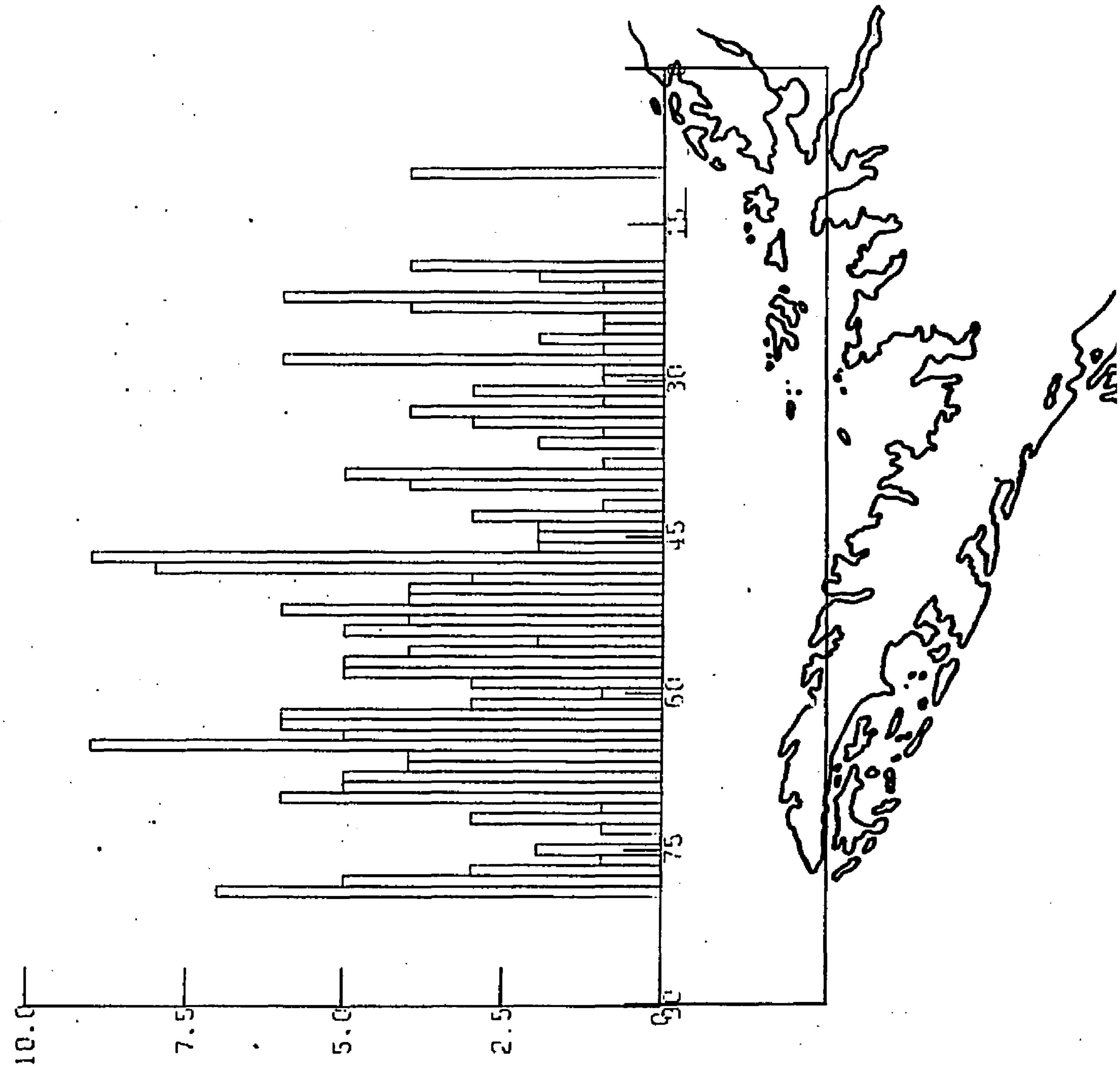



FIGURE D-20




SHORELINE ORTHOGONAL DENSITY
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 315 DEG
LOWER CHES BAY WIND= 25 KTS
EASTERN SHORE

**FIGURE D-21**

SOUTHERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 315 DEG
X AXIS IN NAUTICAL MILES
SHORELINE ORTHOGONAL DENSITY

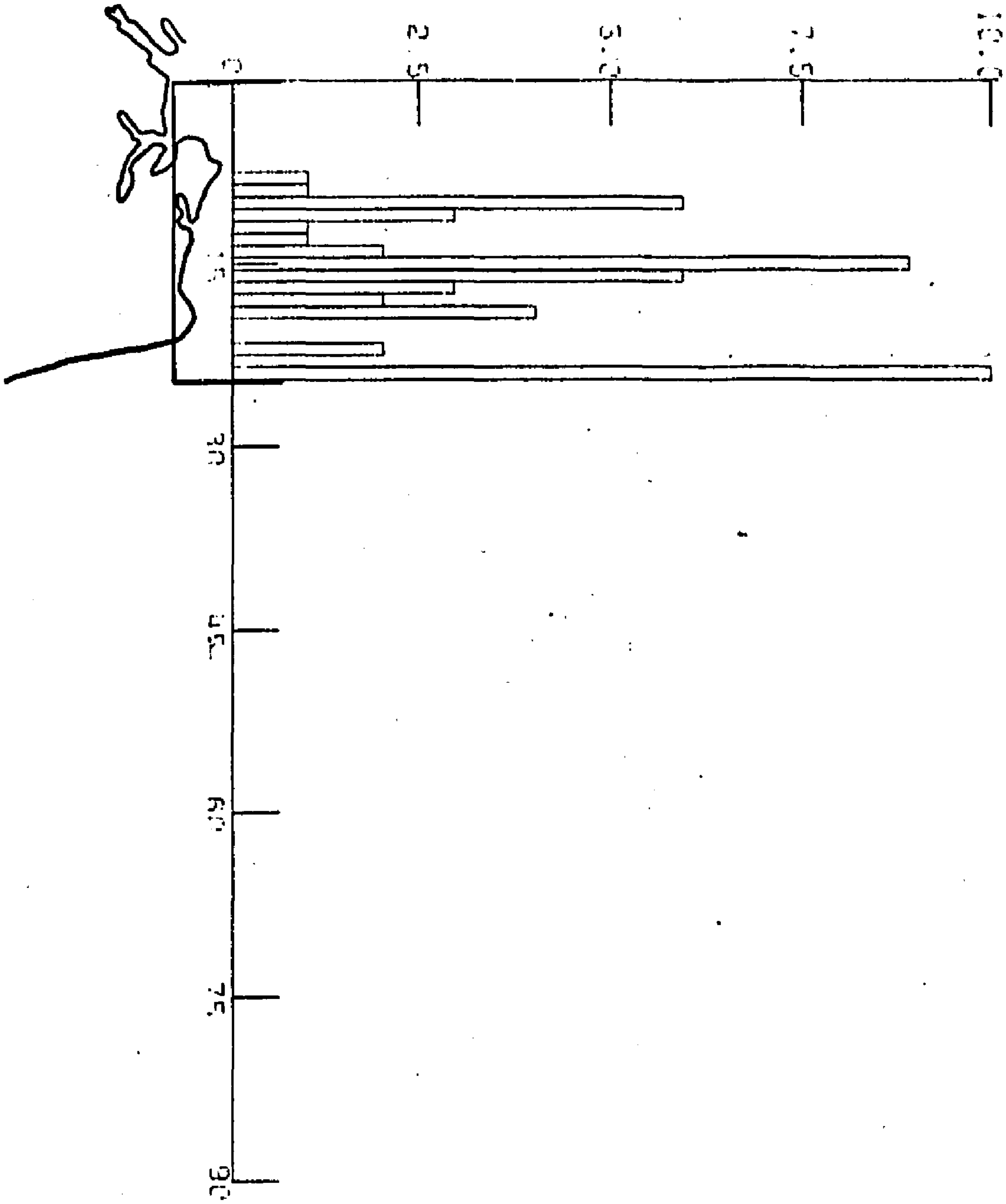
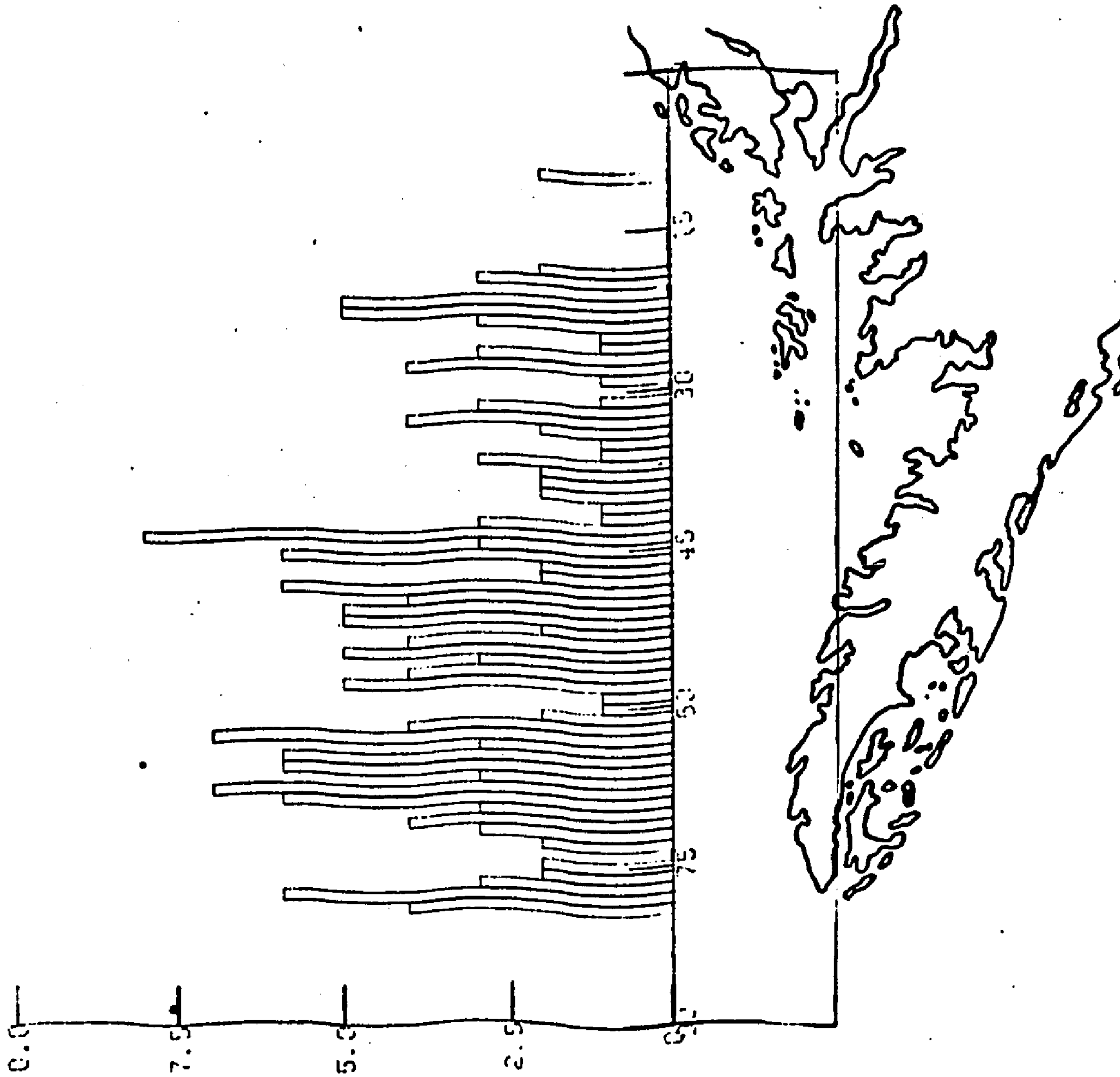



FIGURE D-22




SHORELINE ORTHOGONAL DENSITY
X AXIS IN NAUTICAL MILES.
TIDE= 4 AZ= 315 DEG
LOWER CHES BAY WIND= 40 KTS
EASTERN SHORE

FIGURE D-23

SOUTHERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= 4 AZ= 315 DEG
X AXIS IN NAUTICAL MILES.
SHORELINE ORTHOGONAL DENSITY

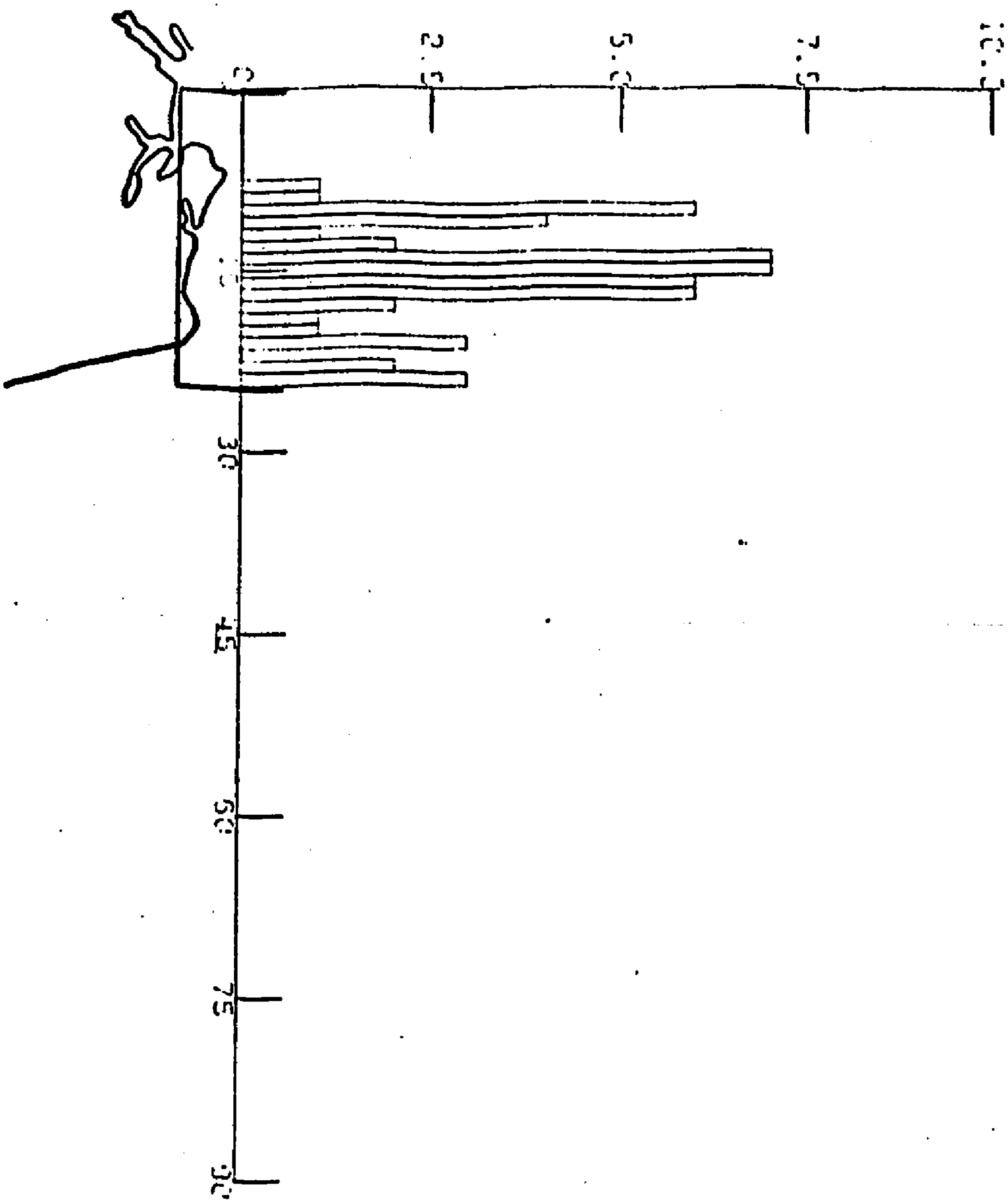



FIGURE D-24

WESTERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

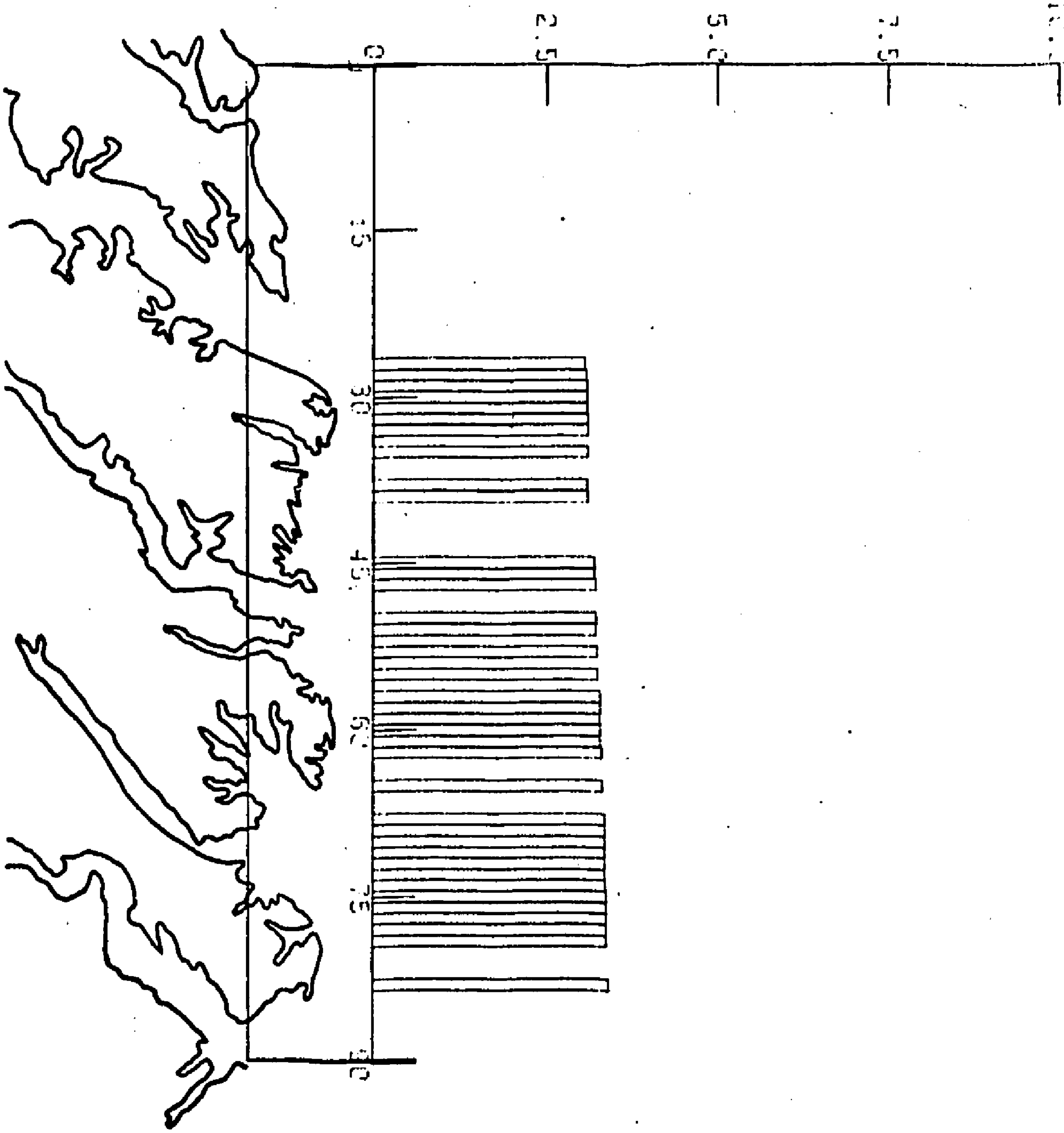
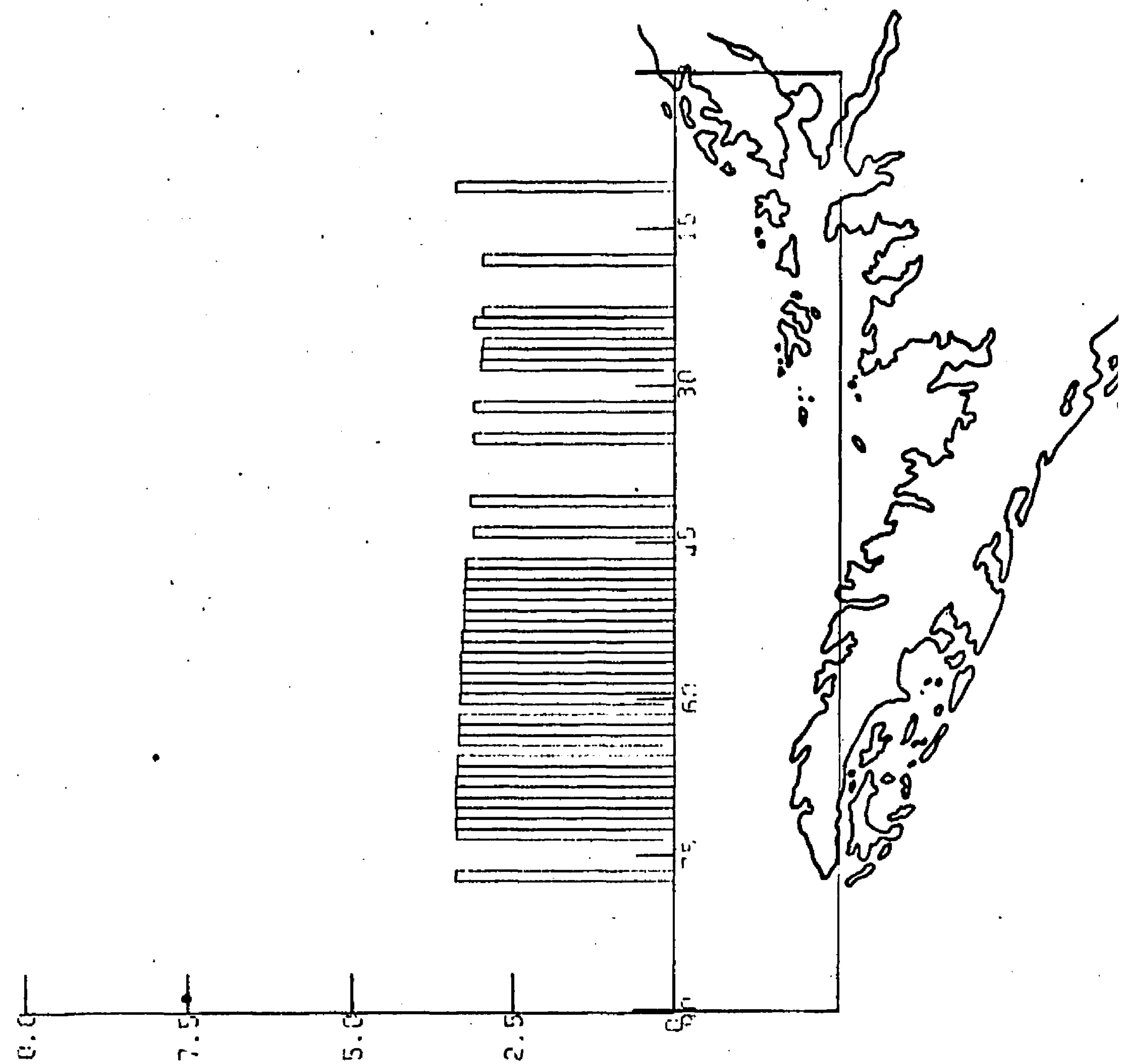



**FIGURE D-25**




PERIOD IN SECONDS
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 0 DEG
LOWER CHES BAY WIND= 10 KTS
EASTERN SHORE

**FIGURE D-26**

SOUTHERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

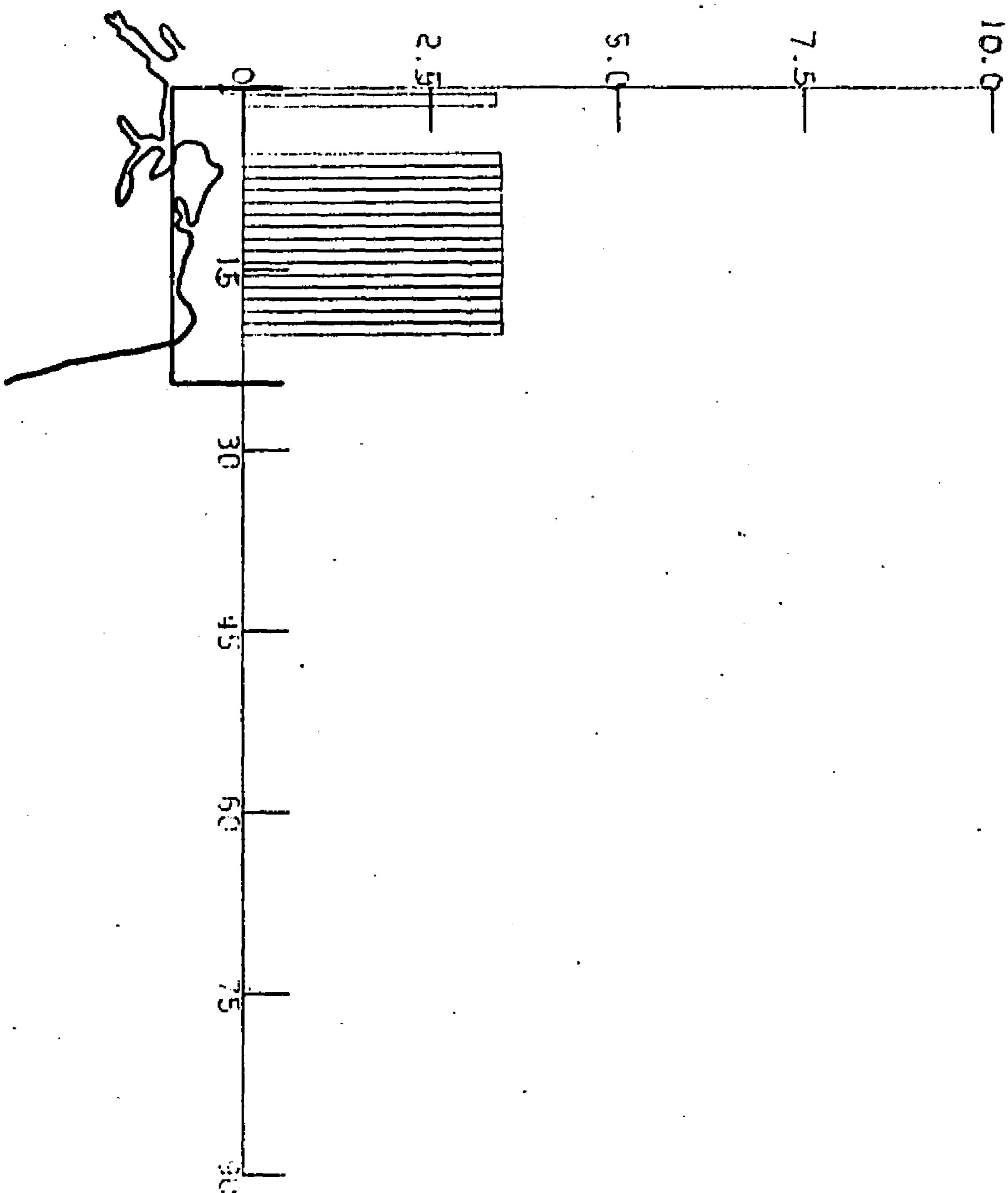



FIGURE D-27

WESTERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

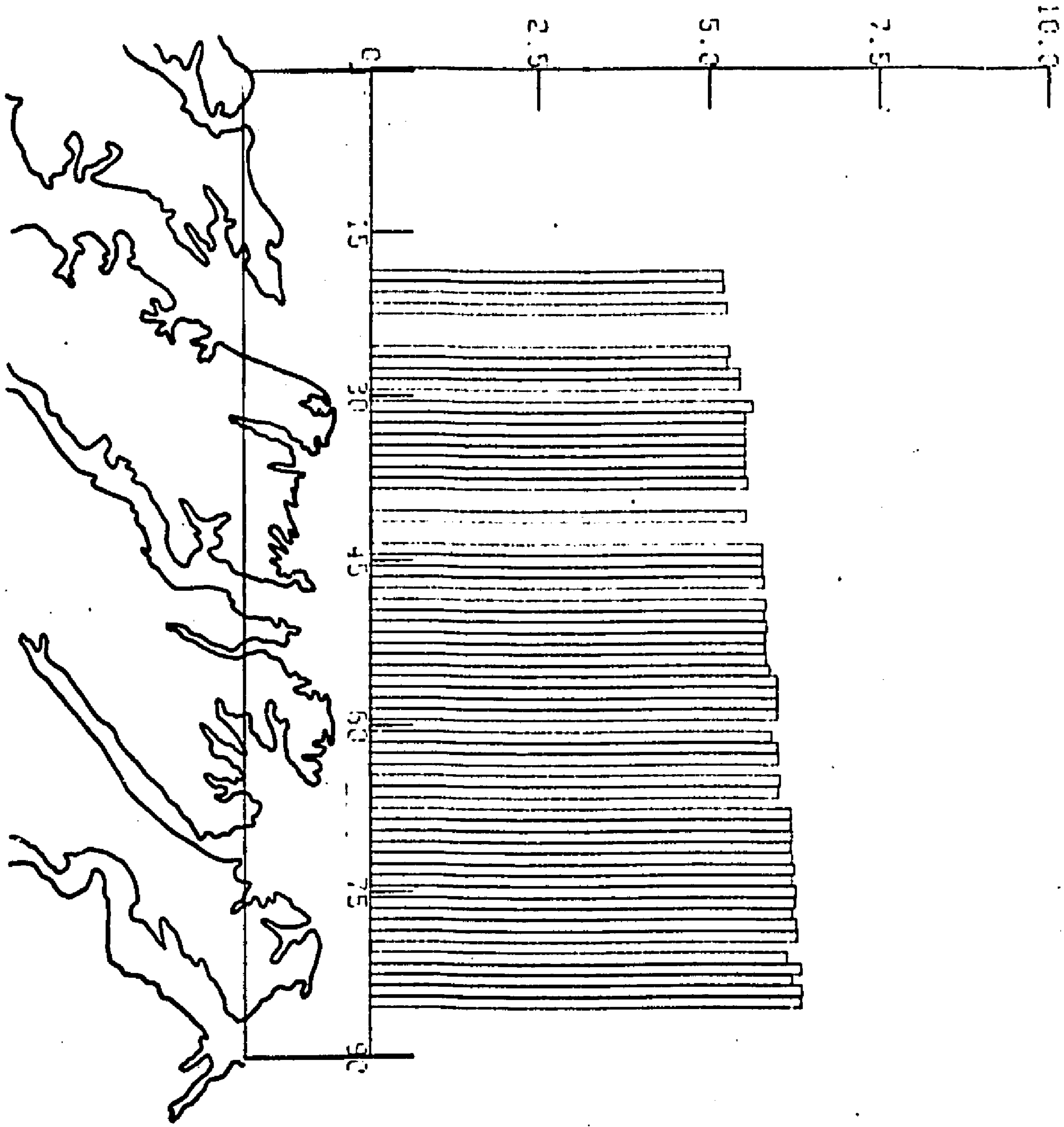
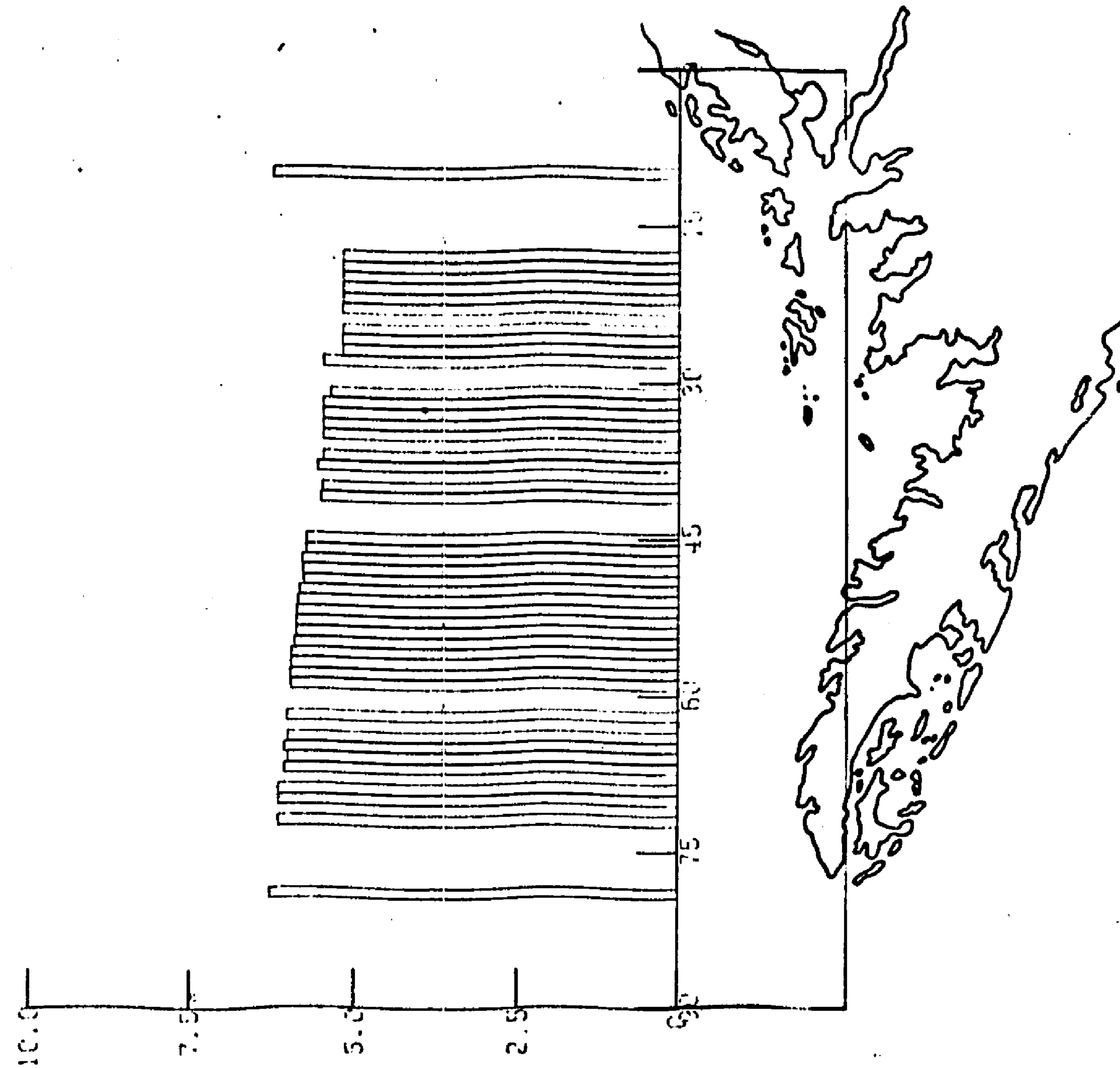



**FIGURE D-28**




PERIOD IN SECONDS .
X AXIS IN NAUTICAL MILES.
TIDE- 0 AZ= 0 DEG
LOWER CHES BAY WIND- 25 KTS
EASTERN SHORE

FIGURE D-29

SOUTHERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

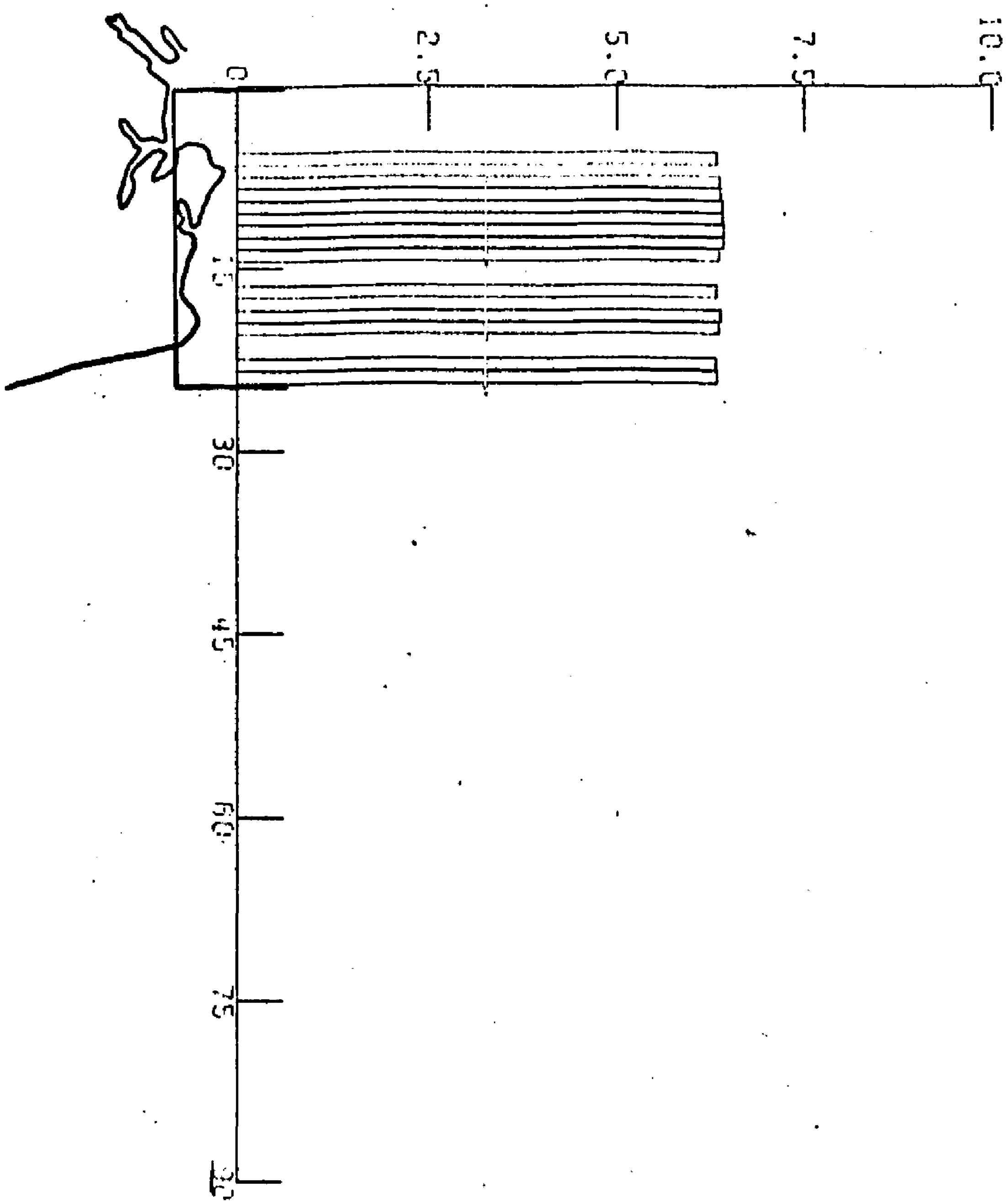



FIGURE D-30

WESTERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= +4 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

