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# System Response of a Nourished Beach in a Low-Energy Estuarine Environment, Gloucester Point, Virginia

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# SYSTEM RESPONSE OF A NOURISHED BEACH IN A LOW-ENERGY ESTUARINE ENVIRONMENT, GLOUCESTER POINT, VIRGINIA

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A Thesis

Presented to

The Faculty of the School of Marine Science

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In Partial Fulfillment

of the Requirements for the Degree of

Master of Arts

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by

Tracy Eanes Skrabal

1987

APPROVAL SHEET

This thesis is submitted in partial fulfillment of
the requirements of the degree of

Master of Arts

Tracy Eanes Skrabal

Approved, December 1987

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TABLE OF CONTENTS

## DEDICATION

This thesis is dedicated to the memory of Dr. John M. Zeigler, whom I greatly admired for his love of science and of life.

## ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my committee chairman, Robert J. Byrne, and committee members John D. Boon, III, Carl "Woody" Hobbs, III, L. Donelson Wright, and Carl Hershner, for guidance, constructive criticism, and encouragement during this project.

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I would also like to thank Gary L. Anderson for his help throughout this project; the staff of the library and the computer center for their assistance and patience; and Malcolm Green for his valuable and willing assistance many times during this study.

Finally, I would like to thank my family for their support over the years, Sandy Booth, for his support and friendship, and my husband Steve, whose faith and understanding will always be appreciated.

LIST OF TABLES

## LIST OF FIGURES

## LIST OF APPENDICES

ABSTRACT

The present study characterizes the response of a nourished beach at an estuarine site fronting the Virginia Institute of Marine Science (VIMS) at Gloucester Point, Virginia, on the York River estuary.

An equilibrium shape has been defined for a typical pre-nourishment profile using Dean's (1977) model for equilibrium beach profiles which assume the form $h = Ax^m$. A least squares approach has been utilized to calculate values for A and m for the study site. The lack of fit of the pre-nourishment profiles to Dean's theoretical equation $h = Ax^{0.67}$ may be explained by differences in geomorphology between this estuarine site and the open ocean sites analyzed by Dean (1977). Emplacement of a relatively thick wedge of sediment during nourishment provided unconsolidated material necessary to achieve smoothly concave form described by Dean. Post-nourishment profiles more closely approximate values of A and m found by Dean (1977).

Results of the definition of an equilibrium beach profile for the pre-nourishment site have been utilized to develop fill criteria for various grain sizes to achieve a given seaward advancement of the shoreline.

Temporal and spatial changes in sediment volume have been characterized to better develop renourishment schedules and minimize fill losses in the future. Approximately 1,255 $m^3$ (net) of material were lost during the 26-month study, or approximately 16% of the fill emplaced in 1983. Material eroded from the sediment-starved northern segments has been continuously supplied to downdrift segments of VIMS and Gloucester County public beach. Net losses from the public beach during the study period were approximately 30% of that lost from VIMS beach. Volume change data suggest that survey intervals which included seasonal northeasterly and easterly storms were characterized by highest net losses of sediment and gross volume changes resulting from sediment transport within the system.

# SYSTEM RESPONSE OF A NOURISHED BEACH IN A LOW-ENERGY ESTUARINE ENVIRONMENT, GLOUCESTER POINT, VIRGINIA

## 1. INTRODUCTION

Increased attention to the rising costs of mitigating shoreline erosion in coastal communities has led to greater public awareness of the need to develop reliable methods of estimating rates and magnitudes of beach erosion over time and during storm events. In addition to the natural erosive processes along coastlines, human intervention in the form of shoreline development, modification of inlets, construction on primary dunes, mining of beach material, and emplacement of shoreline structures for protection increases the potential for shoreline erosion. Such intervention represents a disturbance in the natural supply and/or transport of sand to a beach. The result is sediment starvation and increased erosion of the shoreline. In areas of commercial and private development, therefore it is desirable to conduct preliminary evaluations of alternatives such as the emplacement of coastal structures, beach nourishment and implementation of setback laws.

Shoreline erosion will exist as long as sea level continues to rise. Assuming that the incident forces remain constant, beach nourishment, the emplacement of sand on an eroding shoreline, can be a successful technique for mitigating erosion and protecting against damaging storm events. Nourishment projects are replacing the construction of shoreline structures because they can improve a beach's recreational and aesthetic benefits. They may also present less of an environmental risk than the rock or bulkhead alternatives. Successful nourishment projects result in seaward extension of the shoreline and increased elevation of the beach profile. Widening of a beach increases dissipation of wave energy and supplies additional material for transport in a sediment-starved system. Unsuccessful nourishment, while costly, only results in rapid redistribution of sediment until existing forces restore the shoreline to equilibrium.

Efforts to control shoreline erosion along the more than 12,900 kilometers of shoreline of the Chesapeake Bay have been initiated at many localities. Beach preservation, however, has not been uniformly achieved in all settings. In some areas, a continuous network of groins and bulkheads serves as a partial barrier to the natural supply of sediment from the eroding fastland to the adjacent shorelines.

## 1.1 Research Goal

There have been many project summaries of beach nourishment effects on open ocean coasts. Little research exists, however, regarding the functional behavior of restored beach systems. Even less information exists for micro-tidal, estuarine shorelines of limited fetch. These are settings in which the mechanism of change are relatively short in duration when compared to open coast beaches.

The goal of this study is to characterize the response of a nourished beach at a site on the York River. Results will be used to assess the effectiveness of the design in achieving an equilibrium beach slope. Recommendations will be made to better achieve this goal for future beach nourishment projects. Results and design recommendations may be applied to analogous situations, determined by assessments of the influences of wind, waves, tides and the associated currents, geographic setting and natural beach state. The basic goal can be separated into defined objectives which are summarized below and discussed in detail in the following section.

## 1.2 Objectives

The first objective is to characterize the native beach profile. This will involve description of an equilibrium shape for the site based on its sediment characteristics. The measured profile will be analyzed to assess how well the observed profiles may be represented by Dean's (1977) model for equilibrium beach profiles which assumes the form

$$h = A x^{m}$$

where $h$= water depth

$A$= scale parameter

$m$= shape factor

$x$= distance seaward of the point of origin

A least squares approach will be utilized to determine the best fit of A and m for a given profile for this beach.

Dean's model was developed from the analysis of open ocean sandy beaches along the U.S. Atlantic and Gulf coasts. The present estuarine study site is characterized by chronic erosion and lack of a continuous sediment supply to the shoreline. In contrast to most ocean beaches, this estuarine study site is characterized by relatively large tidal influence in comparison to wave heights, two major forces affecting profile shape. Calculation of a theoretical profile for the study site based on Dean's model will be used to determine if any values found in Dean's ocean sites approximate those found in an estuarine site.

The second objective is to assess the suitability of selected fills for nourishment material. Suitability is generally defined as the ability to achieve an equilibrium shape with minimal loss of material during redistribution. The assessment will be based on the known relationship between grain diameter (D) and the scale value (A) which is presented in Moore (1982). Volume fill criteria will be determined for varying grain sizes to achieve a given seaward advancement of the shoreline. In addition, borrow fill material chosen for the 1983 nourishment project will be compared to native material in terms of grain size characteristics.

The third objective is to categorize changes in profile shape and sediment volume for the nourished shoreline during storm and non-storm periods. It is not expected that the nourishment of the shoreline will provide permanent stability but instead will temporarily dissipate wave energy and will supply sediment to downdrift segments. Changes in shape and sediment volume will be described and the loss of fill material will be characterized as long-term gradual losses or episodic in nature. The spatial variability in volume change, primarily governed by the presence of sediment retaining groin-like structures and piers along this shoreline will be characterized. These structures impede the alongshore transport of sediment creating relatively stable segments of shoreline.

Changes in beach profile form and sediment volume are influences by wind, waves, tides, and the associated currents. Conditions monitored during periods of significant change and periods of minimal change will be used to describe the relative importance of these conditions in altering the study area's shoreline.

### 1.2.1 Equilibrium beach profiles and beach nourishment projects

The ideal condition of a successfully designed nourishment project is one in which the beach is displaced seaward by a defined amount, restoring the shoreline to that of a previous time, when the previous shape represented an equilibrium condition (Komar, 1983). The concept of the equilibrium beach profile represents an ideal condition which will exist only under steady conditions of tides, winds, and waves (Tanner, 1958).

Bruun (1954) analyzed beach profiles from Mission Bay, California and the Danish North Coast. Using rates of erosion at various distances offshore, Bruun developed the empirical equation between water depth, h, and the distance, x, offshore

$$h = A\ x^{2/3}$$

Bruun presented two mechanisms to achieve the equilibrium beach profile:

1. onshore component of shear stress is uniform, and the onshore component of the gradient of transport of wave energy is constant; this approximates the empirical equation

$$h = A\ x^{2/3}$$

2. Losses of wave energy results only from bottom friction, and loss per unit area is constant. The profile then takes the form

$$h = A\ x^{2/3} / \ T^{4/9}$$

Based on the previous work of Bruun (1954, 1962), Dean (1977) presented three mechanisms which produced an equilibrium beach profile of the form

$$h = A\ x^{m}$$

where A depends on the stability characteristics of the bed material, and the exponent, m, depends on the type of destructive force considered. Dean makes the assumption that both constructive and destructive forces exist in the surf zone which transport sediment in the onshore and offshore directions. The three destructive forces presented by Dean were:

1. Uniform longshore shear stress based on the concept of radiation stress (Longuett-Higgins, 1970)
2. Turbulence, considering wave energy dissipation per unit surface area to be uniform
3. Turbulence, considering wave energy dissipation per unit volume of water to be uniform

Development of the three equilibrium beach profile forms are presented in detail in Dean (1977). The form is based on a consideration of spilling breaking waves across the surf zone, where no gradients in energy dissipation exist across the surf zone. The energy dissipation is slope dependent. This implies that a sediment particle in the surf zone, which is typified by a steep energy gradient, will be transported offshore until the gradient is reduced and an equilibrium slope is achieved. Conversely, the particle will be transported landward when the gradient of energy is less than the equilibrium energy dissipation of that particle. This will increase the slope until the equilibrium slope is attained (Moore, 1982).

Dean's application of a least squares procedure to 502 beach profiles along the East and Gulf coasts of the United States yielded values for m and A for each profile. The histogram of m values revealed a dominant value of 0.67, in close agreement with the value of 2/3 determined by Bruun (1954). Dean's findings indicated that turbulence due to uniform wave energy dissipation per unit volume of water was the destructive force responsible for the profile form.

Because of the dynamics involved, the equilibrium beach state is a condition which may be approximated but is seldom achieved in nature as a static state. The concept, however, has value in the evaluation and design of nourishment projects. The nourishment of a shoreline represents a disturbance in the natural beach system. As the newly created profile attempts to achieve a more stable form, there is a seaward shift of the profile, and a straightening of the contours. The result is a wider, flatter beach.

The present study will attempt to describe the equation for Dean's equilibrium model-curve using existing sets of profiles from the VIMS shoreline. Derived values of A and m will be utilized to calculate a theoretical equilibrium model-curve for this shoreline. The model curve will, in turn, be used to develop recommendations for future site design criteria for this site. Post-nourishment profiles and the natural curve will be used to predict present beach profiles. The predicted and measured profiles will be compared and analyzed.

The use of a model curve to evaluate the data set facilitates design of nourishment projects with a minimal loss of fill material. However, certain assumptions are necessary. The equation $h = A x^m$ describes a profile representative of uniform wave energy dissipation per unit volume of water in the surf zone. It assumes a lack of wave energy and transport gradients, so that a condition of no net erosion or accretion results. As such, the equation applies only to that portion of the profile defined by this condition and does not include the upper beach face and berm.

The relative effects of other process parameters are ignored in the conditions which govern the application of this model. Interpretation of the fit of the curve is thus constrained. It is most appropriately used in conjunction with assessments of volume change and analyses of incident conditions.

### 1.2.2 Sediment characteristics

The success of a nourishment project depends largely on the compatibility of native and beach fill material. If the fill material has the same or coarser characteristics as the native bed material, the equilibrium shape for that beach will be approximated with a minimal loss of material during the initial adjustment. An excess of fine material will result in the resuspension and offshore and alongshore transport of the sediment to a point at which the wave energy is sufficiently low to provide a more stable situation. Coarser material results in a landward transport to the beach face and berm, but may not be distributed across the entire profile. In this situation, waves will break closer to shore, resulting in a concentration of energy within a narrowed surf zone (Moore, 1982).

Based on the general relationships of grain size and retention times, the suitability of fill material will be evaluated with reference to the theoretical model for an equilibrium profile. The mean grain diameter of the native material will be determined and compared with hypothetical material of both larger and smaller mean grain diameters. The volume of each material required per unit length of shoreline to achieve any given shoreline advancement will be determined. The methodology to achieve this objective follows that presented in Dean (1983).

The assumption implicit in this analysis is that each data set of profile points may be characterized by a single grain diameter value and an associated scale value. While grain size along a profile obviously varies in relation to the different energy zones, this assumption may be accepted for the purpose of describing that portion of the profile governed by uniform energy dissipation on a gently sloping surf zone. The variation of grain sizes associated with any scale value of A would likely be included within a given data set, given the logarithmic nature of the scale value relationship and grain size, as defined by Moore (1982).

### 1.2.3 Volume change

The emplacement of sand nourishment along a shoreline is a perturbation in the system. Consequently, incident conditions rework the material to create an equilibrium profile for that beach.

Nourishment material often is eroded more quickly than natural sediment until that shoreline approaches the pre-project profile; this transport of material occurs as losses from the ends of the project fill and losses of the finer fraction through resuspension and transport during the initial readjustment of the profile. The process which governs the redistribution is expressed by the diffusion equation. The alongshore transport of sediment is analogous to the diffusion of heat from a warm segment of an insulated bar in that heat flux loss occurs only in the direction of the long axis. With a nourishment project, this process of fill loss will be accelerated on shorelines where project fill length is short relative to the beach width (Dean, 1983).

It is hypothesized that the VIMS nourished beach will experience more rapid volume loss than the pre-project shoreline. This will continue until the beach profile approaches a shape closely approximating the natural form. At that time, the beach will erode at a rate similar to that of the pre-project shoreline.

It is anticipated that the loss of volume from this beach will not occur uniformly along the project length. This is due to the presence of several groin-like structures and piers which trap littoral drift material and provide downdrift protection during storms. The northern segment of shoreline, remains exposed to direct wave attack during storms and lacking of an updrift sediment source, should experience the greatest rate of loss for this site.

During pre-project storm events, some resuspended material was deposited just offshore as a temporary bar. Other resuspended material was transported alongshore, in a narrow zone which terminated at the point in the vicinity of the profile 60.

It is expected that material transported from the VIMS beach may temporarily nourish the downdrift public beach. It is probable that most of this sediment will eventually be transported alongshore and deposited into the deeper channel or in the protected segments near the boat ramp, where wave agitation is sufficiently low to allow deposition of this material.

## 1.3 Process Parameters and Shoreline Changes

The processes of erosion and accretion in estuaries are governed by the relative influences of tides, waves, density gradients, meteorological effects and river inflow (Davis, 1985). The relative contribution of each parameter is site specific, although an understanding of the relative importance of these processes for one site may be applied to beaches with similar geographic setting and incident conditions.

Many studies exist which analyze the relative influence of process parameters in the resulting shoreline changes. Studies of beaches along southern California (Thompson and Thompson, 1919), (LaFond, 1939) have shown that tide-induced changes on the beach profile were more notable during the summer months when wave conditions were relatively constant. During the fall and winter storms, the wave and wind conditions affected the shoreline much more than did the tidal fluctuations.

From studies of the beaches of the Northwest Gulf of California, Inman and Filloux (1960) reported fortnightly cycles of erosion and accretion which result from the combined effects of the wave and tide range cycles. In this area of California, the tide ranges are relatively large when compared to wave heights, resulting in beach profiles with relatively steep sloping faces which terminate at the base into a wide low-tide terrace. As the tide level undergoes maximum changes, the available wave energy is rapidly translated across the terrace. During the high and low water stillstands, this wave energy becomes concentrated at these corresponding still levels. This concentration of energy resulted in a difference in slopes between the beach face, which generally consists of coarse sediment, and the terrace, which was generally rippled, finer-grained material (Komar, 1976).

Warnke et al. (1976) analyzed the processes of shoreline recession in a low-energy coastal environment on the western coast of Florida. He concluded that shoreline recession is primarily controlled by surges which elevate water levels to the back dune ridges, and not by the wave heights during these events. Rosen (1976) observed a similar trend in the Chesapeake Bay. Rosen reported an inverse relationship between tide range and erosion rates in the Chesapeake Bay, indicating a higher tide range resulting in lower erosion rates for a given set of conditions. He suggested that a larger tide range is more effective in creating a shoreline buffer from the erosional processes on Chesapeake Bay's shoreline. In addition, these areas experience a distribution of wave energy over a larger vertical and horizontal area in the course of a tide cycle.

The VIMS shoreline is characterized by a relatively steep beach face which grades abruptly into a gently sloping low-tide terrace. This area has a tide range of 0.7 meter (United States Department of Commerce, 1987). When compared to ocean coasts, the range is relatively large when compared to the incident wave conditions which result from the relatively shallow and protected nature of this estuary. The shoreline and offshore bathymmetry typifies the lower Chesapeake Bay, and is characterized by broad, flat terraces of coarse to fine sediment, which extend from low water to approximately the 3.6 meter contour. A break in slope delineates the seaward extent of the terrace, where the shore bottom grades into deeper water. Rosen (1976) suggested that this feature is primarily a remnant erosional platform. His opinion is based on field investigations which showed that terraces often exist as erosional cuts into pre-Holocene sediments.

For the study shoreline, the winds which blow from the northeast to east, the distance of greatest fetch, have the greatest potential for creating profile response and volume changes. During seasonal storms, the interraction of high tides and winds which blow steadily from these directions create a piling up, or "set-up" of water along the shoreline. Because wind wave energy is inversely proportional to water depth, and tide energy is directly proportional to depth, the maximum bottom wave orbital velocities are decreased during higher water levels, while maximum near-bottom tide velocities increase with increasing depths (Allen, 1971). Maximum wave amplitudes are further constrained by the relatively shallow water depths and short fetches which characterize this shoreline. As a result, it is likely that elevated tide levels, amplified by a storm surge, and currents associated with these events will be more effective processes in resuspending sediment, resulting in changes in the profile shape and sediment volumes of this beach.

## 2. STUDY SETTING

### 2.1 Geological History of the Area

The evolution of Quaternary estuaries was characterized by periods of alternating glacial and interglacial periods and the associated climatic changes and eustatic sea level fluctuations (Schubel and Hirschberg, 1977). Chesapeake Bay estuary was formed during the most recent Pleistocene rise in sea level, which began approximately 15,000-18,000 years ago. The estuary developed as a drowned valley of the Susquehanna River Valley system as sea level rose into the bay basin nearly 10,000 years ago (Schubel et al., 1972). The bay retains the topographic features of a youthful river valley including a meandering outline, triangular cross-section, and a general widening from the head to the bay mouth (Dyer, 1979).

Erosion of the shoreline within as well as outside of the Chesapeake Bay is a principal source of sediment to the beaches. Chart comparisons show a recession of as much as 700 meters on some of the headlands within the bay between the 1840's and the 1940's (Meade, 1974). Summarized results from various studies of erosion rates within the bay estimate a net loss of nearly 27,900 acres ($1.1 \times 10^8$ square meters) between 1850 and 1950 (Hobbs et al., 1981). Byrne and Anderson (1977) indicated that over $2.1 \times 10^8$ cubic meters of material were eroded from the Virginia portion of the Chesapeake Bay over this same period. The sand derived from this erosion is the primary source of material for the estuarine beaches, while the channels and flank areas receive most of the silt and clay fractions (Hobbs et al., 1981).

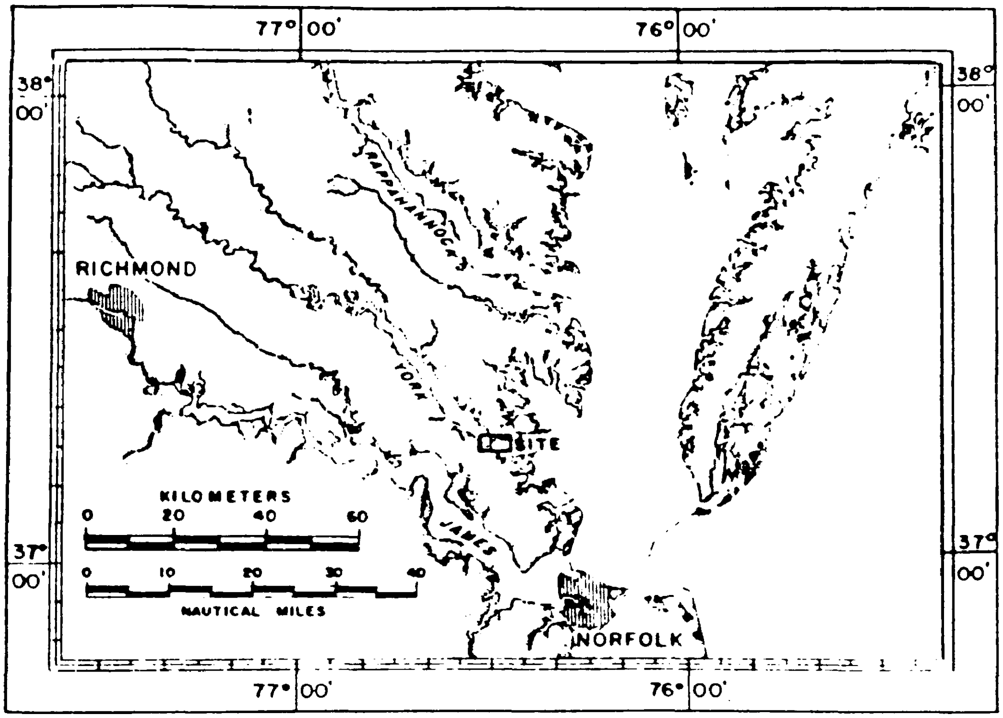
## 2.2 Study Location

The study area is an estuarine beach located at the Virginia Institute of Marine Science at Gloucester Point, Virginia (Figure 1). The south-eastward facing shoreline (approximately 400 meters long) is adjacent to a deep channel of the York River estuary within Chesapeake Bay system. The shoreline is oriented approximately N52$^{o}$E and has an average fetch to the southeast across the York River and Chesapeake Bay of approximately 20.24 kilometers. The greatest exposure to the study shoreline exists for a vector which runs nearly due east. The fetch and offshore bathymmetry dictate the wave climate at the VIMS shoreline.

The offshore bathymmetry along a shore-perpendicular profile shows the 2-meter contour to be approximately 0.18 kilometers offshore, and the 5.5-meter contour approximately 0.31 kilometers offshore. At this point the depths drop off significantly into the central portion of the channel portion of the York River. The mean tidal range at Gloucester Point is 0.72 meters and the spring tidal range is 0.88 meters (United States Department of Commerce, 1987).

The geology of the bank area along this shoreline is given in Figure 2, taken from a 1982 report on test borings. The bank portion is composed of fine- medium sand of the Windsor Formation which overlies the moderately to highly indurated fossiliferous Yorktown Formation. The contact between the Windsor and Yorktown Formations occurs in most places just above Mean Low Water (MLW) and serves as an aquaclude to downward percolating groundwater. Several springs exist along this

Figure 1. Site location in the Chesapeake Bay, Gloucester Point, Virginia.


77° 00'
76° 00'
38° 00'
37° 00'
RICHMOND
RAPPAHANNOCK
YORK
JAMES
SITE
NORFOLK
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0 20 40 60
0 10 20 30 40
NAUTICAL MILES

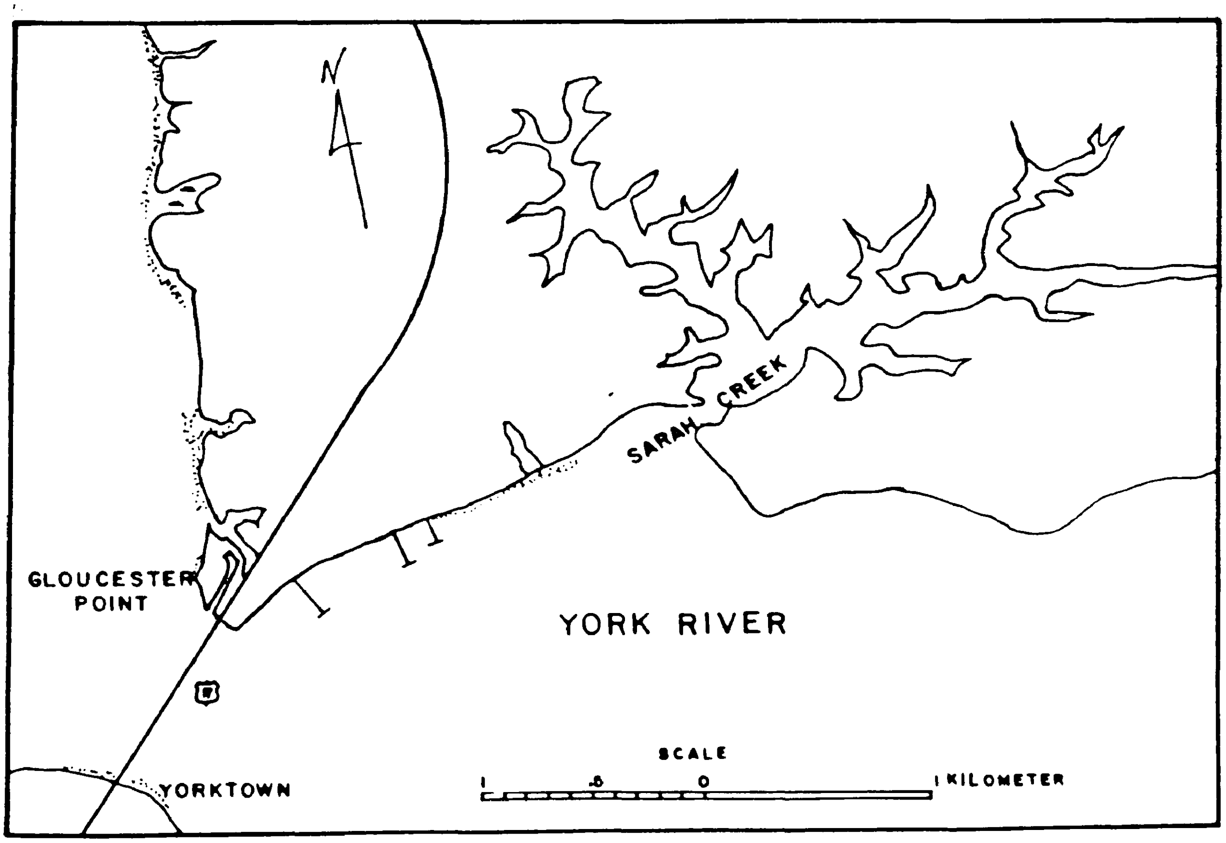

N
GLOUCESTER POINT
SARAH CREEK
YORK RIVER
YORKTOWN
SCALE
1 .5 0 1 KILOMETER

Figure 2. Geology of the bank area at study site, taken from boring log.

SCHNABEL ENGINEERING ASSOCIATES — TEST BORING LOG — BORING NO: B-7

CONSULTING ENGINEERS

Project Proposed Marine Science Service Center, VIMS — Sheet 1 of 1

Client Virginia Institute of Marine Science/Gloucester,Va. Job No. Vb2337

| Water Level Data | Date | Time | Depth | Caved | Drive | Sampler | |
|---|---|---|---|---|---|---|---|
| | | | | | | | Casing Size 25" |
| | Date | Time | Depth | Caved | Type | S.S. | Date Start 8-12-82 |
| Encount. | 8-12 | 12:00 | 35.0′ | - | Dia. | 2OD | Date End 8-12-82 |
| Casing | 8-12 | 12:40 | Dry | 20.1 | Wt. | 140 | Driller: Ayers |
| | 8-13 | 1:50 | Dry | 19.8 | Fall | 30 | Inspector: Adams |

| Depth(Ft.) | Elev. | Symbol | IDENTIFICATION | REMARKS |
|---|---|---|---|---|
| | 30 | | 4"+ Topsoil<br>Fine to Medium Sand, Some Silt,Moist Brown | |
| 7.0 | | | | |
| | 20 | | Fine Sand, Trace Silt, Dry-Tan | Windsor Formation |
| | 10 | | | |
| | 0 | | | |
| 34.0 | | | | |
| 44.0 | -10 | | Fine to Medium Sand, Some Silty Clay With Shell Fragments, Wet-Brown | |
| 50.0 | | | Fine Sandy Clayey Silt, With Shell Fragments, Moist, Gray | Yorktown Formation |
| | | | Boring Terminated at 50.0 Ft. | |

contact on the bank face. Groundwater from these springs issues through and under the existing bulkhead, which along most of its length, sits directly on the Yorktown Formation.

Longshore drift within the littoral system along the east shore has a net component to the S-SW, toward the point adjacent to the river channel. This is evidenced by an accumulation of material on the N-NE side of the existing groins between Gloucester Point and Sarah's Creek.

## 2.3 Recent Shoreline History

Photographic records indicate that VIMS's Eastern shoreline has been losing sand at a substantial rate since the late 1960's. This gradual but steady loss of material over the years can be attributed to the increased number of bulkheads and groins placed updrift of the VIMS shoreline. In 1937, no structures existed between VIMS and Sarah's Creek; 24 groins or bulkheads were present in 1960; and 105 groins, bulkheads or rip-rap projects existed in 1982. The net effect of these structures is a restriction of the source material supplied by bank erosion to the beach. In addition, existing concrete bulkheads along the back beach area reflect incident waves and consequently cause scour of material away from the shoreline.

By 1976 erosion of the unprotected shoreline between Clayton House and Maury Hall had reached a critical state and led to the completion of a continuous bulkhead fronting VIMS in 1977. By 1978 the beach width had reduced significantly in the area of Clayton House, resulting in direct wave attack on the wall during moderate storm activity and the permanent removal of material by reflected waves. During the fall of 1982, Maury Hall was in danger of structural failure due to the loss of material and undermining of the footing of its concrete wall. In addition, the entire beach width along the VIMS shore had been reduced in response to the reduction of updrift fastland material to the shoreline.

The ongoing risks of structural failure and permanent removal of beach material led to the implementation of an Emergency Seawall Project in September of 1983. The project included the design and construction of approximately 402 meters of emplaced granite stone rip-rap fronting the seawall. Design dimensions varied from a crest elevation of 2.0-2.6 meter (above mean low water) extending to -0.6 meter (below mean low water) with a 2:1 face slope (Figure 3). Nourishment of the shoreline was achieved with the emplacement of approximately 7,600 $m^3$ of material to create a beach with a 12 meter berm. Finished design elevations ranged from 1.8-2.1 meter above mean low water. The length of shoreline to be nourished was approximately 244 meters, with a design slope for the beach face of 10:1. The design and implementation of the structures and nourishment were tailored according to existing structures and the degree of exposure at each portion of the beach, which was sectioned into six discrete cells for design purposes (Figure 4). Detailed descriptions and design cross-sections for each segment are provided in the Preliminary Shoreline Erosion Control Plan for the Virginia Institute of Marine Science (Anderson and Hardaway, 1982).

Figure 3. Project design profile cross-section, VIMS, September 1983.