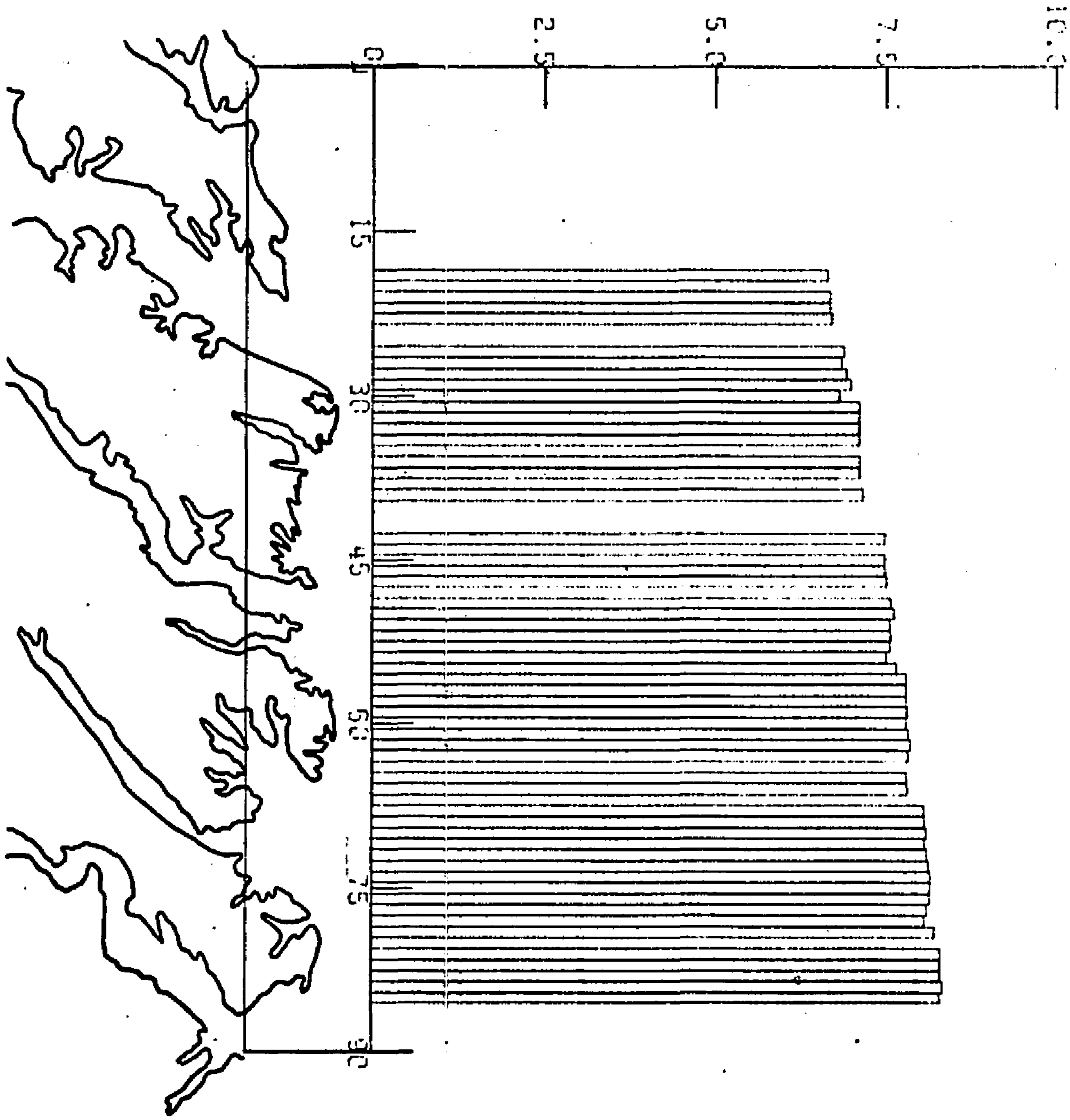
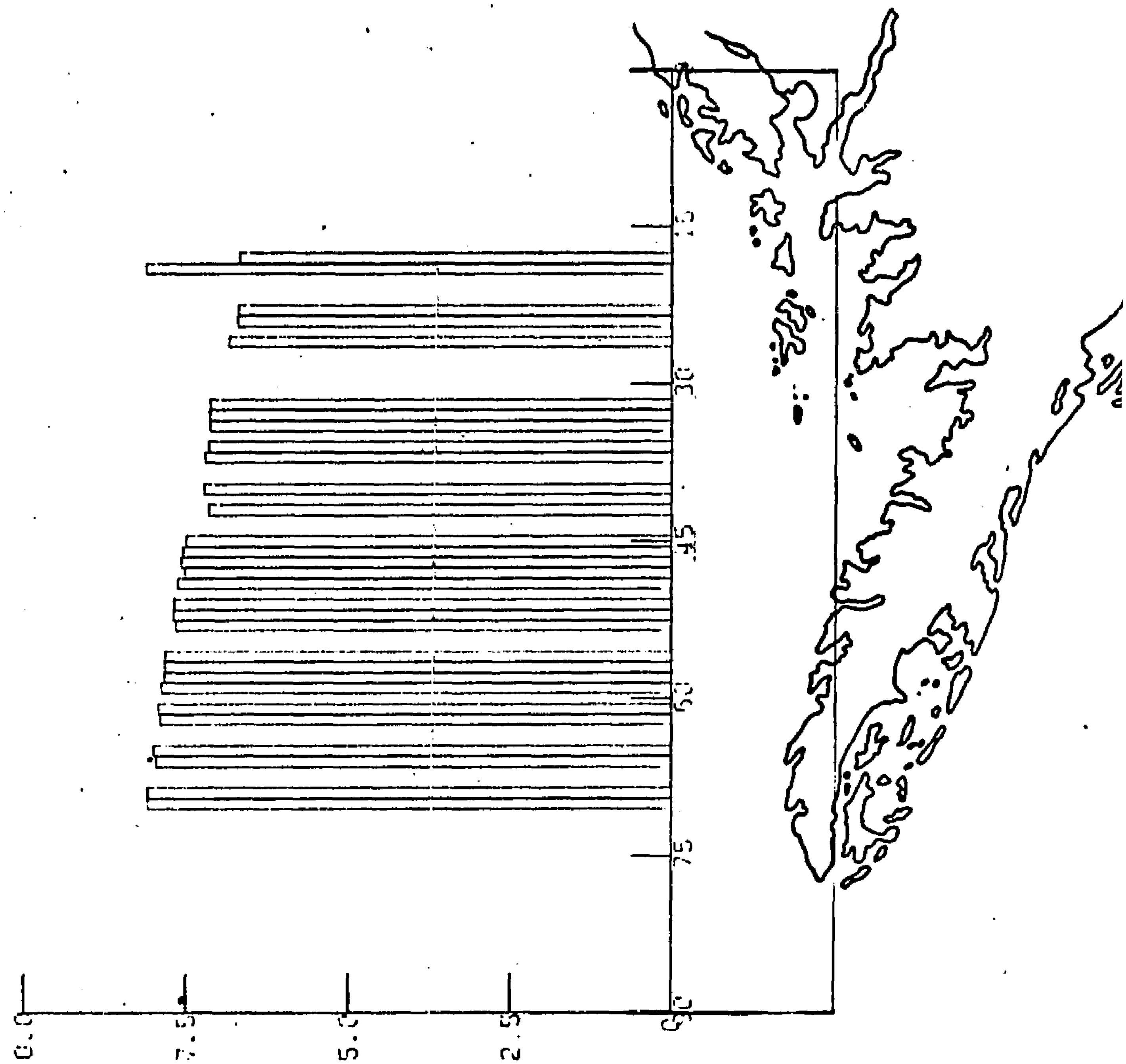



FIGURE D-31




PERIOD IN SECONDS
X AXIS IN NAUTICAL MILES.
TIDE= +4 AZ= 0 DEG
LOWER CHES BAY WIND= 40 KTS
EASTERN SHORE

**FIGURE D-32**

SOUTHERN SHORE
LOWER CHES BAY WIND- 40 KTS
TIDE- +4 AZ- 0 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

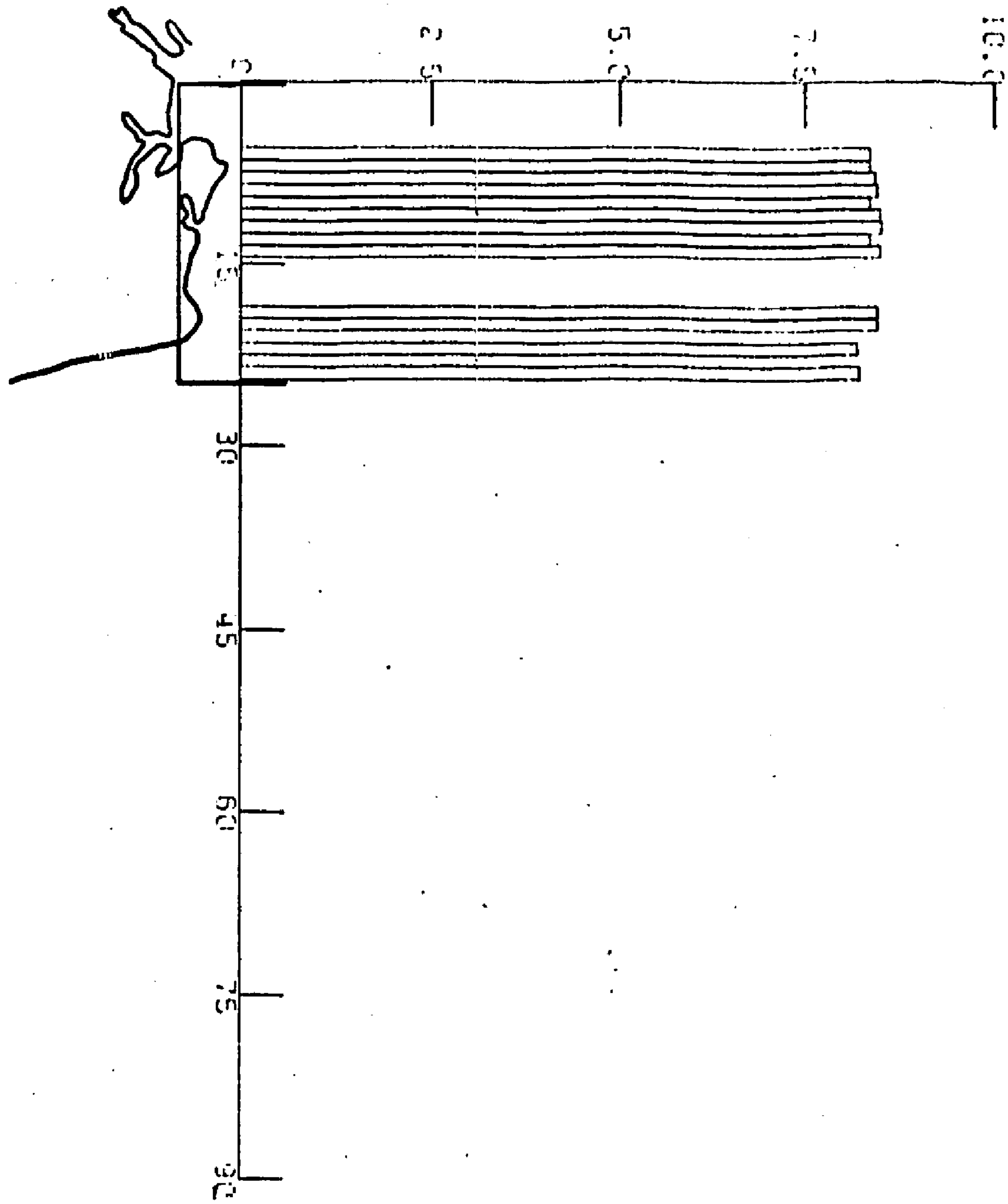



FIGURE D-33

WESTERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

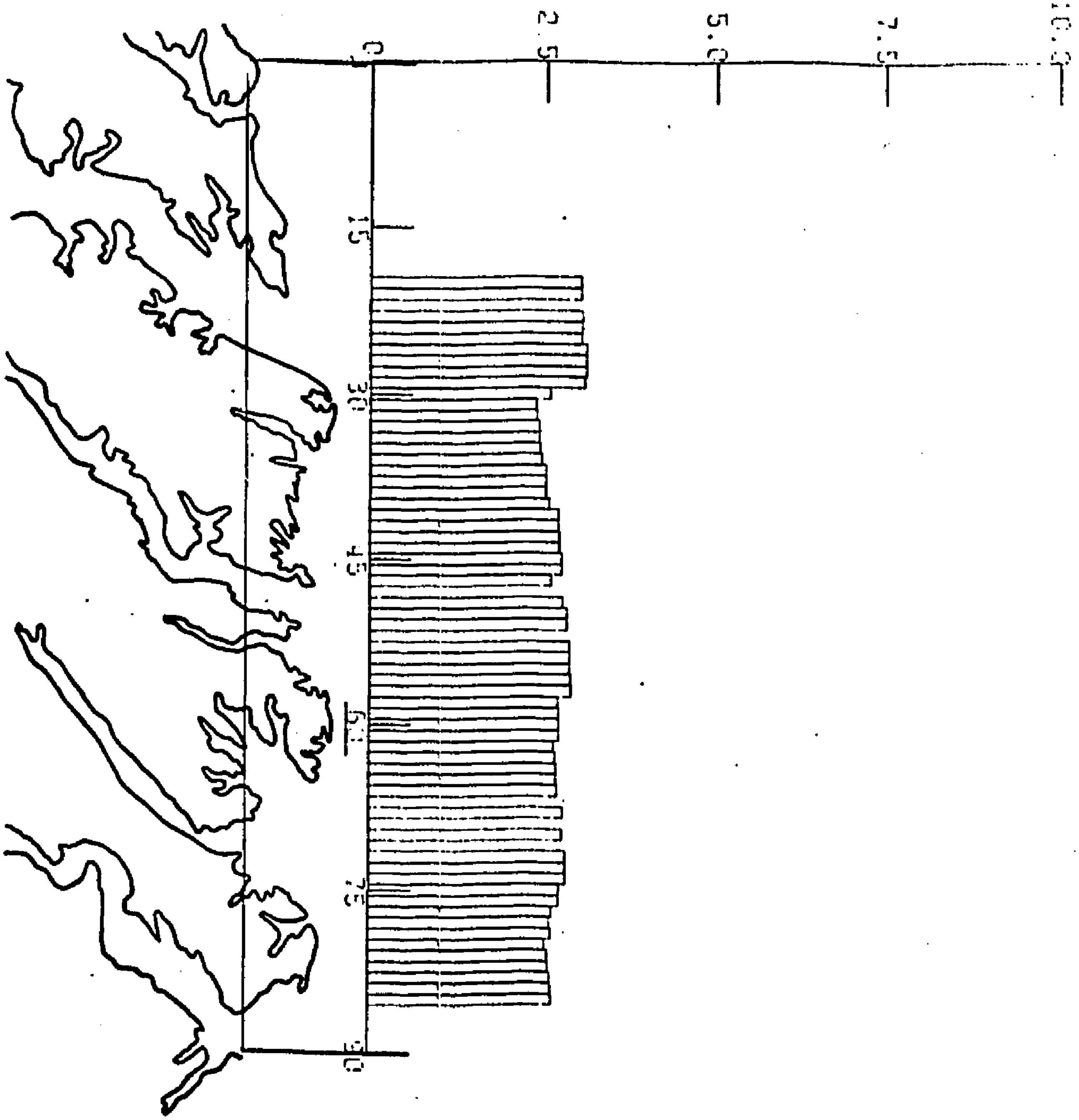



FIGURE D-34

SOUTHERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

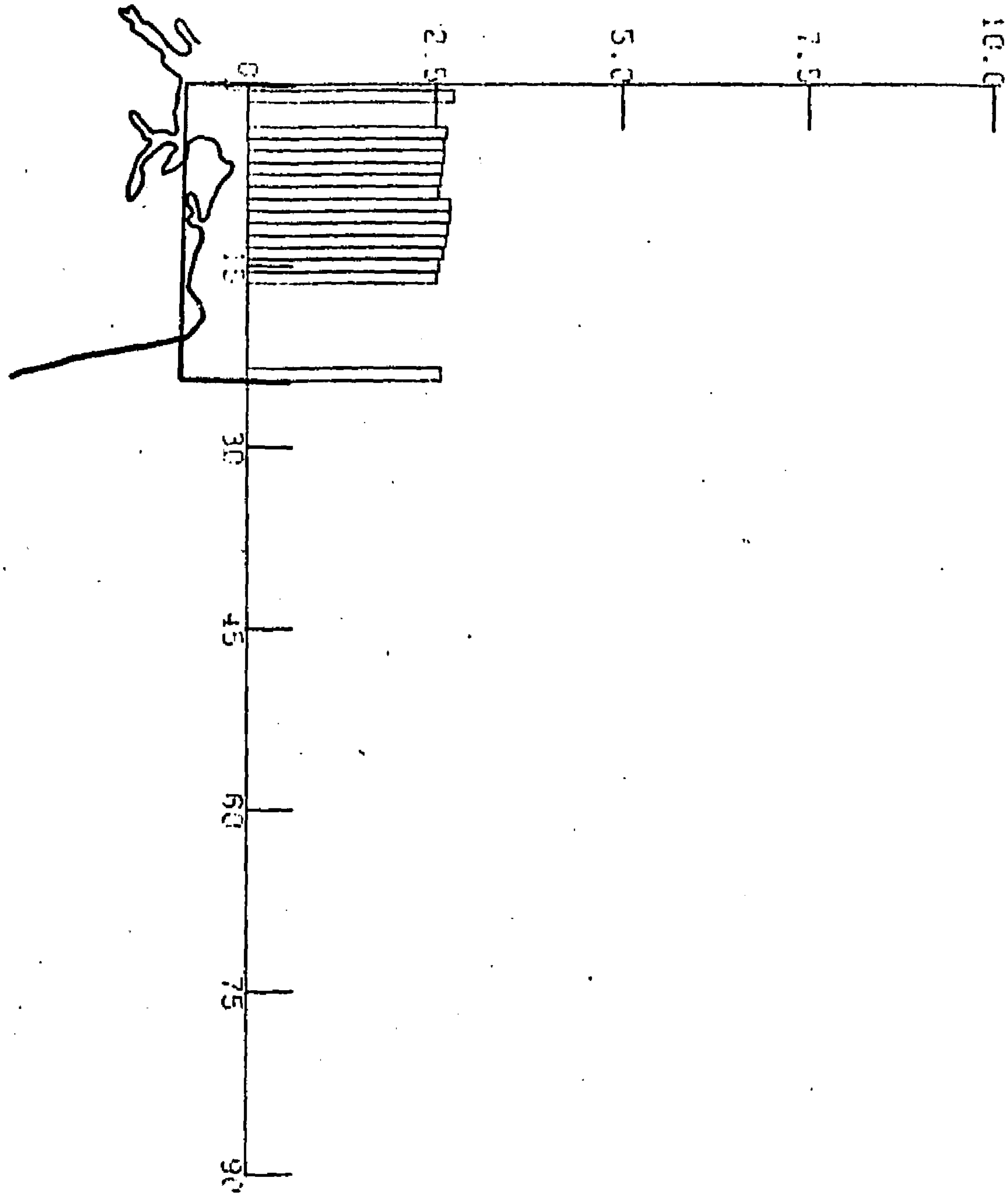



FIGURE D-35

WESTERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0' AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

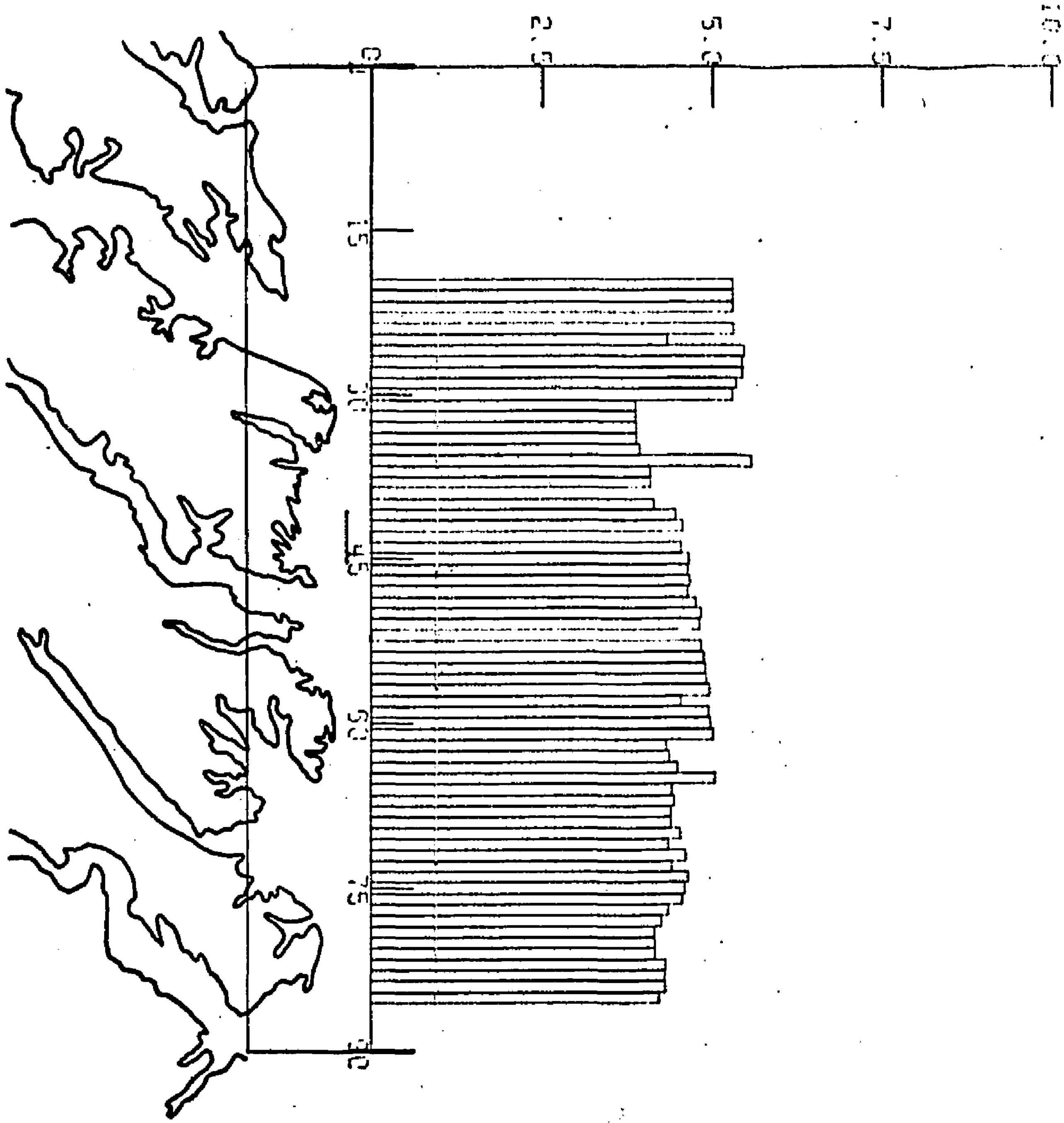


FIGURE D-36

SOUTHERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

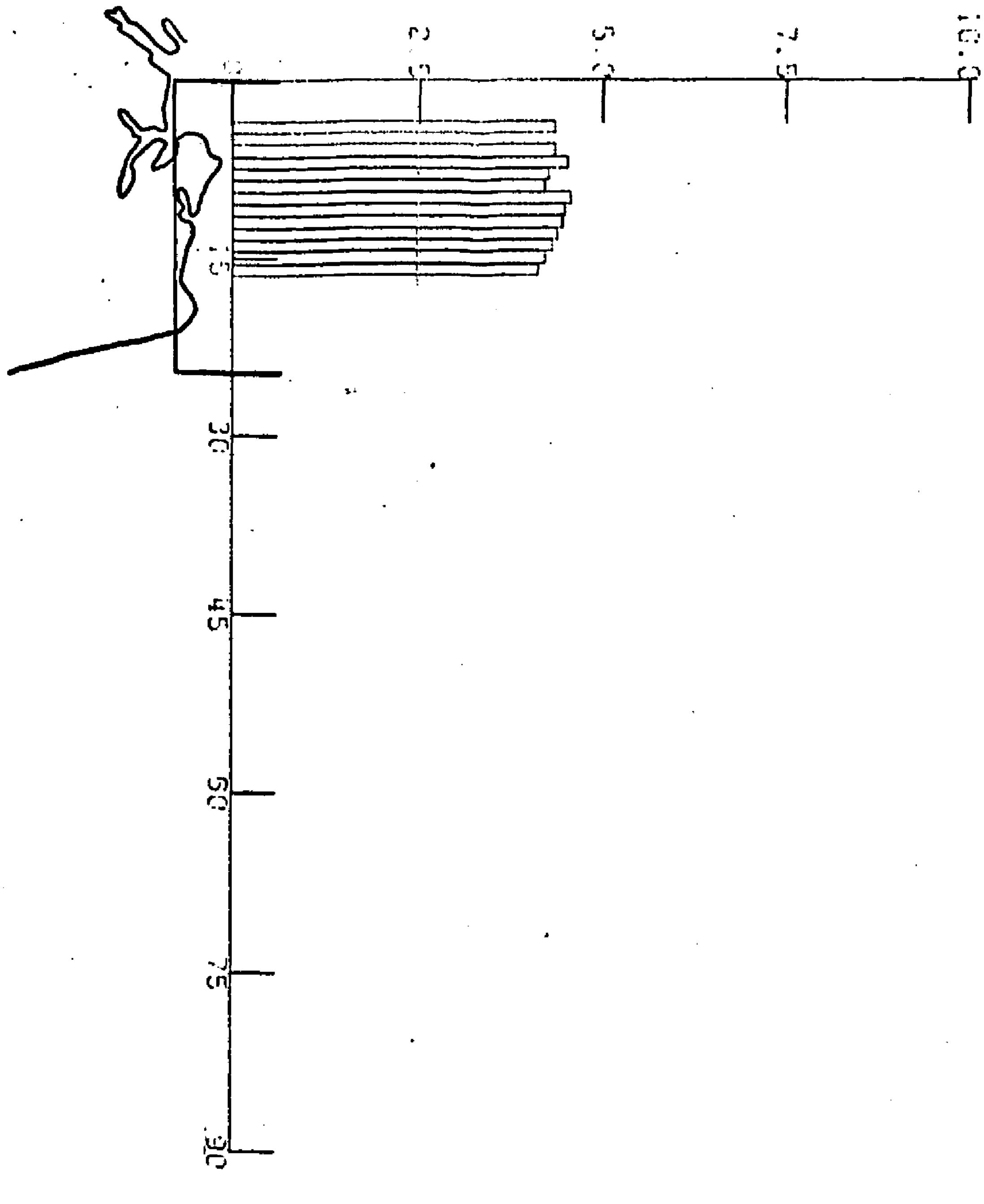


FIGURE D-37

WESTERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= 4 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

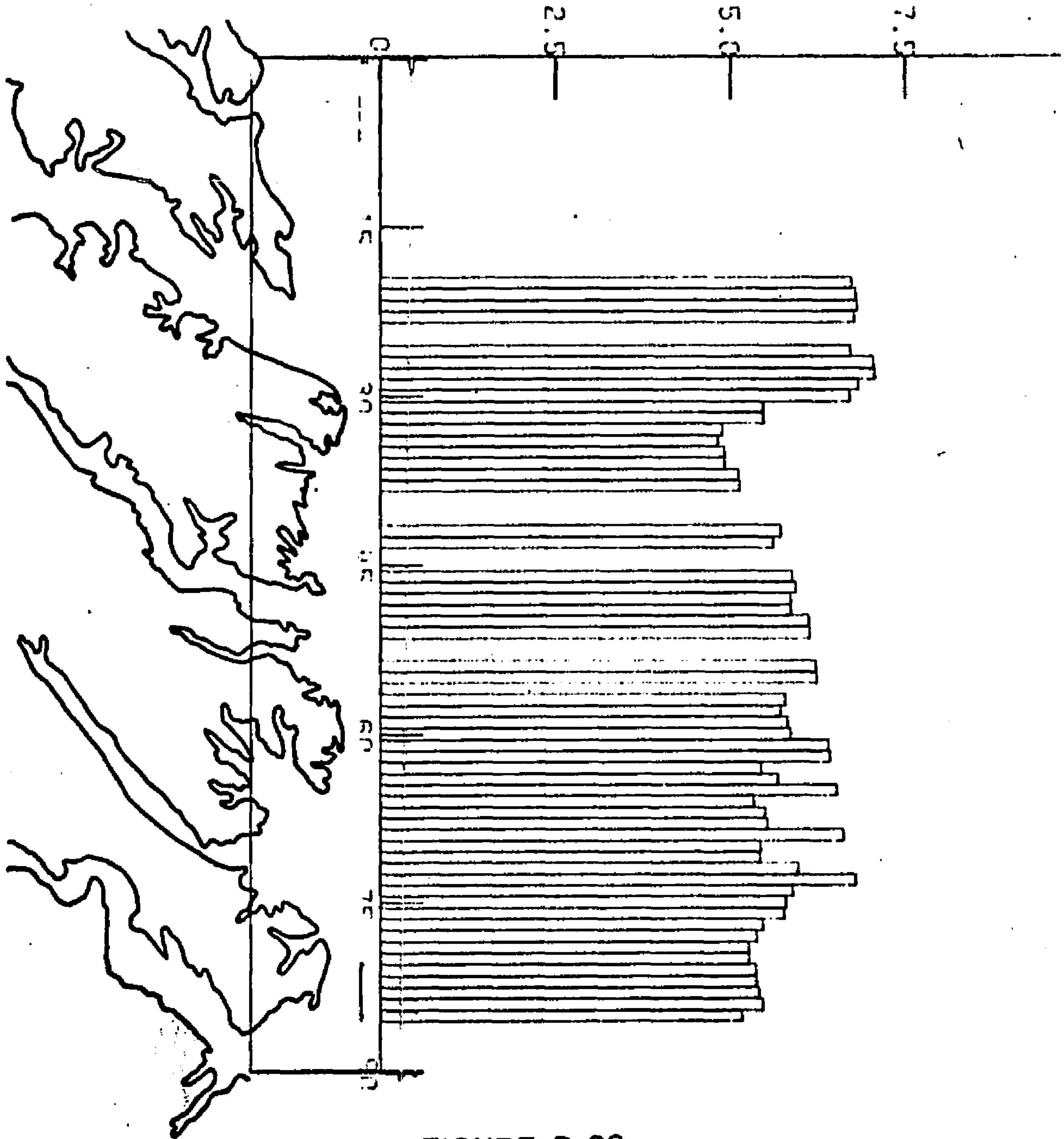



FIGURE D-38

SOUTHERN SHORE
LOWER CHES BAY  WIND= 40 KTS
TIDE= 4  AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

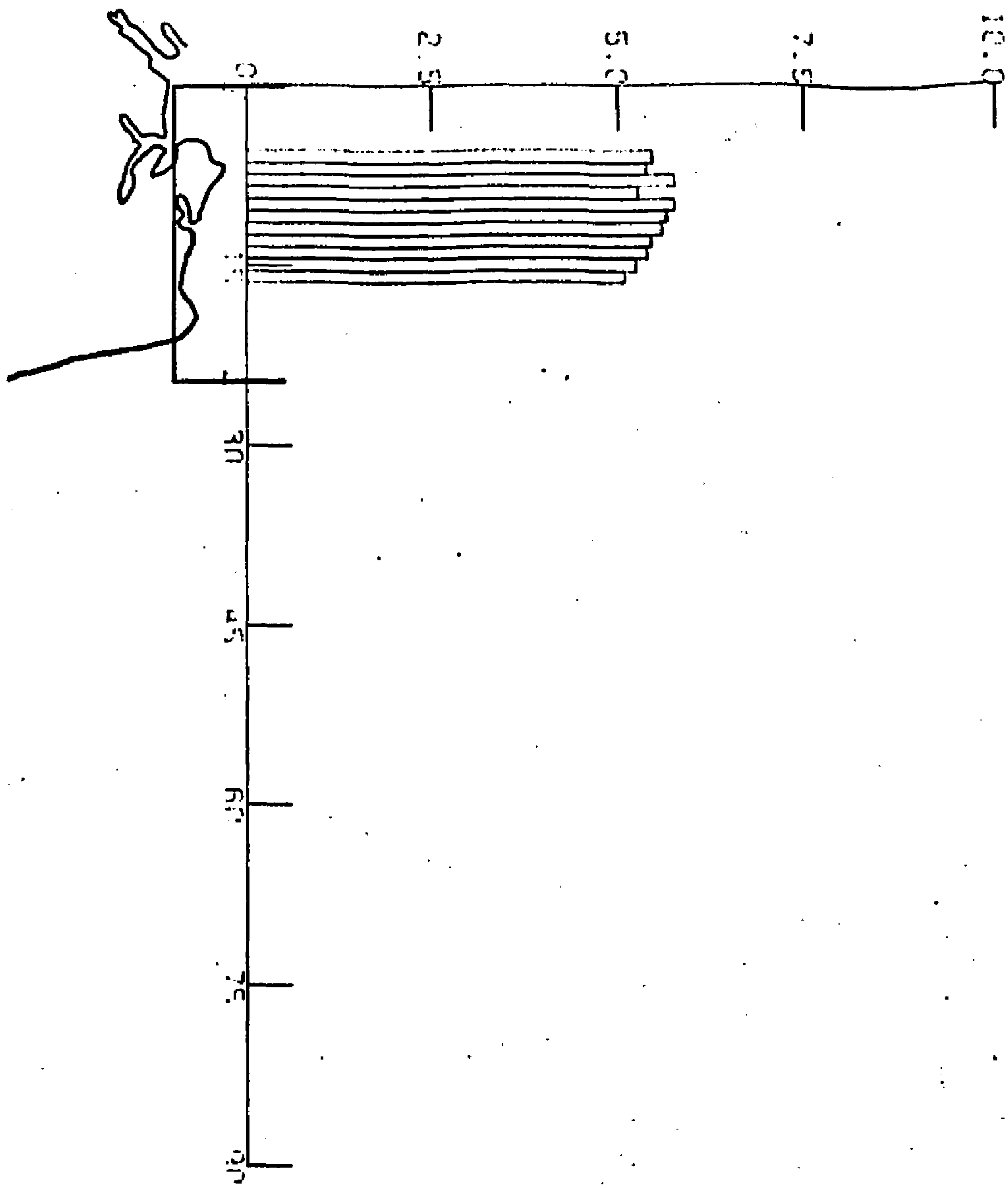
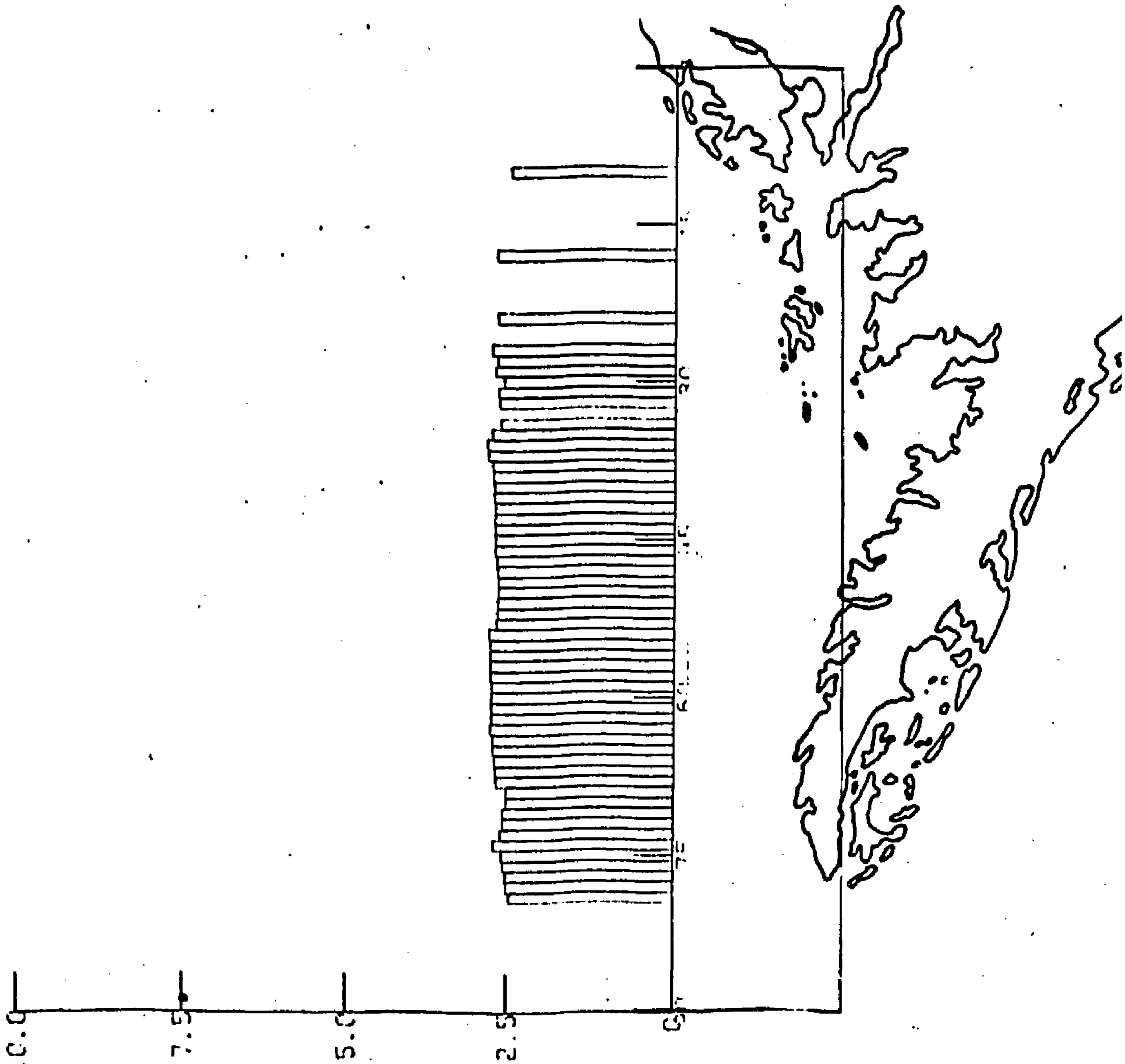
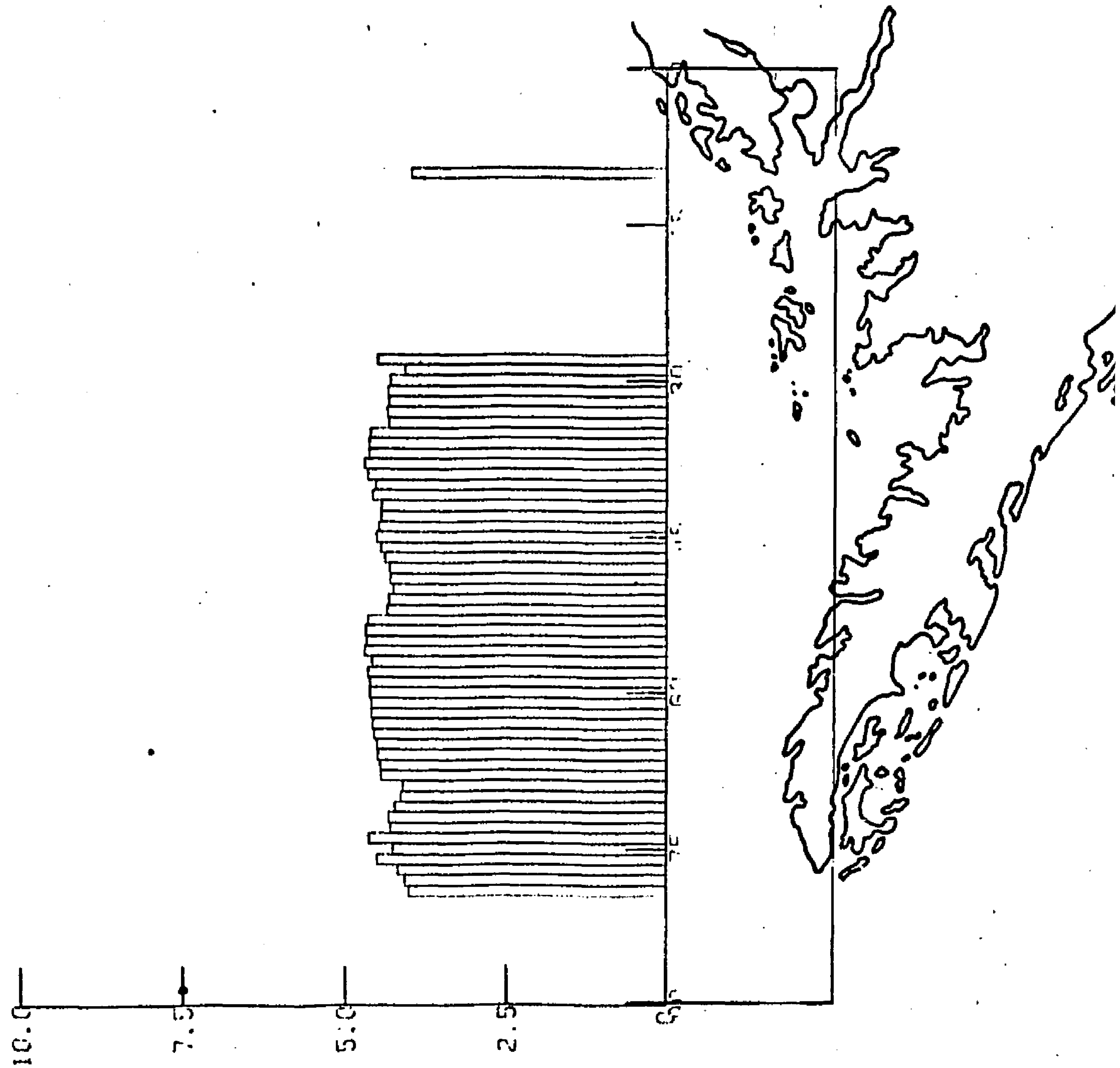