TYPICAL SECTION

VIMS BEACH

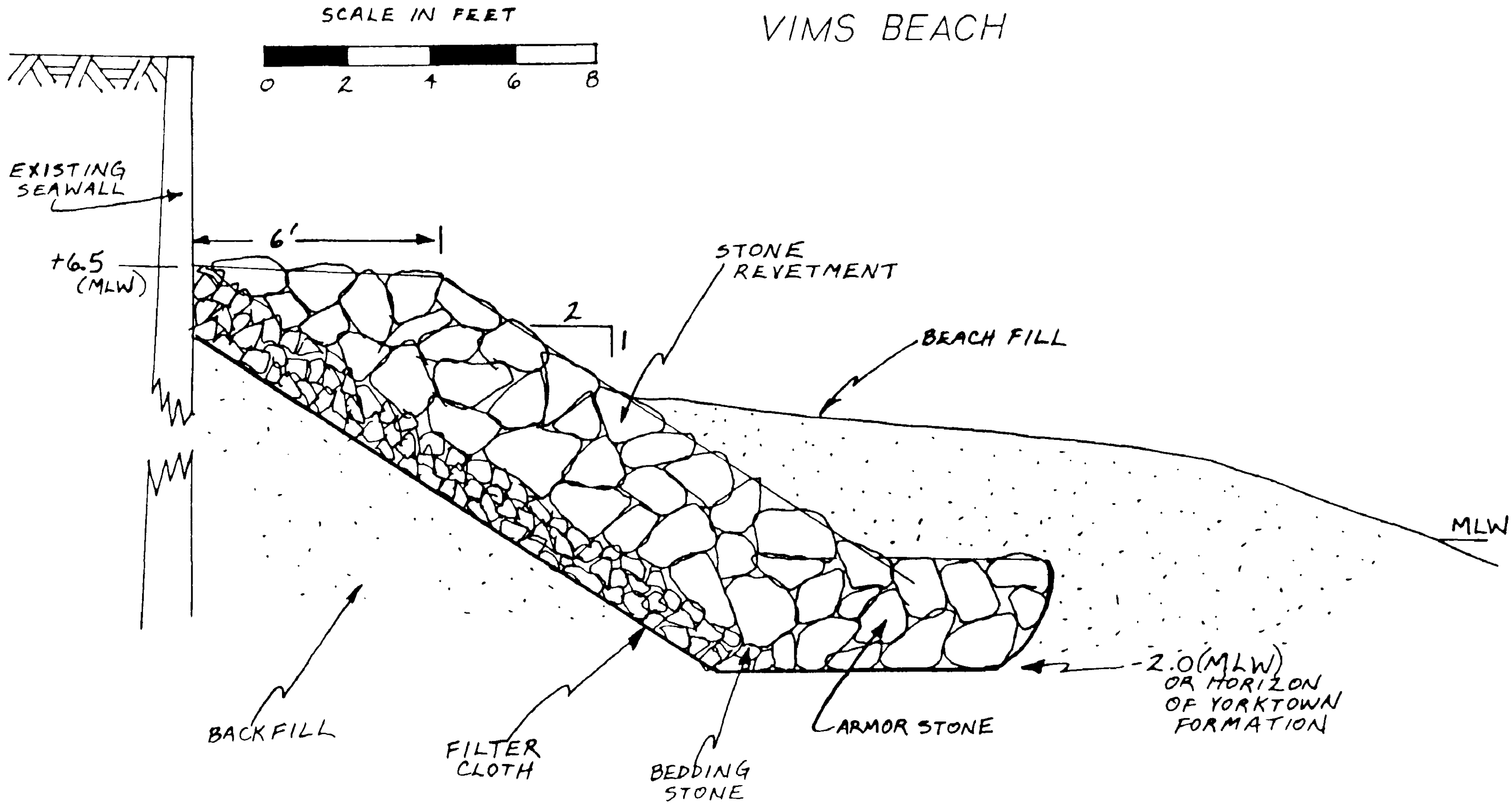
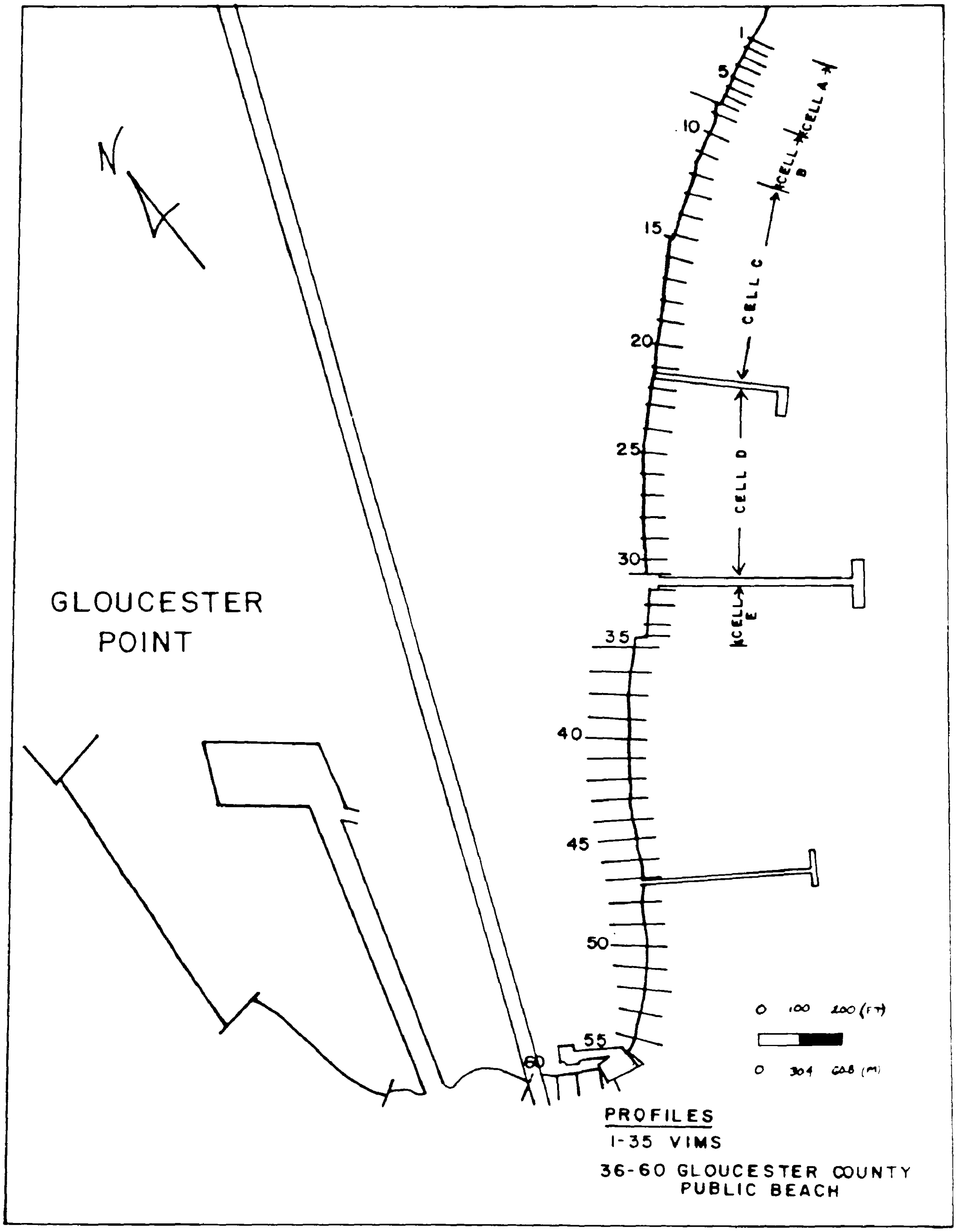


Figure 4. **Location of profile transects, profile cells along VIMS, Gloucester County Public Beach.**


N
GLOUCESTER POINT
1
5
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55
60
CELL A
CELL B
CELL C
CELL D
CELL E
0 100 200 (FT)
0 30.4 60.8 (M)
PROFILES
1-35 VIMS
36-60 GLOUCESTER COUNTY PUBLIC BEACH

## 2.4 Study Summary

The present study examines the beach's response following completion of the nourishment and emplacement of the stone riprap revetment. During the period prior to the construction, preliminary baseline data were collected.

Sixty beach profiles were established along the shoreline at 15.2 meter (50 ft) intervals extending from the southern property line of the Gedding lot to the boat ramp located on the Gloucester County Public Beach. The location of these profile lines are given in Figure 4.

In addition to the beach profiles, pre-nourishment sediment samples were collected along established profiles, as well as from the borrow pit chosen as the source of nourishment material. Grain size analysis of these samples were compared to determine sediment suitability of the borrow material as fill material.

Continuous tidal records are monitored by NOAA tidal gauge on the VIMS oyster pier, and the information stored on a computer system. In addition, wind speeds and direction are recorded continuously with an anemometer located on the roof of Byrd Hall at VIMS. These data have been used to characterize typical and storm conditions. Observations of wave angle of approach were made with a Brunton compass, and wave height and period were estimated from wave staffs attached to stand-off pilings in two offshore locations. This information was monitored frequently during events of high wind and wave activity and during periods of significant sediment entrainment.

## 2.5 Physical Considerations During the Study

The study was initiated in August 1983, during which time baseline data were collected prior to construction of the Emergency Seawall Project. Construction was completed in October 1983; Figure 5 shows pre- and post-construction views northward from the oyster pier, located between profiles 21 and 22.

During the period of the study (August 1983-November 1985) winds ranged from calm to a maximum of 80.5-96.5 km/hr. Wave activity for this period ranged from flat to 1.07 meters. General observations for the duration of the study indicate that the majority of wave activity ranged from 1-2 second wind waves with heights less than 0.15 meter, except during storm events. This results from the fact that this locality is protected in most directions by a relatively limited fetch. Higher wind speeds and wave heights are associated with the longer fetch to the east and northeast, and are most capable of erosive damage to this shoreline. Winds of 16-24 km/hr which blow steadily from the east the northeast for several hours are sufficient to cause entrainment of material and transport of sediment along the shoreline.

Fifteen storms occurred during the study of magnitude sufficient to create significant erosion of the study shoreline. Of these, five were characterized by waves with heights of 1 meter and wind velocities greater than 55 km/hr. Storm surges of 0.3-0.6 meter were characteristic of these events (observed water level minus the predicted tide level).

Figure 5. Pre- and post- construction photographs, taken from VIMS Oyster Pier.

# 3. DATA COLLECTION AND REDUCTION

## 3.1 Beach Profiles

Sixty profile lines were established. The location of these profiles are given in Figure 4.

The profiles were established at 15.2 meter (50 feet) intervals where feasible, although additional lines were surveyed to include areas of concern. Survey measurements were conducted with an automatic level and stadia rod. Permanent monuments were established at points located along the seawall, on driven nails or permanent stakes. These reference points were level surveyed to a fixed NOAA National Ocean Survey Tidal Bench Mark (BENCH MARK NO 8 1950 RESET 1973). Survey lines proceeded seaward approximately perpendicular to the shoreline along established azimuths; horizontal control was maintained for each profile line by the alignment of two separated range objects. Profile points were taken to include the revetment shape, notable breaks in beach slope, and points at approximately 15.2 meter intervals seaward of the nearshore zone, to within 60-90 meters of the shoreline. Readings are precise to +/- 0.3 cm. in the vertical and +/- 0.3 m. in the horizontal plane. Individual surveys took ten to fifteen minutes per profile. The 60-profile set was conducted over several days to coincide with mean low water. For this reason, surveys were staggered to include the entire length of the beach in one survey date, in the event a storm occurred during the survey period. The origin of the coordinate system on which all surveys were based is the fixed monument location on the horizontal and mean sea level in the vertical, as determined from Benchmark No. 8.

Care was taken to maintain alignment of the instrument and the position of the rod holder using range markers along pre-determined azimuths. Distances were calculated in the field to ensure accuracy of the rod readings. Elevations were checked in the field to ensure that the stadia elevation (E) - upper stadia (US) = stadia elevation (E) - lower stadia (LS),

that is

$$US - 2E + LS = \quad = 0$$

Distance is given as

$$D = (US - LS) X 100$$

where

D= distance in meters

US,LS= upper and lower stadia readings

Repetitive surveys of a given profile were conducted and gave acceptable repeatability and an accuracy of +/- 3% from volumes calculated for the 15.2 meter profile cell.

## 3.2 Survey Frequency

Complete surveys of sixty profiles were conducted prior to construction and nourishment, immediately following completion, and on a monthly basis until July 1984. Surveys were continued on a bi-monthly basis until January 1985, and a single survey in November 1985.

In addition to the surveys of the sixty-profiles, unscheduled surveys of selected profiles were made on a daily basis during and after storms and periods of unusually high water. A complete table of survey dates and profiles included in each survey is given in Tables 1 and 2.

3.3 <u>Profile Data Reduction</u>

Survey data were recorded in field notebooks and later transferred to a Prime 9955 Computer for analysis. Programs for entry of the field data enabled one to view the data in plot form to facilitate the detection of spurious data points. Programs were developed for later use in the analysis of changes in area and volume, as well as spatial and temporal analysis with Surface II programs.

Profile lines were reduced to give the following:

1) Changes in individual profile cross-sectional areas above, or between established vertical tidal datums (mean sea level, mean low water, etc.) relative to previous profile surveys or a long-term mean. The cross-sectional area of a single profile was calculated within the following lines: a vertical line projected from the landwardmost point on a single profile; a horizontal line at the chosen datum elevation; the surveyed profile lines. The areal changes were determined by subtraction of the current profile area from previous surveys, or from the established long- term mean cross- sectional area (Figure 6).
2) Volume is determined as a cross-sectional area multiplied by a unit width. Programs developed to calculate total area and volume changes utilize an averaged end-area method which computes cross-sectional areas of vertical slices distributed over the common survey regions being considered and bounded by the established tidal datums for calculations. These volume changes

Table 1. **Profile surveys for VIMS East beach, Gloucester Point, Virginia 1983-1985.**

PROFILE SURVEYS FOR VIMS EAST BEACH, GLOUCESTER POINT, VIRGINIA

1983-1986

| Date | Profile 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *15Aug83 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *28Sep83 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *29Oct83 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *28Nov83 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *25Jan84 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| 24Feb84 |  |  |  | x |  |  |  | x |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |
| 01Mar84 |  |  |  | x |  |  |  | x |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |
| 23Mar84 |  |  |  | x |  |  |  | x |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |
| *03Apr84 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *21May84 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *06Jun84 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *08Aug84 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| 10Sep84 |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x | x | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 12Sep84 |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x | x | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 13Sep84 |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x | x | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 14Sep84 |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x | x | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 30Nov84 | x |  |  |  |  |  | x |  |  | x |  | x |  |  |  | x |  |  |  | x |  | x |  | x |  |  |  | x |  |  |  |  |  |  |  |
| *09Jan85 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *20Mar85 | x |  |  | x |  |  |  |  |  |  |  |  |  |  |  | x |  |  |  |  |  |  |  | x |  |  |  |  |  |  |  |  |  |  |  |
| 26Sep85 |  |  |  |  |  |  |  |  |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  |  |  |  |  |  |  |  |  |
| 27Sep85 |  |  |  |  |  |  |  |  |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  |  |  |  |  |  |  |  |  |
| 28Sep85 |  |  |  |  |  |  |  |  |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  |  |  |  |  |  |  |  |  |
| 29Sep85 |  |  |  |  |  |  |  |  |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  |  |  |  |  |  |  |  |  |
| 30Sep85 |  |  |  |  |  |  |  |  |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  |  |  |  |  |  |  |  |  |
| 06Nov85 |  |  |  |  |  |  |  |  |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  |  |  |  |  |  |  |  |  |
| 08Nov85 |  |  |  |  |  |  |  |  |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  |  |  |  |  |  |  |  |  |
| *10Nov85 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| 09Jan86 |  |  |  |  |  |  |  |  |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  | x |  |  |  |  |  |  |  |  |  |  |  |

* First date of survey set only.

Table 2. **Profile surveys for Gloucester County public beach 1983-1985.**

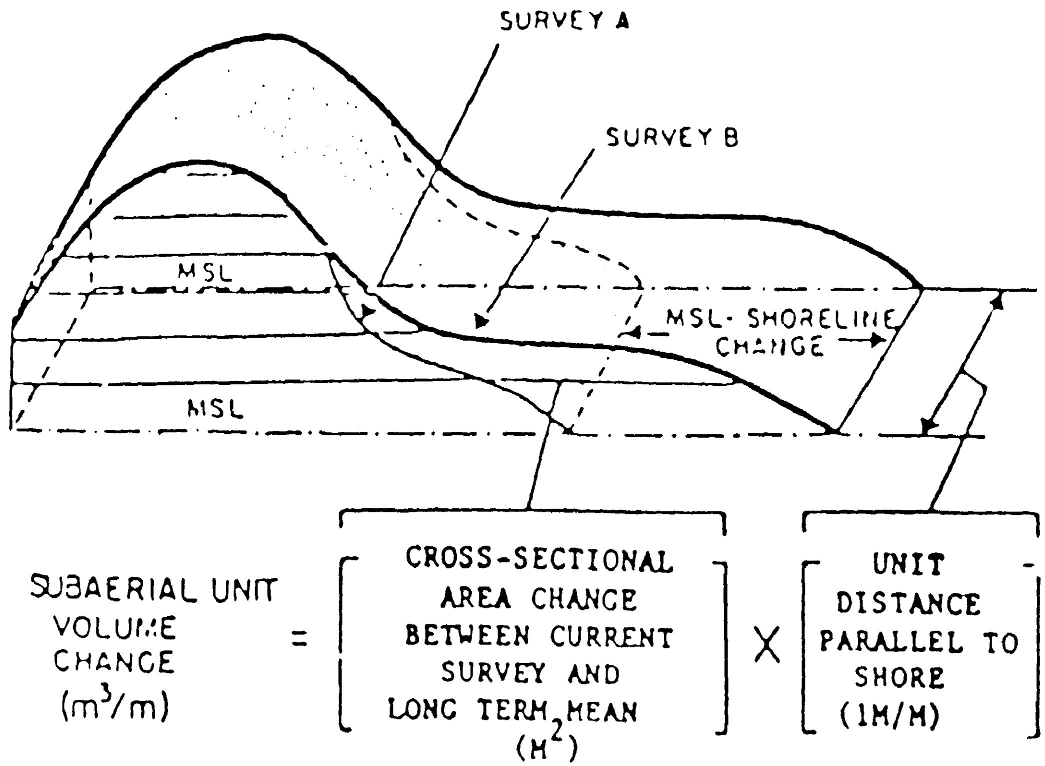
PROFILE SURVEYS FOR GLOUCESTER COUNTY PUBLIC BEACH

1983-1985

| Date | Profile 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *15Aug83 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *28Sep83 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *29Oct83 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *28Nov83 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *25Jan84 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *03Apr84 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *21May84 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *06Jun84 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *08Aug84 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *09Jan85 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| *10Nov85 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |

* First date of survey set only.

Figure 6. Definition of MSL changes and above MSL volume changes.


SURVEY A
SURVEY B
MSL
MSL
MSL- SHORELINE CHANGE
SUBAERIAL UNIT VOLUME CHANGE ($m^3/m$)
=
CROSS-SECTIONAL AREA CHANGE BETWEEN CURRENT SURVEY AND LONG TERM MEAN ($M^2$)
X
UNIT DISTANCE PARALLEL TO SHORE (1M/M)

are presented in terms of erosion (negative values) and accretion (positive values) between chosen datums.

## 3.4 Sediment Sampling

Sediment samples were collected along selected profiles prior to construction and nourishment (May 1983), immediately following completion of construction (October 1983) and again in January 1984, September 1984, and January 1985. Locations chosen along the profile were based on hydrodynamic zones, in order to give the most accurate representation of grain size distribution over time. Fixed distance sampling does not account for the constant mobility of these zones due to tides, waves, and the resultant changes in the profile configuration over time. The zones sampled included back beach, berm, beach face, intertidal zone (as approximated by the zone of mean high water- mean low water), beach step, and points extending offshore.

Samples were collected by two-person crews using a 12 cm long, 5.1 cm diameter core tube and stopper method. Alignment on the profile line was controlled by a third person located on the beach. Distances from the stake points were also recorded by the third person, again using the stadia rod and level technique.

Sediment was collected from three locations within the borrow pit to determine the area most suitable for fill material of the study site. All sediment samples were sieved at 1/2 $\phi$ intervals using standard techniques (Folk, 1968), and the percent sediment in each class calculated to obtain frequency weight percent curves. Results of this analysis were utilized to compute the phi($\phi$) mean and phi($\phi$) standard deviation. The computational procedure used is the method of first and second moments as presented by Folk (1968).

The first moment is given by

$$\text{first moment} = \frac{\Sigma fm\,\phi}{100}$$

where f = frequency (in percent) for each size class

and m 0 = midpoint of each 0 size class.

The second moment represents the measure of the dispersion about the mean and is given as

$$\text{second moment} = \frac{\Sigma f(m\,\phi - x)^2}{100}$$

By definition the first moment equals the sample mean x, so that

$$x = \frac{\Sigma f\, m\,\phi}{100}$$

and the second moment represents the number value of the standard deviation squared, so that the standard deviation ($\sigma$) is obtained by

$$\sigma = \left[\frac{f(m\,0 - x)^2}{100}\right]^{1/2}$$

(Friedman and Sanders, 1978).