FIGURE D-39



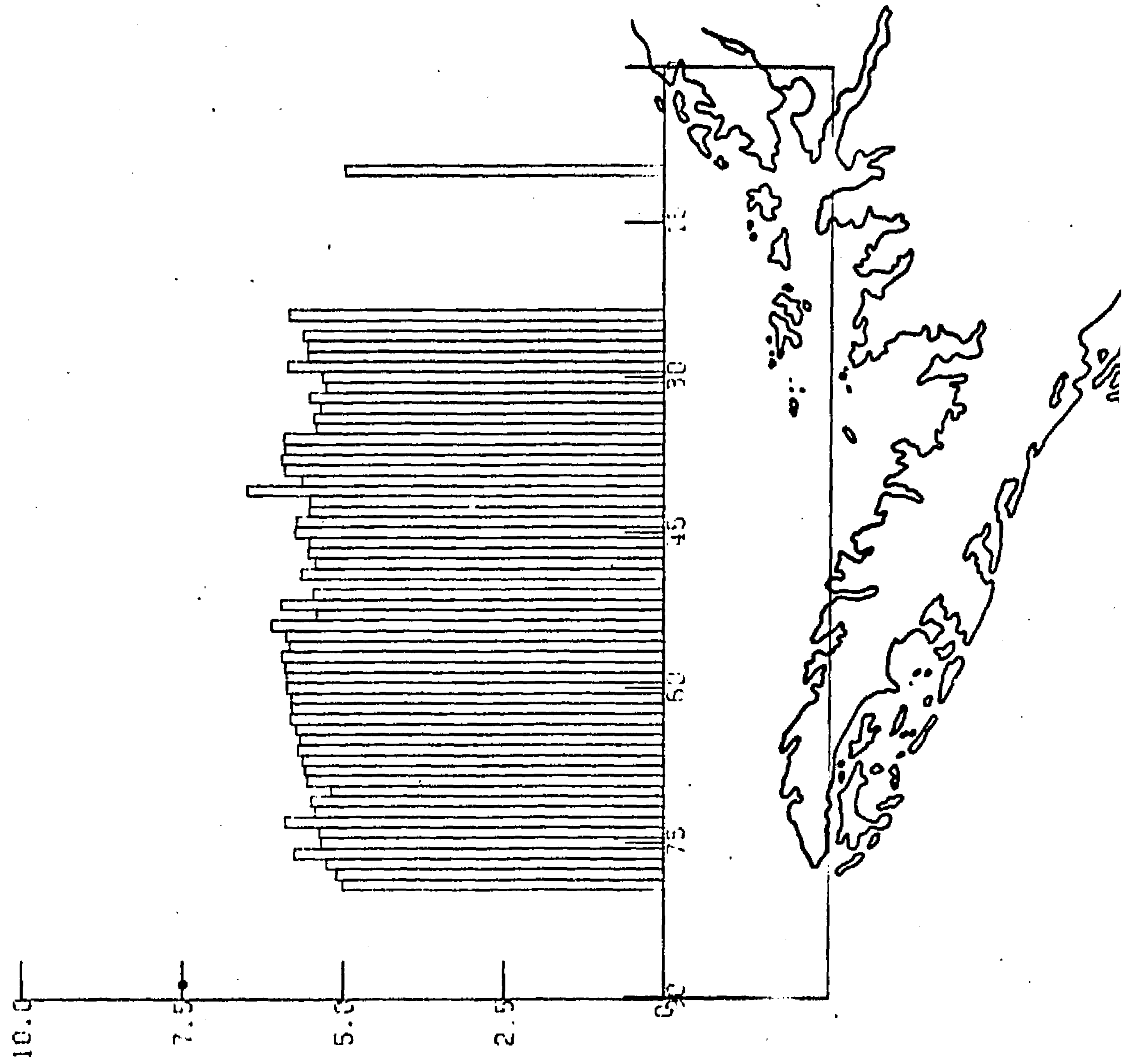
PERIOD IN SECONDS
X AXIS IN NAUTICAL MILES.
TIME= 0 AZ= 225 DEG
LOWER CHES BAY WIND= 10 KTS
EASTERN SHORE

FIGURE D-40



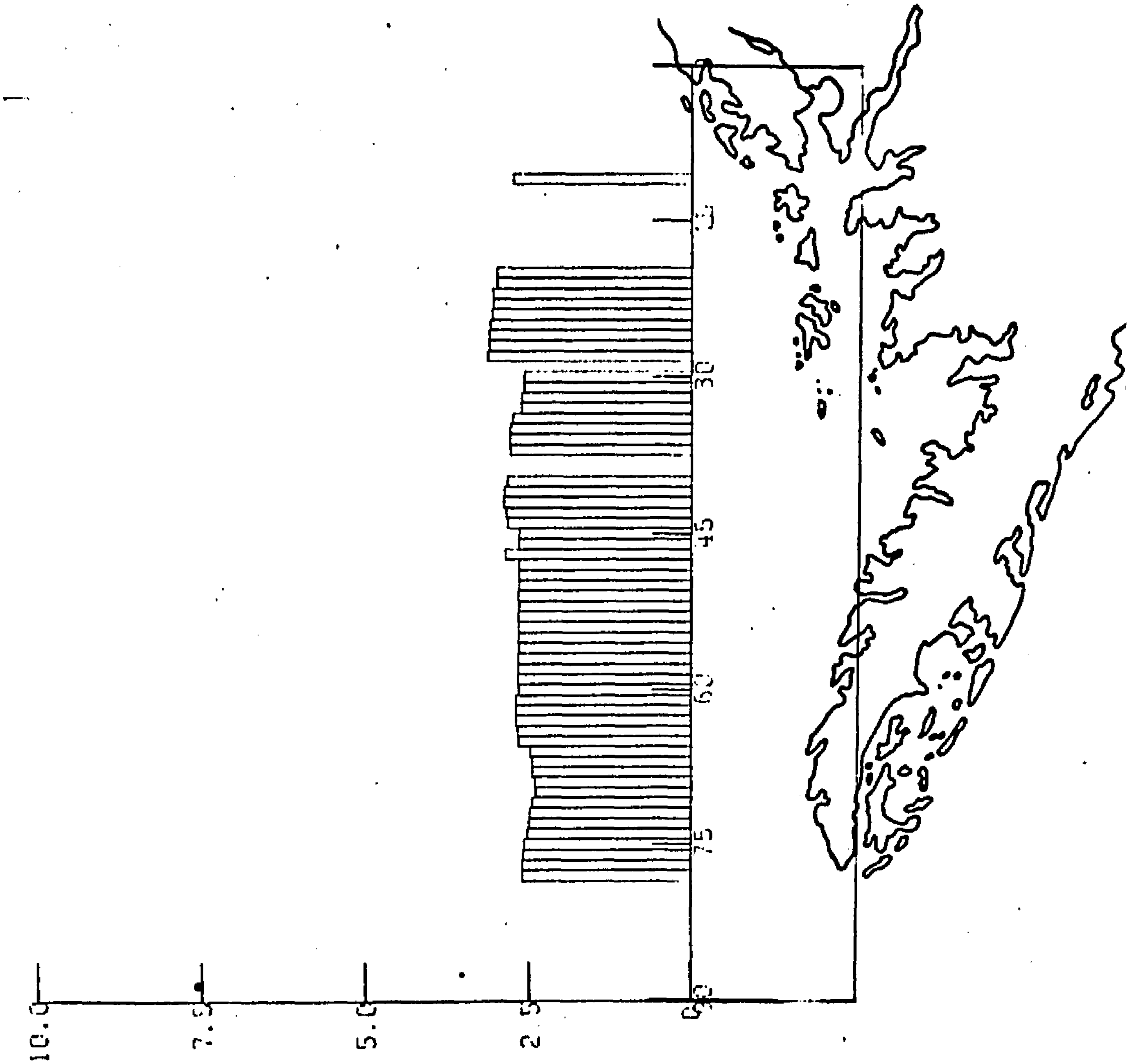

PERIOD IN SECONDS
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 225 DEG
LOWER CHES BAY WIND= 25 KTS
EASTERN SHORE

FIGURE D-41




PERIOD IN SECONDS
X AXIS IN NAUTICAL MILES.
TIDE= 4 AZ= 225 DEG
LOWER CHES BAY WIND= 40 KTS
EASTERN SHORE

FIGURE D-42




PERIOD IN SECONDS
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 315 DEG
LOWER CHES BAY WIND= 10 KTS
EASTERN SHORE

**FIGURE D-43**

SOUTHERN SHORE
LOWER CHES BAY  WIND- 10 KTS
TIDE- 0  AZ- 315 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

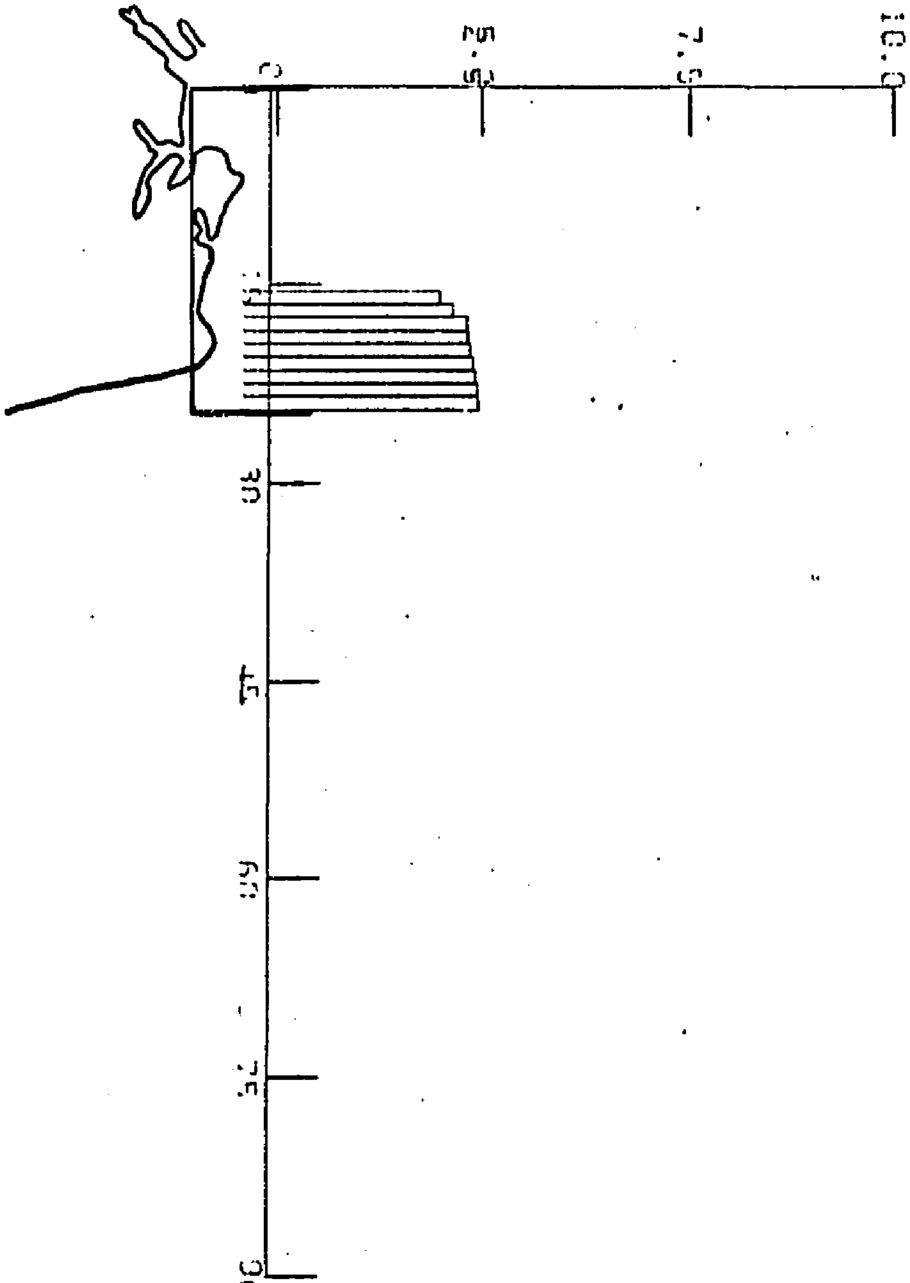


FIGURE D-44


PERIOD IN SECONDS
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 315 DEG
LOWER CHES BAY WIND= 25 KTS
EASTERN SHORE

**FIGURE D-45**

SOUTHERN SHORE
LOWER CHES BAY WIND= 25. KTS
TIDE- 0 AZ= 315 DEG
X AXIS IN NAUTICAL MILES.
PERIOD IN SECONDS

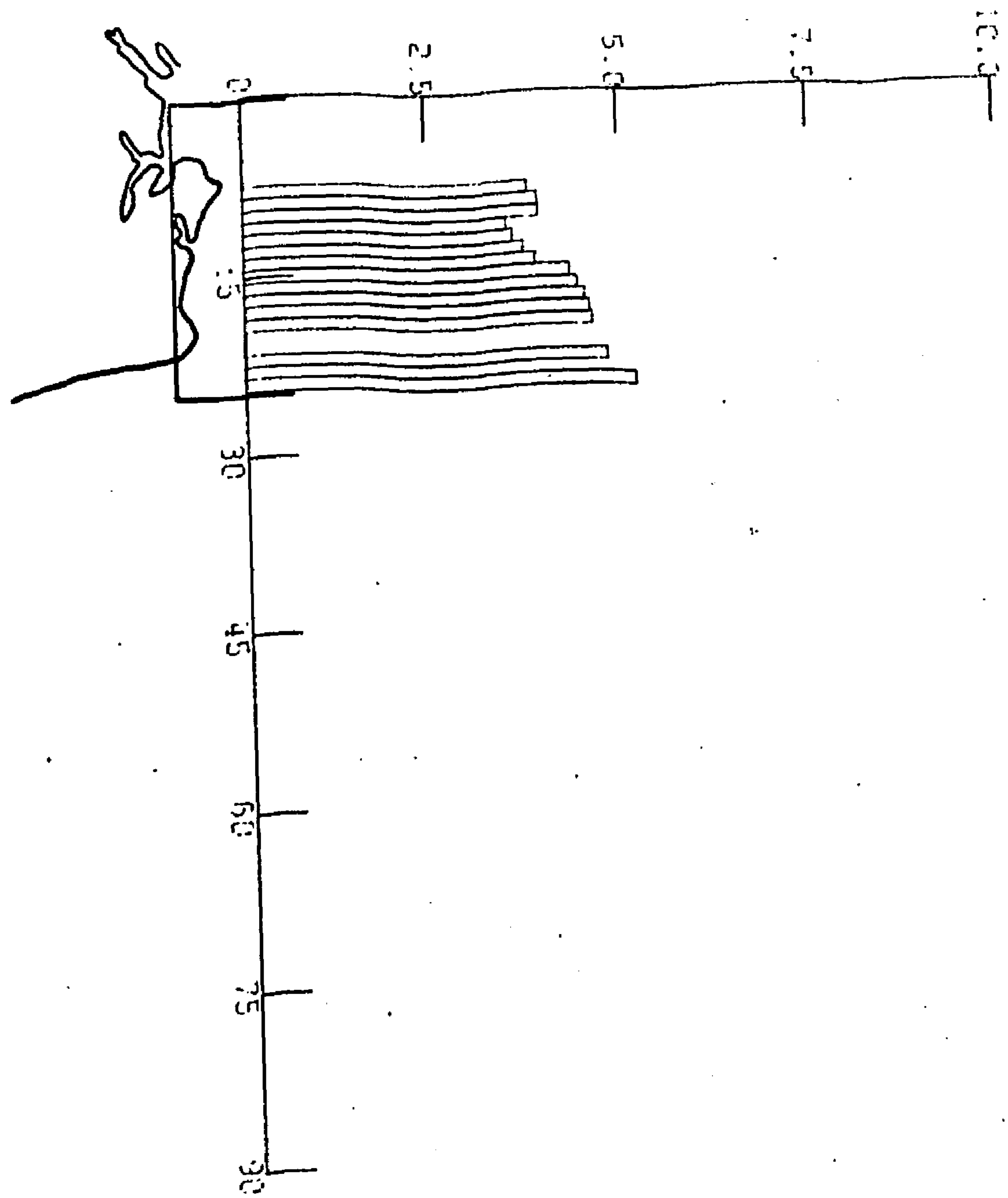
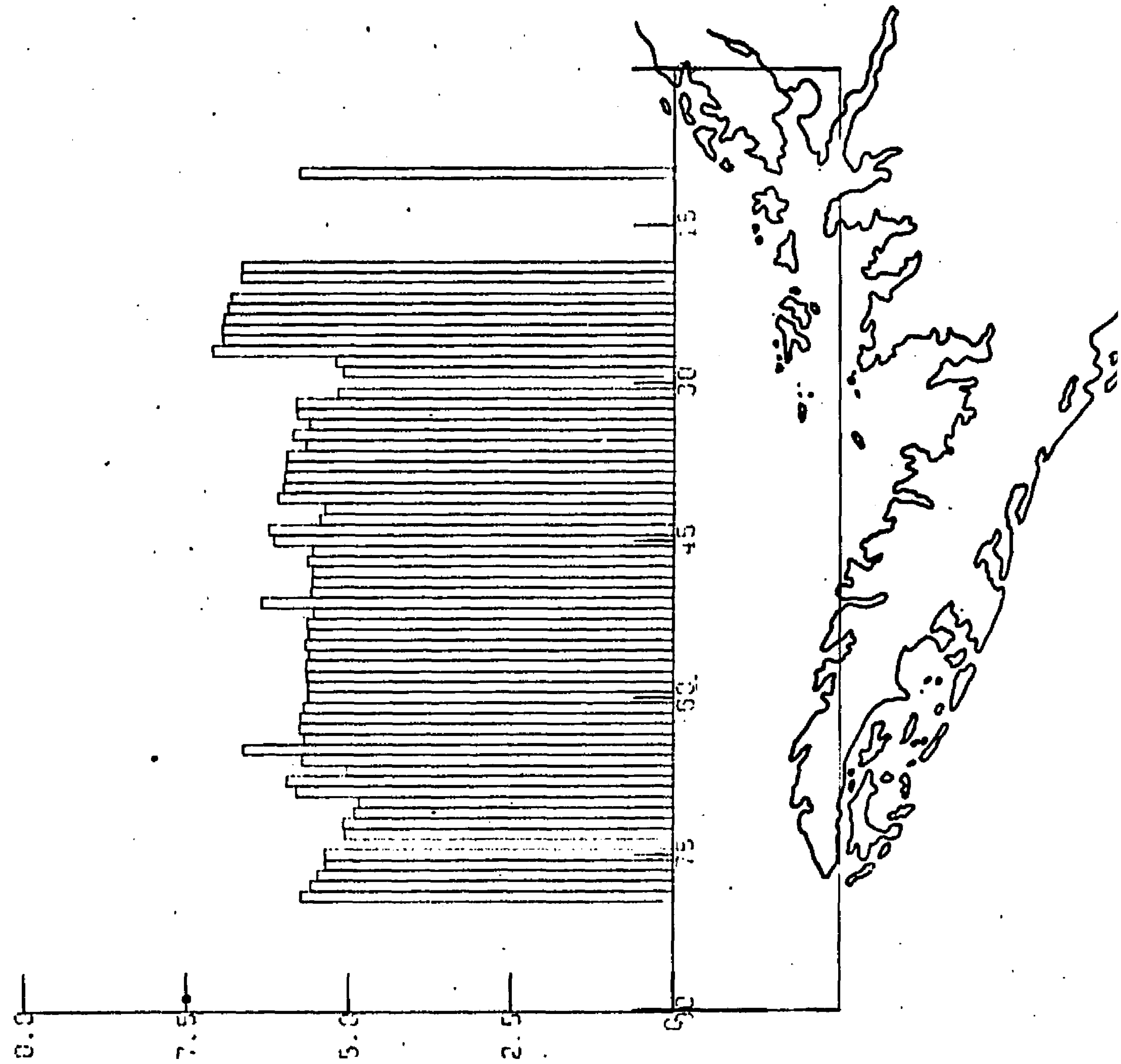



FIGURE D-46




PERIOD IN SECONDS
X AXIS IN NAUTICAL MILES.
TIDE= 4  AZ= 315 DEG
LOWER CHES BAY  WIND= 40 KTS
EASTERN SHORE

FIGURE D-47

SOUTHERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= 4 AZ= 315 DEG
X AXIS IN NAUTICAL MILES
PERIOD IN SECONDS

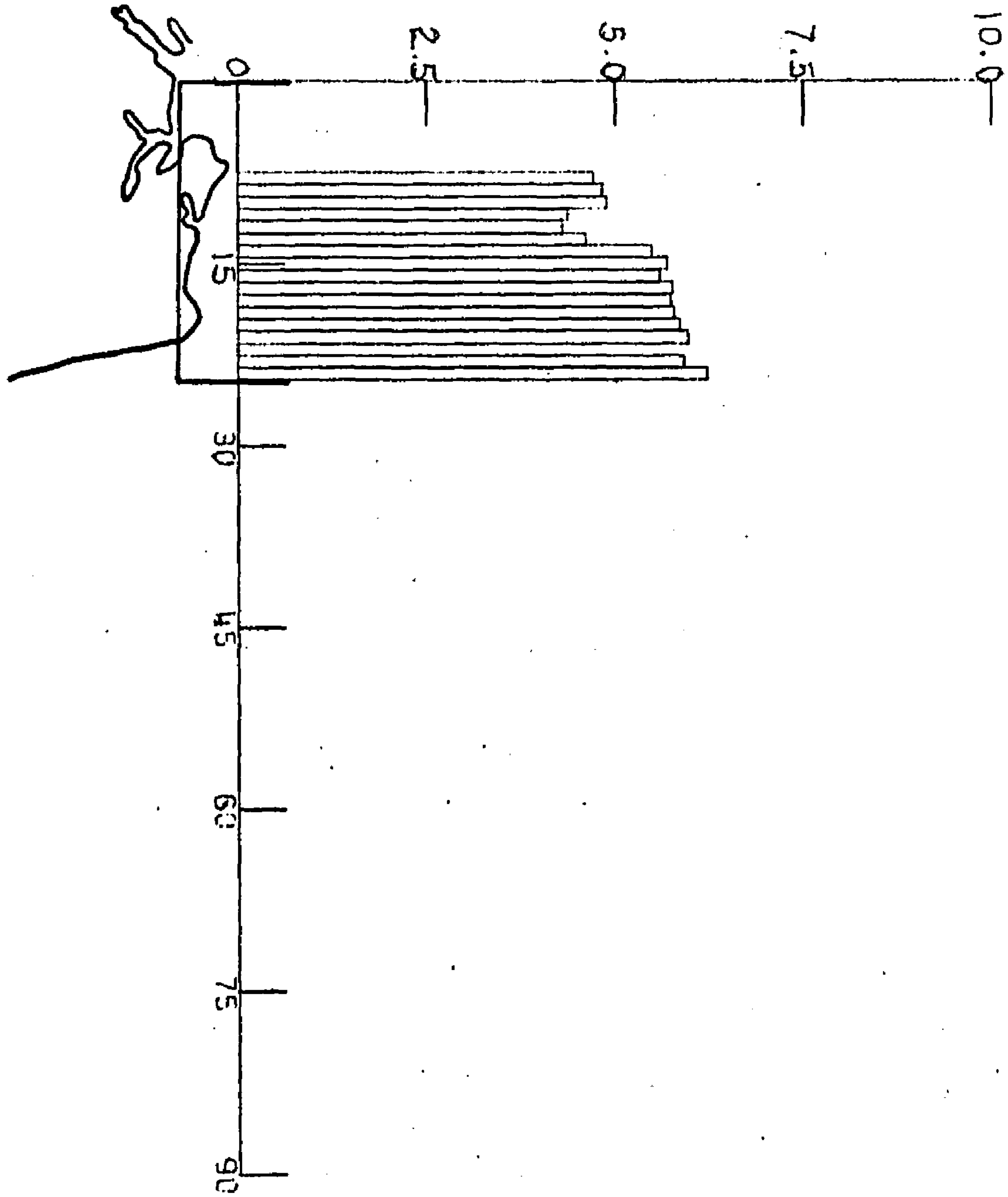



FIGURE D-48

WESTERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

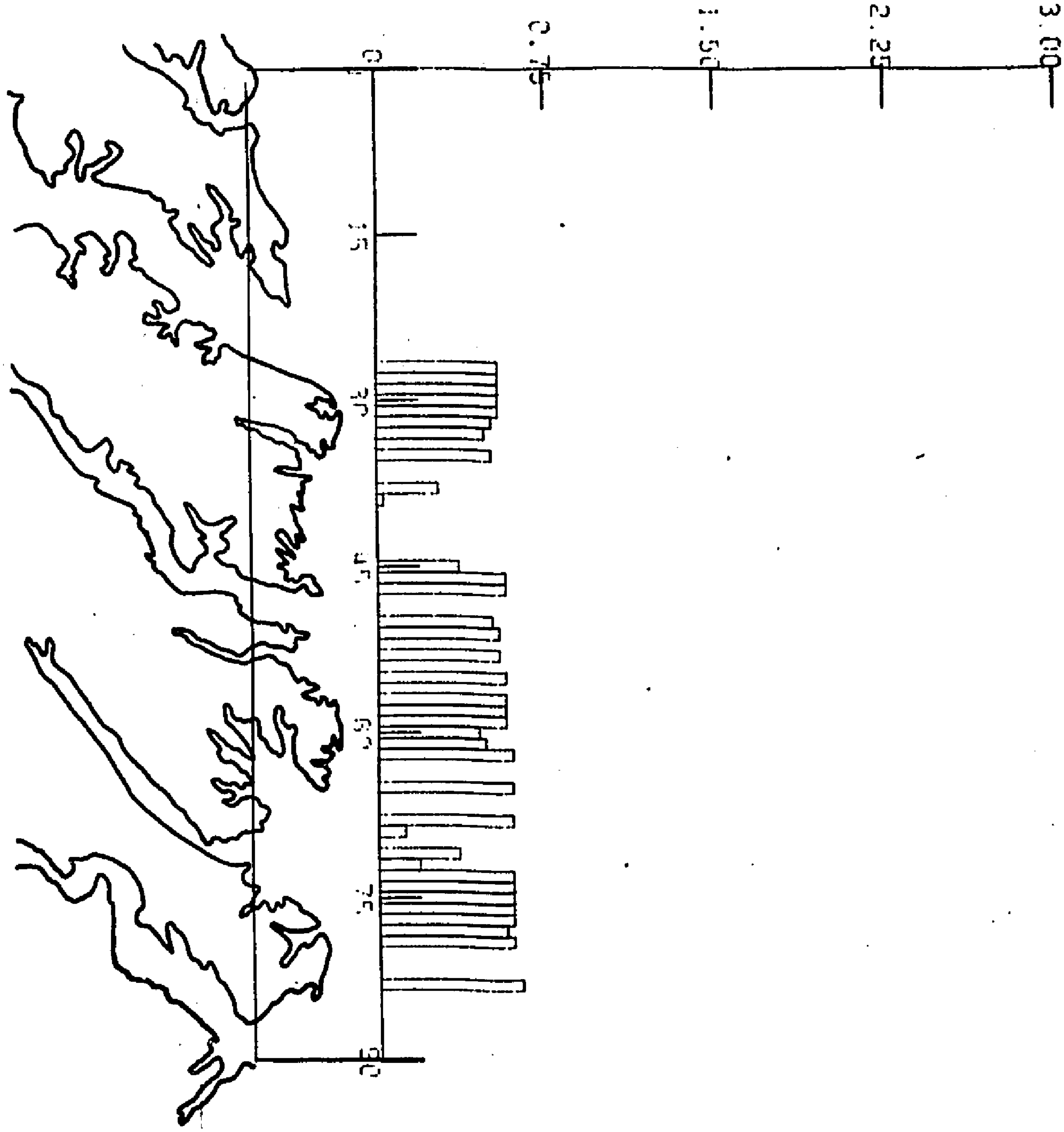
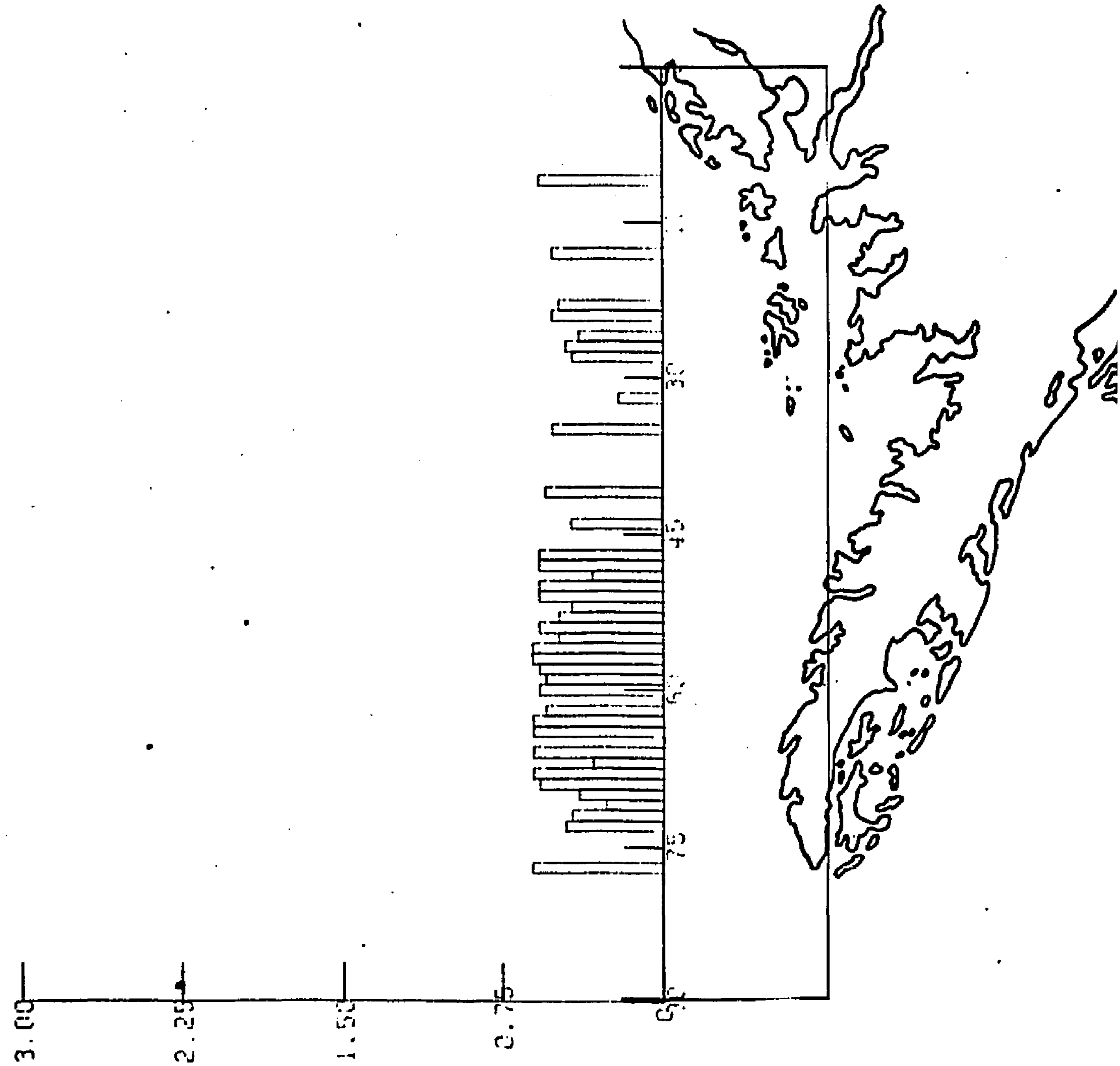



**FIGURE D-49**




WAVE HEIGHT IN METERS
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 0 DEG
LOWER CHES BAY WIND= 10 KTS
EASTERN SHORE