Studies were conducted by Stauble et al. (1983, 1984) to provide an assessment of beach sediment characteristics of nourishment projects in Florida and New Jersey. The studies provided comparisons of grain size distribution curves of borrow versus native material, based on separate composites of the intertidal region (MLW- MHW) and a combined composite of intertidal and offshore samples. Samples from the present study were analyzed to provide the comparisons of borrow to native material. The composites were based on the classification developed by Stauble et al. (1983,1984).

3.5 Processes Data

A permanent tidal station on the oyster pier at VIMS provides a continuous tidal record. Tide levels are recorded at six minute intervals, and the record is stored continuously on a Prime 9955 computer. Tidal predictions are also available for the VIMS pier allowing a comparison of observed versus predicted tides to assess the difference resulting from storm surge.

During a portion of February and March 1984, Marsh- McBirney 2-axis electromagnetic current sensors (3.8 cm sphere) were deployed by Dr. J. D. Boon III off the VIMS oyster pier. These current sensors utilize a burst- mode sampling technique to determine directional orbital velocities. Data were collected at distances of 20 cm. and 70 cm. above the bed. The period of deployment included data collected during a storm on February 23, 1984. These records were analyzed to relate current directions and velocities during a storm in February, 1984 to the beach response.

It is well known that the processes of sediment accretion and erosion are controlled primarily by the interaction of the beach morphology and the existing surface wave field. Visual observations exist for the study area during periods of storm and significant wave activity, and were recorded for wave period and height using wave staffs in two offshore locations. Wave angle of approach on the VIMS and Public Beach shorelines were determined during these events utilizing a Brunton compass.

# 4. RESULTS AND DISCUSSION

## 4.1 Sediment Suitability

### 4.1.1 Background

Current literature of post-nourishment monitoring projects is lacking in consideration of native and beach fill sediment characteristics and the relative compatibility of borrow fill with existing material within the project limits. Limited funding, economically feasible sources of fill material, and the urgent nature of most beach projects rarely allow for comprehensive pre-construction sediment analyses, or analyses of post-fill sediment redistribution following project completion. Yet the compatibility between native and borrow grain size distributions is a critical element in the success of beach nourishment projects, as determined by retention time of fill material within the limits of the project area.

Retention of fill involves the process of incipient motion and transport of sediment. The initial motion for sediment of a given grain size depends on the forces of the fluid flow and the resisting forces of a particle to that flow. For spherical particles, the forces acting on a particle at rest are surface forces of drag and lift and the opposing body forces of gravity. In general, for material in the range of fine to coarse sands, an increase in grain size requires greater mean velocity of the flow to initiate motion of the sediment (Middleton and Southard, 1984). In terms of nourishment, then, material equal to or greater in grain size than the native material would result in increased retention time. Material which contains a high fraction of silts and clays may act as cohesive sediments with increased resistance to initial motion, but will remain suspended for long periods of time once resuspended in the water column, and may be transported permanently out of the system.

Stauble et al. (1984), pointed out that fill criterion presently is based on theoretical models such as those developed by Krumbein and James (1965), Dean (1974), James (1975), and Hobson (1977), and that field testing of such models has been conducted only on a limited basis. They argued that present methods of selecting beach fill are erroneous in several areas. When developing fill criteria, these theoretical models do not consider $CaCO_3$ shell material or other statistically non-normal grain size distributions found within the project areas; present practices often utilize a profile composite sample containing finer grained material found seaward of mean low water, which give a grain size distribution skewed in the fines from which to develop fill criteria.

The question investigated in the 1984 assessment by Stauble et al. was: What is a representative sample of native material for computing suitable beach fill material? Their study's results indicated that for the beach projects examined, sediment collected from the intertidal area (where most fill material was placed) was found to be the most representative of the native sediment in that zone and most closely approximated existing material in beach fill redistribution after placement.

The present study utilizes profile composites as developed by

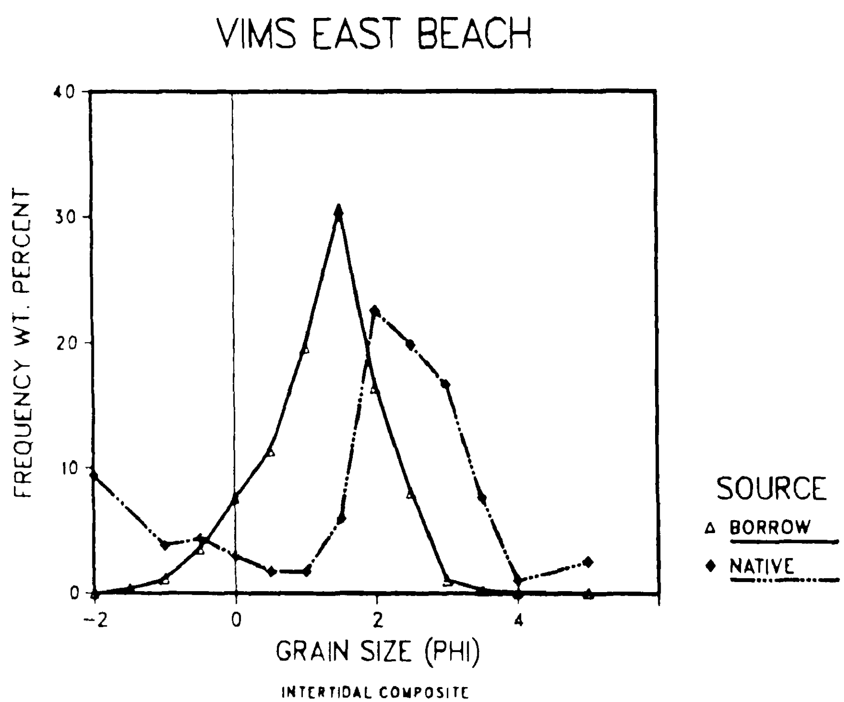
Stauble et al. (1984), to compare the fill material to native sediment. The samples include the intertidal composite, as approximated by the Mean High Water- Mean Low Water zone, and the combined composite, which includes the intertidal samples and samples collected seaward of Mean Low Water in the subtidal zone.

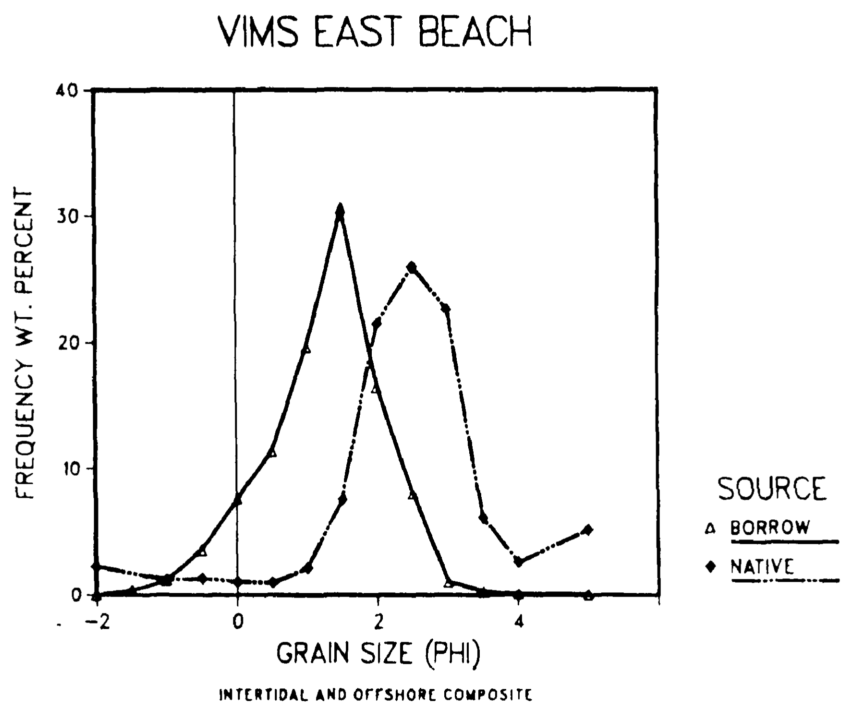
### 4.1.2 Comparison of Native and Borrow Composites

It is evident from Figure 7 that the borrow material sampled is better sorted and coarser than either the intertidal or combined composites of the native material. The fill material is dominated by an obvious peak in the medium sand range (1.5 ), according to the classification presented by Wentworth (1922), with very small percentages of very coarse sands and gravels and very fine sands and silts, and negligible clay.

While both the intertidal and combined samples are poorly sorted, it is obvious that the borrow material is more congruent with the intertidal sample than with the combined composite. Compared with the approximately 25% of material finer than 2 O (medium-fine sand) in the borrow sample, the intertidal sample contains approximately 55% of this material, while the combined composite consisted of as much as 85% of material finer than 2 O. The intertidal native material contains approximately 15% coarse sands and gravels, while the combined sample contains less than 5%. Thus, the combined composite sample would depict native material as being relatively fine material. The intertidal material, which would ultimately be the zone of emplacement and reworking for most beach projects, would give a closer approximation of the grain size distribution from which to develop the fill criterion.

Figure 7. Comparison of borrow and native grain size distributions for intertidal and combined composition.


VIMS EAST BEACH
40
30
20
10
0
FREQUENCY WT. PERCENT
-2
0
2
4
GRAIN SIZE (PHI)
INTERTIDAL COMPOSITE
SOURCE
BORROW
NATIVE


VIMS EAST BEACH
40
30
20
10
0
FREQUENCY WT. PERCENT
-2
0
2
4
GRAIN SIZE (PHI)
INTERTIDAL AND OFFSHORE COMPOSITE
SOURCE
BORROW
NATIVE

In addition, the subtidal portion of the study site may be characterized as a flat, low-tide terrace believed to be primarily an erosional remnant cut into pre-Holocene sediments.

It must be noted here that the borrow and native materials were sampled prior to construction to determine the general suitability of material from the designated pit. The reality of construction, however, included the use of material from several locations within the pit, some of which was taken from areas containing significantly finer material than that sampled. This was evidenced by visual inspection during the construction stage, and later confirmed in the post-fill analysis of the grain size distributions.

## 4.2 Application of Dean's Equilibrium Model Curve

### 4.2.1 Model curve fit

Four profiles were utilized from the VIMS data set to develop a theoretical model curve for the natural shoreline. Post-nourishment curves were also evaluated with the natural curve to determine how closely the present beach has approximated the profile calculated prior to nourishment.

The profiles chosen to characterize the VIMS shoreline were relatively free of groin and pier effects which would alter the natural profile shape. Two profiles were selected to represent the conditions of the Gloucester County Public Beach for scale and shape factor values. All profiles were analyzed by a least squares method to determine values of A and m for each profile. Six profile data sets were analyzed from August 1983 (pre-nourishment) and January 1985 (approximately fifteen months after nourishment). The results of this analysis are presented in Table 3.

Results

Scale Parameter A- The scale factor, A, varies with the degree of profile magnitude, and exhibits an association with the stability characteristics of the sediment (Moore, 1982). The dimensions of A are length to some exponent (1-m) so that A varies from profile to profile (Dean, 1977). Dean (1977) found a range of values for A from 0.0025-6.31, and an average value of 0.36, based on his examination of 502 beach profiles of the U.S. Atlantic and Gulf coasts. The most commonmly occurring values for the 502 profiles were between 0.00 and 0.30 (Dean, 1977).

The value of A for the VIMS study site ranged from 0.55 to 0.67 in August 1983. The mean value of A for the four profiles was 0.58. In January, 1985 the values ranged from 0.06 to 0.10, with a mean value for A of 0.08.

The A values for profiles 42 and 51 on the Gloucester County Public Beach in August 1983 were 0.07 and 0.10, respectively. The same profile values for January 1985 were 0.17 and 0.38.

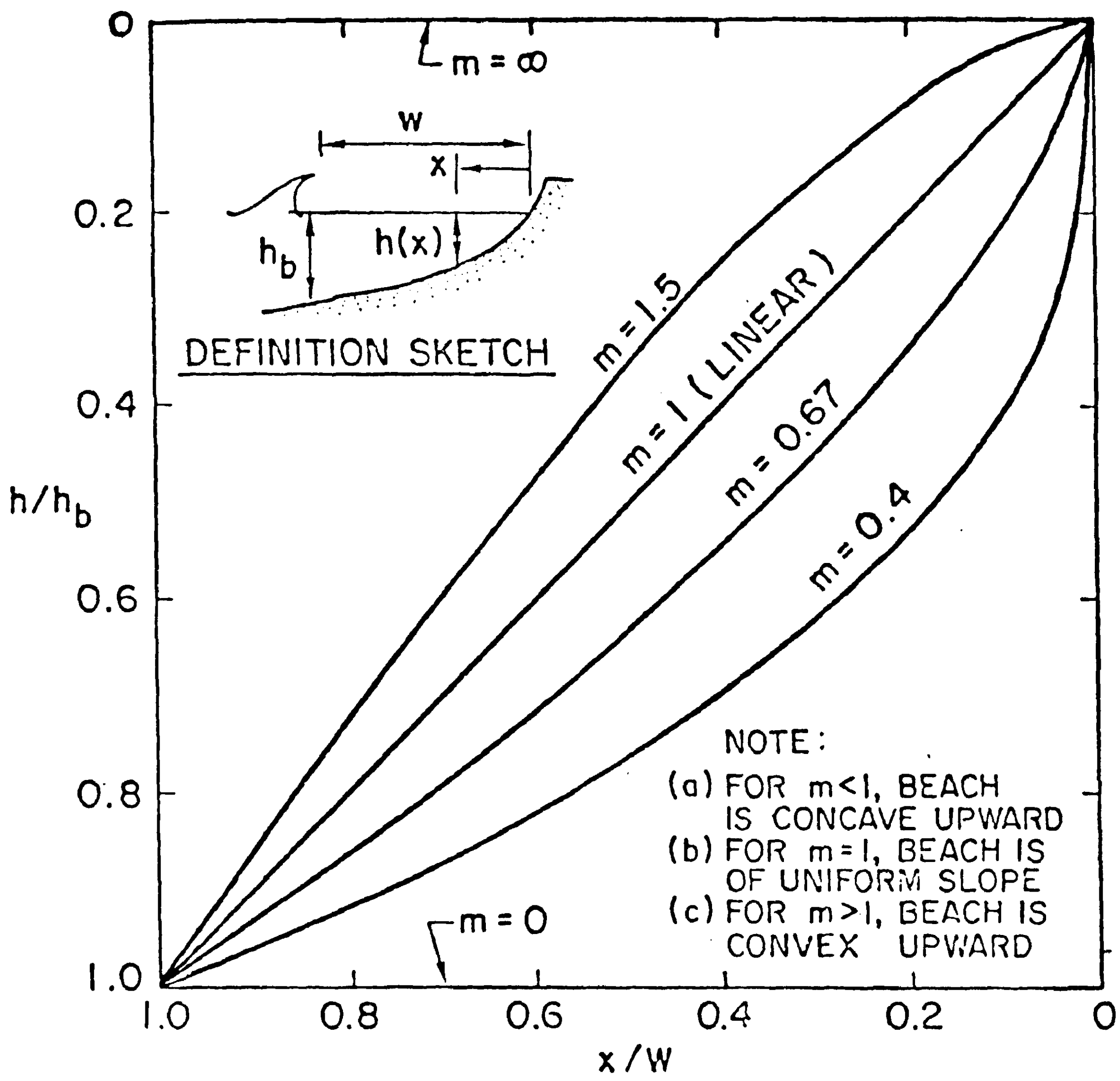
Shape Factor m- The values of m vary with the incident forces affecting a given shoreline and varies from concave upward ($m<1$) to linear ($m=1$) to convex upward ($m>1$)(Figure 8). Dean (1977) found a range of m values from 0.52 to 0.82 and an average value for m of 0.66 for all 502 study profiles. While the inference of geographical trends are questionable from the data available, Dean notes initial low values

Table 3. Characteristics of beach profiles with scale value A and shape factor m.

| PROFILE | LOCATION | CHARACTERISTICS OF BEACH PROFILES | | | | | |
|---|---|---|---|---|---|---|---|
| | | AUGUST 1983 | | | JANUARY 1985 | | |
| | | m | A(FT.) | A(M.) | m | A(FT.) | A(M.) |
| 12 | VIMS EAST BEACH | 0.18 | 1.46 | 0.55 | 0.63 | 0.16 | 0.10 |
| 17 | VIMS EAST BEACH | 0.21 | 1.42 | 0.55 | 0.70 | 0.13 | 0.09 |
| 18 | VIMS EAST BEACH | 0.15 | 1.84 | 0.67 | 0.72 | 0.11 | 0.08 |
| 27 | VIMS EAST BEACH | 0.16 | 1.49 | 0.55 | 0.82 | 0.07 | 0.06 |
| 42 | GLOUCESTER CO. PUBLIC BEACH | 0.70 | 0.10 | 0.07 | 0.43 | 0.33 | 0.17 |
| 51 | GLOUCESTER CO. PUBLIC BEACH | 0.68 | 0.15 | 0.10 | 0.27 | 0.90 | 0.38 |

*Locations of profiles are shown in Figure 3.

Figure 8. Profile shape for a dimensionless beach profile.



m = ∞
W
x
h(x)
h_b
DEFINITION SKETCH
m = 1.5
m = 1 (LINEAR)
m = 0.67
m = 0.4
m = 0
h/h_b
x/W
0
0.2
0.4
0.6
0.8
1.0
NOTE:
(a) FOR m<1, BEACH IS CONCAVE UPWARD
(b) FOR m=1, BEACH IS OF UNIFORM SLOPE
(c) FOR m>1, BEACH IS CONVEX UPWARD

on Long Island, rather high values to Ocracoke Inlet, North Carolina, then lower than average values to Florida and around the Gulf coast to Texas. A generally increasing trend is evident for the last few data groups in Texas (Dean, 1977).

The VIMS profiles were characterized in August 1983 by exponent m values of 0.16-0.21, with a mean of 0.17. In January 1985, these values had increased to 0.62-0.82, with a mean of 0.72.

Profiles 42 and 51 on the Gloucester Public Beach were characterized in 1983 by values of 0.68 and 0.70, respectively. The values in January 1985 for the same profiles were 0.27 and 0.43.

Goodness of Fit Parameter- The goodness of fit is expressed by Dean (1977) as the root-mean-square (RMS) deviation between the average profile and the best fit to that profile. The RMS value for the profile groups ranged from 0.17 ft (0.05 m) to 1.54 ft (0.47 m).

In August 1983, the RMS values for profiles 12, 17, 18, and 27 ranged from 0.08 ft (0.02 m) to 0.77 ft (0.23 m). The mean RMS value for the public beach profiles (42, 51) was 0.60 ft (0.18 m).

In January 1985, the RMS values for the same VIMS profiles ranged from 0.26 ft (0.08 m) to 0.97 ft (0.30 m). The mean value for the public beach profiles was 0.91 ft (0.28 m).

These values indicate a slightly better fit of all profiles in August 1983 than in January 1985. The profiles from VIMS and the Gloucester County Public Beach showed a slightly lower range of RMS values than those found by Dean (1977). All appear to demonstrate a reasonably good fit of the average profile.

Discussion

The predicted curves derived from VIMS and the Gloucester Public Beach data sets are presented in Figures 9 and 10. Actual profile sets for each date have been plotted and indicate a reasonable fit for the nearshore portion of the profile. The calculated curve from August 1983 indicates a highly concave profile form, with average m values of 0.17. Fifteen months after nourishment of the beach, the new calculated profile appears steepened, with a mean value of 0.72. While both values are less than 1 and therefore concave in profile, the trend over time is toward a more uniform slope where m=1 approaches a true linear form (Figure 9).

The values of A and m from VIMS and Gloucester County Public Beach were compared to Dean's results from the ten geographic data groups. It is evident that the pre-nourishment values for VIMS beach are significantly less than those found at any of Dean's sites. The average m value of 0.17 fall well below the minimum value of 0.52 found by Dean. The average calculated values for Gloucester County Public Beach in August were 0.69 (m) and 0.13 (A). These values most closely approximated the values found by Dean from Virginia Beach, Virginia, to Ocracoke Inlet, North Carolina, where m was 0.709, and A was 0.128.

The post-fill values for VIMS in January 1985 showed consistent changes in all profiles for values of A and m. At this time, the average values of 0.72 more closely approximated Dean's average of 0.66 for m. In addition, the average m values (0.72) and A value (0.12) closely approximated those values found from Virginia Beach, Virginia, to Ocracoke Inlet, North Carolina. This is notable beacuse of the ten geographical groups analyzed by Dean, the Virginia Beach, Virginia, to

Figure 9. Predicted beach profile curve for VIMS data set for August 1983 and January 1985.

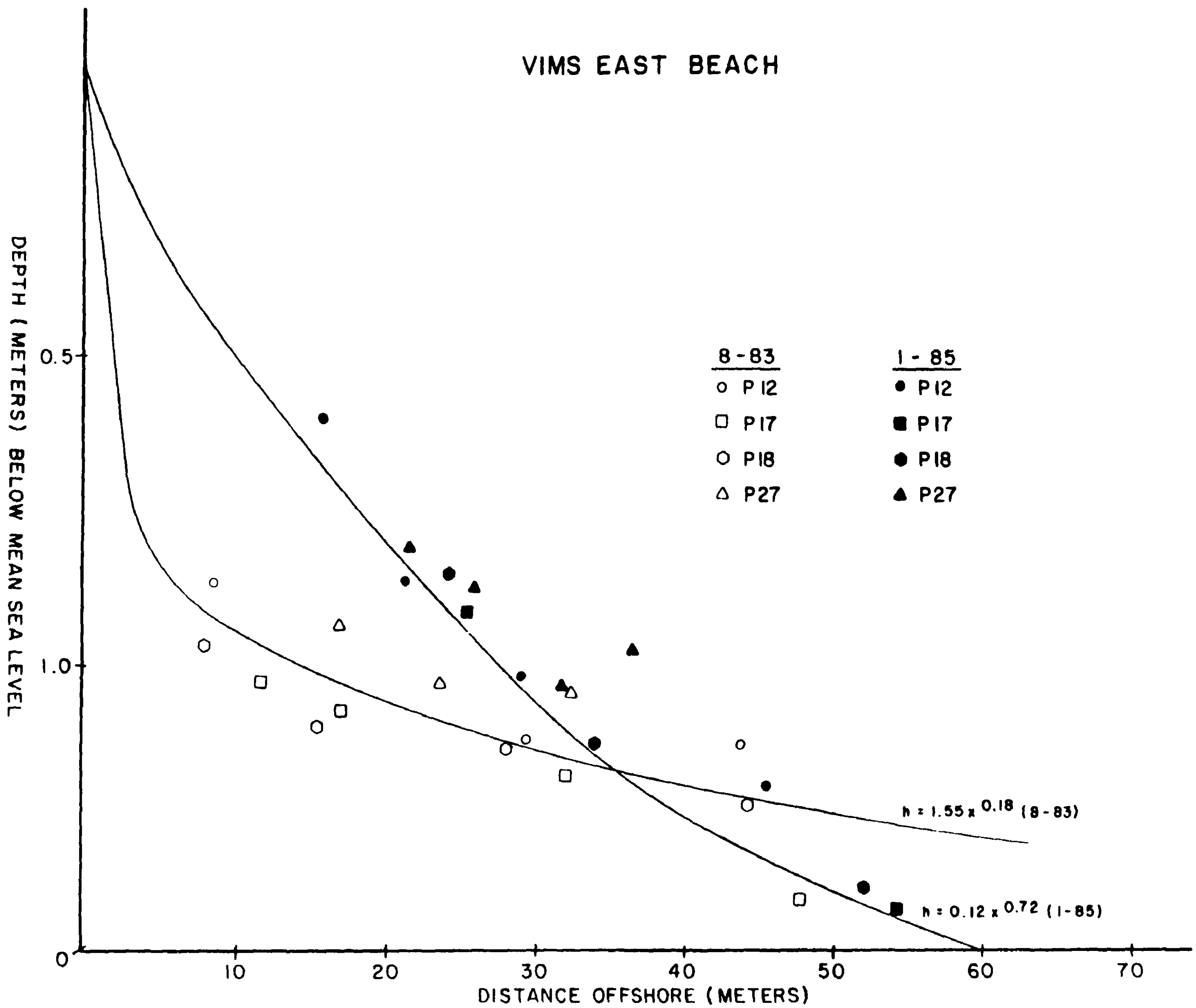
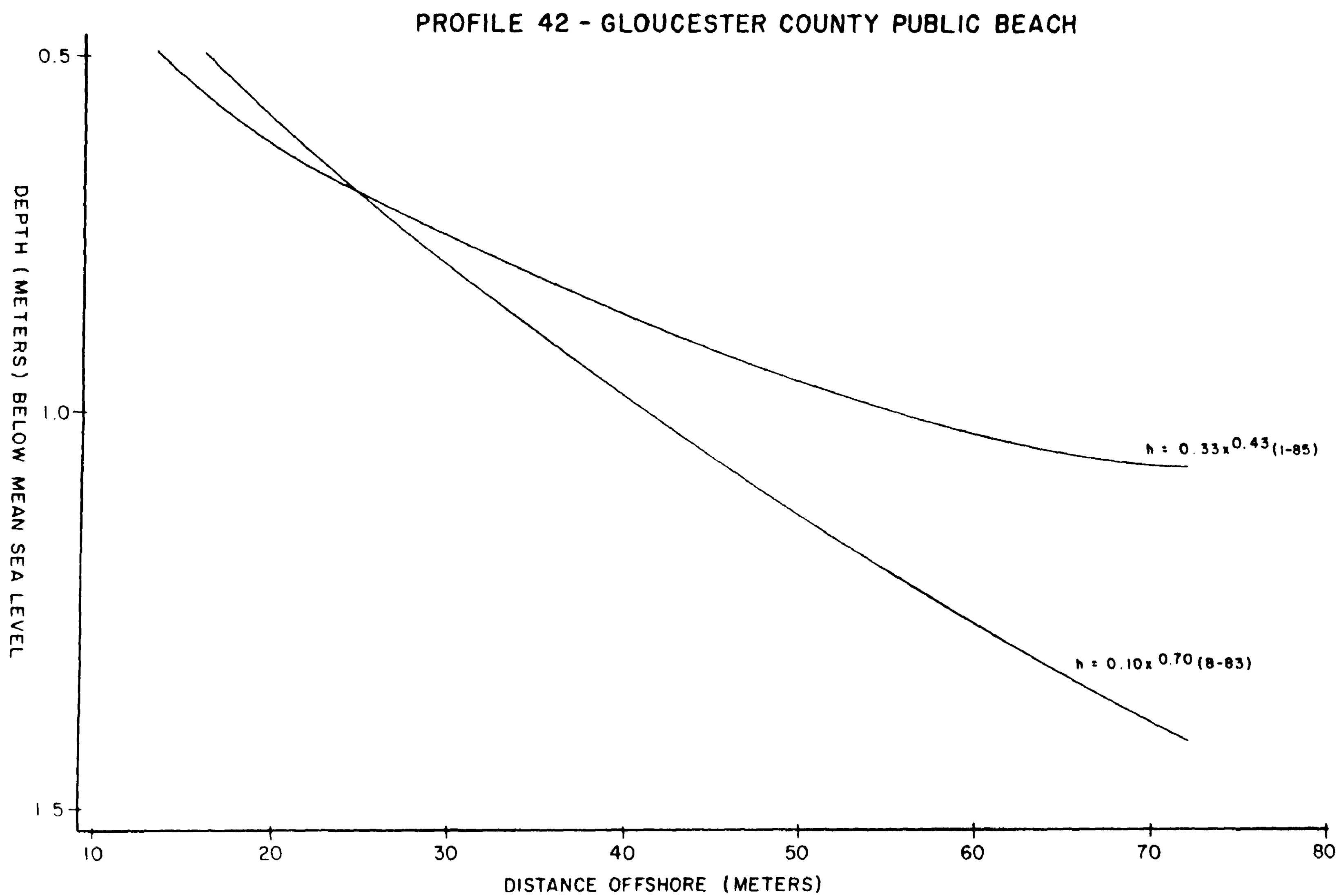

VIMS EAST BEACH
8-83
P12
P17
P18
P27
1-85
P12
P17
P18
P27
h = 1.55 x 0.18 (8-83)
h = 0.12 x 0.72 (1-85)
DEPTH (METERS) BELOW MEAN SEA LEVEL
0.5
1.0
0
10
20
30
40
50
60
70
DISTANCE OFFSHORE (METERS)

Figure 10. Predicted beach profile curve for Gloucester County Public beach data set for August 1093 and January 1985.


PROFILE 42 - GLOUCESTER COUNTY PUBLIC BEACH
h = 0.33x^0.43 (1-85)
h = 0.10x^0.70 (8-83)
DEPTH (METERS) BELOW MEAN SEA LEVEL
0.5
1.0
1.5
DISTANCE OFFSHORE (METERS)
10
20
30
40
50
60
70
80

Ocracoke Inlet, North Carolina group is the closest in proximity to the VIMS study site.

The apparent lack of fit of the 1983 model curve to Dean's predicted $h = A x^{2/3}$ may be influenced by lithologic considerations of this study site. Whereas Dean's model generally has application along unconsolidated sand beaches, the study shoreline has been highly eroded and starved of a continuous sediment supply for at least ten years due to the updrift stabilization of the shorelines. The natural profile along the VIMS shoreline is truncated in some places at approximately mean low water (MLW) by the indurated, highly fossiliferous Yorktown Formation. As a result, the presence of this formation may prohibit the profile from achieving a smooth concave form as described by Dean for unconsolidated sandy coast beaches. Following emplacement of a thick wedge of nourishment material, the reworked profile appears to more closely approximate that of Dean's hypothetical form. This may be explained by the approximation of the newly nourished beach to the sandy, unconsolidated conditions studied by Dean. It is assumed, however, that those areas of the site which remain exposed and lacking in a continuous sediment source will continue to erode until the impermeable Yorktown Formation is again truncated. At this time, the profile will resume the pre-emplacement profile form.

The conditions of the Gloucester County Public Beach indicate less chronic erosion and direct exposure to wave attack than the VIMS beach. In addition, supply of sediment to this segment has remained relatively constant from the erosion of VIMS beach. The beach planform in this segment appears more stable over time, and the Yorktown Formation is visible only in the northernmost area of the County Beach, which is immediately downdrift and in the shadow of the Ferry Pier.

The trend for the two profiles chosen from this segment is toward a more shallow, but concave profile (Figure 10). The alterations of this profile form were less appreciable than that of the VIMS shoreline, and may result from the seasonal fluctuations in incident conditions and variability in the profile shape and lack of direct emplacement of nourishment.

4.2.2 Fill Volume Criteria

The calculations of a model curve for this study site have been presented using Dean's (1977) theoretical profile form developed from beach profile data from U.S. Atlantic and Gulf coasts. These results can be utilized with the associated scale values for given grain size diameters (Moore, 1982) to illustrate the relationship of Dean's equilibrium profile model with beach nourishment projects. Dean (1983) outlines the methodology used to calculate volume fill requirements to achieve a given seaward advancement of the shoreline. The calculations of volume fill are presented here for the VIMS shoreline based on the analysis presented by Dean (1983).

4.3.1 Results

Sediment samples were taken from the zone of MHW-MLW for this analysis. The mean sediment size for the pre-nourishment profile was 1.85 O, or 0.30 mm. Depth of closure was approximated from scatter plots of field data to discern the point at which profile data drastically departs from the log plot. These points were then removed from the profile set and from further use in the least squares fit to calculate values for A and m. For the profiles chosen in this analysis, closure depth was determined to be at a depth of 1.2 meters.

The sediment characteristics and the associated factors are calculated for VIMS beach as:

Native Material= $D_N$ = 0.30 mm

$A_N$ = 0.11 $m^{1/3}$ (Moore, 1982)

Placed Material=

| | |
|---|---|
| $P_1$= 0.12 mm | $A_1$ = 0.08 $m^{1/3}$ |
| $P_2$= 0.20 mm | $A_2$ = 0.09 $m^{1/3}$ |
| $P_3$= 0.40 mm | $A_3$ = 0.13 $m^{1/3}$ |
| $P_4$= 0.50 mm | $A_4$ = 0.15 $m^{1/3}$ |

Depth of Closure = $h_c$= 1.2 meters

Assumed berm height = B = 1 meter

If the desired seaward advancement of the VIMS shoreline is given as $\Delta x$ = 15 m ( 50 ft) then distances calculated to the 1.2 m depth for natural and nourishment material profiles are given by

$$X_c = (h_c / A)^{3/2}$$

The volume of fill required for each size material is then calculated by

$$V_{p1} = B \quad x + \int_0^{xp1+\Delta x} A_N \, x^{2/3} \, dx - \int_0^{xp1} A_{p1} x^{2/3} \, dx$$

$$= B \quad x + 3/5\ [A_N(xp_1 + \Delta x)^{5/3} - A\ p_1\ xp_1^{5/3}]$$

Results of the calculations for the VIMS beach for native material and four alternative sizes of nourishment material are summarized in Table 4. Characteristics of the natural beach profile and the four profiles composed of different grain diameters are shown in Figure 11. The desired shoreline advancement for these profiles was 15 meters (50 ft).

These results indicate significantly differing volume fill requirements for the different grain sizes to achieve the same seaward extension of the shoreline. When the results are applied over the length of the nourished beach (approximately 300 m) volume fill requirements vary from 11,160 $m^3$ for 0.12 mm material to 6,360 $m^3$ for 0.5 mm material, or as much as 1,560 $m^3$ difference in required material for 0.12 mm and 0.20 mm material. Shown graphically in Figure 11, the profiles composed of 0.50 mm and 0.40 mm material intersect the natural profile at a shallower depth than 1.2 meter. Conversely, the profiles composed of 0.12 mm and 0.20 mm material intersect the 1.2 meter contour a considerable distance seaward of the intersection of the native profile and the closure depth of 1.2 meter.