FIGURE D-50

SOUTHERN SHORE
LOWER CHES BAY WIND- 10 KTS
TIDE: 0 AZ- 0 DEG
X AXIS IN NAUTICAL MILES
WAVE HEIGHT IN METERS

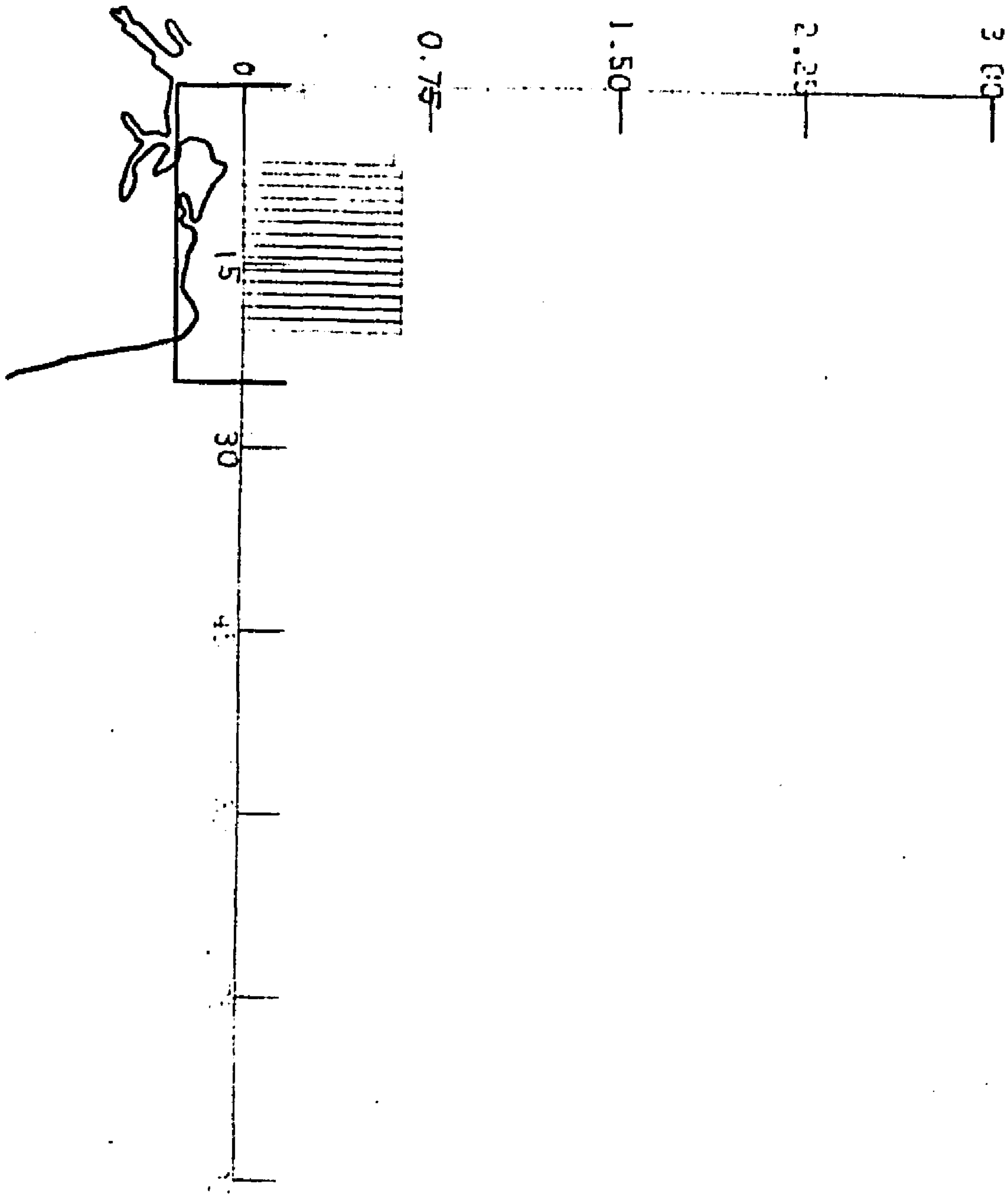



FIGURE D-51

WESTERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

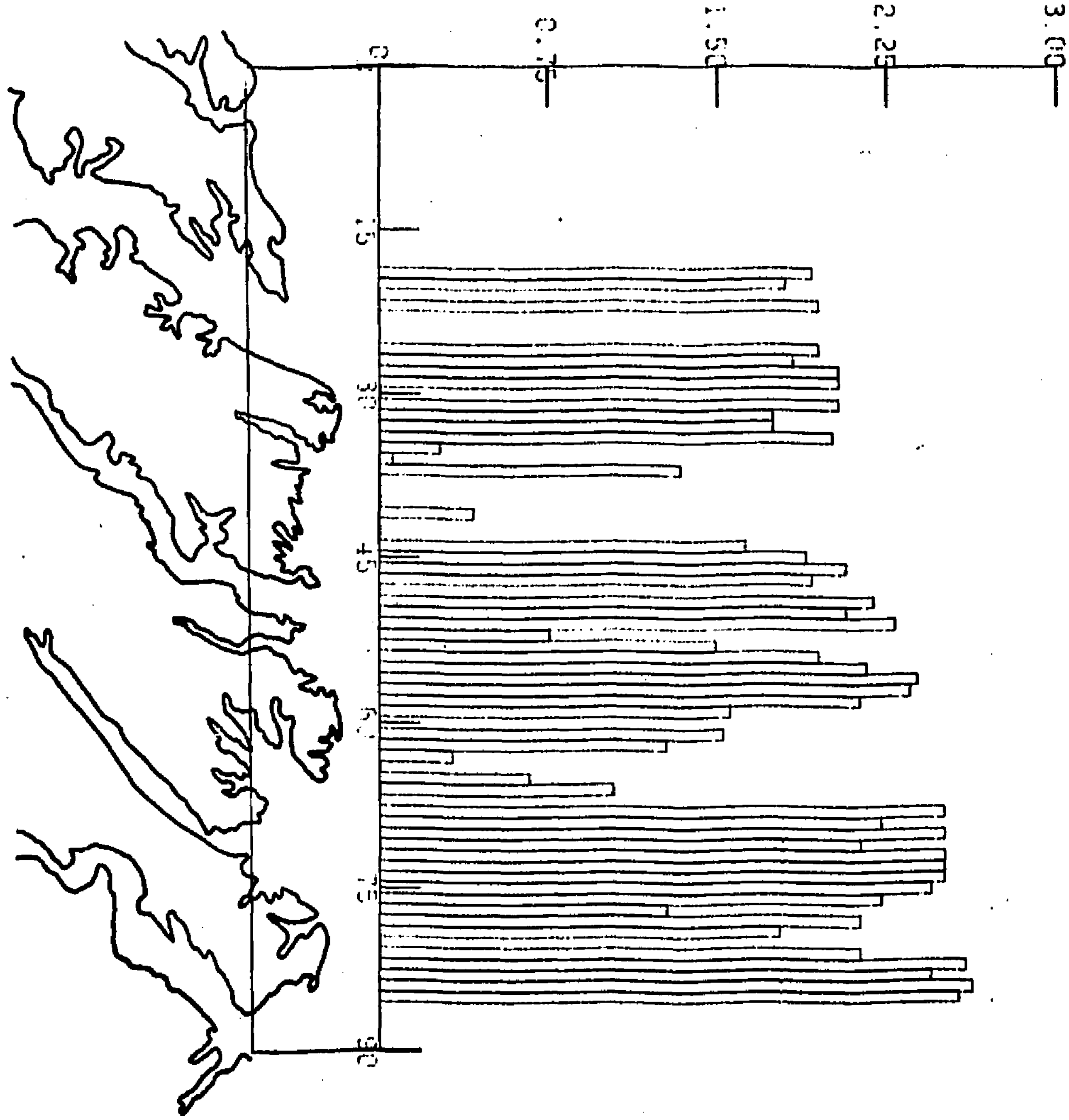
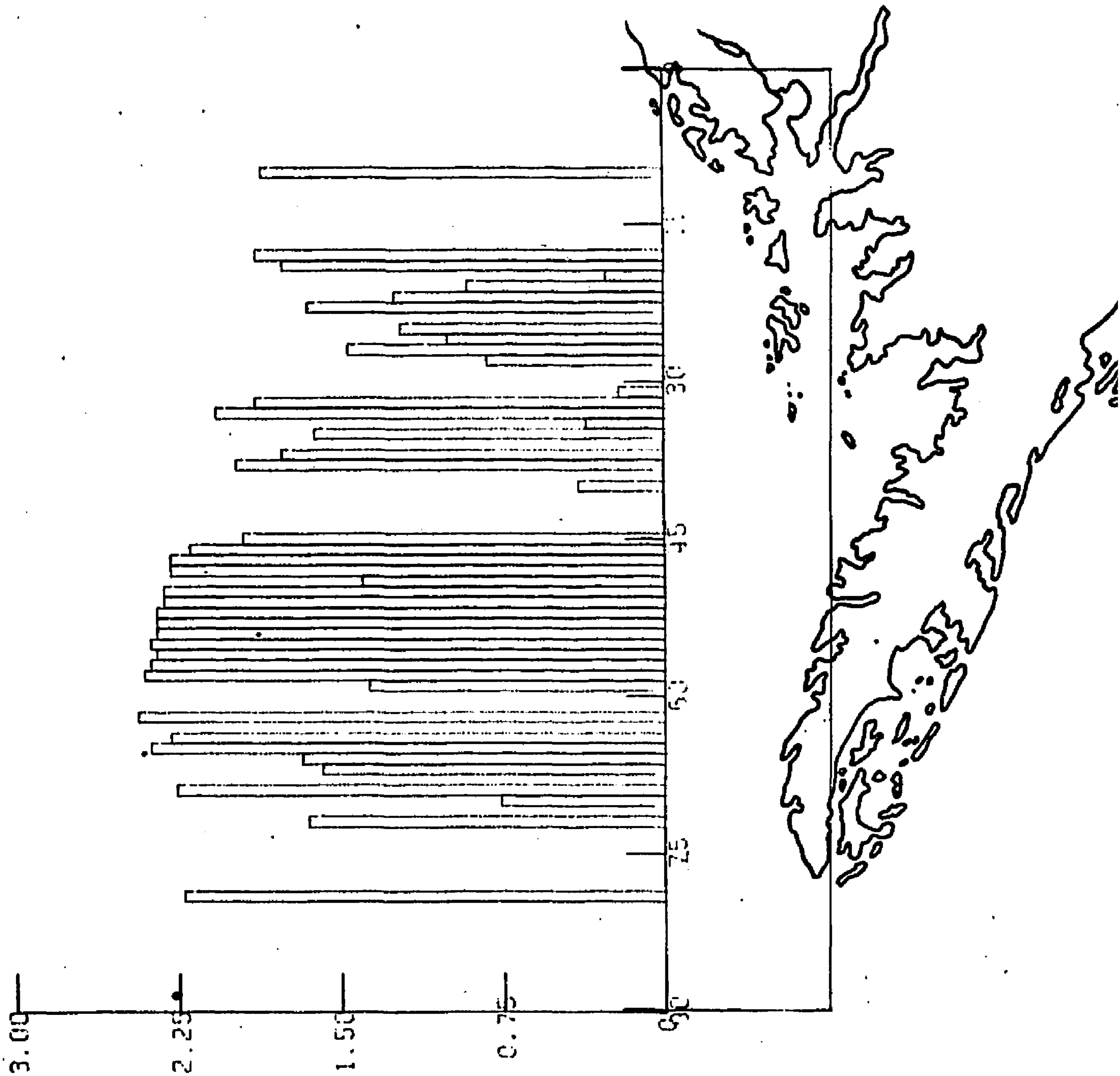



**FIGURE D-52**




WAVE HEIGHT IN METERS
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 0 DEG
LOWER CHES BAY WIND= 25 KTS
EASTERN SHORE

FIGURE D-53

SOUTHERN SHORE
LOWER CHES BAY WIND- 25 KTS
TIDE- 0 AZ- 0 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

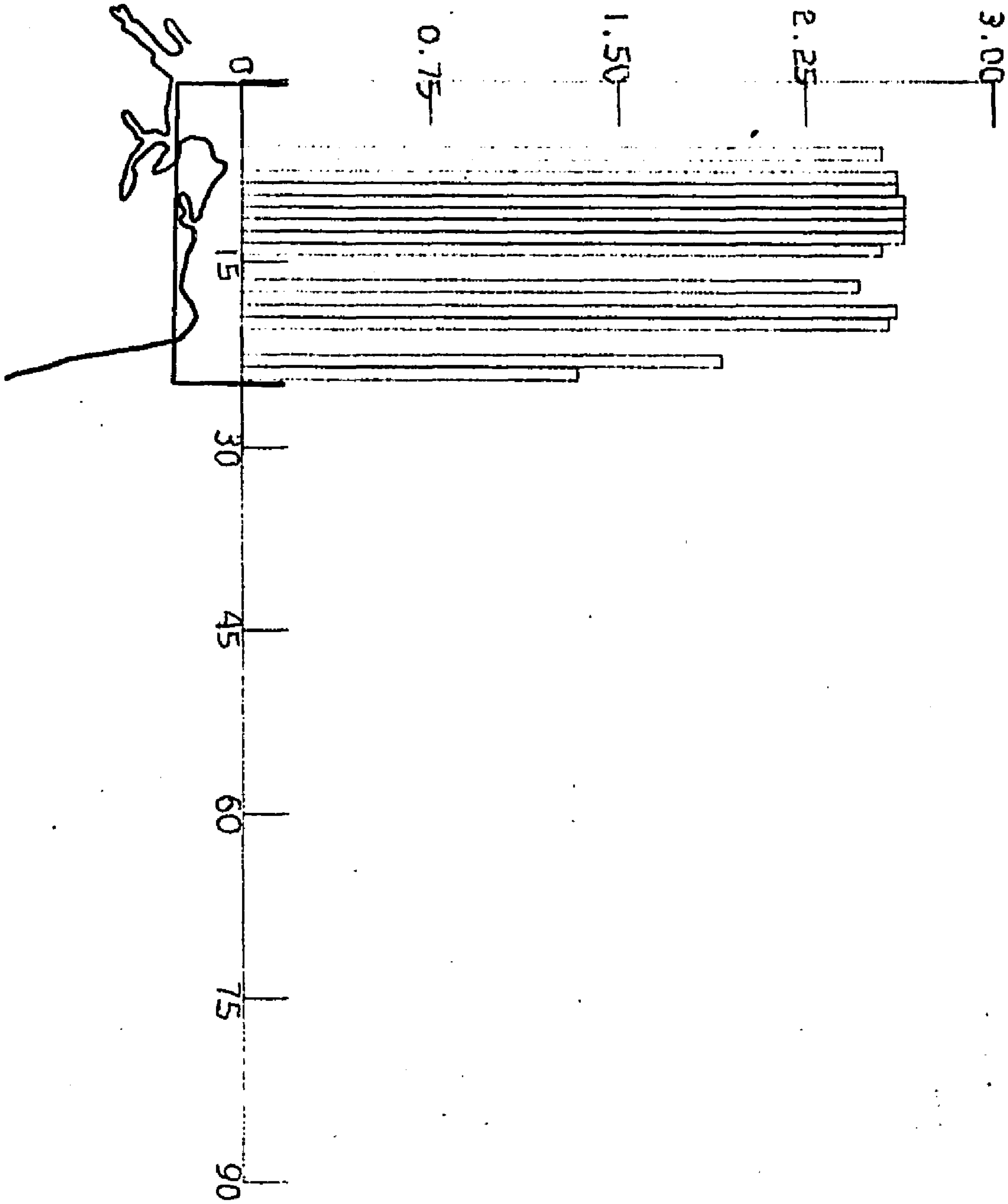



FIGURE D-54

WESTERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= +4 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

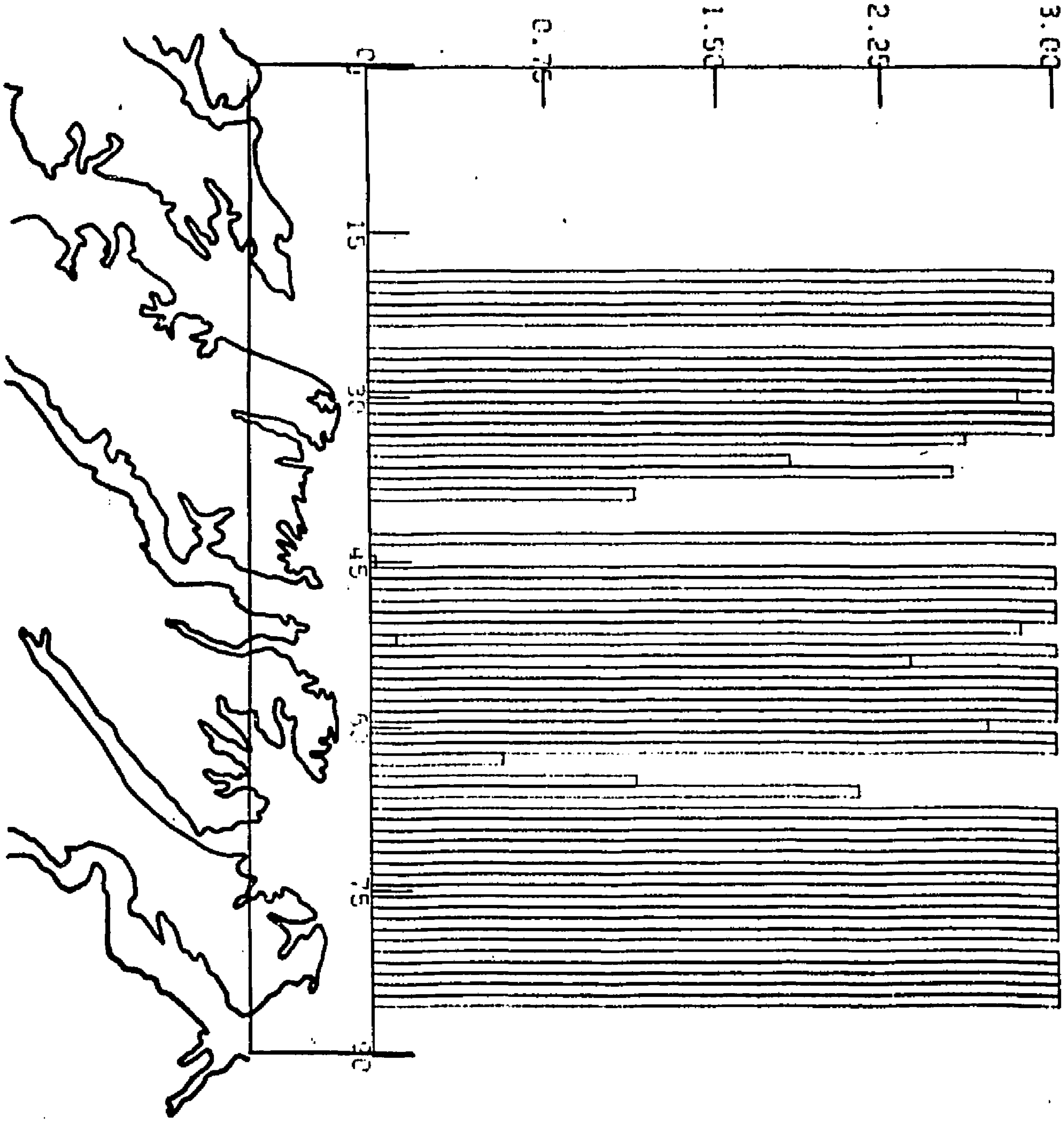
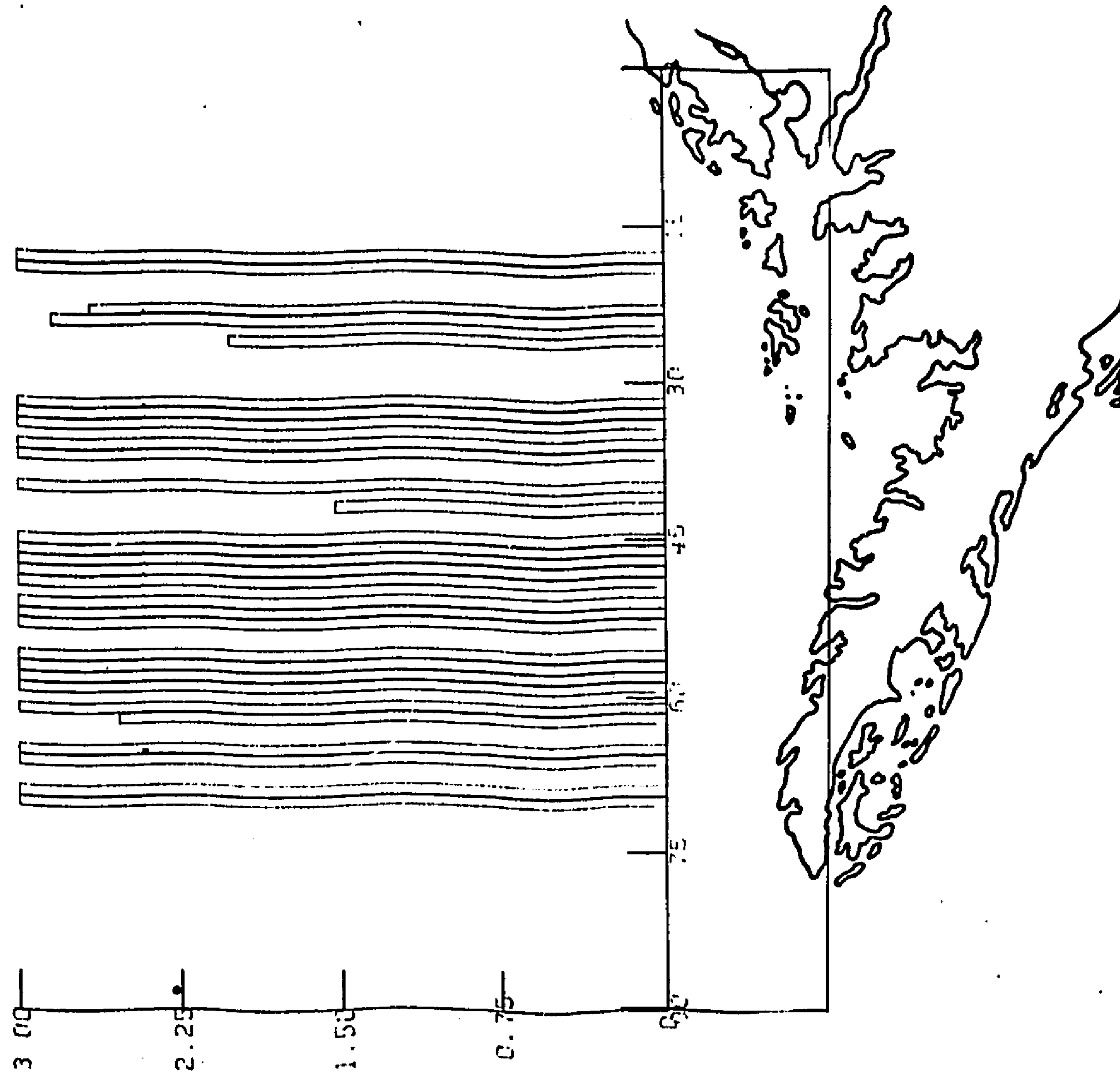



**FIGURE D-55**




WAVE HEIGHT IN METERS
X AXIS IN NAUTICAL MILES.
TIDE= +4 AZ= 0 DEG
LOWER CHES BAY WIND= 40 KTS
EASTERN SHORE

**FIGURE D-56**

SOUTHERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= +4 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

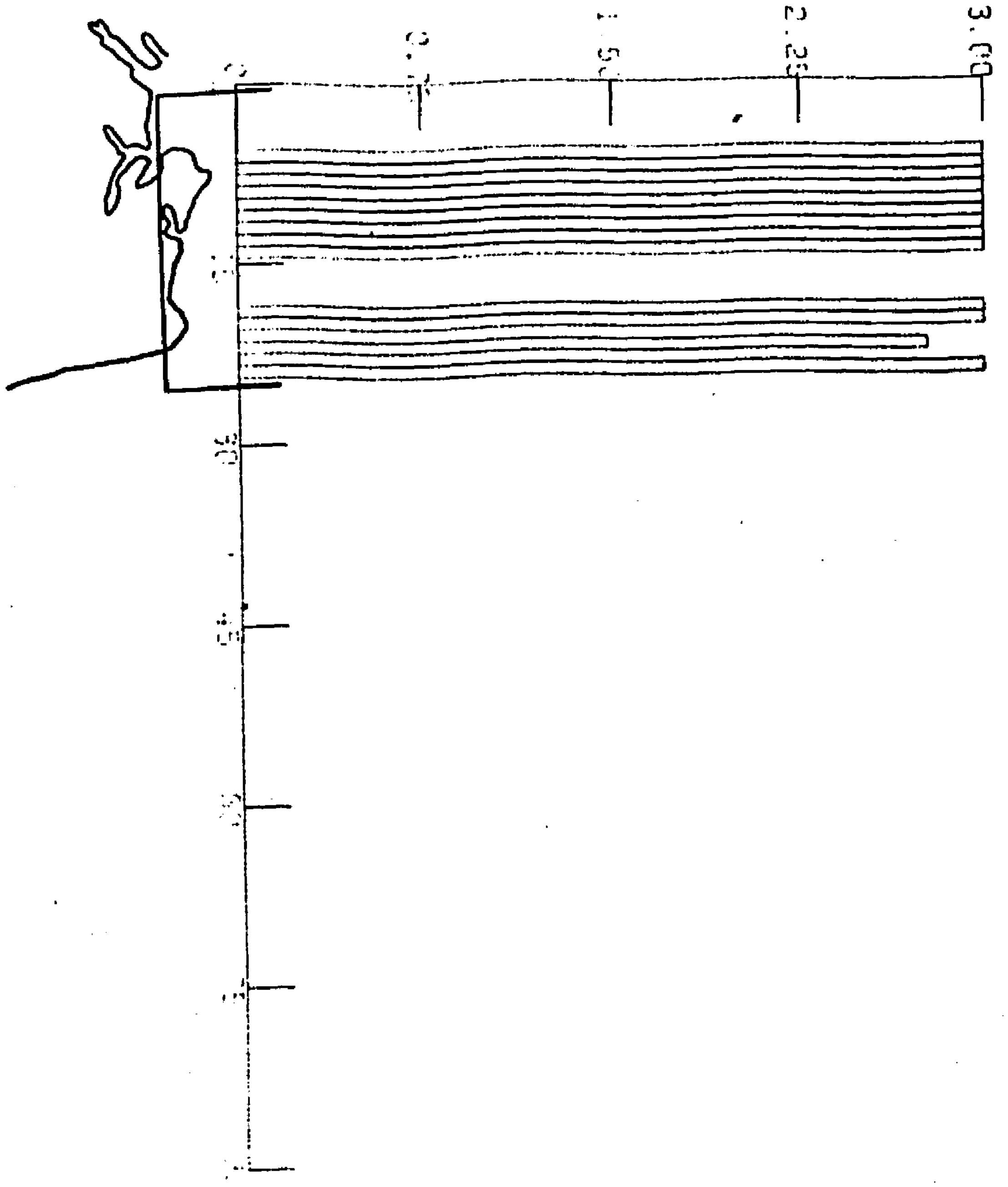



FIGURE D-57

WESTERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

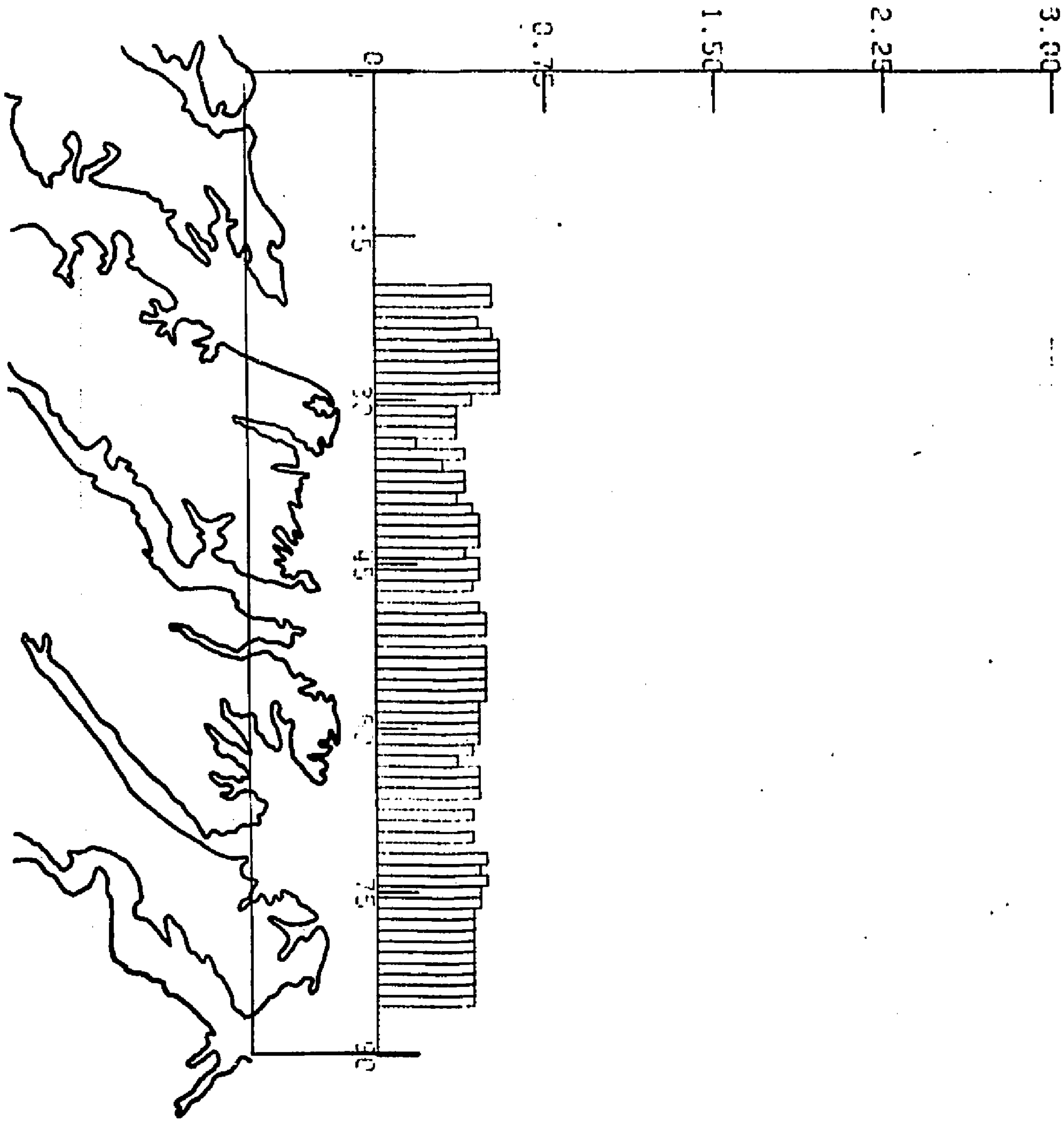



FIGURE D-58

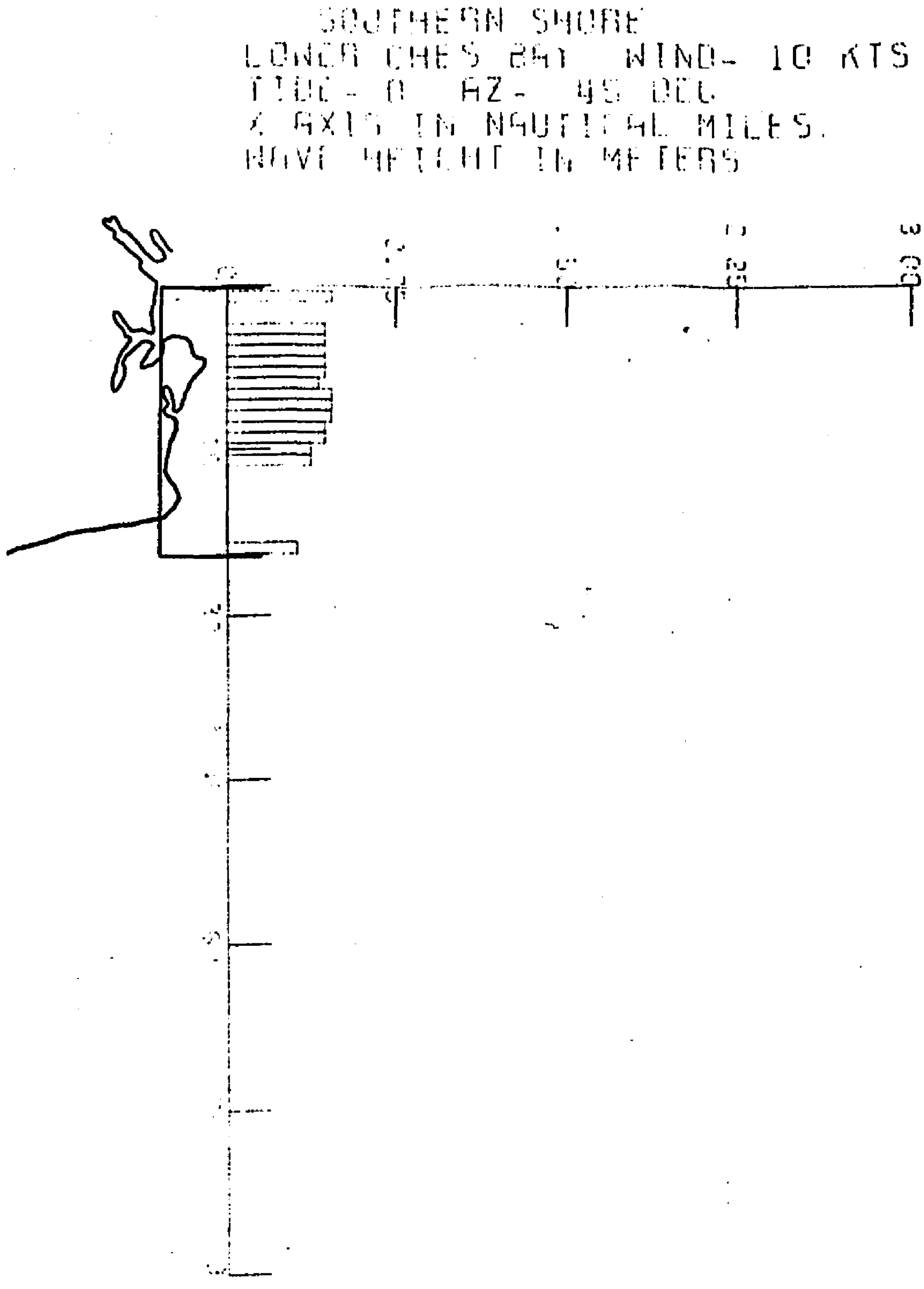

SOUTHERN SHORE
LOWER CHES BAY WIND- 10 KTS
TIDE- 0 AZ- 45 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

FIGURE D-59

WESTERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

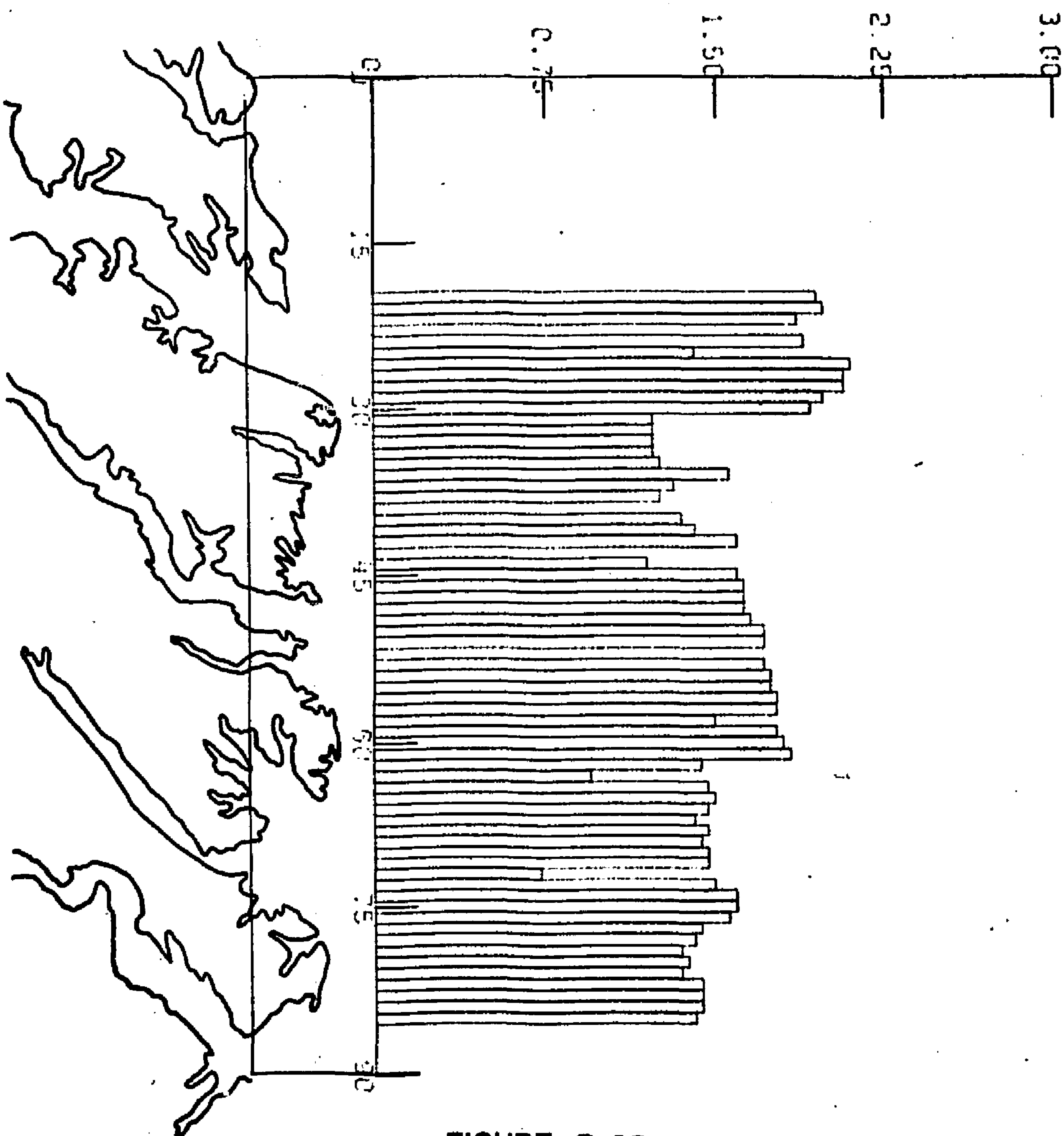



FIGURE D-60

SOUTHERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

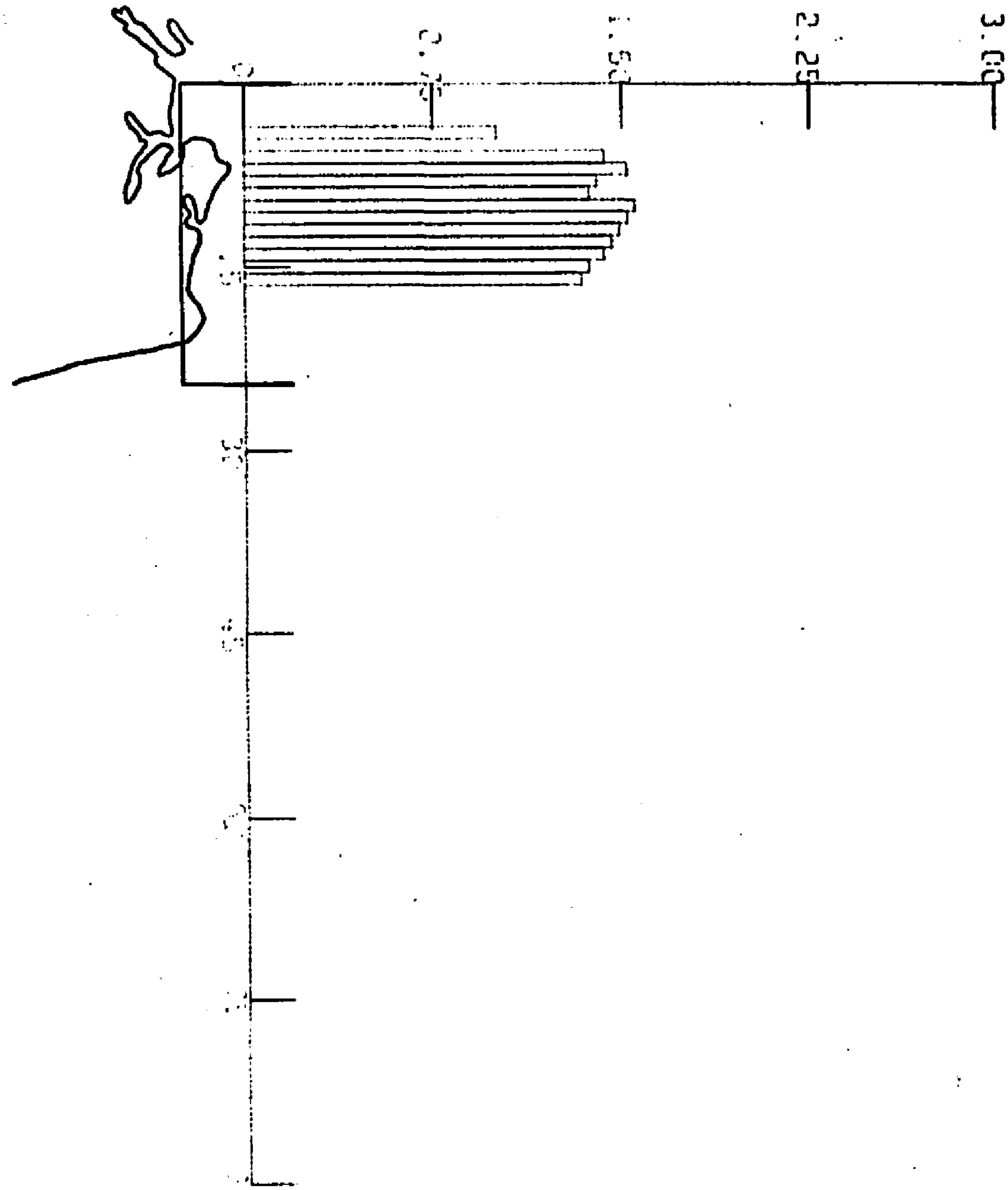



**FIGURE D-61**

WESTERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= 4 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