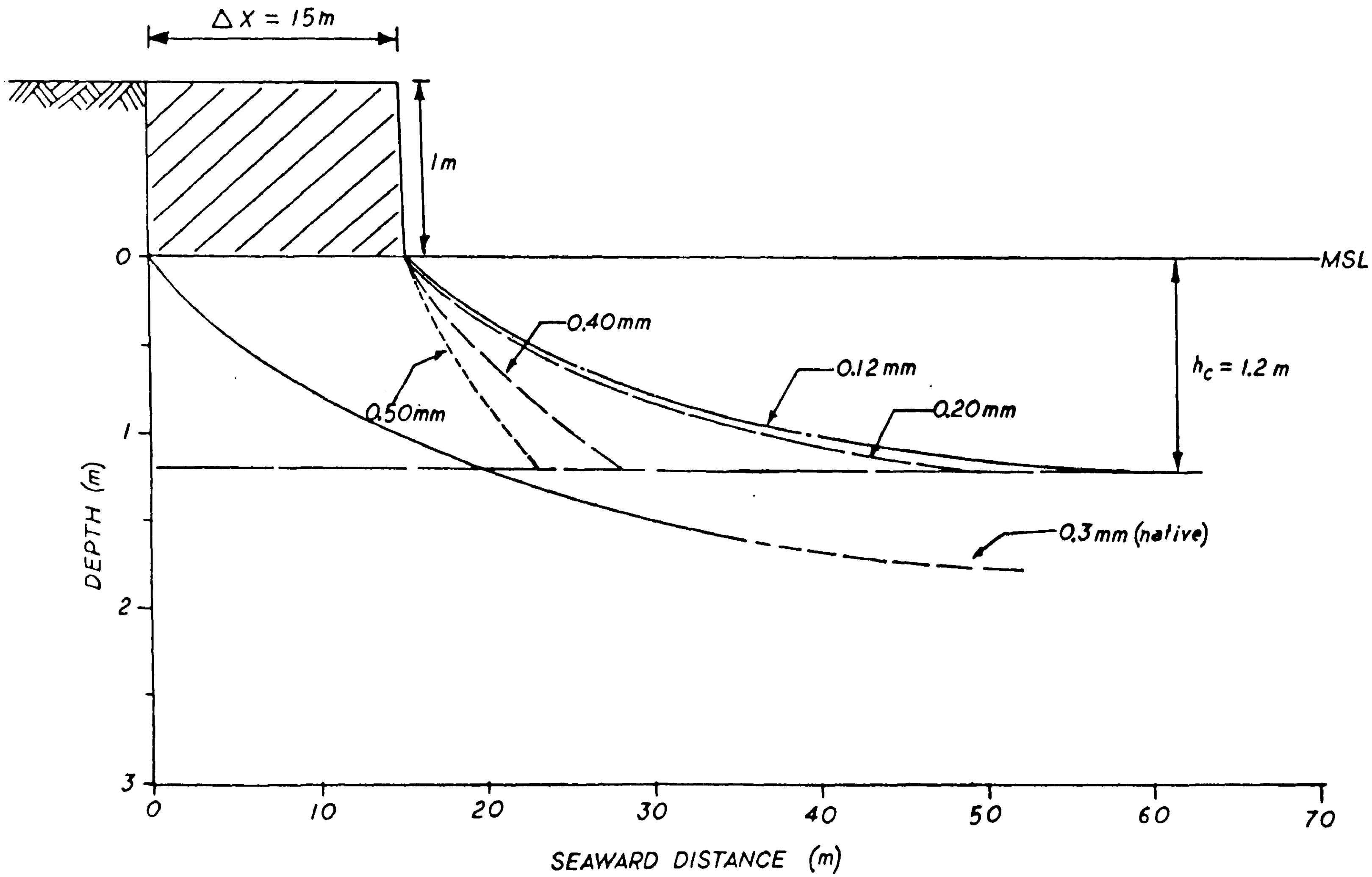
The findings of this calculation suggests some important considerations in the practical application of Dean's model curve for the calculations of fill for potential nourishment sites. The calculations require the assumption of a single grain size to approximate an average profile; the results of this analysis, however, reveals the extreme sensitivity of the calculated volumes to the grain size parameter. Thus, careful sampling and analyses of the sediment

Table 4. Characteristics of beach fills for native and four fill diameters to achieve shoreline advancement of fifteen meters.

| SAND | DIAMETER (mm) | WENTWORTH SIZE CLASS | A | DISTANCE TO 1.2 m DEPTH (m) | REQUIRED VOLUME/ UNIT LENGTH BEACH (m3/m) |
|---|---|---|---|---|---|
| Native | 0.30 | Medium | $0.11m^{1/3}$ | 36.0 | --- |
| $P_1$ | 0.12 | Fine/V. Fine | $0.08m^{1/3}$ | 58.1 | 37.2 |
| $P_2$ | 0.20 | Fine | $0.09m^{1/3}$ | 49.0 | 32.0 |
| $P_3$ | 0.40 | Medium | $0.13m^{1/3}$ | 28.0 | 22.8 |
| $P_4$ | 0.50 | Med./Coarse | $0.15m^{1/3}$ | 22.6 | 21.2 |

*Native material represented by Profile 12.

Figure 11. Calculated profiles for differing grain size diameters.



ΔX = 15m
1m
MSL
0.40mm
0.12 mm
0.20mm
0.50mm
$h_c$ = 1.2 m
0.3mm (native)
DEPTH (m)
0
1
2
3
0
10
20
30
40
50
60
70
SEAWARD DISTANCE (m)

samples from the native profile should be conducted to achieve maximum benefit and cost-effectiveness of the fill criteria.

It should also be noted that the relationship presented by Moore (1982) assumes a theoretical profile form $h = Ax^m$ where m= 0.67. The scale value A has units of length raised to some exponent given by 1-m, so that A may vary from profile to profile. The relationship given between A and grain diameters in Moore (1982), which is often used to calculate volume fill requirements, may only be valid for profiles approximated by $h = Ax^{2/3}$, where $A = \text{length}^{1/3}$. When m varies significantly from Dean's approximation of 2/3, the relationship should only be used as an approximation with the stated assumption. An analysis of the relationship between grain sizes and A values should be made for profiles of varying m values.

Finally, other site-specific conditions must be considered before using the results of this analysis in a project fill design. It is obvious that less volume of the 0.4 and 0.5 mm material (medium to medium coarse) would be required to achieve a slope which intersects the 1.2 m contour than of the 0.12 or 0.20 mm material. In addition, the finer material would be more rapidly resuspended and transported from the system than the coarse material under similar incident conditions. These are important criteria in choosing suitable fill material. However, Figure 11 indicates that slopes composed of coarser material intersect the natural profile at shallower depths, which would not be optimal at the VIMS site due to the presence of the highly indurated Yorktown Formation. For this site, it would be of greater advantage to design a flatter beach planform with finer material to create a thicker wedge of sediment and avoid intersection of the profile with this impervious Yorktown Formation in the nearshore zone.

### 4.3 Sediment Volume Changes

The results of the monitoring program and analysis of volume changes and beach profile response data are presented in this section. The study results encompass the period from October 1983 to November 1985. A total of 15 storms were documented during the 26-month study. Of these, 5 were considered to be storms of considerable magnitude and erosion potential, effecting sediment resuspension and transport of material within the system. Notation of minor and major storms are presented through September 1984. The documentation of the events after this one-year period is limited to 2 major events in 1985. Information from these events was added to the data set due to their severity and value in determining the VIMS beach response to events of such magnitude.

#### 4.3.1 Long-term Sediment Volume Changes

VIMS Beach

Analysis of aerial photographs and profile records confirmed the relationship between historical trends of erosion along the VIMS shoreline and the construction of a nearly continuous series of bulkheads and groins updrift of the project site. Given this, it was anticipated that the nourishment of VIMS shoreline would not result in a stable equilibrium form with no net erosion or accretion. With no natural source of sediment for the beach, it was expected that successive patterns of erosion would occur. The beach fill would provide a temporary source of protection for the dissipation of wave energy. Continued effectiveness would require a schedule of periodic renourishment. Knowledge of rates and amounts of change for the 26-month study period, and documentation of spatial patterns of gains and losses are useful in the design and implementation of a renourishment schedule. Volumetric data is presented for the VIMS shoreline in Tables 5, 6, and 7.

During the period from September 1983 to November 1985 the 472 m of shoreline experienced a net loss of 1,254 $m^3$ of sediment, calculated to MLW datum. The loss calculated to the SLW datum was 1,064 $m^3$, which indicated deposition of 190 $m^3$ within the zone of MLW-SLW.

While the net loss of 1,254 $m^3$ suggested continuing erosion along the VIMS shoreline, gross volume changes were important indicators of total transport of sediment within the littoral system. During the 26-month survey period, total gross volume changes for this system were 1,442 $m^3$ of material lost, and 186 $m^3$ of material gained, for a total of 1,628 $m^3$ of material transported within the system at some point, or approximately 20% of the amount of beach fill emplaced in 1983. Gross volume changes calculated to SLW for this period approximate the amount calculated to MLW, suggesting deposition in the region below MLW.

### Slope Changes

Changes in slope for profiles 1-35 based on surveys in October 1983 and November 1985 are shown in Figure 12. The zone of investigation was defined as that between MLW and MHW.

Of the thirty-five profiles examined, only eight profiles became steeper than the initial state following nourishment. Five of the eight

Table 5. Sediment volume calculations to Mean Low Water datum for VIMS beach.

SEDIMENT VOLUMES (CU.METERS)
VIMS EAST BEACH

| PROFILES | P1-7 | P8-11 | P1-11 | P12-21 | P22-30 | P31-35 | P1-30 | P1-35 |
|---|---|---|---|---|---|---|---|---|
| SURVEY DATE | | | | | | | | |
| September83 | 660 | 2,106 | 2,766 | 4,862 | 3,915 | 1,363 | 11,542 | 12,905 |
| October83 | 585 | 1,978 | 2,563 | 4,838 | 3,922 | 1,357 | 11,324 | 12,681 |
| November83 | 583 | 1,922 | 2,505 | 4,990 | 3,925 | 1,383 | 10,915 | 12,298 |
| January84 | 586 | 2,007 | 2,593 | 4,706 | 3,820 | 1,319 | 11,119 | 12,437 |
| April84 | 563 | 1,733 | 2,297 | 4,674 | 4,061 | 1,297 | 11,032 | 12,329 |
| May84 | 561 | 1,601 | 2,162 | 4,648 | 4,200 | 1,310 | 11,010 | 12,321 |
| June84 | 559 | 1,611 | 2,170 | 4,601 | 4,288 | 1,325 | 11,059 | 12,384 |
| August84 | 549 | 1,597 | 2,145 | 4,646 | 4,282 | 1,312 | 11,073 | 12,386 |
| January85 | 644 | 1,464 | 2,108 | 4,505 | 4,445 | 1,305 | 11,059 | 12,364 |
| November85 | 517 | 1,242 | 1,759 | 3,853 | 4,596 | 1,442 | 10,207 | 11,650 |
| Net Change- | -143 | -440 | -583 | -1,008 | 681 | 79 | -1,334 | -1,255 |

* Volumes calculated to MEAN LOW WATER

Table 6. Sediment volume calculations to Spring Low Water datum for VIMS beach.

SEDIMENT VOLUMES (CU.METERS)
VIMS EAST BEACH

| PROFILES | P1-7 | P8-11 | P1-11 | P12-21 | P22-30 | P31-35 | P1-30 | P1-35 |
|---|---|---|---|---|---|---|---|---|
| SURVEY DATE | | | | | | | | |
| September83 | 898 | 2,440 | 3,339 | 5,522 | 4,550 | 1,653 | 13,411 | 15,064 |
| October83 | 869 | 2,318 | 3,187 | 5,508 | 4,562 | 1,647 | 13,258 | 14,905 |
| November83 | 832 | 2,273 | 3,105 | 5,701 | 4,549 | 1,664 | 13,355 | 15,019 |
| January84 | 848 | 2,352 | 3,200 | 5,359 | 4,415 | 1,608 | 12,974 | 14,582 |
| April84 | 818 | 2,016 | 2,834 | 5,377 | 4,750 | 1,590 | 12,961 | 14,552 |
| May84 | 819 | 1,877 | 2,696 | 5,318 | 4,894 | 1,612 | 12,908 | 14,520 |
| June84 | 836 | 1,906 | 2,742 | 5,271 | 4,988 | 1,635 | 13,001 | 14,636 |
| August84 | 809 | 1,869 | 2,677 | 5,315 | 4,961 | 1,617 | 12,953 | 14,590 |
| January85 | 913 | 1,740 | 2,653 | 5,176 | 5,182 | 1,616 | 13,010 | 14,627 |
| November85 | 774 | 1,522 | 2,296 | 4,551 | 5,372 | 1,779 | 12,218 | 13,997 |
| Net Change- | -125 | -422 | -547 | -971 | 821 | 126 | -1,192 | -1,066 |

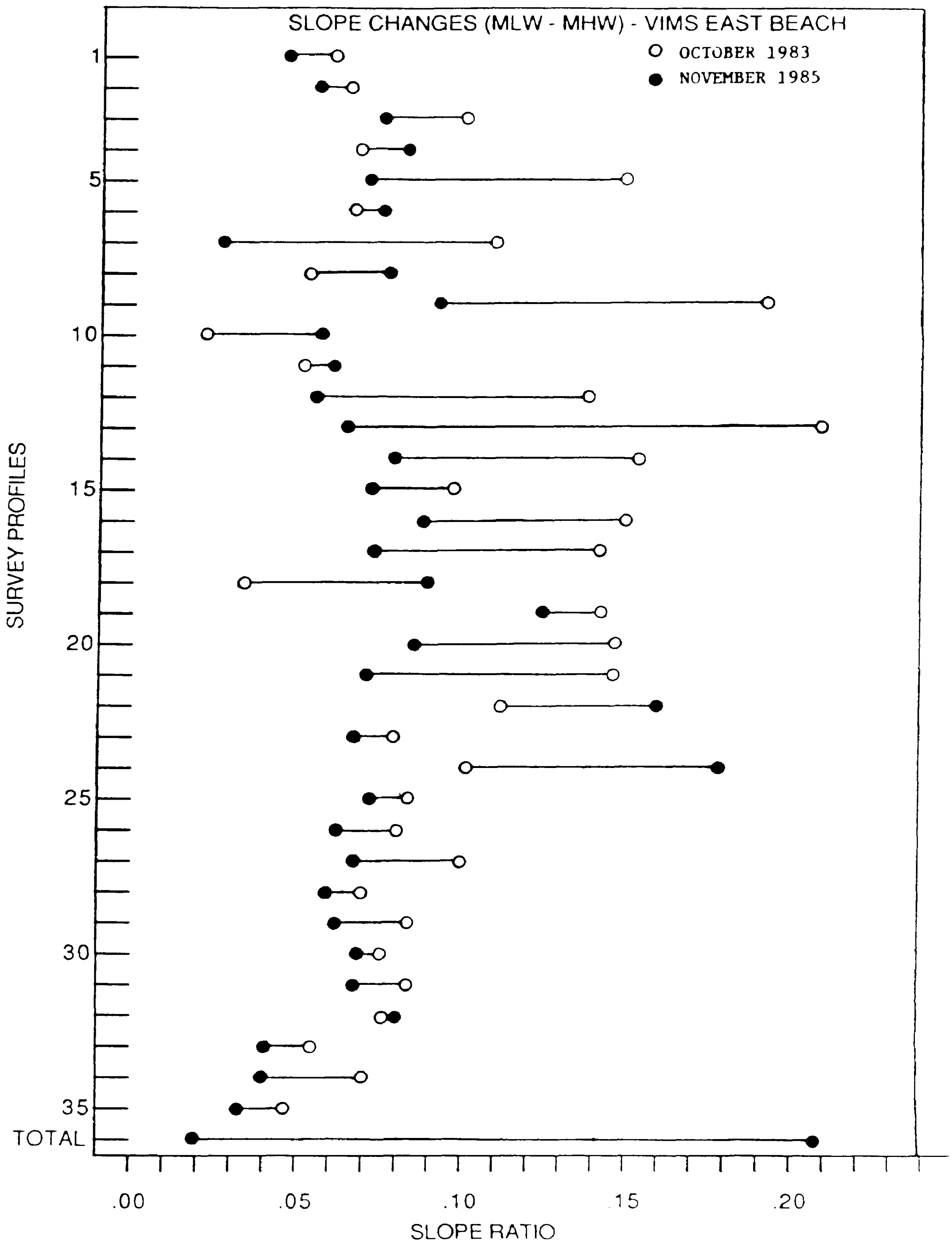
* Volumes calculated to SPRING LOW WATER

Table 7. Sediment volume changes for VIMS beach from September 1983 to November 1985.

VOLUME CHANGES (CU.METERS)- VIMS EAST BEACH-

| | P1-35 | P1-30 | P31-35 | P22-30 | P12-21 | P8-11 | P1-7 |
|---|---|---|---|---|---|---|---|
| | | | MEAN LOW WATER | | | | |
| SEP83-OCT83 | -224 | -218 | -6 | 8 | -23 | -127 | -74 |
| OCT83-NOV83 | 122 | 96 | 26 | 2 | 152 | -56 | -2 |
| NOV83-JAN84 | -365 | -301 | -65 | -105 | -284 | 85 | 3 |
| JAN84-APR84 | -108 | -87 | -21 | 242 | -32 | -274 | -23 |
| APR84-MAY84 | -8 | -21 | 13 | 139 | -26 | -132 | -2 |
| MAY84-JUN84 | 63 | 48 | 15 | 87 | -47 | 10 | -2 |
| JUN84-AUG84 | 1 | 14 | -13 | -6 | 45 | -14 | -10 |
| AUG84-JAN85 | -22 | -14 | -8 | 163 | -141 | -132 | 95 |
| JAN85-NOV85 | -714 | -851 | 137 | 150 | -652 | -223 | -127 |
| NET CHANGE | -1255 | -1334 | +79 | +681 | -1008 | -864 | -143 |
| | | | SPRING LOW WATER | | | | |
| SEP83-OCT83 | -159 | -153 | -6 | 12 | -14 | -122 | -29 |
| OCT83-NOV83 | 114 | 97 | 17 | -13 | 193 | -45 | -37 |
| NOV83-JAN84 | -437 | -381 | -55 | -134 | -343 | 79 | 16 |
| JAN84-APR84 | -30 | -13 | -17 | 335 | 18 | -336 | -30 |
| APR84-MAY84 | -31 | -52 | 21 | 144 | -58 | -139 | 1 |
| MAY84-JUN84 | 115 | 93 | 23 | 94 | -47 | 29 | 17 |
| JUN84-AUG84 | -65 | -48 | -17 | -27 | 43 | -37 | -27 |
| AUG84-JAN85 | 56 | 57 | -1 | 220 | -139 | -129 | 105 |
| JAN85-NOV85 | -629 | -792 | 163 | 190 | -624 | -217 | -140 |
| NET CHANGE | -1066 | -1192 | +126 | +821 | -971 | -918 | -125 |

Figure 12. Changes in slope from MLW-MHW zone for profiles 1-35 of VIMS beach.