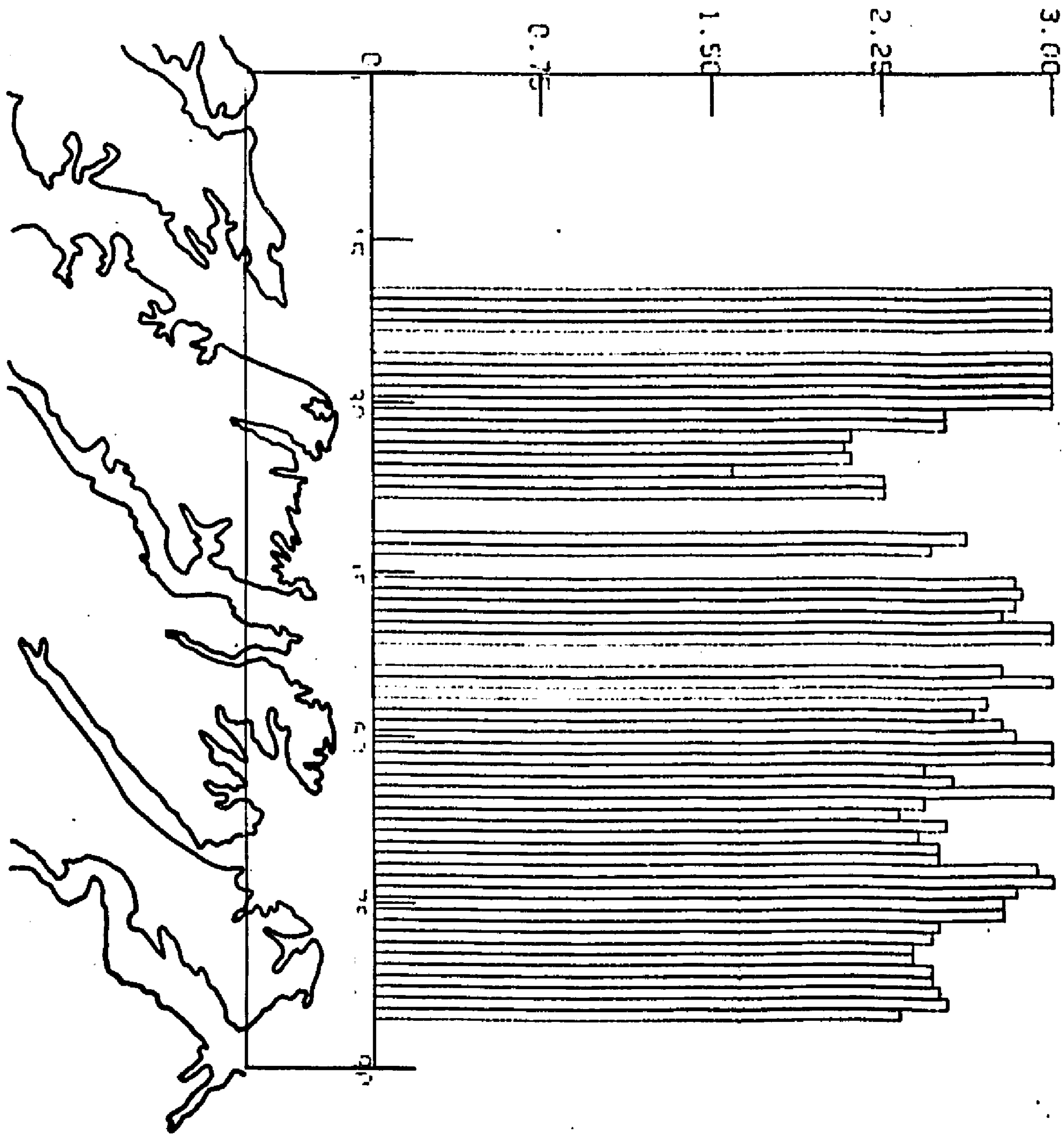



FIGURE D-62

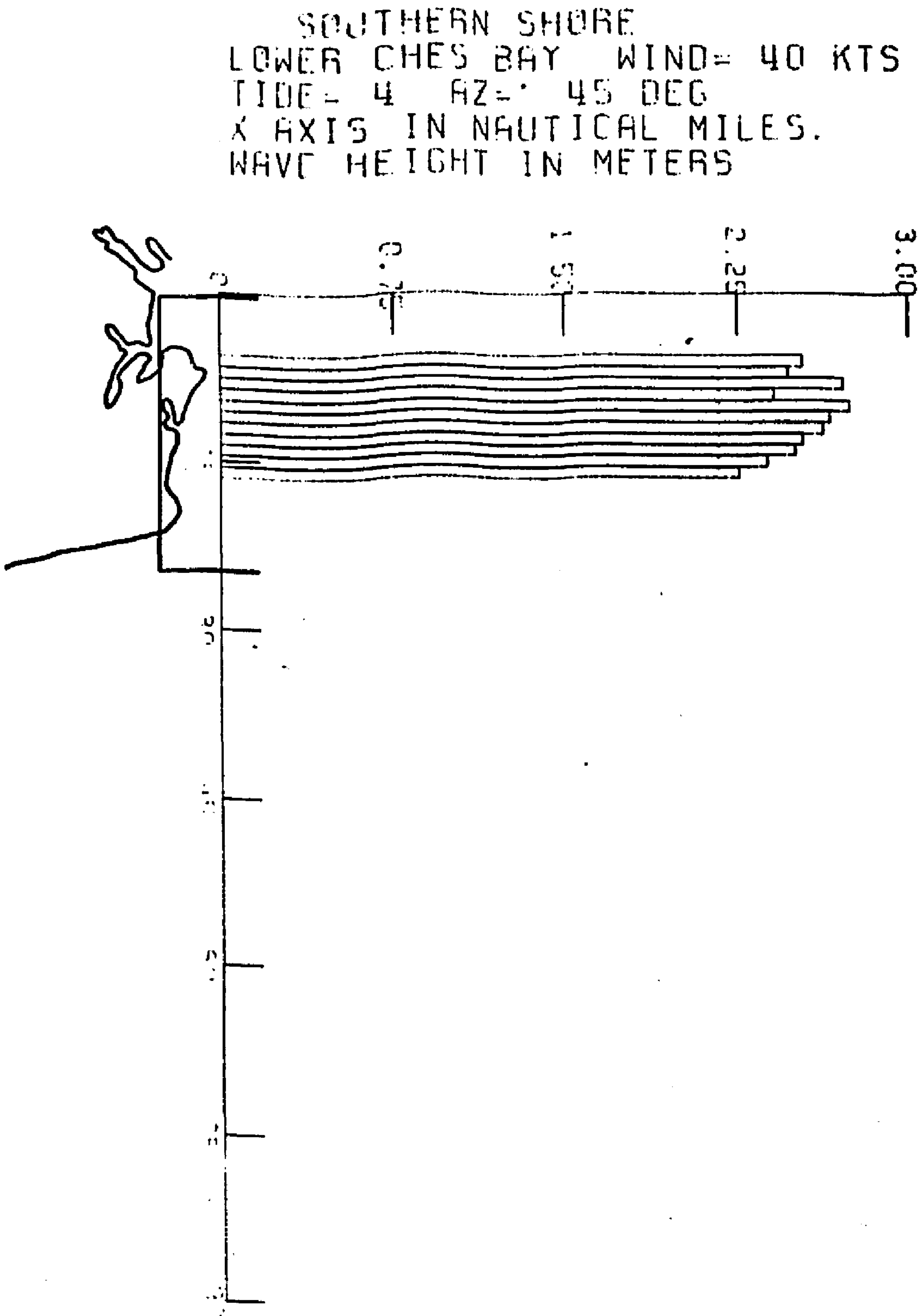
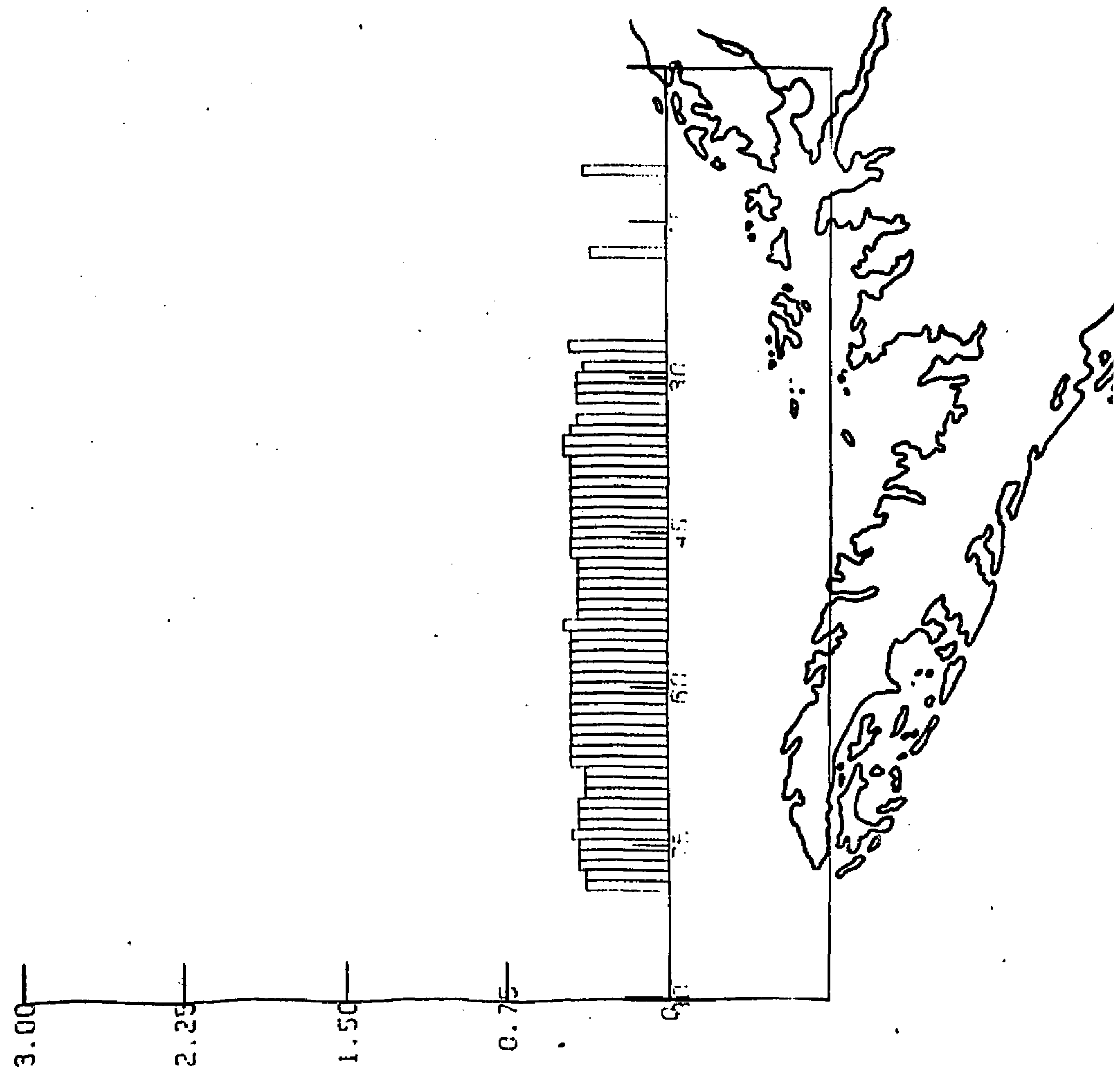
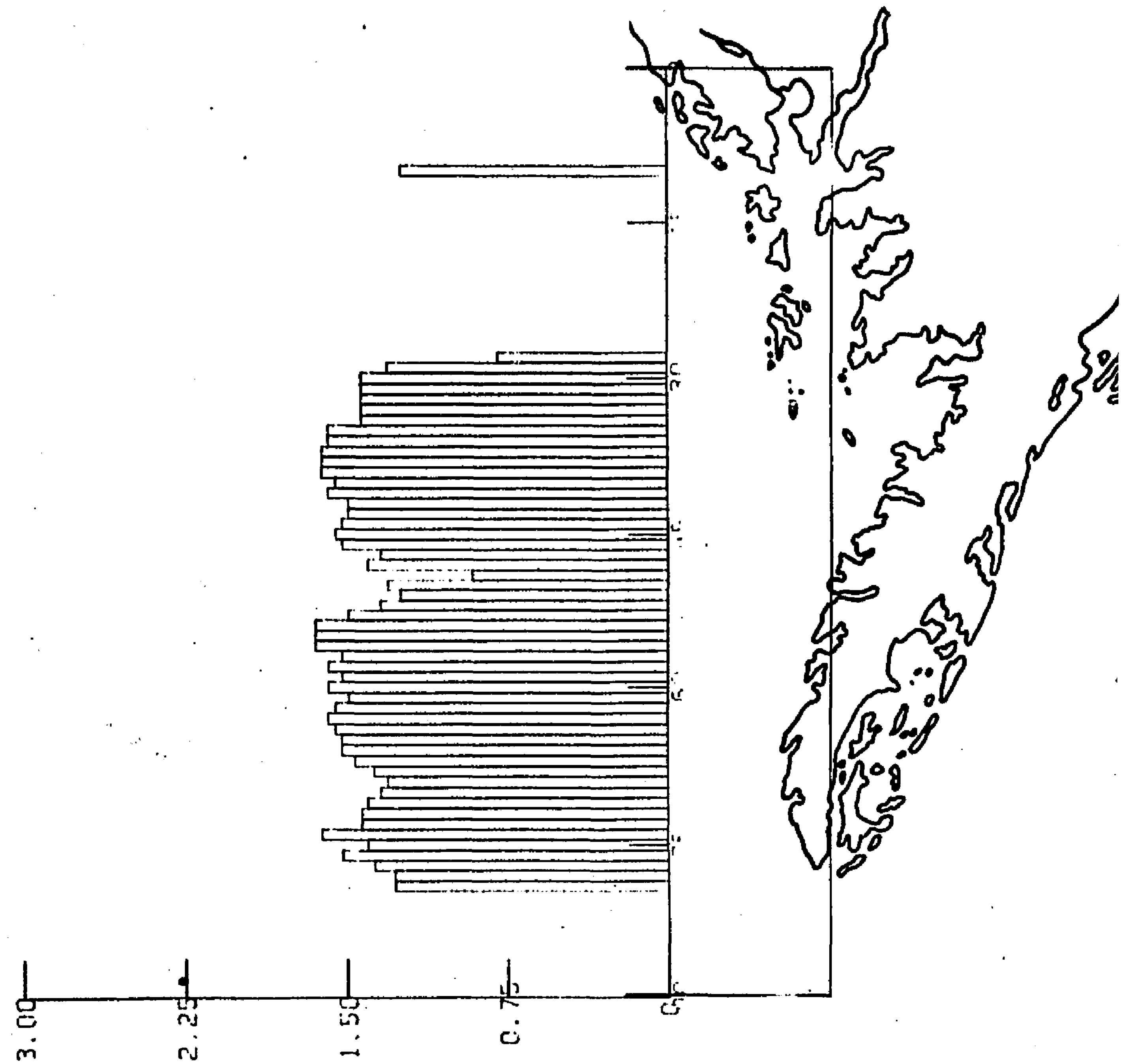

SOUTHERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= 4 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS
1.50
2.25
3.00

FIGURE D-63



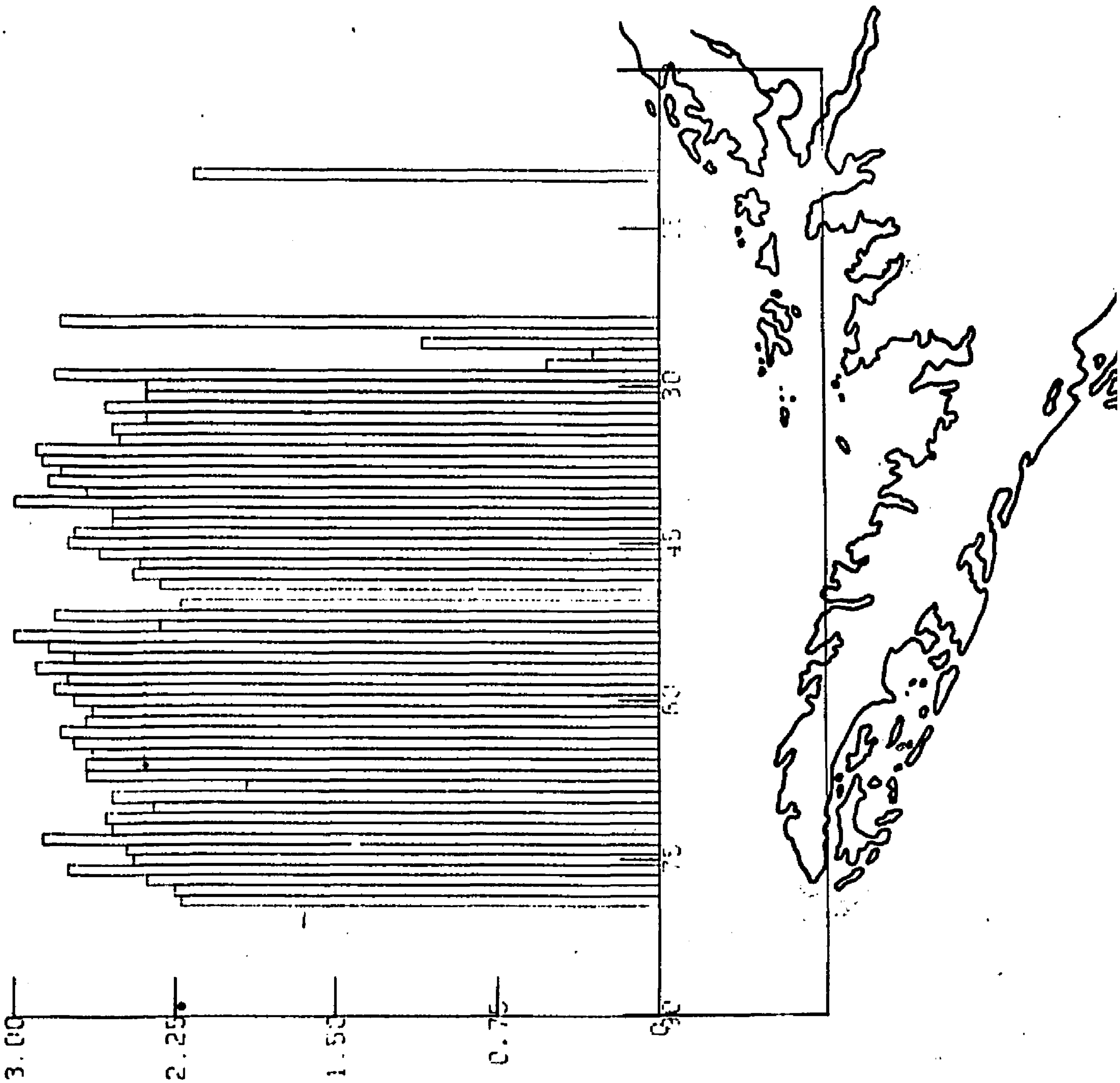

WAVE HEIGHT IN METERS
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 225 DEG
LOWER CHES BAY WIND= 10 KTS
EASTERN SHORE

FIGURE D-64



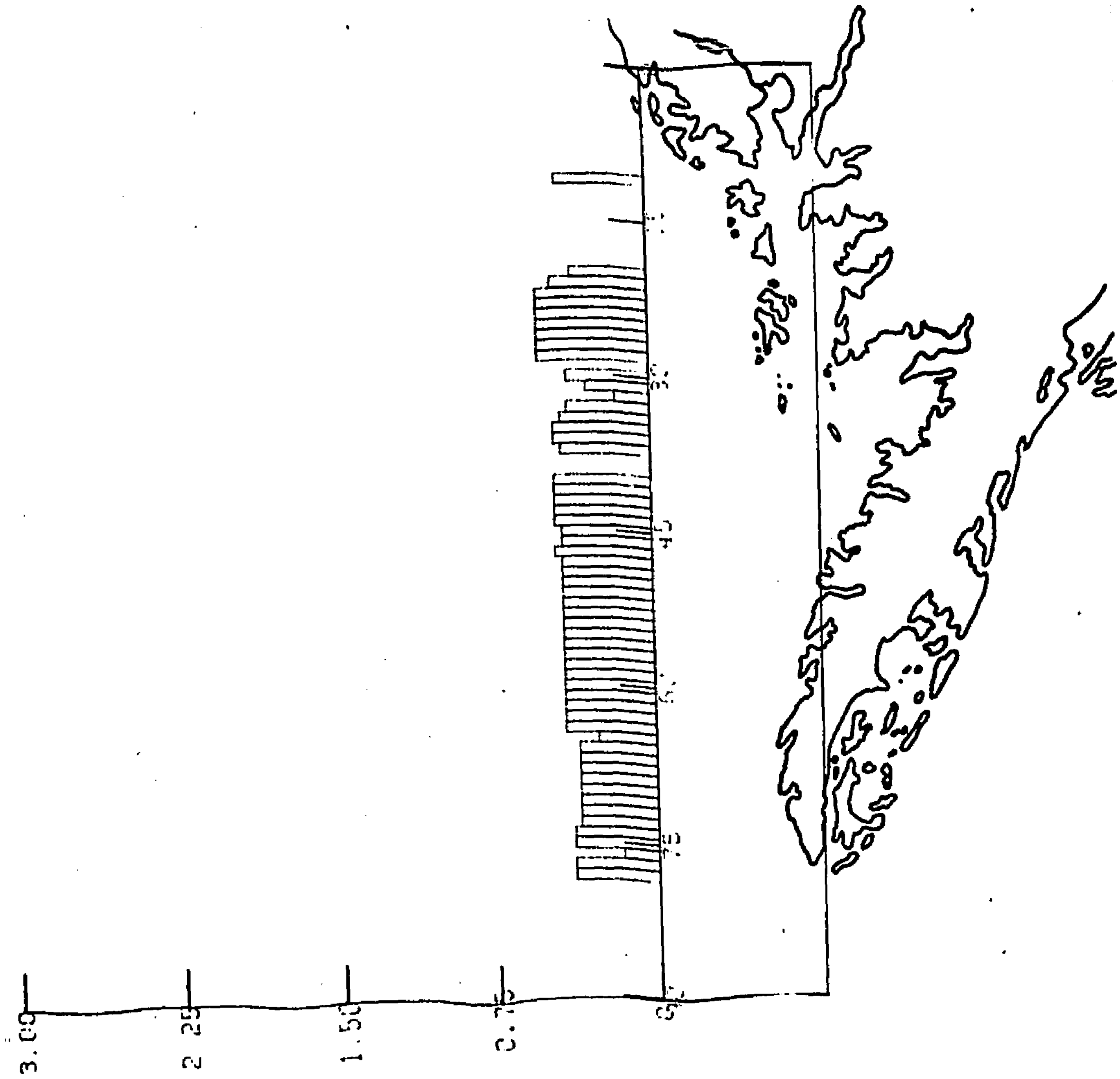

WAVE HEIGHT IN METERS
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 225 DEG
LOWER CHES BAY WIND= 25 KTS
EASTERN SHORE

FIGURE D-65




WAVE HEIGHT IN METERS
X AXIS IN NAUTICAL MILES.
TIDE= 4 AZ= 225 DEG
LOWER CHES BAY WIND= 40 KTS
EASTERN SHORE

FIGURE D-66




WAVE HEIGHT IN METERS
X AXIS IN NAUTICAL MILES.
TIDE= 0  AZ= 315 DEG
LOWER CHES BAY  WIND= 10 KTS
EASTERN SHORE

FIGURE D-67

SOUTHERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 315 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

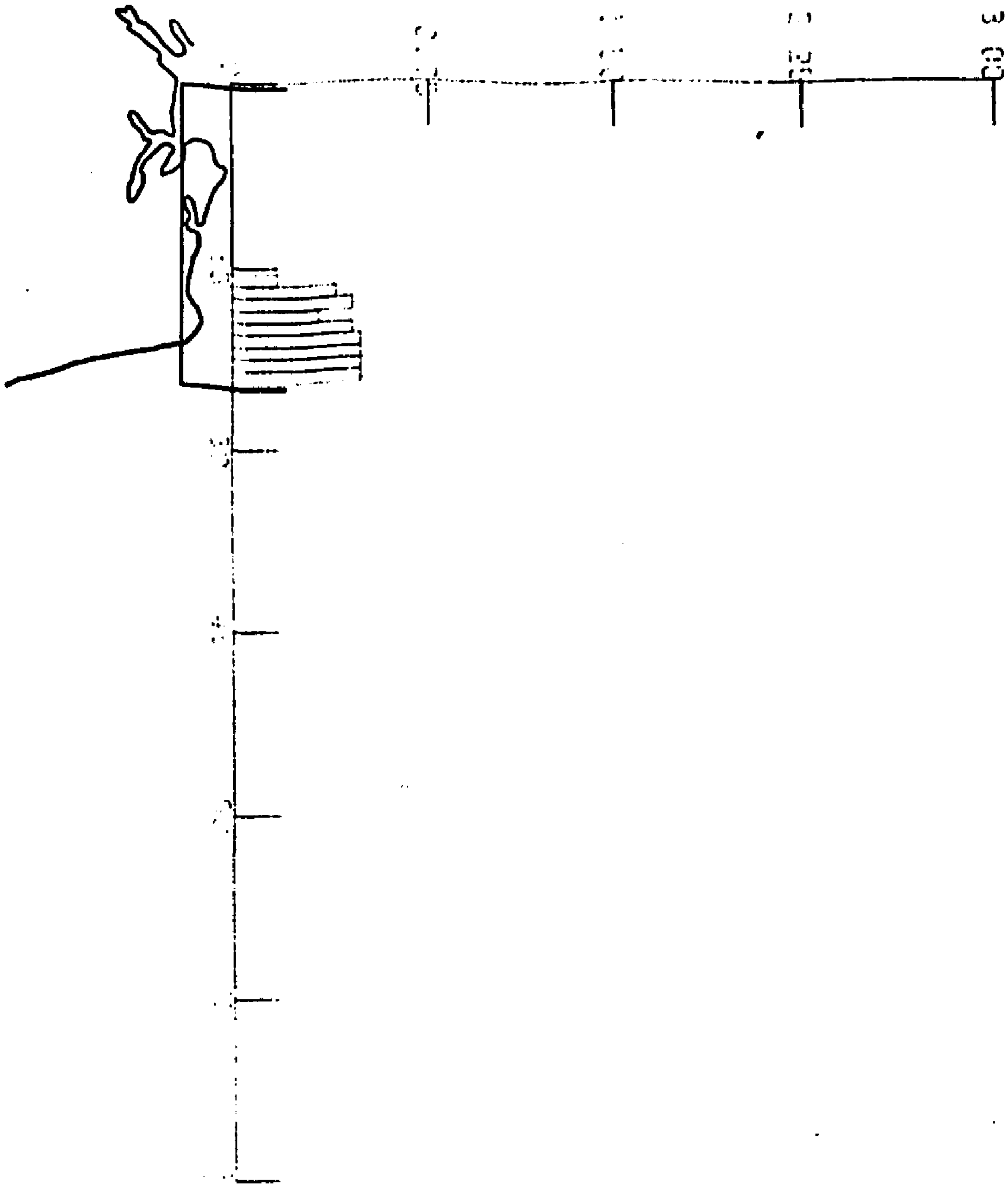


FIGURE D-68


WAVE HEIGHT IN METERS
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 315 DEG
LOWER CHES BAY WIND= 25 KTS
EASTERN SHORE

FIGURE D-69

SOUTHERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 315 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

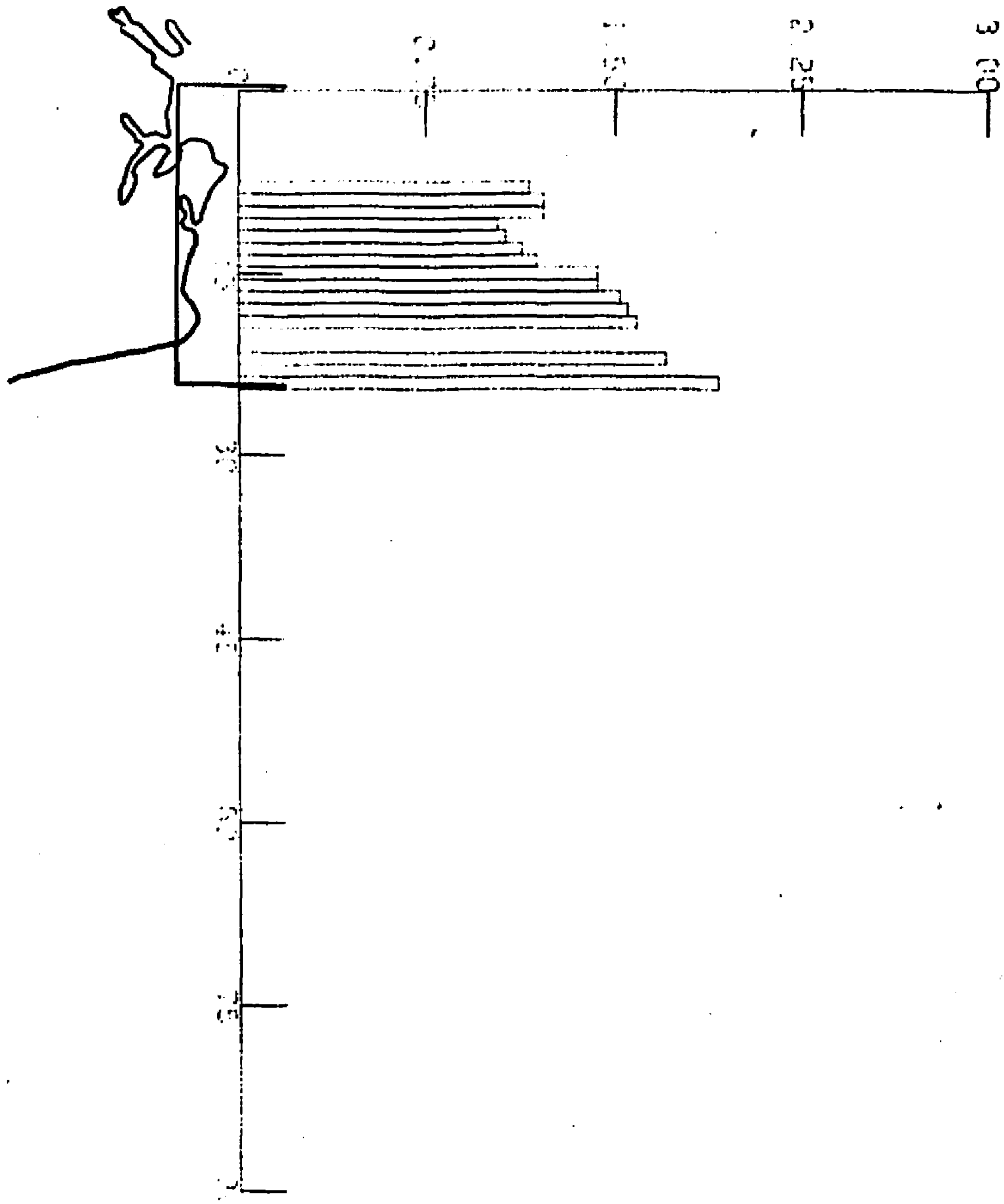
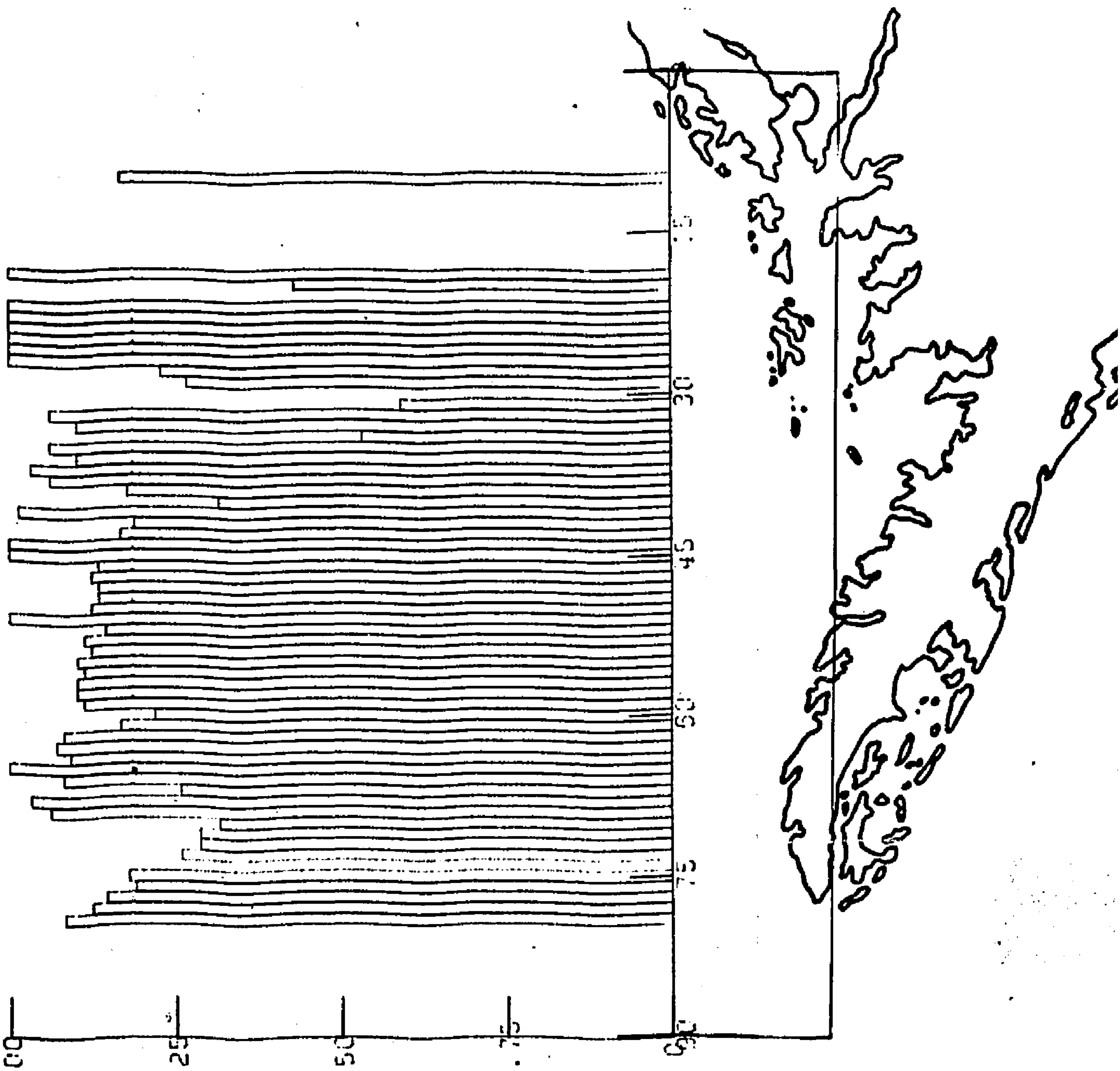