SLOPE CHANGES (MLW - MHW) - VIMS EAST BEACH
OCTOBER 1983
NOVEMBER 1985
SURVEY PROFILES
1
5
10
15
20
25
30
35
TOTAL
.00
.05
.10
.15
.20
SLOPE RATIO

profiles were located in the northern segment, where direct exposure to storm waves and proximity to updrift groins resulted in continual erosion of this section. Two of the other profiles, 18 and 22 were located directly downdrift of outfall structures, accounting for the relatively steep slope in November 1985. These structures function as groins by impeding the downdrift transport of sediment. The result is a steeper, eroded profile immediately downdrift of the structure.

Considerable variation existed in slopes recorded during October 1983. It is notable that twenty-seven of the thirty-five profiles fell within a relatively narrow range of slope ratio from 0.05 to 0.10 in November 1985. The greatest readjustment occurred within the segment defined by cell C (profiles 12-21). This segment experienced a significant alteration of the slope toward a flatter profile. By contrast, the slope change for the shoreline from Cells D and E indicated a relatively narrow range of slopes between MLW-MHW. It would be of value to investigate the rate of change of the slopes over short-term intervals of hours, days, or weeks, especially just prior to and following storm events; the findings of this study, however, further support the classification of the study shoreline into cells which respond similarly to conditions present during the study period.

Profile Cells

Profile cells were defined by small sections of the shoreline with similar orientations, or as segments bounded by groin-like structures such as the oyster and ferry piers. These cells were grouped for analysis of erosion and accretion along the study shoreline (Figure 4).

In analysis of long term trends, the length of beach from profile 1 to profile 21 (approximately 274 m in length) was erosional, losing 2,016 $m^3$ of material, or approximately 7.4 $m^3/m$. The segments defined by cells D and E accreted 760 $m^3$(3.7 $m^3/m$) for the same period. This is not surprising considering the relative orientations of the shoreline, the natural longshore drift from northeast to southwest in this area, and the constructed barriers to littoral drift within these cells.

In recent years, the northern section, particularly the portion defined by profiles 8-11, has received very little sediment from updrift sources due to the presence of updrift bulkheads and groins. As a result, this segment was not resupplied with material following erosion from storm surges associated with seasonal northeasterly and easterly winds. Thus, this segment reflected a state of disequilibrium and ongoing erosion, and provided a source of sediment for downdrift sections of the VIMS shoreline.

### Effect of Outfalls

As part of the beach renovation project, six existing outfall pipes were stabilized and protected with 330-1100 kg stone armourment and gabion basket T-heads. The result of this armourment has been to effect a groin-like entrapment of sediment in the areas of emplacement. These outfalls are located in the vicinity of profiles 9-10, profiles 16-17, profiles 17-18, the oyster and ferry piers, and along profile 25 (Figure 13). The effect has been most obvious in the area of profile 25, which is further protected by the two piers. In addition, the smaller cells created by the outfalls have created the typical offset configuration of the shoreline due to the accretion of littoral material on the updrift

Figure 13. Armoured outfall pipes with gabion basket T-head structures.

side. The outfall in the vicinity of profiles 9 and 10, while initially successful in capturing nourishment material, has been limited in the long-term retention of fill by its relatively low elevation and the severity of wave attack in this section of the shoreline.

Volume Comparisons-Vims East Beach/ Gloucester County Public Beach

Tables 8, 9, and 10 give volumetric data from surveys of the Gloucester County Public Beach as calculated to Mean Low Water (MLW) and Spring Low Water (SLW) datums. A graphic depiction of the comparison of volume changes for the Gloucester County and VIMS beaches, as calculated to Mean Low Water and Spring Low Water, is also presented in Figure 14.

Examination of volume changes shows that VIMS beach lost 1,255 $m^3$ (MLW) and 1,066 $m^3$ (SLW) for the period from September 1983 to January 1985. For this same period, the losses for the County Beach were 439 $m^3$ (MLW) and 190 $m^3$(SLW). In terms of volume change per linear meter of shoreline, the loss at VIMS was 2.6 $m^3/m$, while Gloucester County lost 0.92 $m^3/m$ for this same period, or approximately 30% of the loss at the VIMS site.

In closer analysis of the total changes, the segment of the public beach shoreline from Profile 36-Profile 54 lost 764 $m^3$ during the study period (MLW) and 570 $m^3$ in volume calculated to SLW, indicating the deposition of approximately 190 $m^3$ of material within the zone between MLW-SLW. In addition, the area adjacent to the channel from Profile 55-Profile 59 experienced a net accretion of 324 $m^3$ (MLW) and 380 $m^3$(SLW). This confirmed the visual observation that losses of sediment during the reworking of the beach fill and during storm events were offset by accretion along this 60 meters of shoreline which terminates at the

Table 8. Sediment volumes calculated to Mean Low Water datum for Gloucester County public beach.

GLOUCESTER COUNTY PUBLIC BEACH
SEDIMENT VOLUMES (CU. METERS)

| PROFILES | P36-54 | P55-59 | P36-59 |
|---|---|---|---|
| SURVEY DATE | | | |
| September83 | 14,503 | 973 | 15,477 |
| October83 | 14,175 | 992 | 15,169 |
| November83 | 14,171 | 944 | 15,115 |
| January83 | 14,232 | 935 | 15,166 |
| April84 | 14,372 | 958 | 15,331 |
| May84 | 14,197 | 954 | 15,151 |
| June84 | 14,169 | 979 | 15,148 |
| August84 | 14,227 | 951 | 15,179 |
| January85 | 14,231 | 1,015 | 15,246 |
| November85 | 13,739 | 1,298 | 15,037 |

*Volumes calculated to MEAN LOW WATER

Table 9. Sediment volume calculations to Spring Low Water datum for Gloucester County public beach.

GLOUCESTER COUNTY PUBLIC BEACH
SEDIMENT VOLUMES (CU.METERS)

| PROFILES | P36-54 | P55-59 | P36-59 |
|---|---|---|---|
| SURVEY DATE | | | |
| September83 | 16,593 | 1,150 | 17,743 |
| October83 | 16,249 | 1,177 | 17,427 |
| November83 | 16,256 | 1,119 | 17,375 |
| January84 | 16,306 | 1,108 | 17,414 |
| April84 | 16,532 | 1,143 | 17,675 |
| May84 | 16,355 | 1,141 | 17,497 |
| June84 | 16,299 | 1,162 | 17,461 |
| August84 | 16,319 | 1,135 | 17,455 |
| January85 | 16,329 | 1,206 | 17,535 |
| November85 | 16,023 | 1,530 | 17,553 |

*Volumes calculated to SPRING LOW WATER

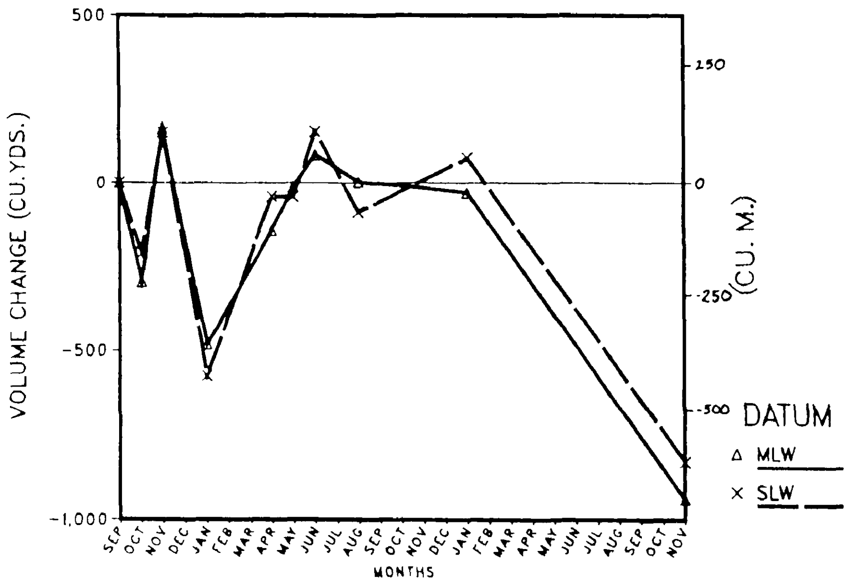
Table 10. Sediment volume changes for Gloucester County public beach from September 1983 to November 1985.

VOLUME CHANGES (CU.METERS)- GLOUCESTER COUNTY PUBLIC BEACH

| | P36-54 | P55-59 | P36-59 |
|---|---|---|---|
| | MEAN LOW WATER | | |
| SEP83-OCT83 | -327 | 19 | -308 |
| OCT83-NOV83 | -5 | -49 | -54 |
| NOV83-JAN84 | 61 | -9 | 52 |
| JAN84-APR84 | 141 | 23 | 164 |
| APR84-MAY84 | -175 | -4 | -180 |
| MAY84-JUN84 | -27 | 25 | -2 |
| JUN84-AUG84 | 58 | -27 | 30 |
| AUG84-JAN85 | 4 | 64 | 68 |
| JAN85-NOV85 | -492 | 283 | -209 |
| NET CHANGE | -764 | +324 | -439 |
| | SPRING LOW WATER | | |
| SEP83-OCT83 | -343 | 27 | -316 |
| OCT83-NOV83 | 6 | -58 | -52 |
| NOV83-JAN84 | 50 | -11 | 39 |
| JAN84-APR84 | 226 | 35 | 261 |
| APR84-MAY84 | -177 | -1 | -179 |
| MAY84-JUN84 | -56 | 20 | -36 |
| JUN84-AUG84 | 20 | -27 | -6 |
| AUG84-JAN85 | 10 | 71 | 80 |
| JAN85-NOV85 | -306 | 324 | 17 |
| NET CHANGE | -570 | +380 | -190 |

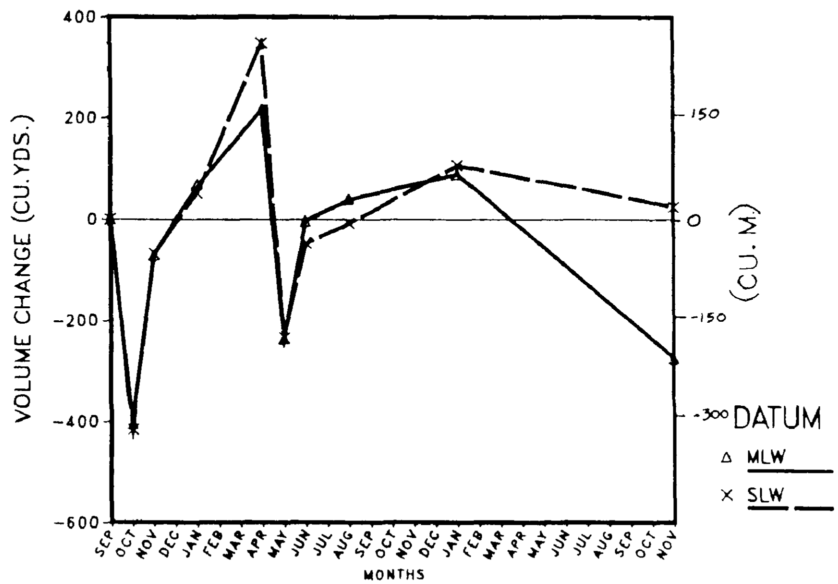
Figure 14. Comparison of sediment volume changes of VIMS and Gloucester County Public Beach

SEDIMENT VOLUME CHANGES
1983–1985




PROFILES 1–35

SEDIMENT VOLUME CHANGES
1983–1985




PROFILES 36–59

public boat ramp. Visual observations were made of the longshore transport of the resuspended nourishment material along the public beach shoreline to the vicinity of this cell, and into the adjacent channel as a plume of fine material. The orientation of this segment provides protection from the direct wave attack of the northeast storms, and is exposed directly to winds which blow across a limited fetch from the southwest and west.

A significant period of deposition along the public beach shoreline occurred during the January-April 1984 sampling interval, which included a storm on February 23. During this time, 164 $m^3$ of sediment were accreted along the public beach shoreline, and 109 $m^3$ was eroded from the VIMS shoreline. Notably, the accretion occurred along the length of the County shoreline and not primarily in the cell from Profile 55-59.

During the following month, the Gloucester County Public Beach lost approximately 182 $m^3$, which suggests that the material accreted during the February storm was subsequently lost, presumably as longshore drift southward into the York River channel. Unlike the VIMS shoreline, much of the southern portion of the county beach's offshore bathymetry drops off rapidly into the central portion of the York River's channel. Following storm events, some of the sediment transported in the zone below MLW subsequently returns to the VIMS shoreline as post-storm onshore transport. This phenomenon has not been observed to occur along the southern portion of the public beach's shoreline, and it is assumed that much of the material eroded from this segment during storm events is transported offshore and lost to the deep channel.

The most significant change occurred during the period from January 1985 to November 1985. While several smaller events occurred during this period, the magnitude of the November 1-4 storm indicated that the majority of sediment loss could be attributed to the effects of this storm. During this period, VIMS lost approximately 714 $m^3$, most of which eroded from the northern section of the study site. For this same time, Gloucester County's public beach lost 492 $m^3$ from Profile 36-54, and gained 283 $m^3$ in the cell from Profile 55-59, for a net loss of 209 $m^3$. The values calculated to SLW, however, show that much of the material lost from the segment of shoreline between Profile 36-54 was transported into the zone below MLW, as well as around the point into the cell terminating at the boat ramp. Total volume changes calculated to SLW for this period indicate a period of net accretion of 178 $m^3$, resulting from material deposited below MLW and between Profile 55-59.

4.3.2 Annual Sediment Volume Changes

The VIMS beach shoreline lost 520 $m^3$ of material (MLW) and 736 $m^3$ (SLW) during the period from September 1983 to August 1984. During this period, 836 $m^3$ of sediment were eroded between Profile 1-21, or 3.04 $m^3$/m of shoreline. During this same period, the shoreline from cell D experienced accretion of 411 $m^3$(2.82 $m^3$/m), while cell E lost approximately 51 $m^3$ (0.77 $m^3$/m). Excluding the cell from Profile 8-11, which lost an additional 62 $m^3$of material within the zone from MLW-SLW, calculations of volume change to the SLW datum for the year indicate accretion of the shoreline cells within this zone of MLW-SLW.

A comparison of the annual changes for the first year to those of the following 14 months suggests that the second year was one of greater net losses along the VIMS shoreline, primarily attributable to the storm events of September and November 1985. As in the first year, the segments defined by the northern 21 profiles were characterized by erosion (1,179 $m^3$), and the profiles from 22-35 by accretion (444 $m^3$), as calculated to MLW.

To understand the total volume of material transported within the system annually, gross volume changes were calculated. For the period from September 1983 to August 1984, a total of 2,174 $m^3$(MLW) and 2,579 $m^3$ (SLW) were transported within the system. For the period from August 1984 to November 1985, gross volume changes were 1,830 $m^3$(MLW) and 1,929 $m^3$(SLW). This indicates that less total transport of material occurred during the second year; however, more net erosion occurred during this period than during the first year following completion of nourishment. Again, this may be explained by the severity and significant erosion of the 2 storm events of 1985.

Approximately 16% of the total gross changes from the first year resulted from the transportation of material within the MLW-SLW zone, whereas only 9% of the total material transported occurred within this zone from August 1984 to November 1985. Due to the duration of high winds and tides and subsequent erosion, more material was resuspended and transported alongshore and into the vicinity of the York River channel during the storms of 1985 (particularly the November 1-4 event). Profile cross-sections show that some of this material was deposited in the cell defined by Profiles 55-59, however, an offshore zone of resuspended material was visible in the area of the channel, indicating that much of this material has been permanently removed from the system into the adjacent deep channel in the vicinity of the point.

### 4.3.3 Short-term Sediment Volume Changes

A detailed characterization of volume changes and incident conditions for each interval from September 1983 to November 1985 is found in Appendix I.

The initial survey period coincided with the completion of the stone revetment and the armourment of the outfall pipes along VIMS beach. 228 $m^3$ of material were lost during the initial survey period from September to October 1983. Of this, 57% was eroded from the segment encompassing cells A and B. During this time, relatively small volume losses occurred in the sections of cells D and E. Initial redistribution and removal of the fine fraction of nourishment material accounted for the erosion, some of which provided the source of accretion for the downdrift sections of the beach.

The period from October-November was one of overall accretion, although the northern segments (cells A and B) continued to erode. Two relatively brief southeast storms occurred during this interval. During the next two months, this segment reversed its trend with accretion of 87 $m^3$. Approximately 365 $m^3$ of sediment was eroded from cells C, D, and E during this interval from November 1983 to January 1984. Two storms occurred during this period which resulted in the resuspension of the beach fill. Maximum wave heights for these storms were 0.4 m.

Minimal net volume change occurred for the VIMS shoreline from January-April, although gross changes in volume were notable during this period. The first major storm occurred on February 23, 1984, which resulted in much sediment transport within the system. Significant losses from the northern segments were offset by accretion in the protected downdrift sections. In addition, some material deposited below

MLW during the storm returned to the upper beach face during a post-storm recovery period. It was observed that an offshore ridge formed below MLW during storms. These ridges provided temporary storage of sediment, which later returned to the shoreline during post-storm incident conditions. These short-term storm cycles have been observed along many open coast shorelines, and are recognized in the reportings of Shepard (1950), Bascom (1959), Kana (1977), and others.

The trend of erosion of the northern section offset by accretion in the downdrift shoreline continued through May 1984. Very little net volume change occurred during the summer months from June to August, and during the next 4 months small changes in net volume were noted for the VIMS shoreline. During this period, however, approximately 547 $m^3$ of material were transported within the beach system, reflecting continuing erosion of the northern segments offset by accretion in cell D.