FIGURE D-70




WAVE HEIGHT IN METERS
X AXIS IN NAUTICAL MILES.
TIDE= 4 AZ= 315 DEG
LOWER CHES BAY WIND= 40 KTS
EASTERN SHORE

FIGURE D-71

SOUTHERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= 4 AZ= 315 DEG
X AXIS IN NAUTICAL MILES.
WAVE HEIGHT IN METERS

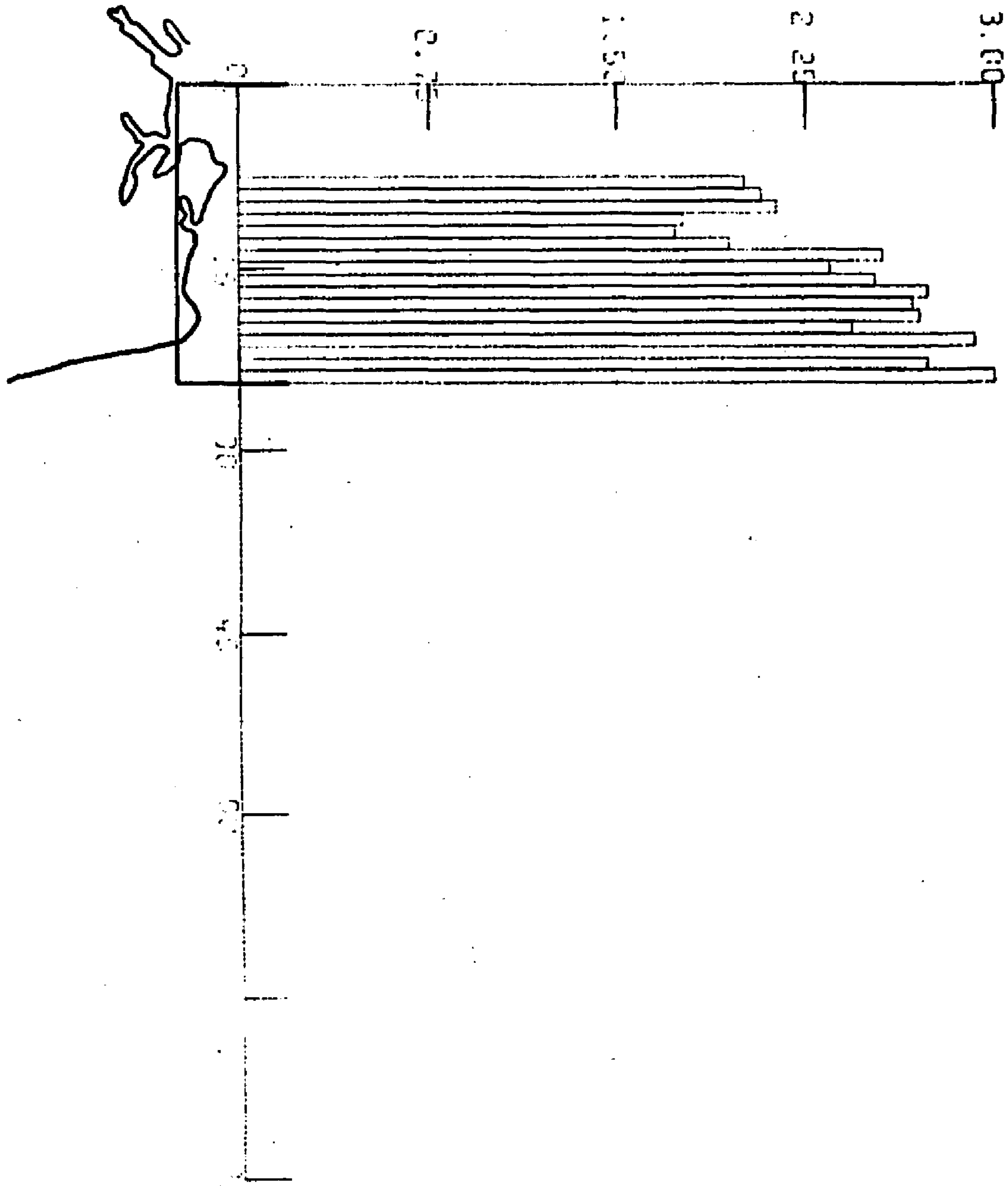



FIGURE D-72

WESTERN SHORE
LOWER CHES BAY   WIND= 10 KTS
TIDE= 0   AZ=   0 DEG
X AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES

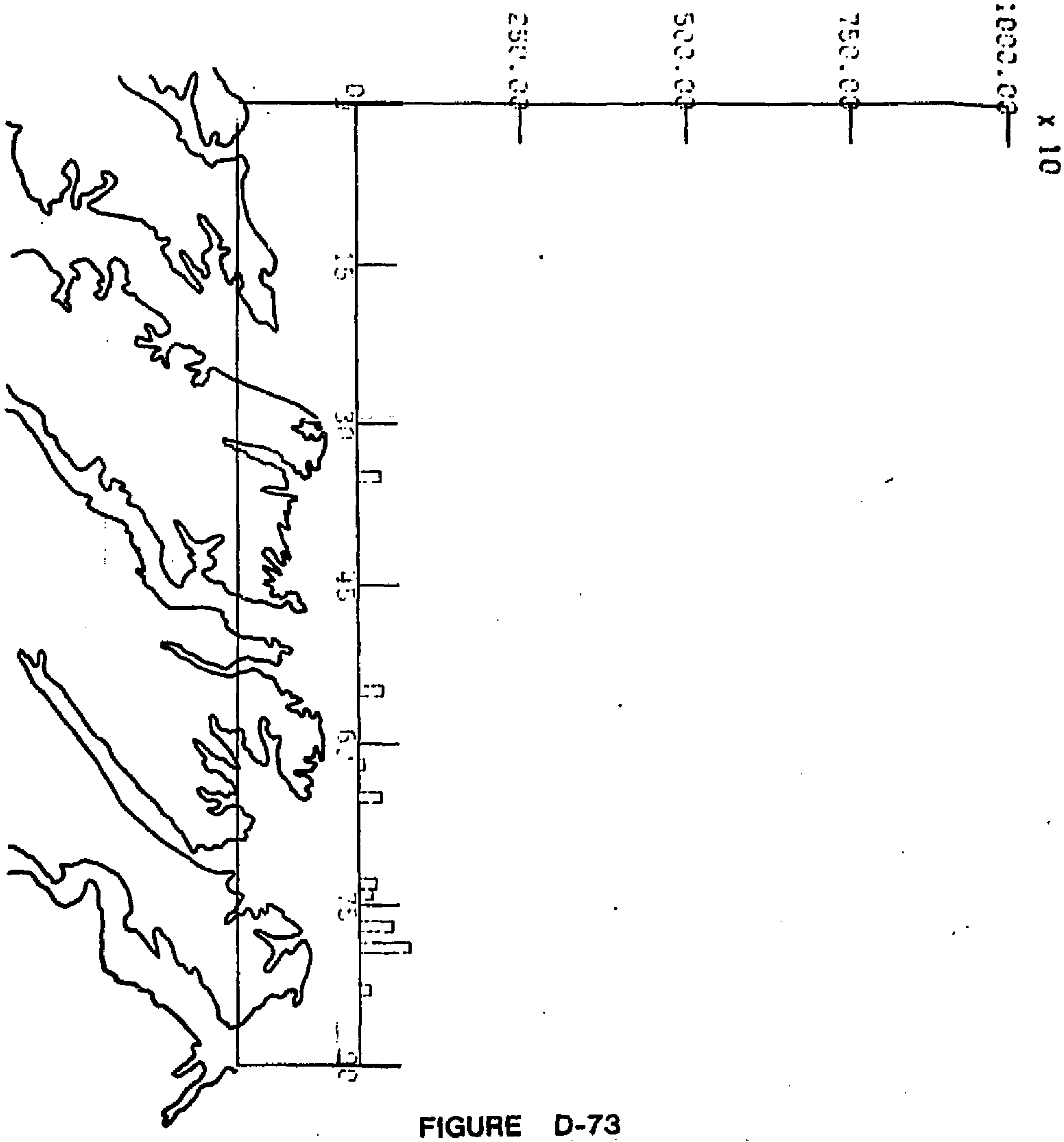
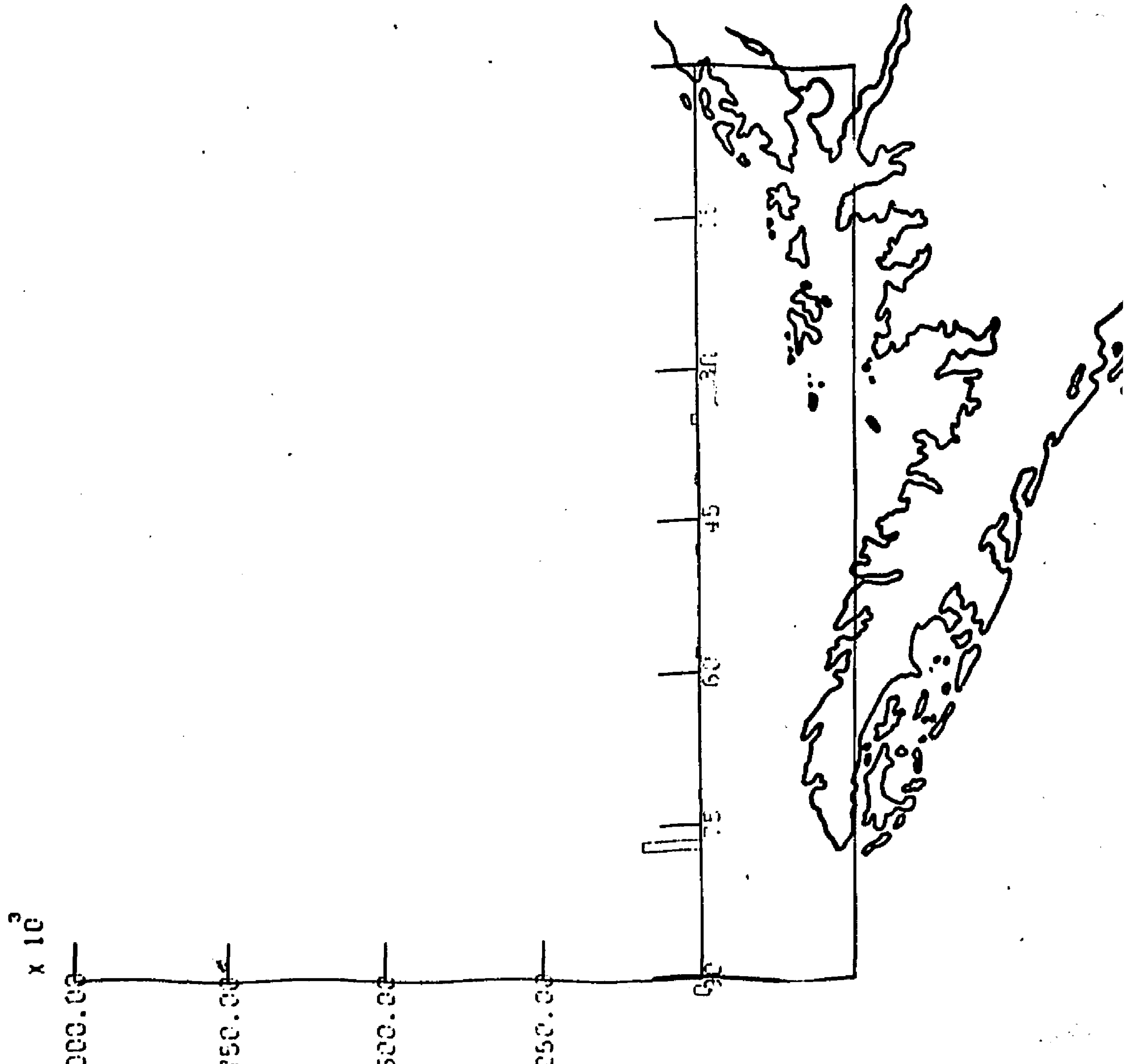



FIGURE D-73




ENERGY TOTAL IN JOULES
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 0 DEG
LOWER CHES BAY WIND= 10 KTS
EASTERN SHORE

FIGURE D-74

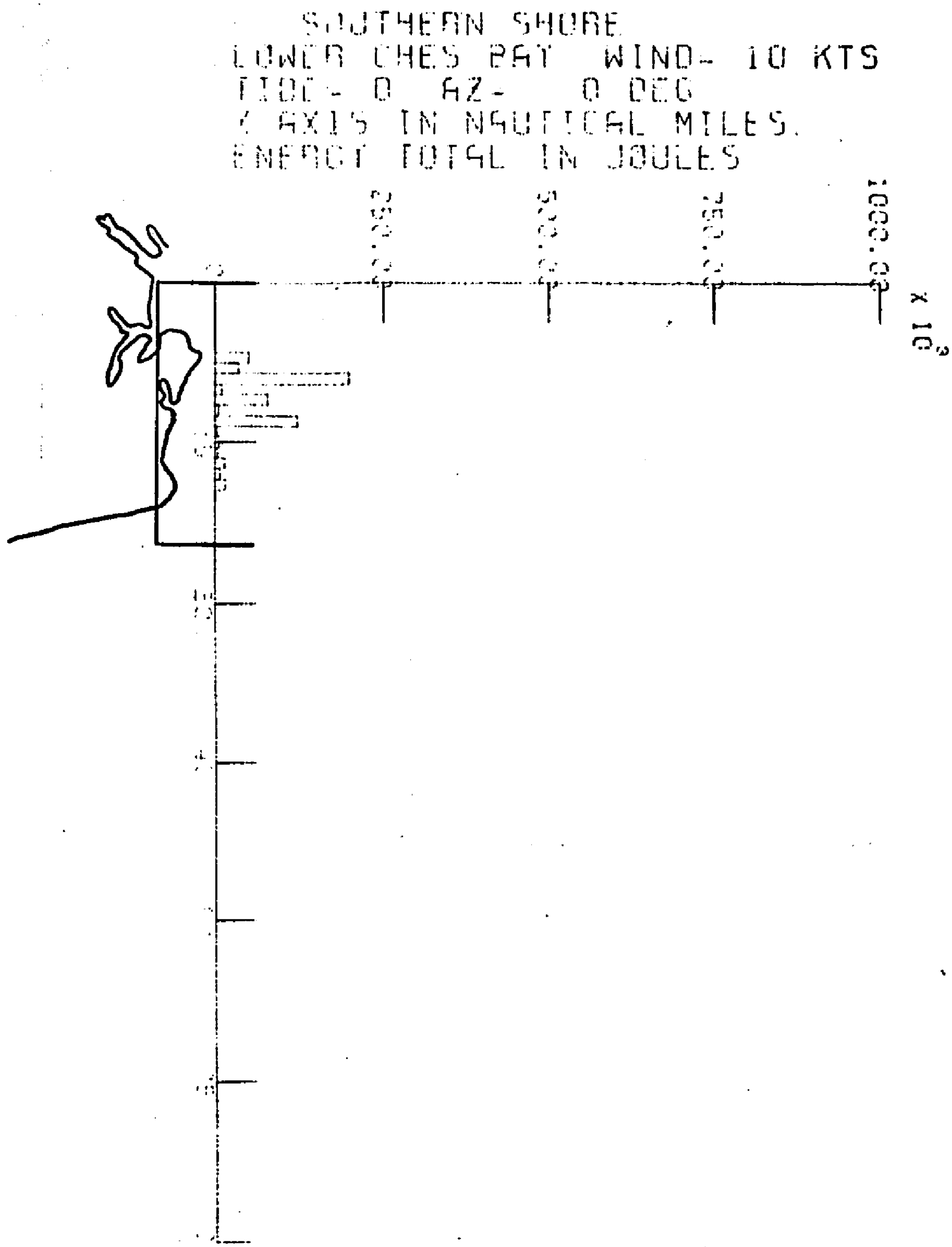

SOUTHERN SHORE
LOWER CHES BAY WIND- 10 KTS
TIDE- 0 AZ- 0 DEG
Y AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES
250.00
500.00
750.00
1000.00
x 10³

FIGURE D-75

WESTERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES

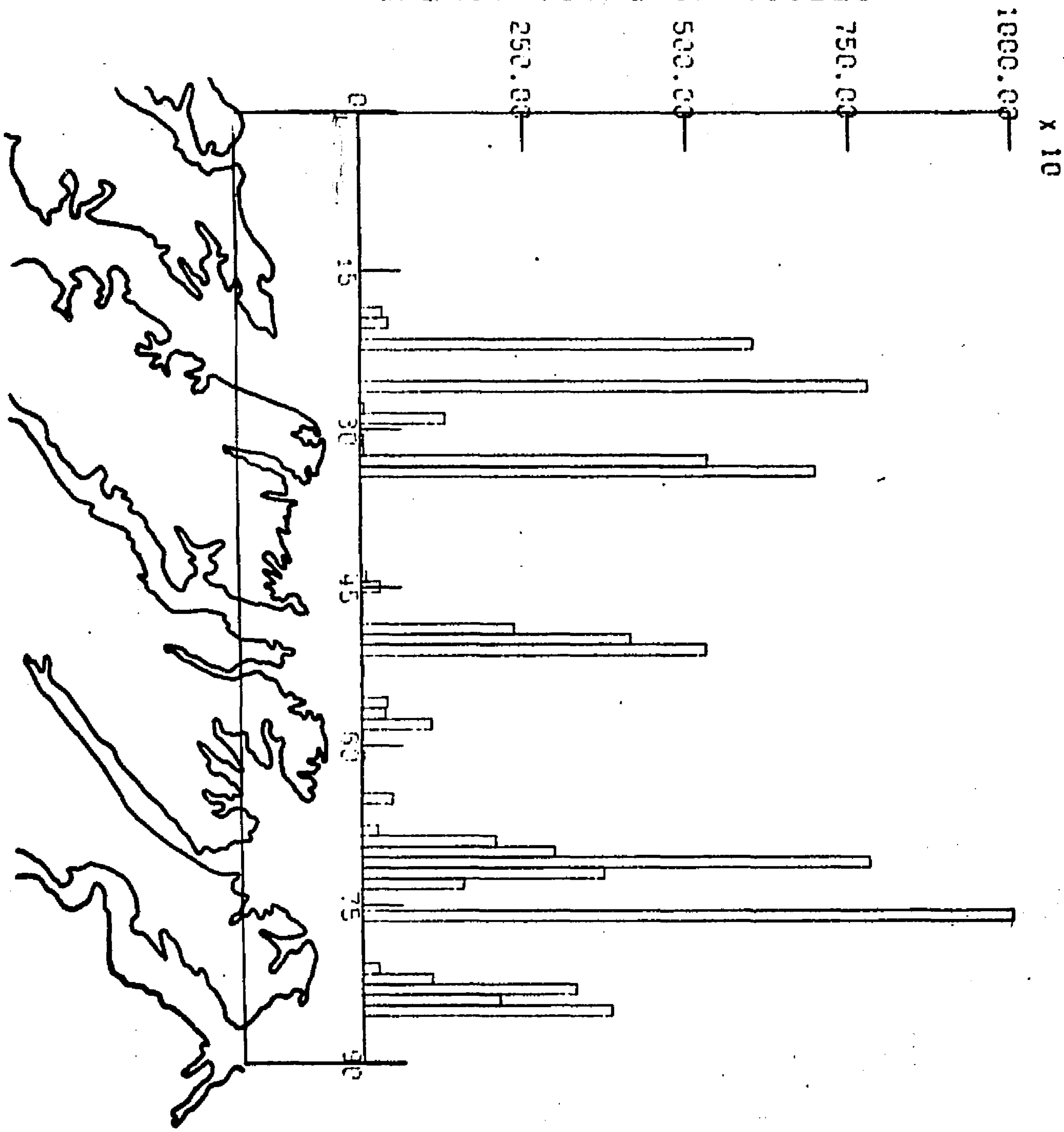
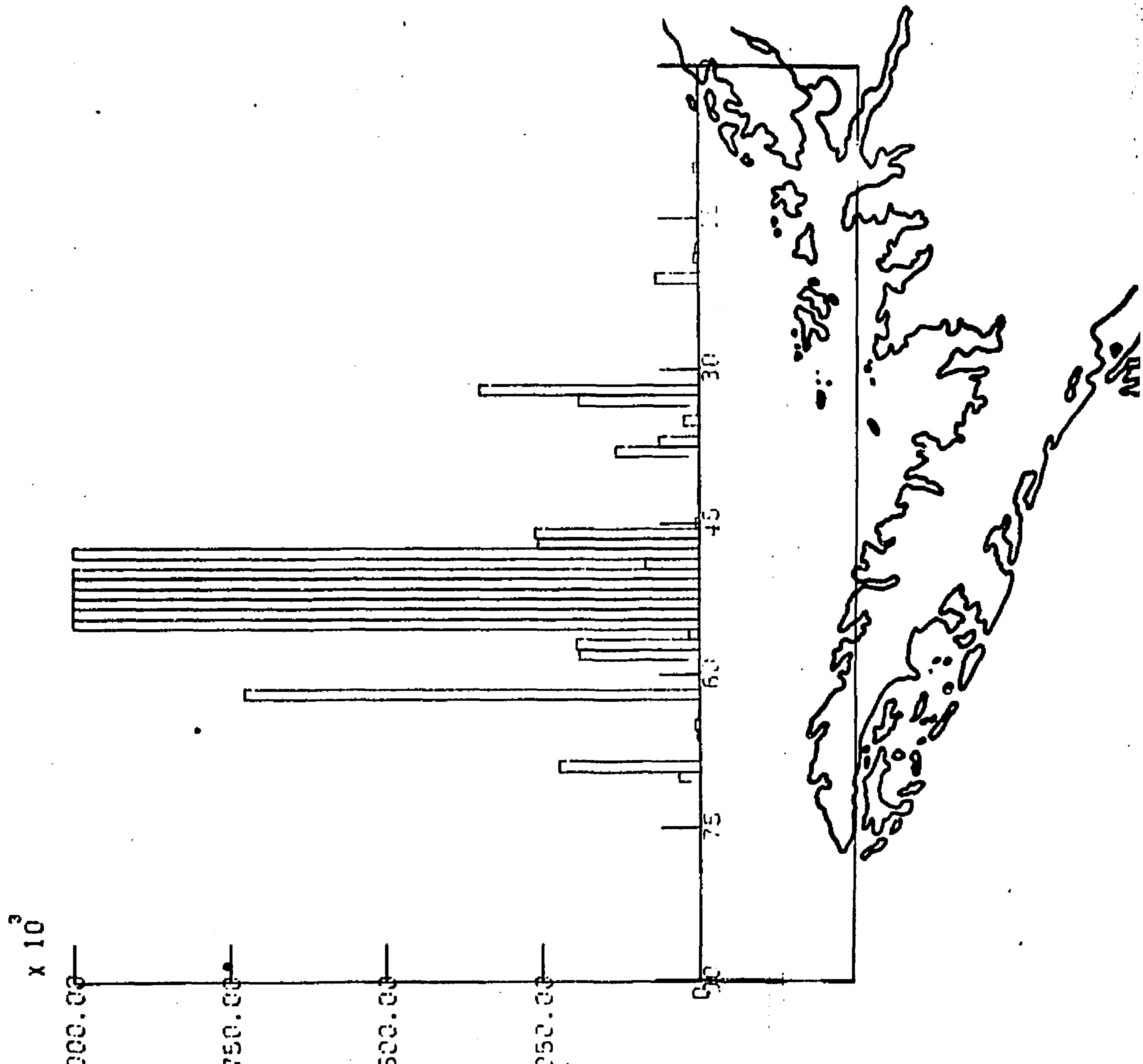



**FIGURE D-76**




ENERGY TOTAL IN JOULES
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 0 DEG
LOWER CHES BAY WIND= 25 KTS
EASTERN SHORE

FIGURE D-77

SOUTHERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 0 DEG
X AXIS IN NAUTICAL MILES
ENERGY TOTAL IN JOULES

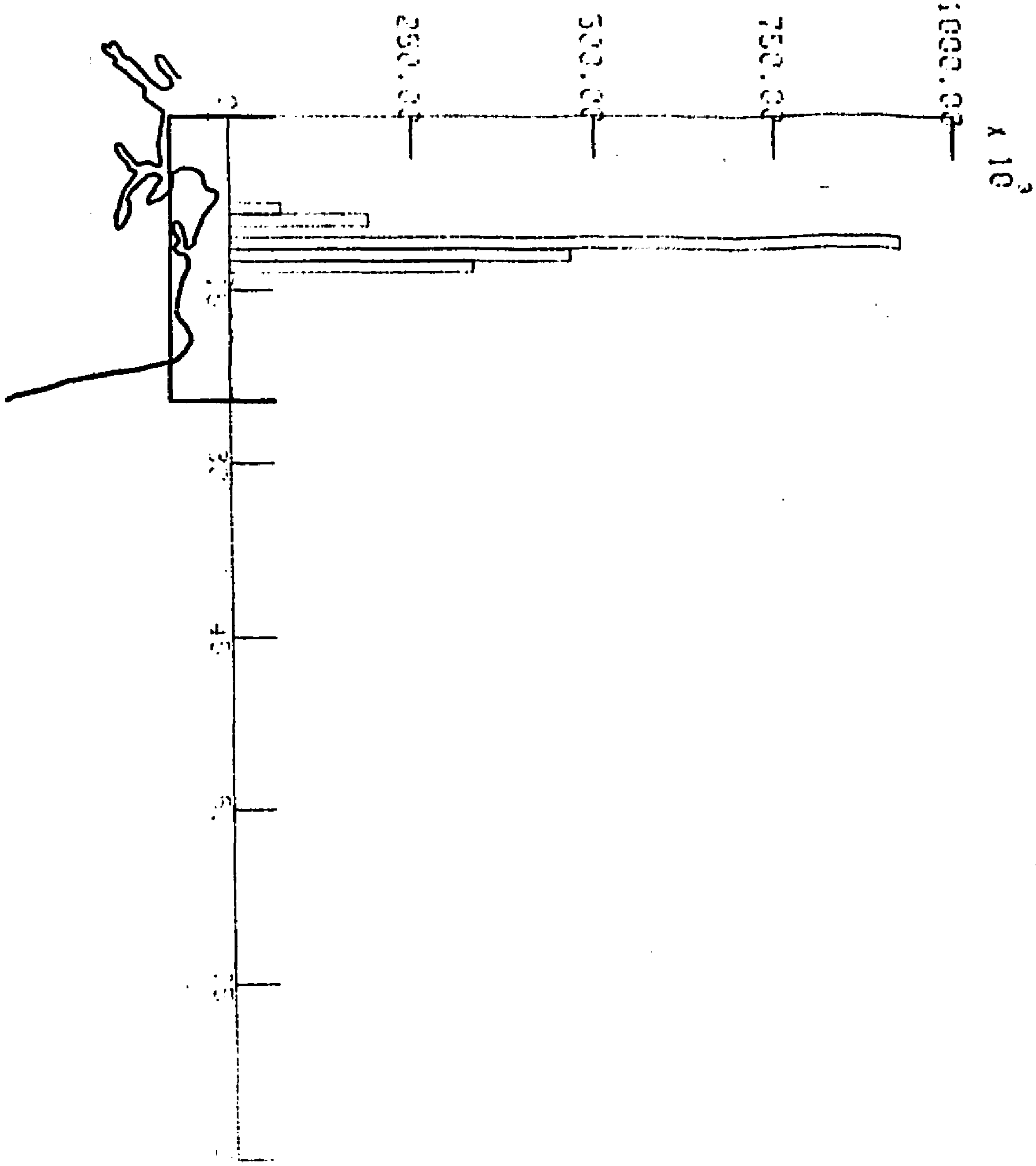



FIGURE D-78

WESTERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= +4 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES

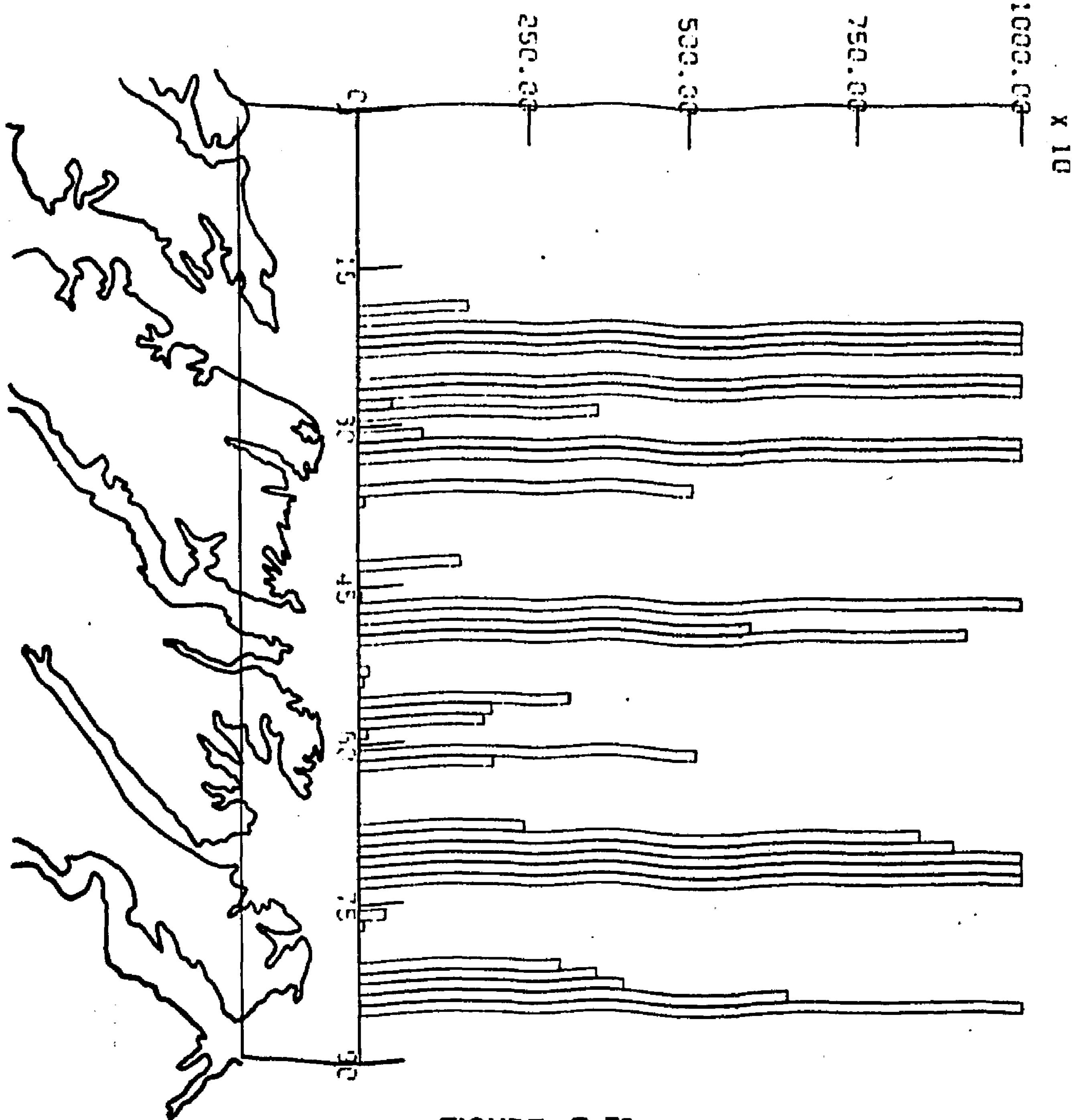
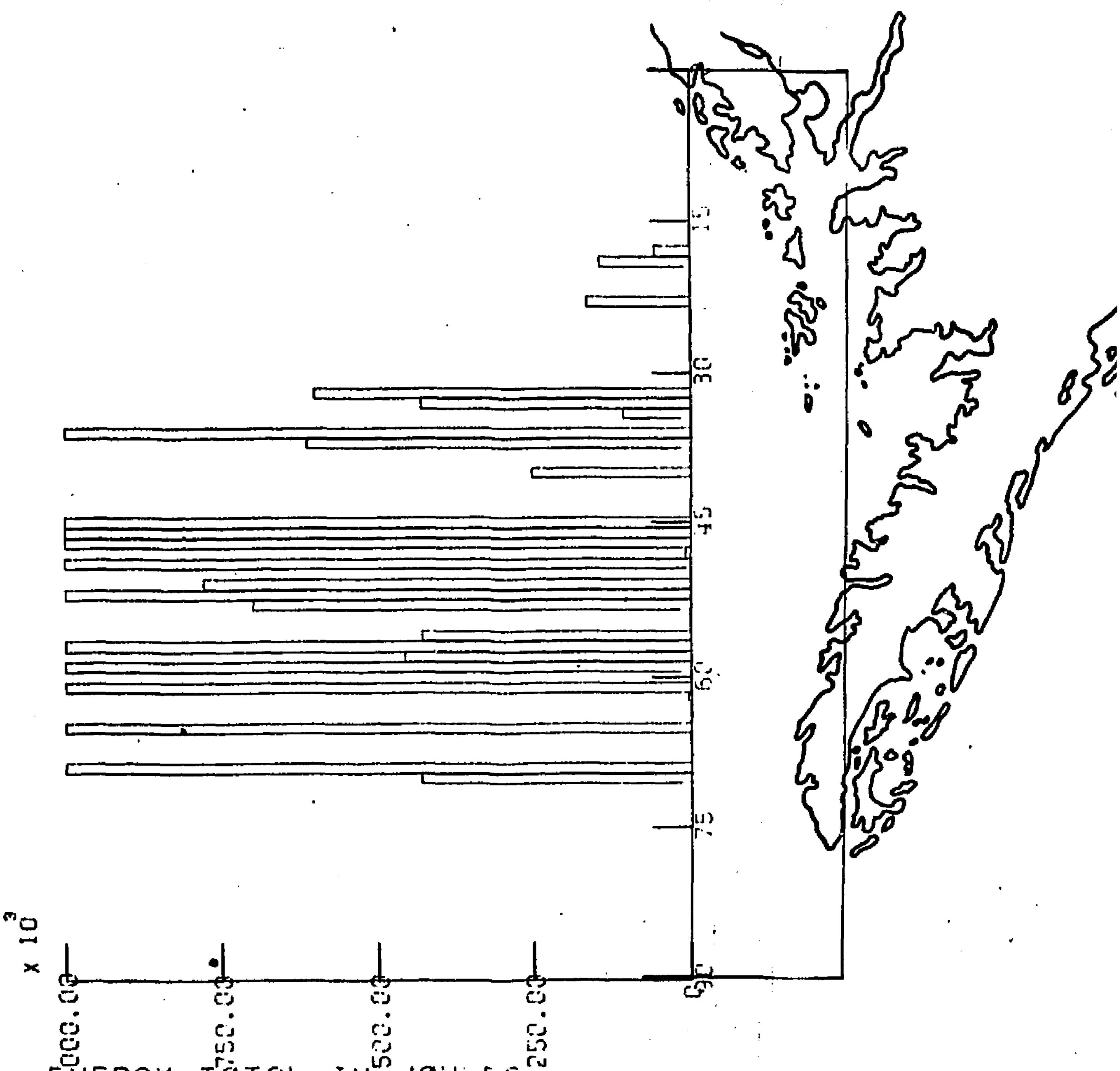



FIGURE D-79




ENERGY TOTAL IN JOULES
X AXIS IN NAUTICAL MILES.
TIDE= +4 AZ= 0 DEG
LOWER CHES BAY WIND= 40 KTS
EASTERN SHORE

FIGURE D-80

SOUTHERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= +4 AZ= 0 DEG
X AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES

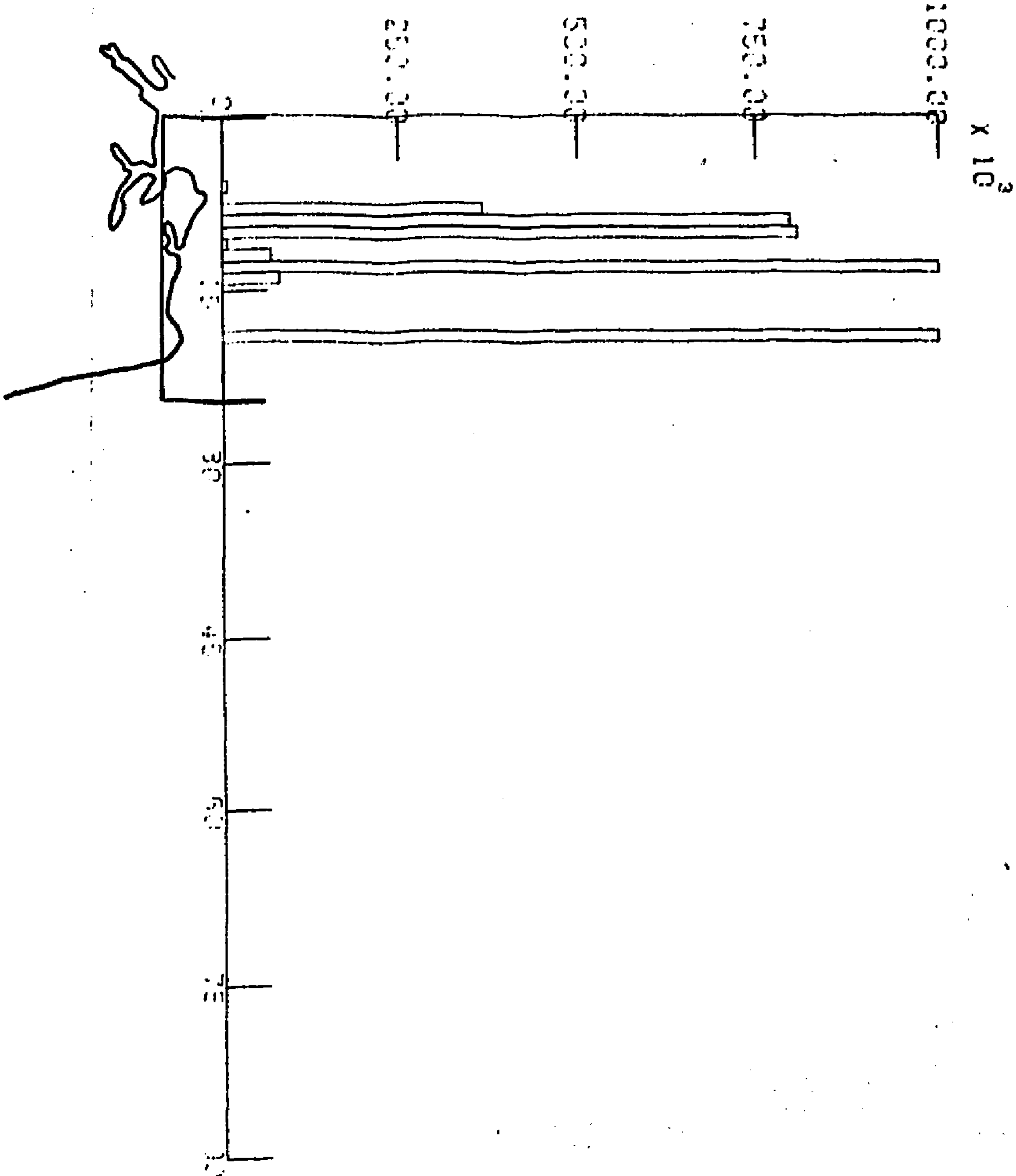



FIGURE D-81

WESTERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES

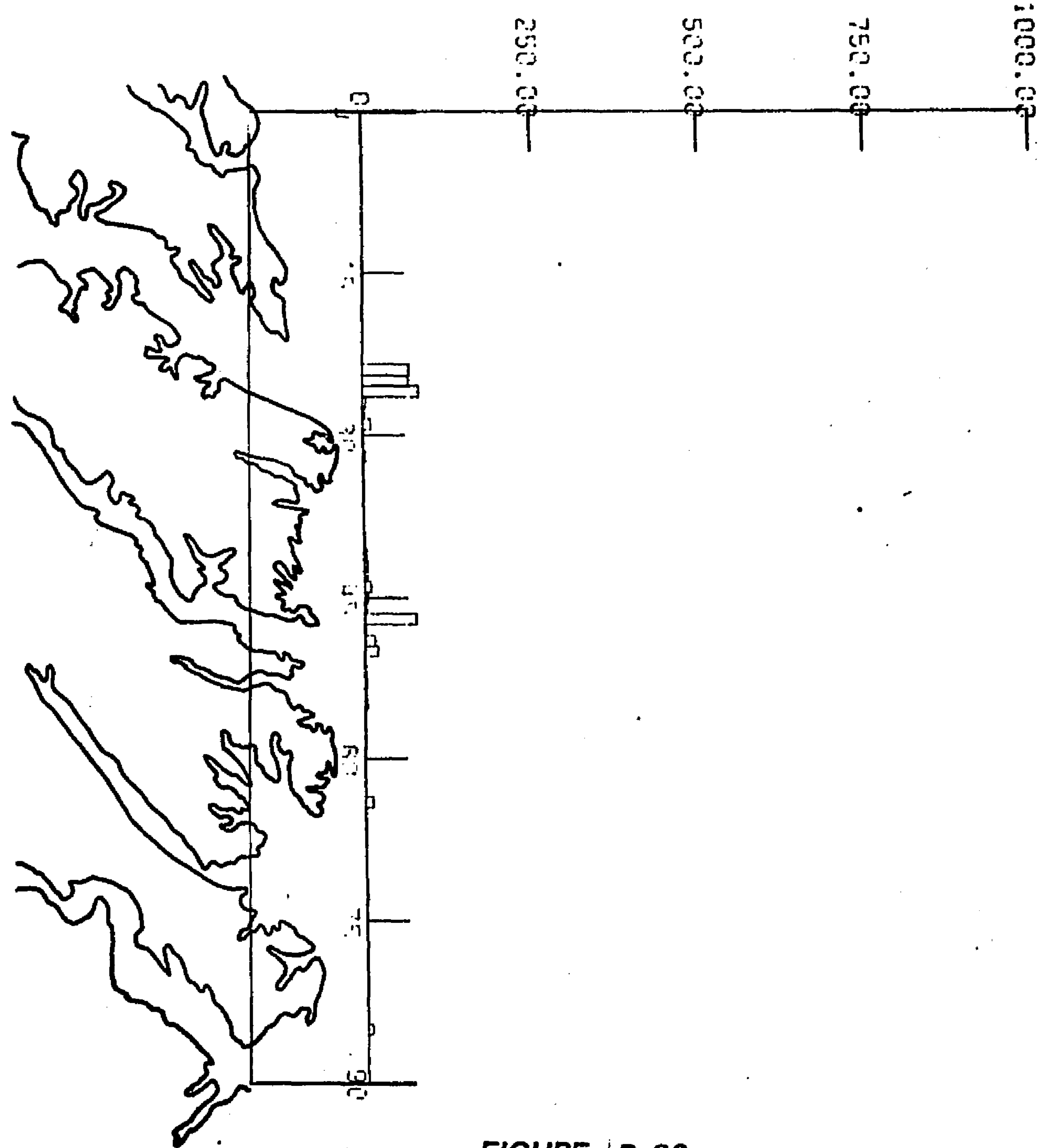



FIGURE D-82

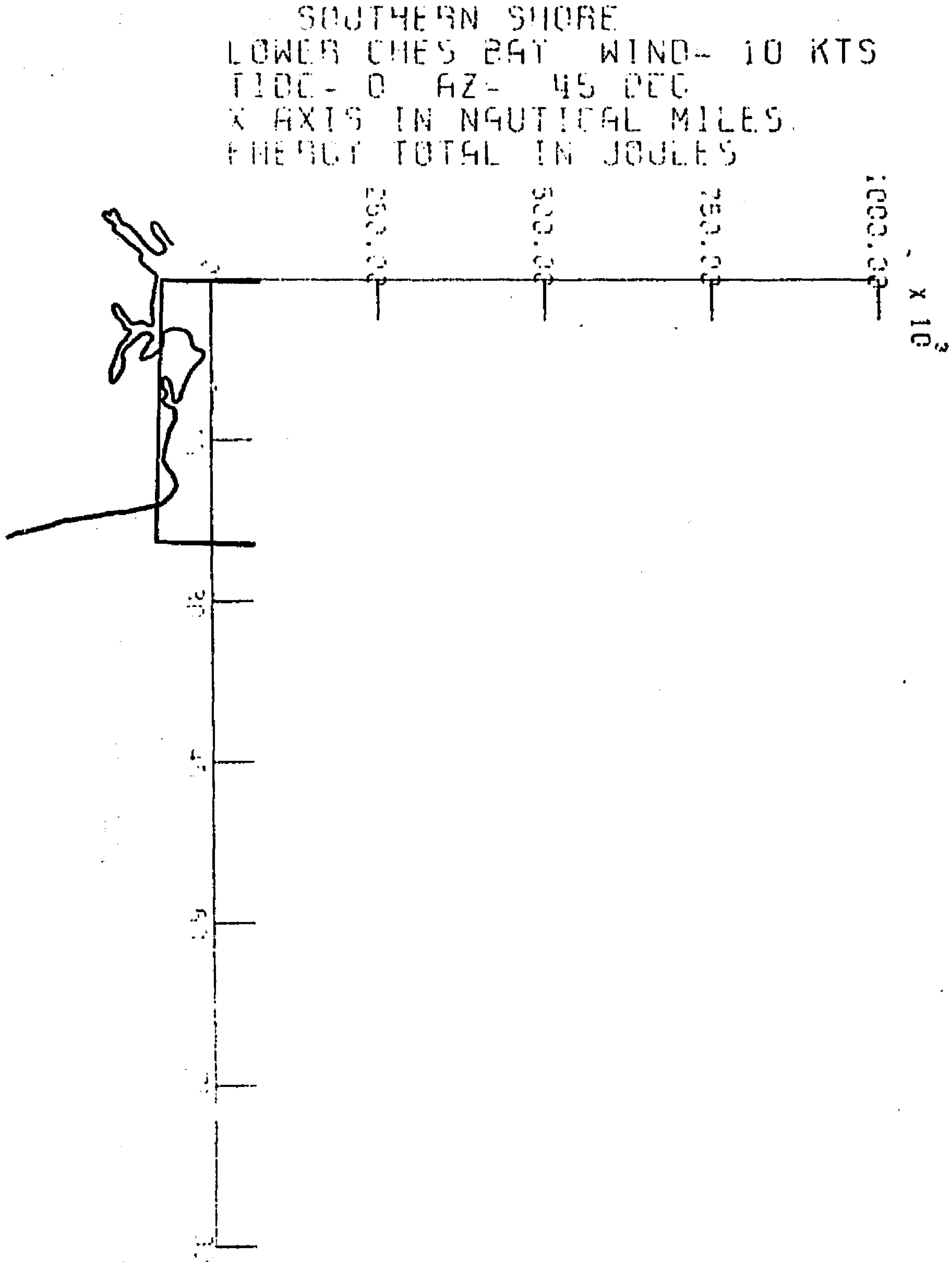

SOUTHERN SHORE
LOWER CHES BAY WIND- 10 KTS
TIDE- 0 AZ- 45 DEG
X AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES
250.00
500.00
750.00
1000.00
x 10^3

FIGURE D-83

WESTERN SHORE
LOWER CHES BAY WIND= 25 KTS
TIDE= 0 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES

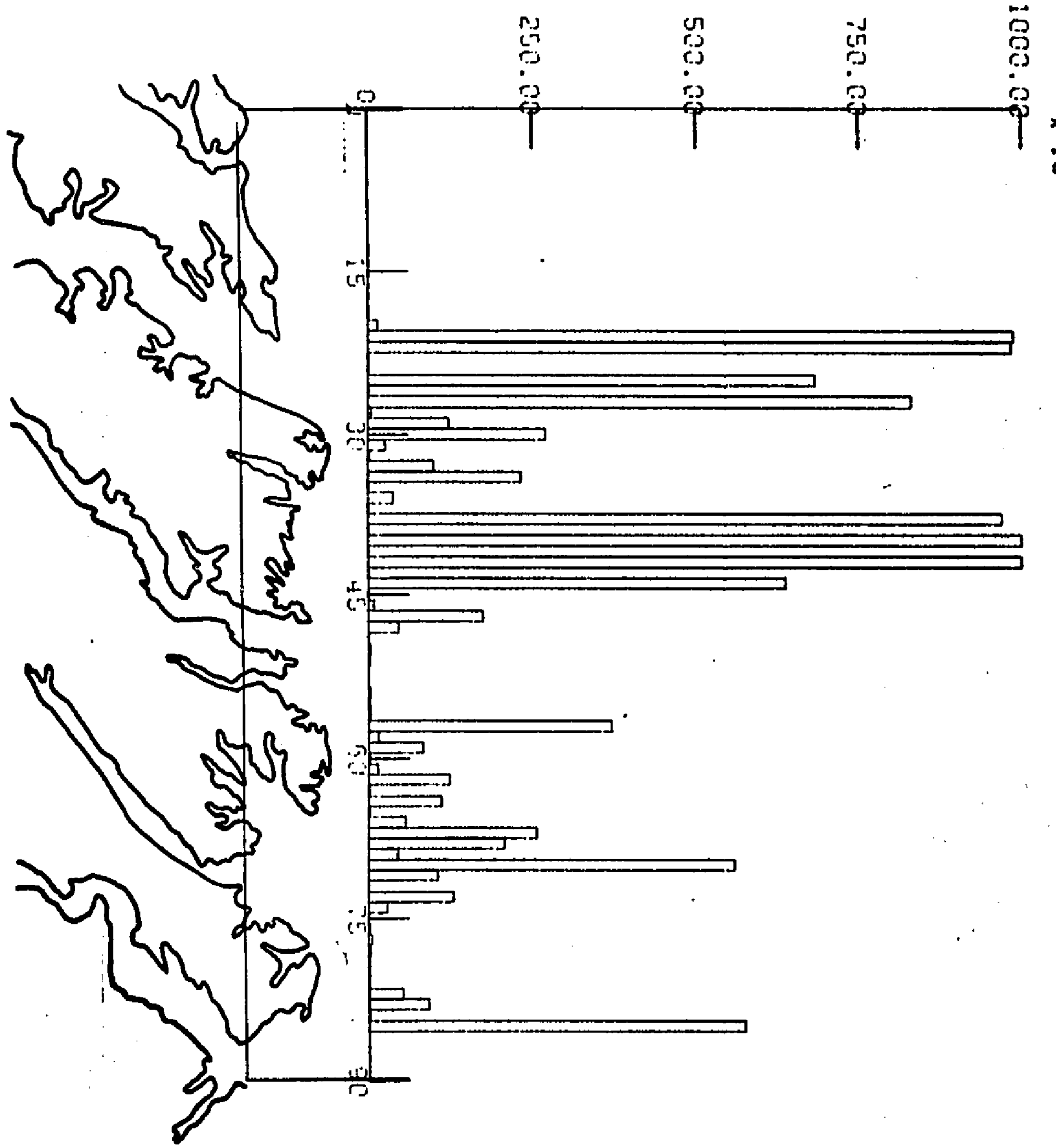



FIGURE D-84

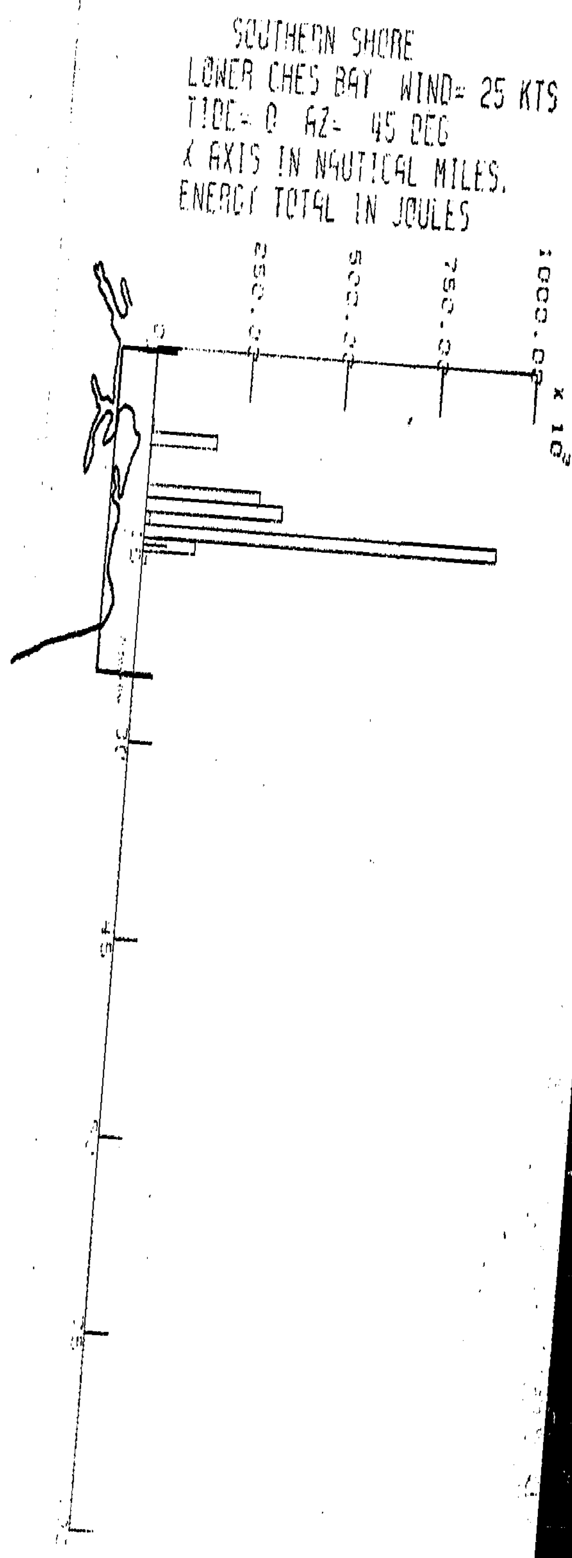



FIGURE D-85

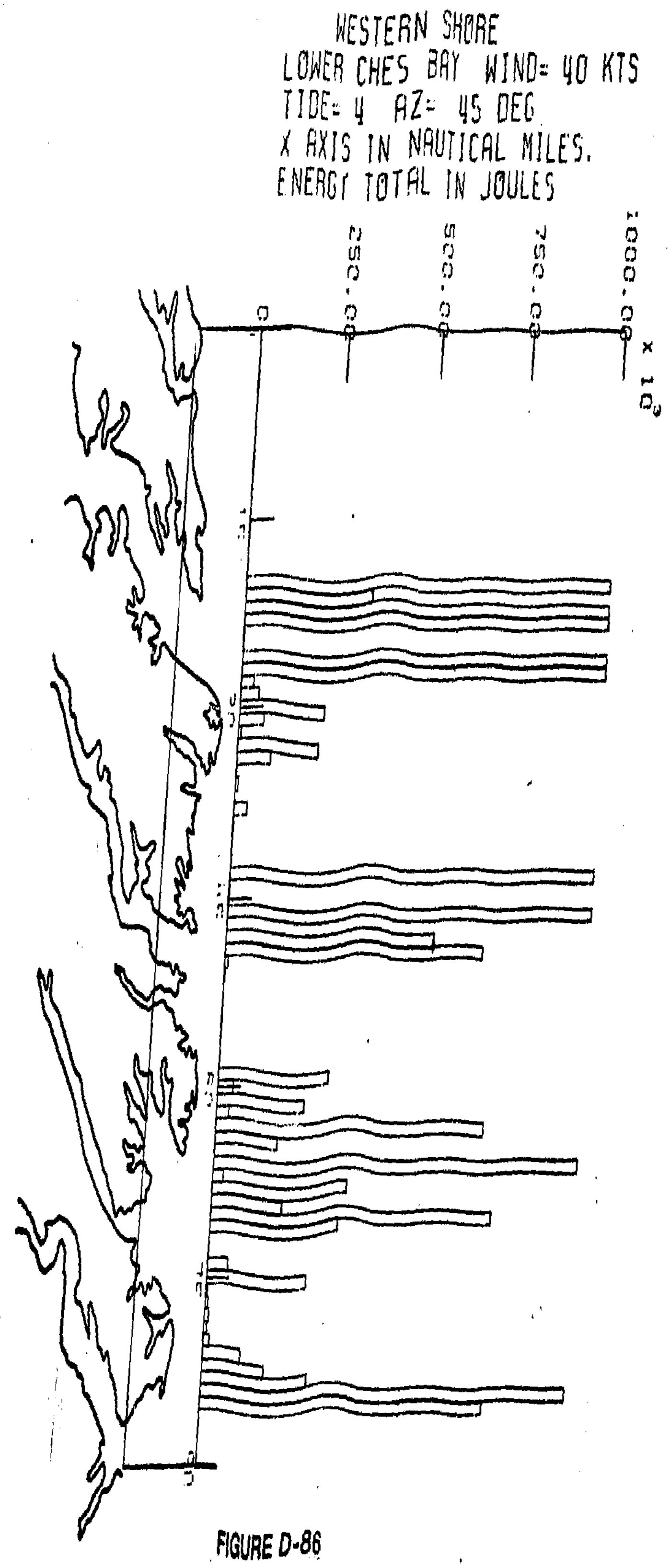



FIGURE D-86

SOUTHERN SHORE
LOWER CHES BAY WIND= 40 KTS
TIDE= 4 AZ= 45 DEG
X AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES

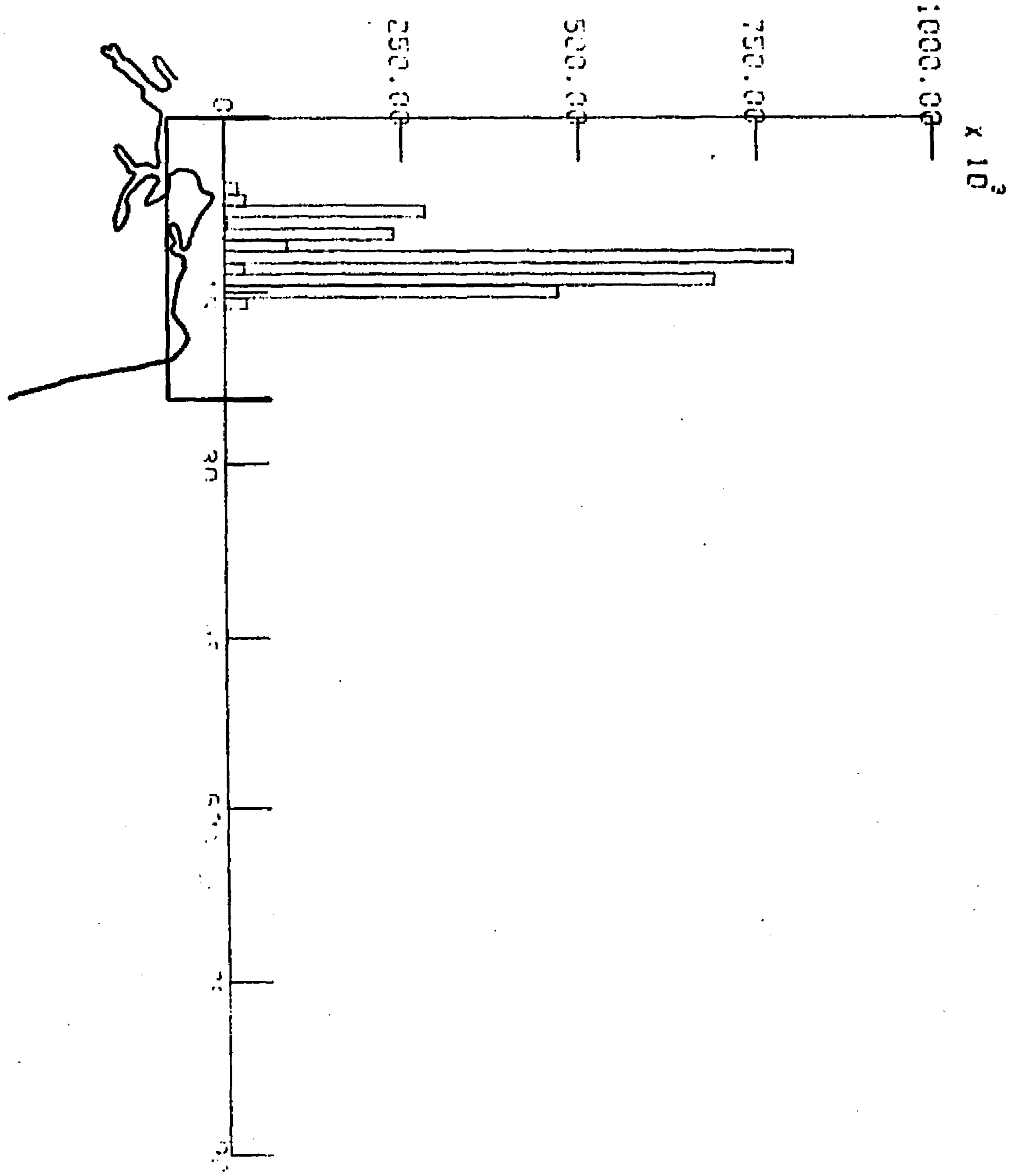



**FIGURE D-87**

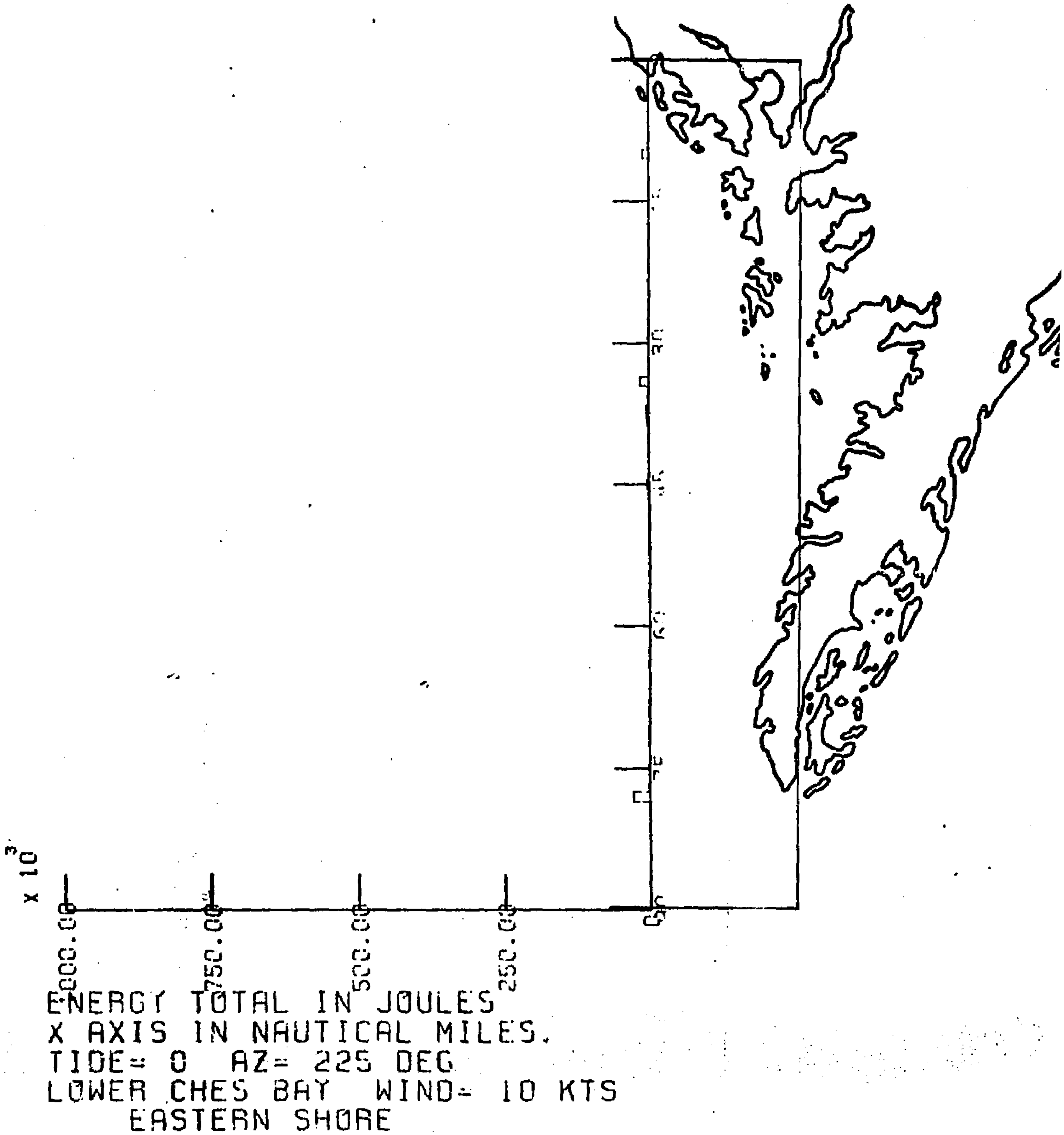
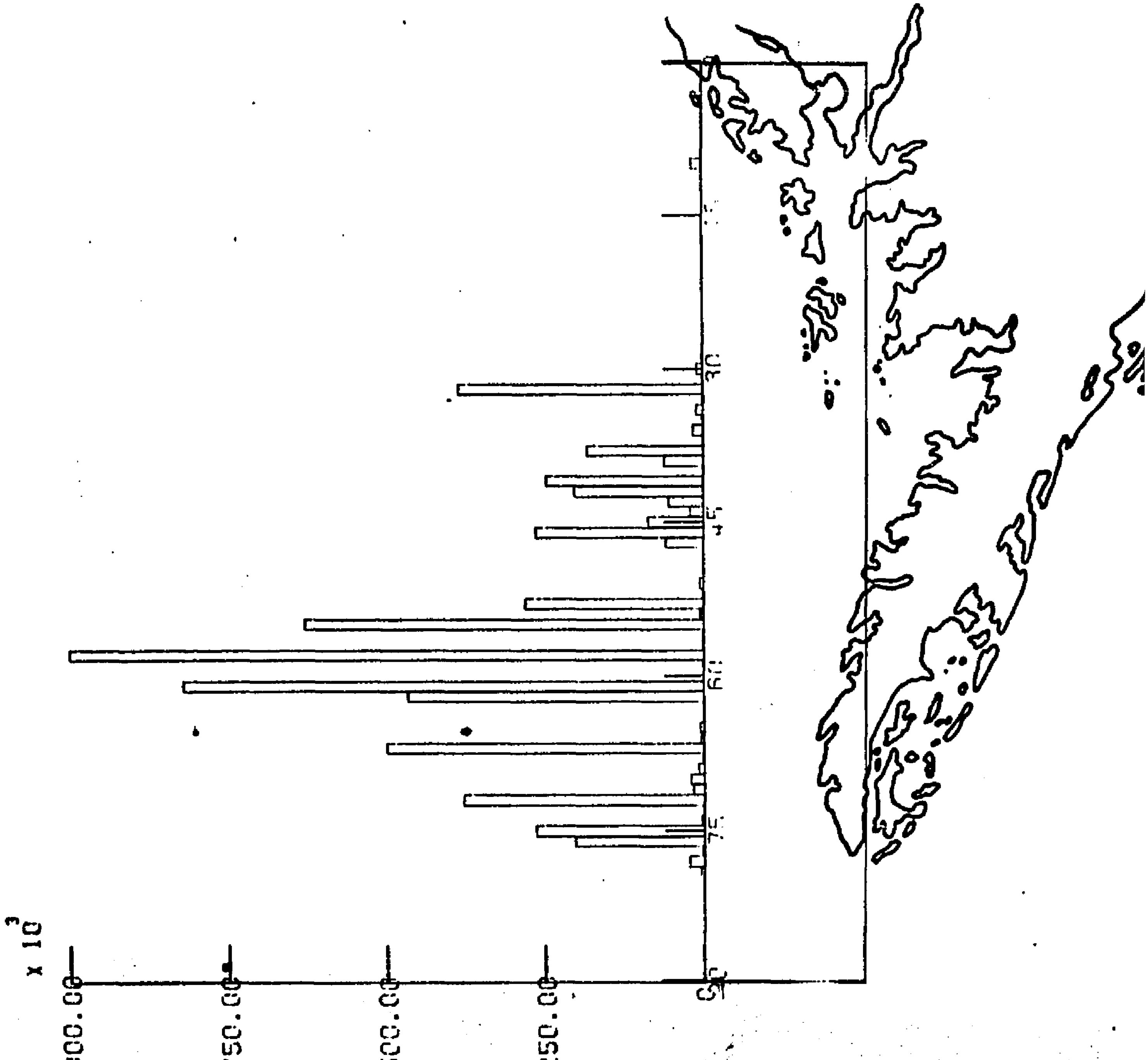
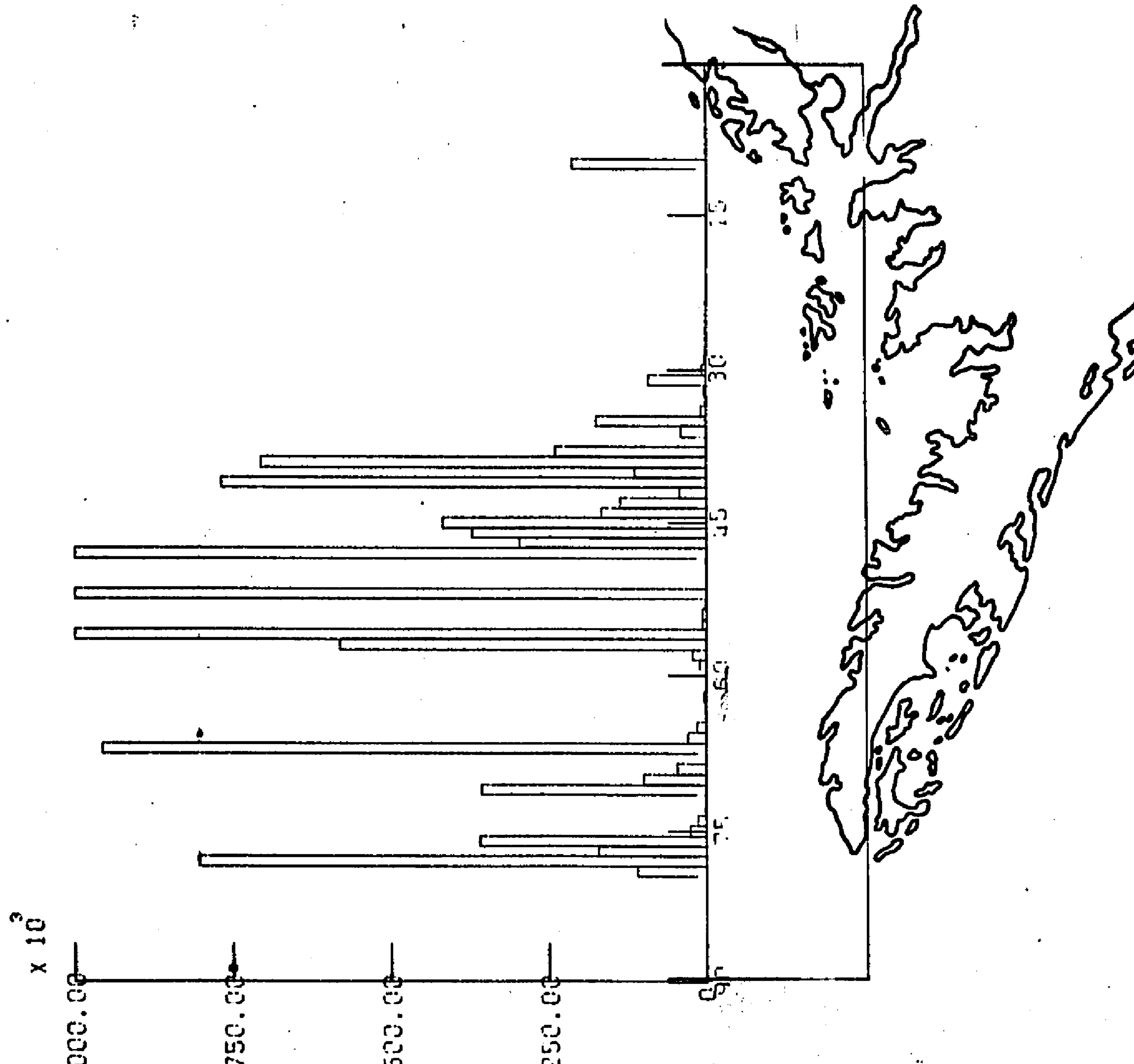

x 10^3
1000.00
750.00
500.00
250.00
ENERGY TOTAL IN JOULES
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 225 DEG
LOWER CHES BAY WIND= 10 KTS
EASTERN SHORE

FIGURE D-88



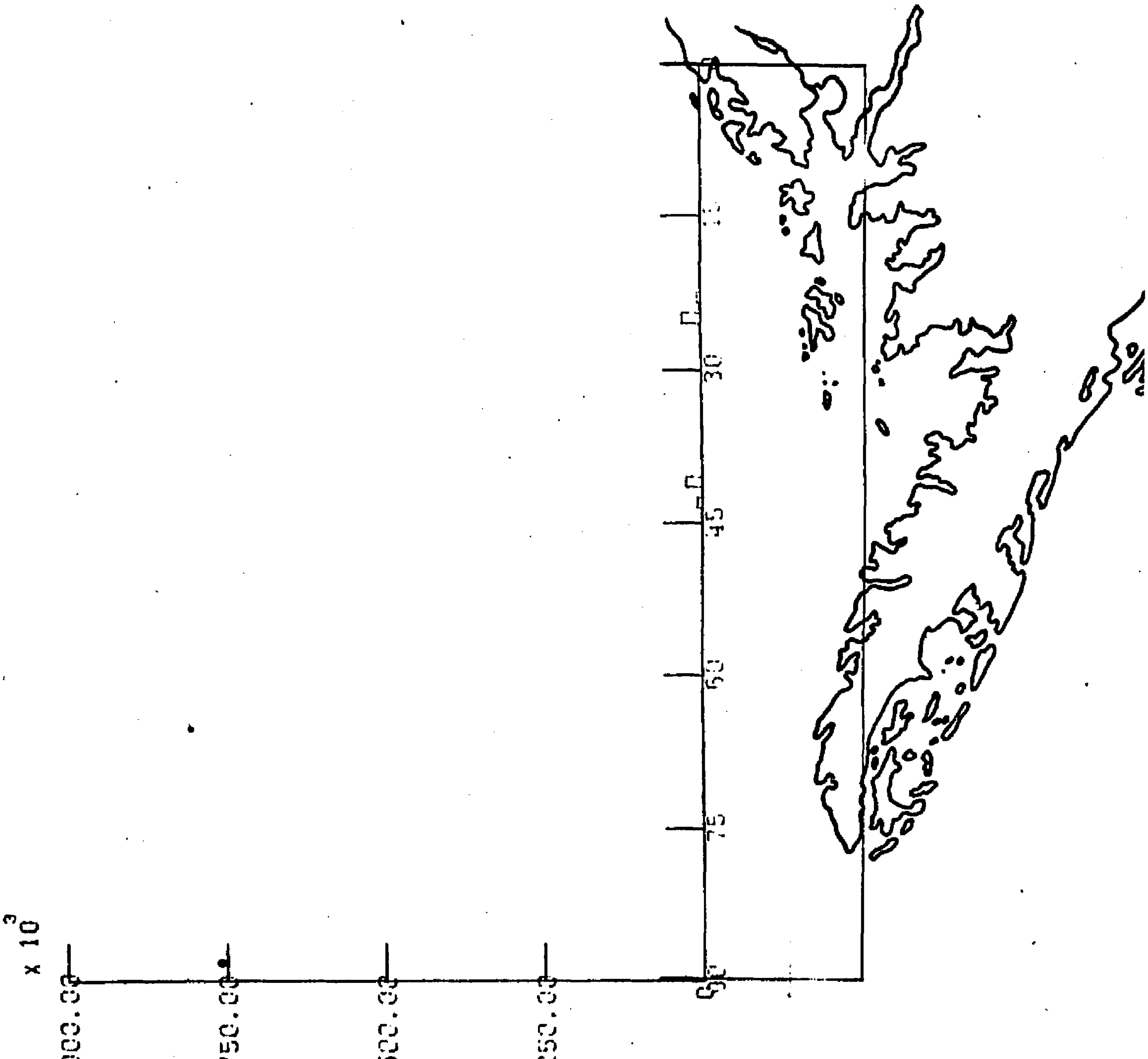

ENERGY TOTAL IN JOULES
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 225 DEG
LOWER CHES BAY WIND= 25 KTS
EASTERN SHORE

**FIGURE D-89**




ENERGY TOTAL IN JOULES
X AXIS IN NAUTICAL MILES.
TIDE= 4 AZ= 225 DEG
LOWER CHES BAY WIND= 40 KTS
EASTERN SHORE

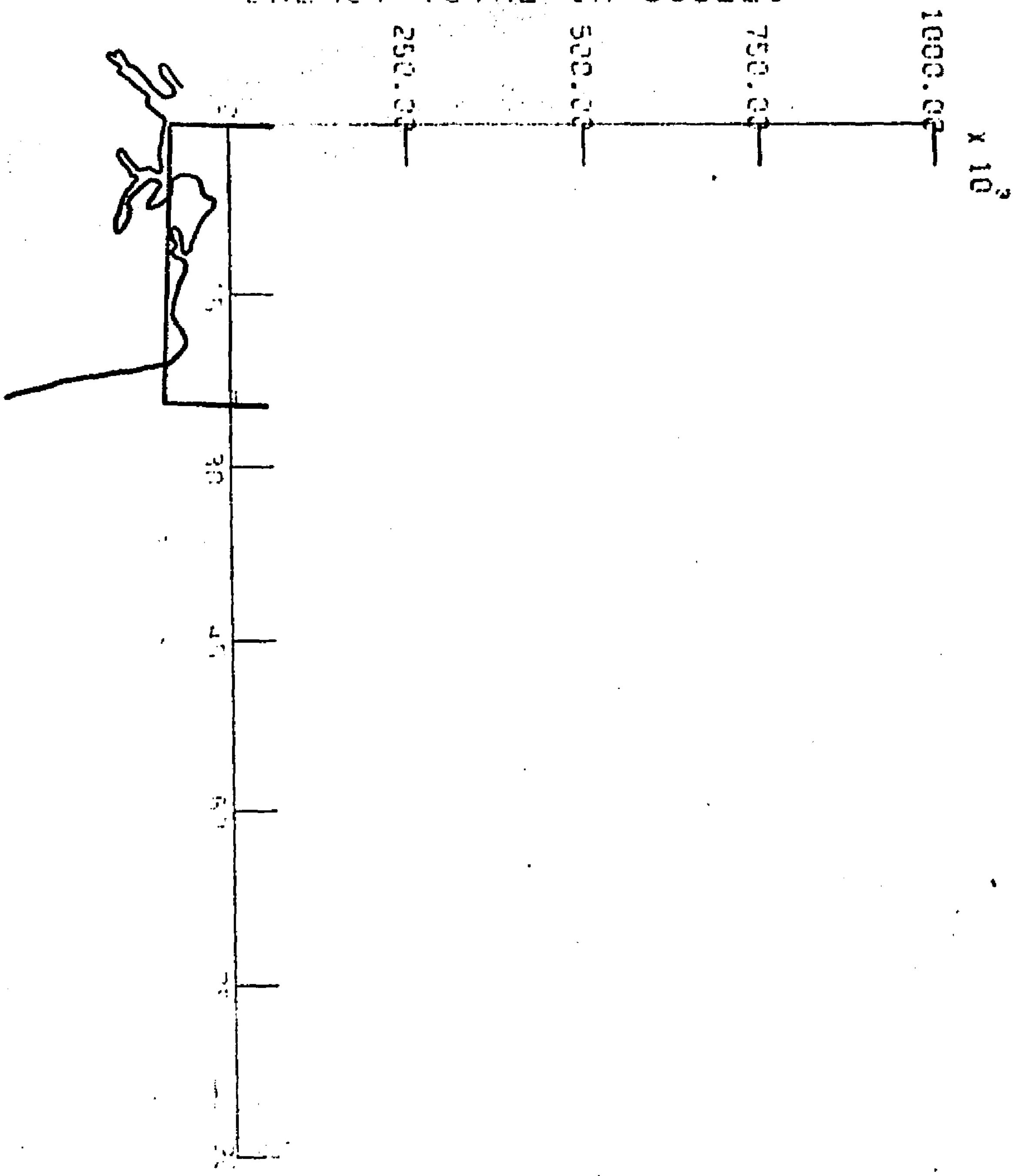
**FIGURE D-90**



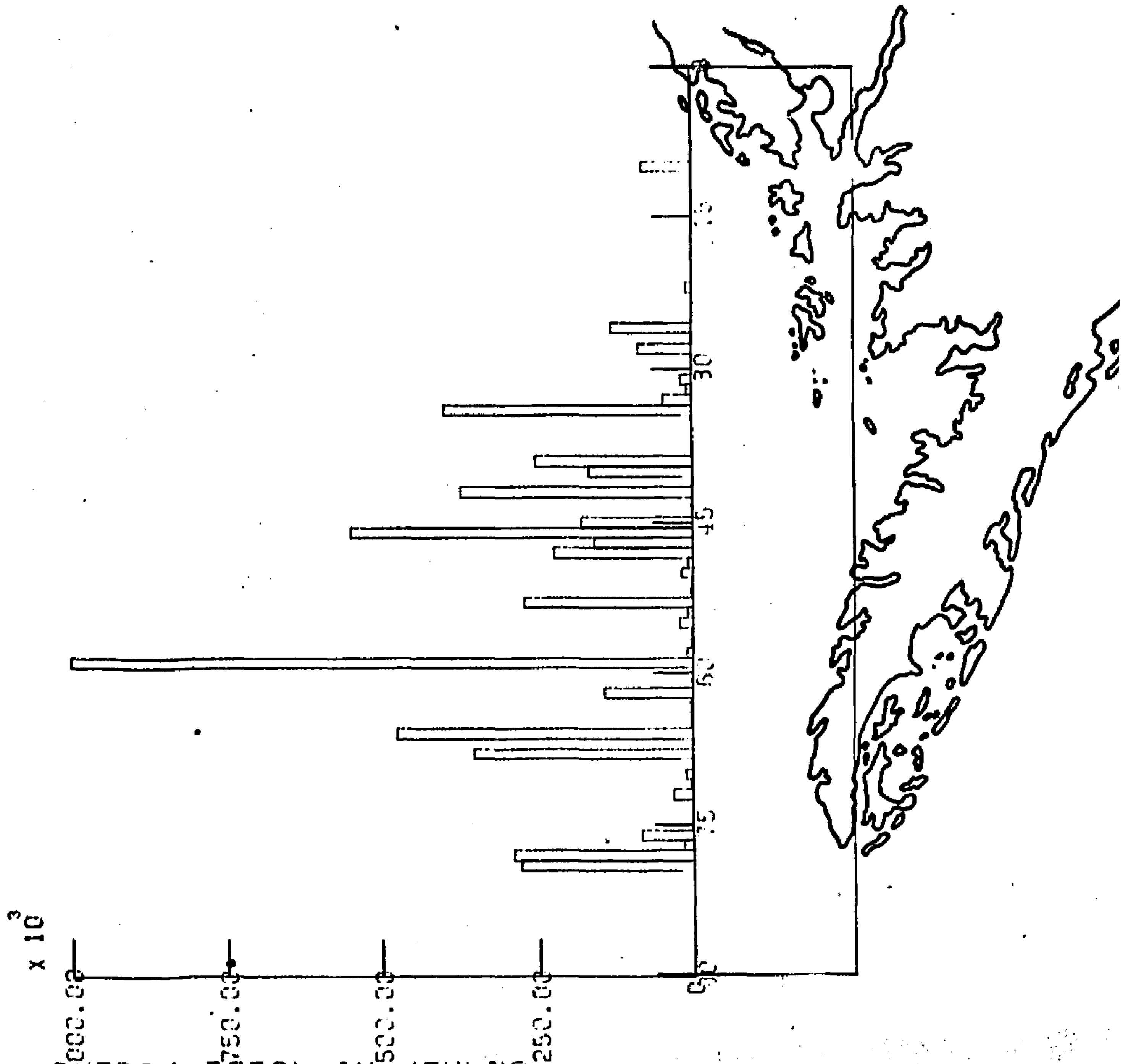

ENERGY TOTAL IN JOULES
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 315 DEG
LOWER CHES BAY WIND= 10 KTS
EASTERN SHORE

**FIGURE D-91**

SOUTHERN SHORE
LOWER CHES BAY WIND= 10 KTS
TIDE= 0 AZ= 315 DEG
X AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES




.FIGURE D-92




ENERGY TOTAL IN JOULES
X AXIS IN NAUTICAL MILES.
TIDE= 0 AZ= 315 DEG
LOWER CHES BAY WIND= 25 KTS
EASTERN SHORE

FIGURE D-93

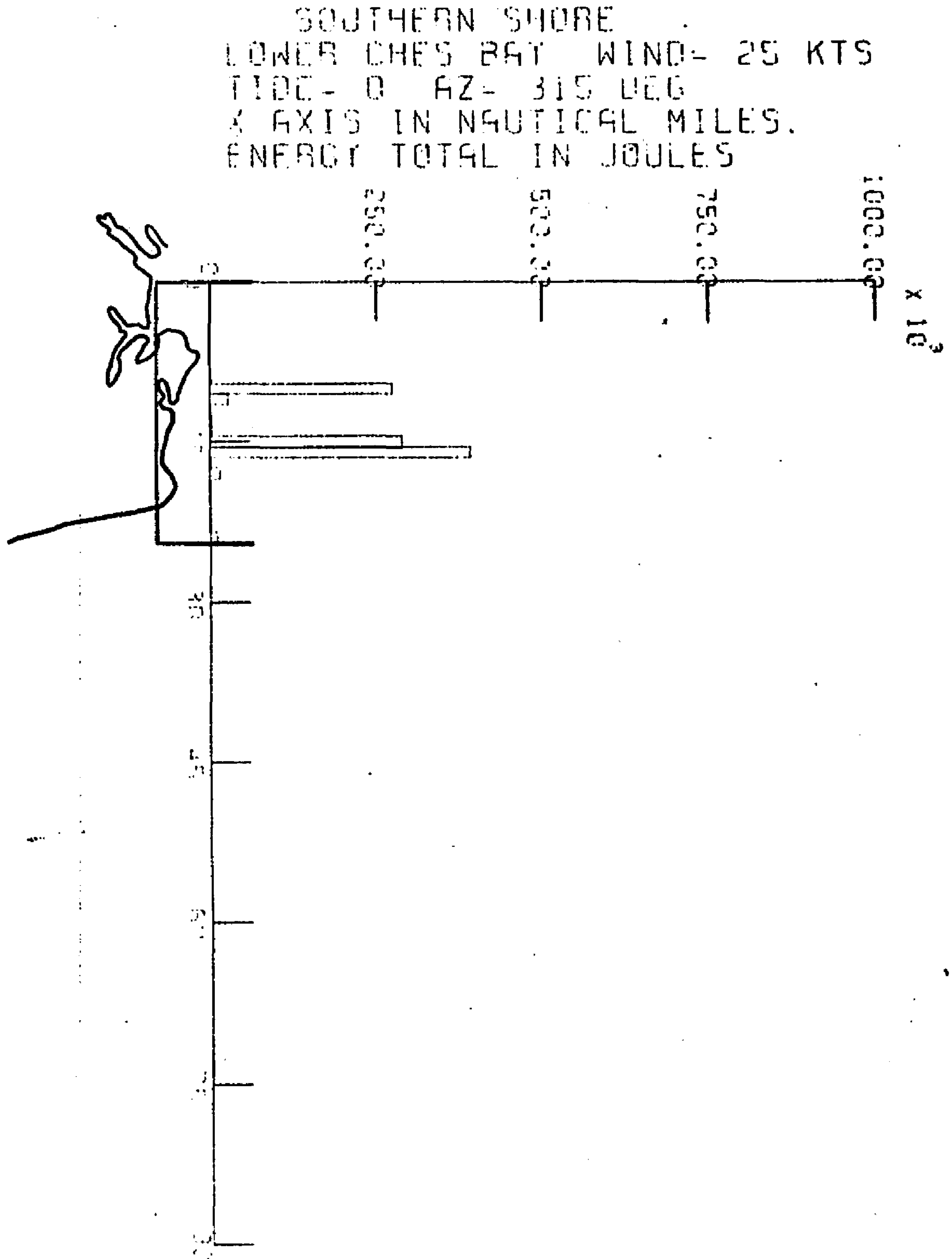
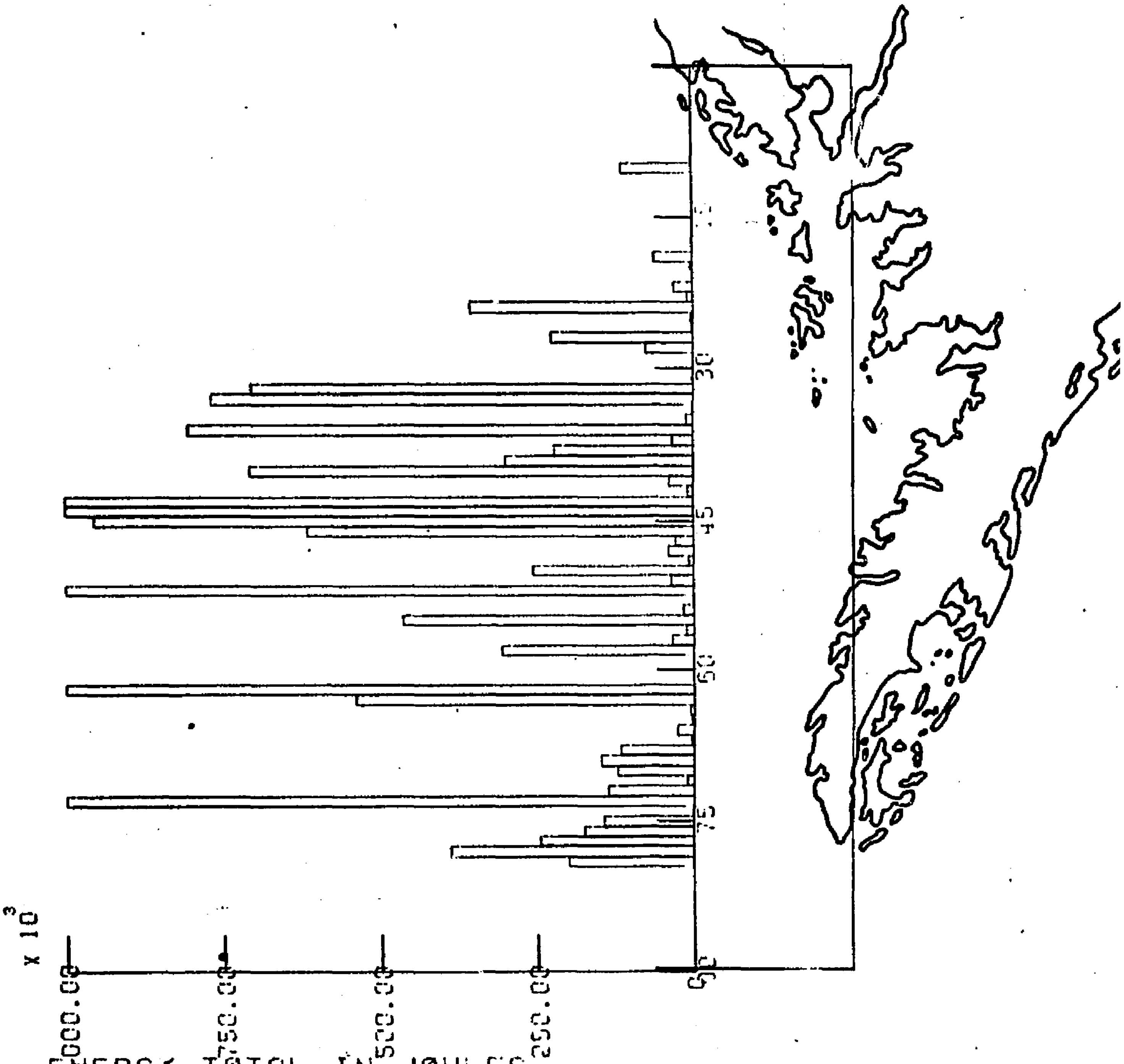

SOUTHERN SHORE
LOWER CHES BAY WIND- 25 KTS
TIDE- 0 AZ- 315 DEG
X AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES
250.00
500.00
750.00
1000.00
x 10^3

FIGURE D-94




ENERGY TOTAL IN JOULES
X AXIS IN NAUTICAL MILES.
TIDE= 4   AZ= 315 DEG
LOWER CHES BAY   WIND= 40 KTS
EASTERN SHORE

**FIGURE D-95**

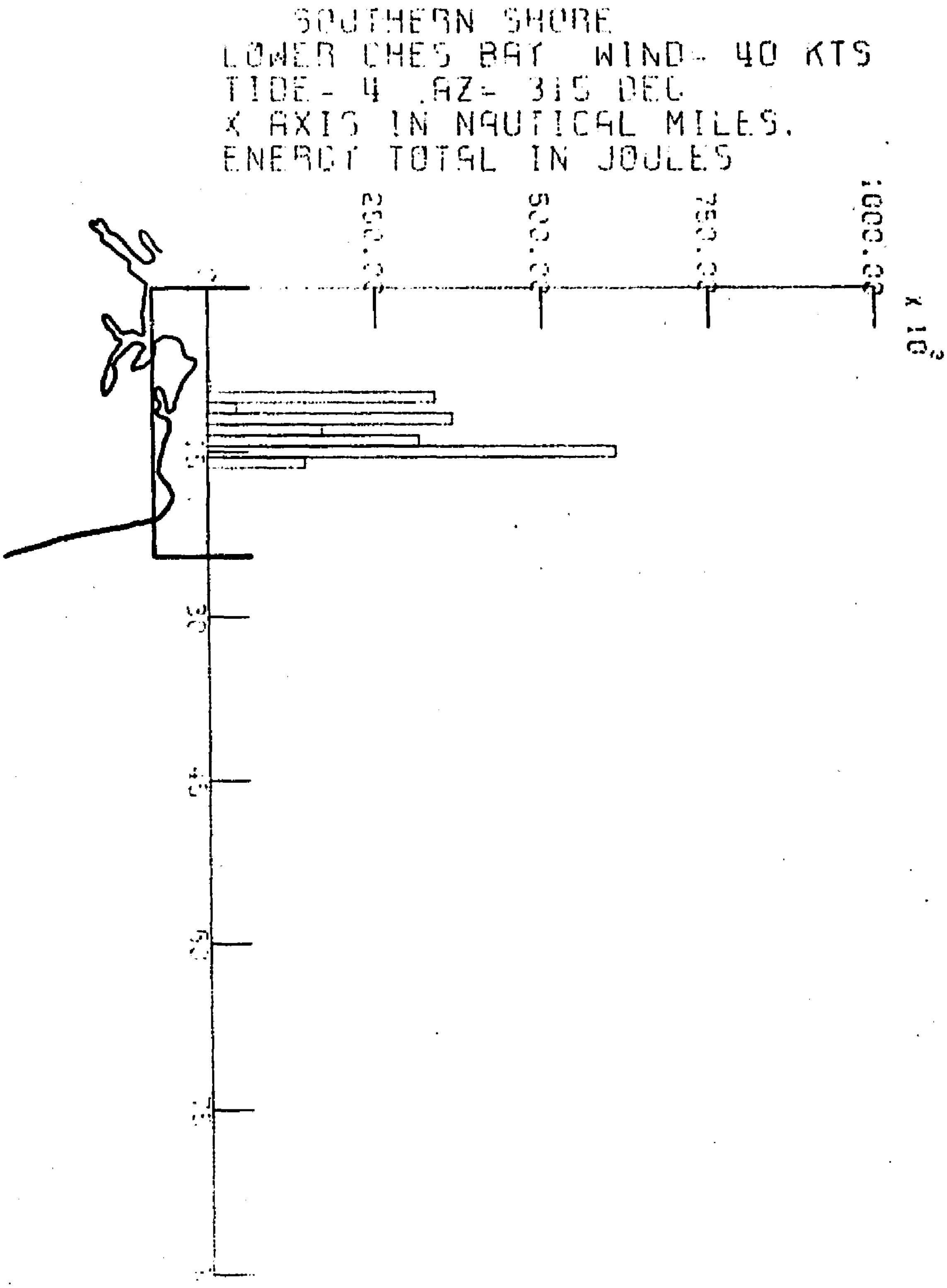

SOUTHERN SHORE
LOWER CHES BAY WIND- 40 KTS
TIDE- 4 AZ= 315 DEG
X AXIS IN NAUTICAL MILES.
ENERGY TOTAL IN JOULES
250.00
500.00
750.00
1000.00

FIGURE D-96

# REFERENCES

# BIBLIOGRAPHY


Athearn, W. D., G. L. Anderson, R. J. Byrne, C. H. Hobbs, III, and Zeigler, J. M., 1974. Shoreline Situation Report: Northampton County, Virginia: SRAMSOE No. 54, Virginia Institute of Marine Science, Gloucester Point, Virginia, 153 p.

Bagnold, R. A., 1940. Beach Formation by Waves; some model-experiments in a wave tank: J. Inst. Civ. Eng., v. 15, n. 1, pp. 27-52.

Biggs, R. B., 1962. Modern Sediments of Chesapeake Bay (abs.) in Proceedings First National Coastal and Shallow Water Research Conference, p. 166.

Biggs, R.B., 1967. The Sediments of Chesapeake Bay, p. 239-260 in Lauff, G.H. (ed.), Estuaries: Publication No. 83, American Association for the Advancement of Science, Washington, D.C., 557 p.

Biggs, R. B., 1970. Sources and Distribution of Suspended Sediment in Northern Chesapeake Bay: Mar. Geol., v. 9, pp. 187-201.

Bond, G. C., and R. H. Mead, 1966. Size Distribution of Minderal Grains Suspended in Chesapeake Bay and Nearby Coastal Waters: Ches. Sci., v. 7, pp. 208-212.

Bretschneider, C. L., 1959. Hurricane Surge Predictions for Chesapeake Bay: Beach Erosion Board Misc. Paper 3-59, U.S. Corps of Engineers, Washington, D.C., 51 p.

Bruun, P., 1962. Sealevel Rise as a Cause of Shore Erosion: Am. Soc. Civ. Eng. Proc., Jour. Waterways and Harbors Div., v. 88, pp. 117-130.

Byrne, R. J., G. L. Anderson, and A. Sallenger, 1972. Shore Erosion in Tidewater, Virginia, pp. 216-229 in Chesapeake Research Consortium, Inc., Ann. Rpt. June 1971-May 1972, Virginia Institute of Marine Science, 754 p.

Byrne, R. J., and G. L. Anderson, 1973. Shoreline Erosion in Virginia's Tidal Rivers and Chesapeake Bay (abs): Va. Jour. Sci., v. 24, n. 3, p. 158.

Carter, G. F., 1951. A Study of Soils and Landforms of the Chesapeake Bay Margins: The John Hopkins Magazine, v. 12, n. 8, pp. 24-33.

Chapman, V. J., 1964. Coastal Vegetation: The MacMillan Company, New York, 245 p.

Clarke, W. D., L. C. Murdock, and H. D. Palmer, 1973. The Chester River Study, Volume II: Maryland Dept. Nat. Res., Baltimore.

Courtier, A., 1938. Marees. Service Hydrographique de la Marine, Paris, pp. 149-159.

Davis, R., E. Seibel, and W. Fox, 1973. Coastal Erosion in Eastern Lake Michigan: Causes and Effects: Proc. 16th Conf. Great Lakes Res., pp. 404-412.

DuBöis, R. N., 1975. Support and Refinement of the Bruun Rule on Beach Erosion: Jour. Geol., v. 83, pp. 651-657.

Duncan, J. R., 1964. The Effects of Water Table and Tide Cycle on Swash-backwash Sediment Distribution and Beach Profile Development: Mar. Geol., v. 2, n. 1, pp. 186-197.

Emery, K. O., 1961. A Simple Method of Measuring Beach Profiles: Limnology and Oceanography, v. 6, pp. 90-93.

Emery, K. O., and J. F. Foster, 1948. Water Tables in Marine Beaches: J. Marine Research, v. 7, n. 3, pp. 644-654.

Folk, R. L., 1968. Petrology of Sedimentary Rocks: Hemphill's, Austin, Texas, 170 p.

Fox, W. T., and R. A. Davis, 1971. Computer Simulation Model of Coastal Processes in Eastern Lake Michigan: Technical Report No. 5, Contract N00014-69-C-0151, Office of Naval Research, Geography Branch, Washington, D.C., 114 p.

Garner, H. F., 1974. The Origin of Landscapes: Oxford University Press, London, 549 p.

Geise, G. S., 1966. Beach Pebble Movements and Shape Sorting Indices of Swash Zone Mechanics, unpub. Ph.D. thesis, Univ. Chicago, 65 p.

Goldsmith, V., W. D. Morris, R. J. Byrne, C. H. Whitlock, 1974. Wave Climate Model of the Mid-Atlantic Shelf and Shoreline (Virginian Sea), Model Development, Shelf Geomorphology, and Prelimary Results: SRAMSOE No. 38, Virginia Institute of Marine Science, Gloucester Point, Virginia, 146 p.

Grant, U.S., 1948. Influence of the Water Table on Beach Aggradation and Degradation: J. Marine Res., v. 7, n. 3, pp. 655-660.

Hack, J. T., 1957. Submerged River System of Chesapeake Bay: Geol. Soc. Am. Bul., v. 68, pp. 817-830.

Haight, F. J., H. E. Finnegan, and G. L. Anderson, 1930. Tides and Currents in Chesapeake Bay and Tributaries: U.S.C.G.S. Spec. Pub. 162.

Harris, R. A., 1907. Currents, Shallow-Water Tides, Meteorological Tides, and Miscellaneous Matters. Chapter VI, Part V, Manual of Tides, Appendix 6, Annual Report for 1907, U.S. Coast and Geodetic Survey, Washington, D.C., 357 p.

Harrison, W., J. D. Boon, C. S. Fang, L. Favsak, and S. Wang, 1971. Investigation of the Water Table in a Tidal Beach: Special Scientific Report No. 60, Virginia Institute of Marine Science, Gloucester Point, Virginia.

Harrison, W., M. Lynch, and C. Altschaefl, 1964. Sediments of Lower Chesapeake Bay, with emphasis on mass properties: J. Sed. Pet., v. 34, n. 4, pp. 727-755.

Harrison, W., R. Molloy, and G. Rusnak, 1965. Possible Late Pleistocene Uplift, Chesapeake Bay Entrance: J. Geol., v. 72, n. 2, pp. 201-229.

Hicks, S. D., 1964. Tidal Wave Characteristics of Chesapeake Bay: Ches. Sci., v. 5, n. 3, pp. 103-113.

Hicks, S. D., 1972. On the Classification and Trends of Long Period Sea-Level Series: Shore and Beach, v. 40, n. 1, pp. 20-23.

Hicks, S. D., and J. E. Crosby, 1974. Trends and Variability of Yearly Mean Sea Level, 1893-1972: NOAA Tech. Mem. NOS 13, 14 p.

Holdahl, S. and Morrison, N., 1974. Regional Investigations of Vertical Crustal Movements in the U.S., using precise releveling and mareograph data: Tectonophysics, v. 23, pp. 373-390.

Hunter, J. F., 1914. Erosion and Sedimentation in Chesapeake Bay around the Mouth of Choptank River: U.S.G.S. Prof. Pap. 90-B, p. 7-15

Isaacs, J. D. and W. N. Bascom, 1949. Water Table Elevations in some Pacific Coast Beaches: Trans., Am. Geophy. Un., v. 30, n. 2, pp. 293-294.

Jordan, G. F., 1961. Erosion and Sedimentation, Eastern Chesapeake Bay at the Choptank River: U.S.C.G.S. Tech. Bul. No. 16, 8 p.

Kay, C., and E. Barghoorn, 1964. Late Quaternary Sealevel Change and Crustal Rise at Boston, Mass., with notes on the autocompaction of peat: Geol. Soc. Am. Bul., v. 75, pp. 63-80.

Krumbein, W. C., 1960. Some Problems in Applying Statistics to Geology: Applied Statistics, v. 9, pp. 82-91.

Krumbein, W. C., and L. L. Sloss, 1963. Stratigraphy and Sedimentation (2nd Edition): W. H. Freeman and Co., San Francisco, 660 p.

Lewis, W. F., 1938. The Evolution of Shoreline Curves: Proceedings of Geol. Assoc., v. 49, pp. 107-127.

McCormick, C. L., 1968. Holocene Stratigraphy of the Marshes of Plum Island, Massachusetts: Univ. of Mass. unpub. Ph.D. thesis, 104 p.

Mudge, B. F., 1858. The Salt Marsh Formations of Lynn: Proc. Essex Inst., v. 2, pp. 117-119.

Newman, W. S., and G. A. Rusnak, 1965. Holocene Submergence of the Eastern Shore of Virginia: Science, v. 148, pp. 1464-1466.

O'Brien, M., 1968. Multiple Bar Systems in Chesapeake Bay: V.I.M.S. unpub. M.S. thesis.

Palmer, H. D., 1973. Shoreline Erosion in Upper Chesapeake Bay: The Role of Groundwater: Shore and Beach, v. 41, n. 2, pp. 18-22.

Palmer, H. D., 1974. Estuarine Sedimentation, Chesapeake Bay, Maryland, U.S.A.: Memoires de l'Institut de Geologie du Bassin d' Aquitaine, n. 7, pp. 215-224.

Pore, A., 1960. Chesapeake Bay Hurricane Surges: Ches. Sci., v. 1, pp. 178-186.

Redfield, A. C., 1958. The Barnstable Marsh, pp. 37-42, in Proceedings, Salt Marsh Conference, University of Georgia, Sapelo Island, Georgia, 133 p.

Redfield, A. C., 1967. Postglacial Change in Sealevel in the Western North Atlantic Ocean: Science, v. 157, n. 3789, pp. 687-692.

Rosen, P. S., 1975. Origin and Processes of Cuspate Spit Shorelines, p. 77-92, in Cronin, L.E., (ed.), Estuarine Research, Volume 2: Academic Press, New York, 585 p.

Rosen, P. S., V. Goldsmith, W. Richardson and C. Sutton, 1976. Chesapeake Bay Wave Forecast-Refraction Model: SRAMSOE No. 89, Virginia Institute of Marine Science, Gloucester Point, Virginia, in press.

Ryan, J. D., 1953. The Sediments of Chesapeake Bay: Maryland Dept. of Geology, Mines and Water Resources Bulletin 12, Baltimore, Maryland, 120 p.

Sallenger, A., and P. S. Rosen, 1974. Beach Ridges on a Low Energy Beach, VIMS Beach, Gloucester Point, Virginia (abs): Virginia Journal of Science, v. 25, n. 2.

Schubel, J. R., 1968. Shore Erosion of the Northern Chesapeake Bay: Shore and Beach, v. 36, n. 1, pp. 22-26.

Schubel, J. R., 1972. The Physical and Chemical Conditions of the Chesapeake Bay: Jour. Washington Acad. Sci., v. 62, n. 2, pp. 56-87.

Schubel, J. R., H. H. Carter, E. W. Schiener, and R. C. Whaley, 1972. A case study of littoral drift based on longterm patterns of erosion and deposition: Ches. Sci., v. 13, n. 2, pp. 80-86.

Schwartz, M. L., 1965. Laboratory Study of Sealevel Rise as a cause of Shore Erosion: J. Geol., v. 73, n. 3, pp. 528-534.

Schwartz, M. L., 1967. The Bruun Theory of Sealevel Rise as a cause of Shore Erosion: J. Geol., v. 75, n. 1, pp. 76-92.

Schwartz, M. L., 1968. The Scale of Shore Erosion: J. Geol., v. 76, pp. 508-517.

Shaler, N. S., 1886. Preliminary Report on Sea-Coast Swamps of the Eastern United States: U.S. Geol. Surv., 6th Annual Report, 364 p.

Shepard, F. P., 1973. Submarine Geology: Harper and Row, New York, 517 p.

Shideler, G. L., 1975. Physical Parameters in Bottom Sediments of the Lower Chesapeake Bay Estuary, Virginia: Jour. Sed. Pet., v. 45, n. 3, pp. 728-737.

Singewald, J. T., and T. H. Slaughter. 1949. Shore Erosion in Tidewater Maryland: Maryland Dept. of Geology, Mines, and Water Resources Bulletin 6, Baltimore, Maryland, 141 p.

Slaughter, T. H., 1964. Shore Erosion in Tidewater Maryland: Shore and Beach, v. 32, n. 1, 15 p.

Slaughter, T. H., 1966. Are We Conserving Maryland's Tidal Lands?: Maryland Conservationist, v. 43, n. 1, pp. 9-13.

Slaughter, T. H., 1967a. Vertical Protective Structures in the Maryland Chesapeake Bay: Shore and Beach, v. 35, n. 2, 11 p.

Slaughter, T. H., 1967b. Shore Erosion Control in Tidewater Maryland: Washington Acad. Sci., Jour., v. 57, pp. 117-129.

Sokal, R., and F. Rohlf, 1969. Biometry: W. H. Freeman & Co., San Francisco, pp. 239-241.

Stephenson, L. W., C. Cooke, and W. C. Mansfield, 1933. Chesapeake Bay Region: XVI Inter. Geol. Congr., Guidebook 5, 49 p.

Strahler, A., 1966. Tidal Cycle Changes in an Equilibrium Beach, Sandy Hook, New Jersey: J. Geol., v. 74, n. 3, pp. 247-268.

Thrall, D. E., 1973. Development of a Computer Program to Simulate Wind Wave Generation, Refraction, and Shoaling in the Gulf of Maine: Edal Rpt. No. 113 (Rpt. No. UNH-SG-106), Univ. of New Hampshire, 43 p.

Trident Engineering Associates, Inc., 1968. Chesapeake Bay Case Study: Clearinghouse for Federal Scientific and Technical Information, No. PB, pp. 179-844.

U.S. Navy, 1963. A Climatology of the Virginia Capes Operating Area: U.S. Fleet Weather Facility, Norfolk, Virginia, 113 p.

U.S. Navy, 1972. Local Area Forecaster's Handbook for Naval Air Station, Norfolk, Virginia: U. S. Fleet Weather Central, Norfolk, Virginia.

U.S. Weather Bureau, 1956. Hurricane Characteristics, Chesapeake Bay Area, 1904-1955: U. S. Weather Bureau Memorandum HUR 7-19.

Virginia Agricultural Experiment Station, 1962. The Virginia Tidal Riverbank Erosion Survey: Research Report 65, V.P.I., Blacksburg, Virginia.

Walcott, R. I., 1975. Recent and Late Quaternary Changes in Water Levels: Trans., Am. Geophy. Un., v. 56, n. 2, pp. 62-72.

Warnke, D. A., V. Goldsmith, P. Grose, and J. J. Holt, 1966. Drastic Beach Changes in a Low-Energy Environment caused by Hurricane Betsy: J. Geophy. Res., v. 71, n. 6, pp. 2013-2016.

Wayne, C. J., 1976. The Effect of Sea and Marsh Grass on Wave Energy: Coastal Research, v. 4, n. 7, pp. 6-8.

Whitten, E., 1964. Process-response Models in Geology: Geol. Soc. Am. Bul., v. 75, pp. 455-464.

Wilson, B. W., 1965. Numerical Prediction of Ocean Waves in the North Atlantic for December, 1959: Deutsche Hydrographische Zeitschrift, Heft 3, p. 126.

Wolman, M. G., 1968. The Chesapeake Bay: Geology and Geography, p. II-7 to II-49, in Proc. of the Governor's Conf. on the Chesapeake Bay, Baltimore, Maryland.

Zeigler, J. M., and B. Gill, 1959. Tables and Graphs for the Settling Velocity of Quartz in Water, above the range of Stokes' Law: Ref. 59-36, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, 13 p.

Zeigler, J. M., G. G. Whitney, and C. R. Hayes, 1960. Woods Hole Rapid Sediment Analyzer: Jour. Sed. Pet., v. 30, n. 3, pp. 490-495.

# VITA

## Peter Stuart Rosen

Born in Brooklyn, New York, August 15, 1949. Graduated from Glen Cove High School, Glen Cove, New York, June, 1966 and State University College, Potsdam, New York, June, 1970 (B.A., Geology). Received M.S. degree in Geology at the University of Massachusetts, Amherst in 1972 (Thesis title: Evolution and Processes of Coatve Beach, Nantucket Island, Massachusetts: A cuspate spit shoreline).

Entered the Virginia Institute of Marine Science in January, 1973.