The final survey interval from January 1985-November 1985 was one of heavy net losses from the VIMS shoreline, primarily due to the major storms which occurred in September and November 1985. Approximately 715 $m^3$ was eroded during this time. Again, heaviest losses occurred along the exposed northern segments of the shoreline, which were offset by accretion of 288 $m^3$ from cells D and E.

Figures 1 through 6 in Appendix II provide a qualitative view of the short-term system changes for the survey intervals from September 1983 to November 1985. These graphs are grouped into shoreline cells of P1-12, P12-21, and P22-30.

Several trends are apparent from examination of these contour and 3-dimensional plots. One observation is the immediate alteration and redistribution of material immediately following nourishment of the shoreline. A flattening of the upper beach area and the loss of contour elevations greater than +1.5 m (5.0 ft) resulted from the reworking and redistribution of the material from the artificially created profile. Examination of the 2-dimensional plots over time also reveal a gradual alignment and straightening of the contours after the initial survey. This is particulary evident during the summer months and the November 1985 survey.

The most active area of change during the study occurred in the zone from the -0.6 m (-2.0 ft) to +0.9 m (+3.0 ft) contours. Little variation was found in the zone below the -0.7 m contour, or in the upper beach area of the +1.2 m (4.0 ft) and +1.5 m (5.0 ft) contours. Initially, however, the area was reworked, which resulted in the permanent removal of continuous +1.8 m (6.0 ft) and +2.1 m (7.0 ft) contours in the upper beach area. The typical offset configuration of contours is evident from the plots in the vicinity of the groin-like structures at P17 and P25, although some variation of the offset is revealed from the plots over the survey intervals.

Some seasonal variation can be observed from the two and three-dimensional presentation of the contour elevations. The profile shape observed in January 1984 is one of an elevated upper beach berm, a steeper beach face, and a low flat terrace below MLW. The profiles presented during the May, June, and August surveys indicate less localized relief, straighter contours with more parallel alignment, and a more gently sloping concave beach profile. The breaks between upper beach berm, beach face and nearshore zones are less evident during the spring and summer surveys.

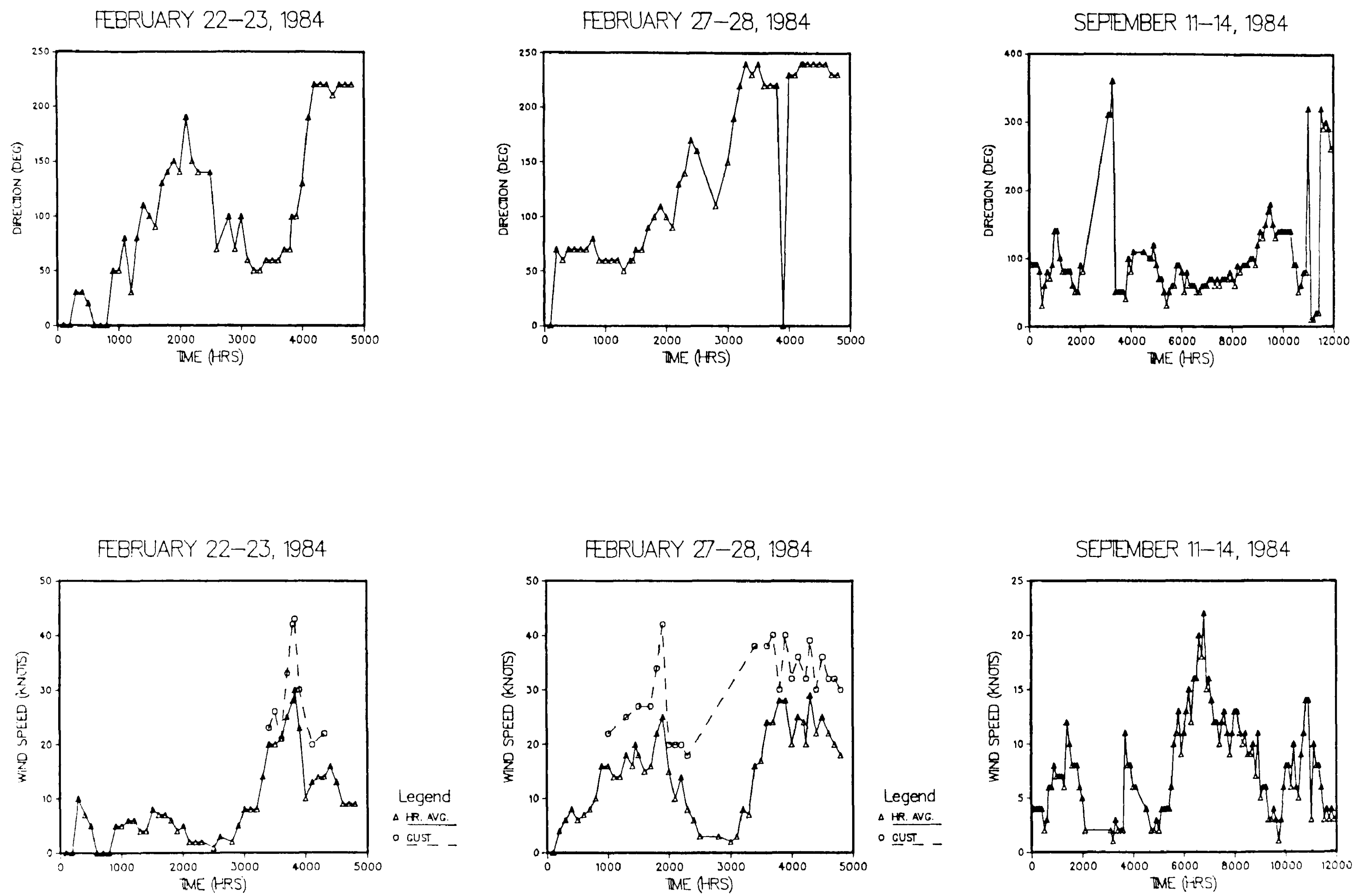
By January 1985, the profile had again become modified into one of an upper beach berm, steeper beach face, and low nearshore terrace. The final interval from January 1985 to November 1985 primarily depicts the system response to the storm events of September and November. Figures 1-6 in Appendix II reveal the similarity of these plots to those generated from the spring and summer intervals. Distinctions between the upper beach berm, beach face and nearshore terrace were not observed; instead, the profile appears concave and gently sloping, with deposition of material in a low, flat terrace below MLW not previously observed. The variations observed for the VIMS beach system were less evident in the relatively protected segments of cell D. This cell remained relatively stable and consistent from January 1984 to November 1985.

4.3.4 Major Storms 1983-1985

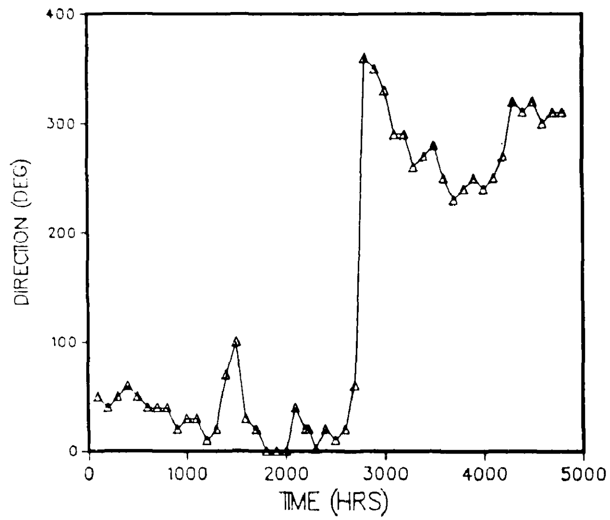
Property owners along the east coast of North America are familiar with the destructive capabilities of the seasonal storms, or "northeasters". The northeast winds generally are associated with extra-tropical cyclones which travel along the east coast over the ocean, or from high pressure weather systems which originate over the central United States (Kana, 1977).

Five storms occurred during the study period of significant erosion potential to warrent a closer examination of the associated processes of wind and tides. A brief outline of each event is presented in this section; associated wind and tide conditions are presented in Figures 15 and 16. The process parameters associated with each of these events are summarized and presented in Table 11.

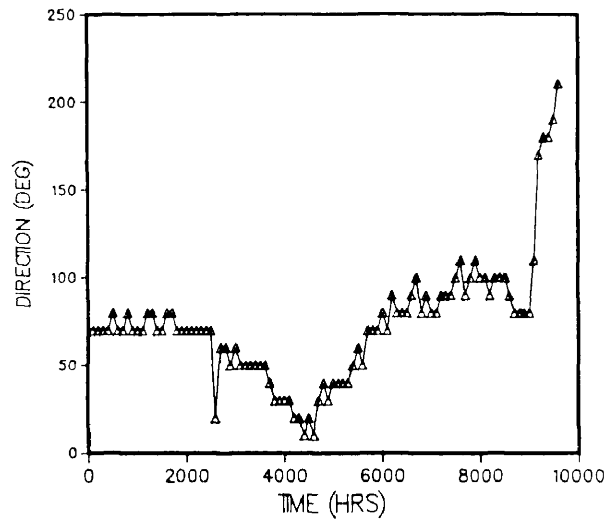
Figure 15. Wind conditions for VIMS beach during five major storms 1984-1985.


FEBRUARY 22–23, 1984
DIRECTION (DEG)
TIME (HRS)
FEBRUARY 27–28, 1984
DIRECTION (DEG)
TIME (HRS)
SEPTEMBER 11–14, 1984
DIRECTION (DEG)
TIME (HRS)
FEBRUARY 22–23, 1984
WIND SPEED (KNOTS)
TIME (HRS)
Legend
HR. AVG.
GUST
FEBRUARY 27–28, 1984
WIND SPEED (KNOTS)
TIME (HRS)
Legend
HR. AVG.
GUST
SEPTEMBER 11–14, 1984
WIND SPEED (KNOTS)
TIME (HRS)

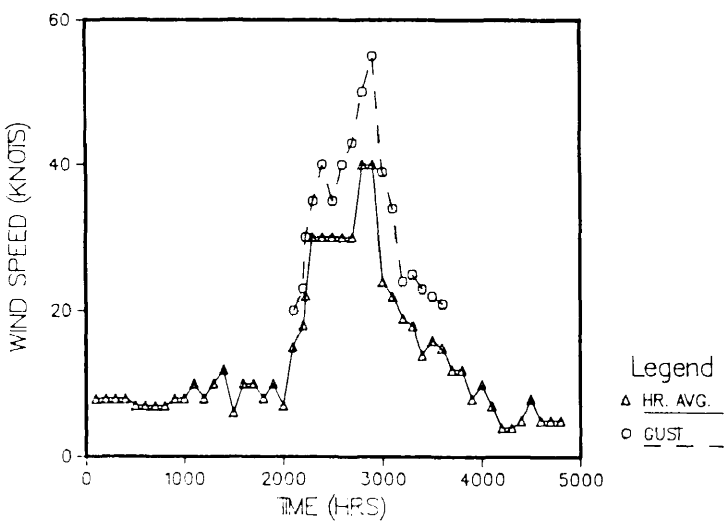
SEPTEMBER 26–28, 1985




NOVEMBER 1–4, 1985




SEPTEMBER 26–28, 1985




NOVEMBER 1–4, 1985

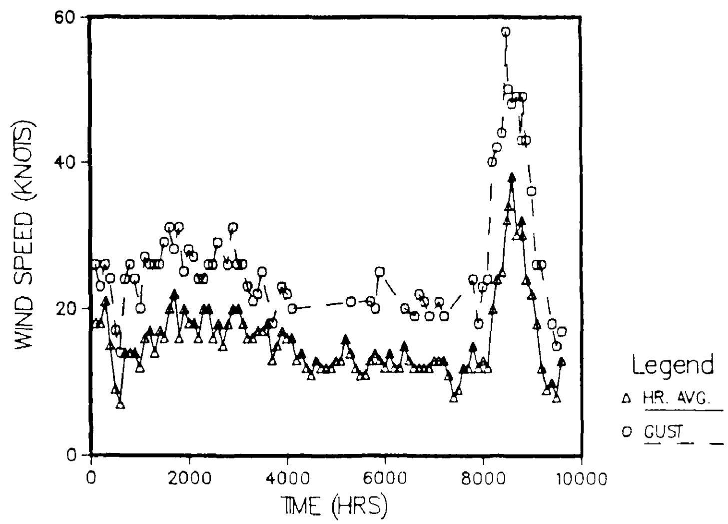
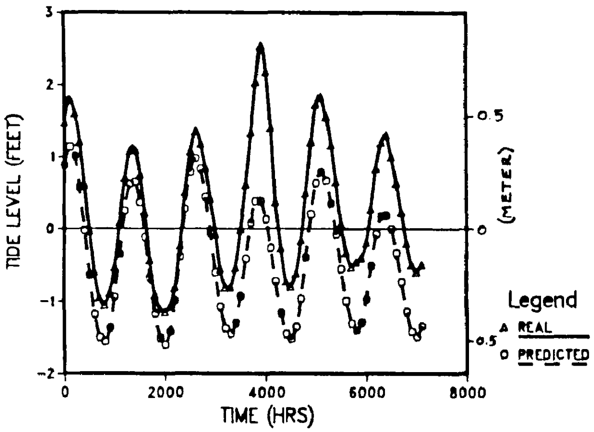
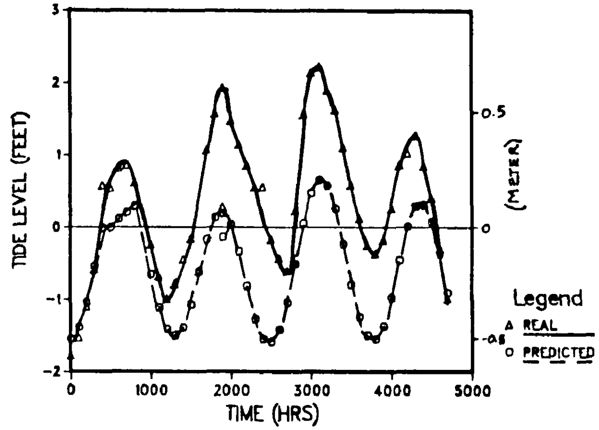


Figure 16. Tide conditions for VIMS beach during five major storms 1984-1985.

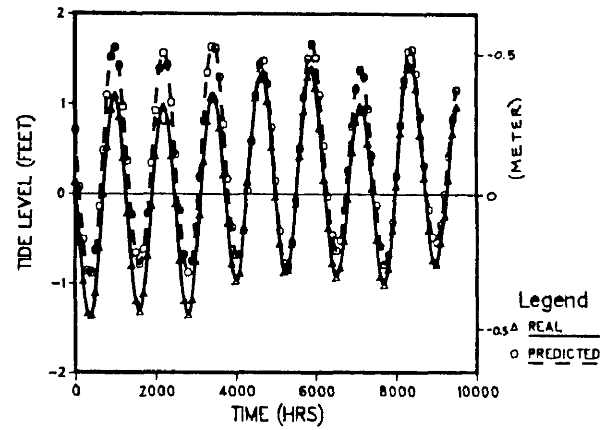
FEBRUARY 22–23, 1984



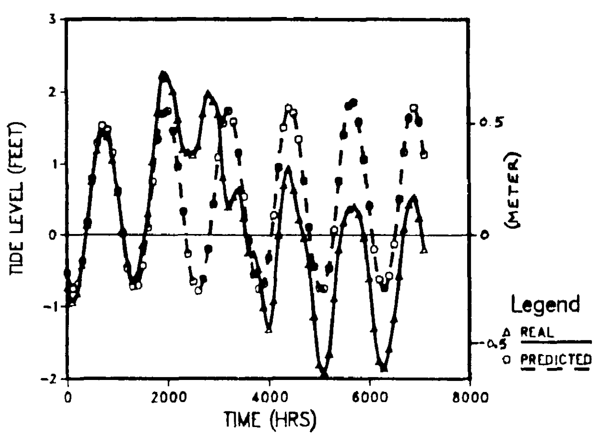

FEBRUARY 27–28, 1984




SEPTEMBER 11–14, 1984




SEPTEMBER 26–28, 1985




NOVEMBER 1–4, 1985

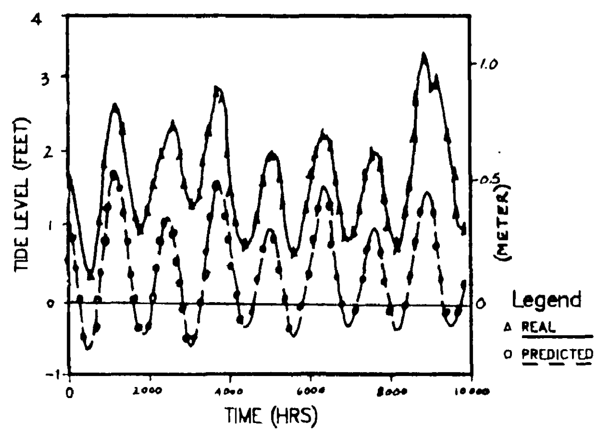


Table 11. Storm process measurements for VIMS beach, Gloucester Point, Virginia 1984-1985.

STORM PROCESS MEASUREMENTS AT VIMS BEACH, GLOUCESTER POINT, VIRGINIA
OCTOBER 1983- NOVEMBER 1985

| Date | Duration (Hrs.) | Max. Wave Ht. (Ft.) | Wave Period (Secs.) | Max. Wind Speed (MPH) |
|---|---|---|---|---|
| Oct.10,1983 | ~8 | 1.0 | 1.5-2.0 | 15 |
| Oct.13,1983 | ~6 | 1.0 | 1.0-2.0 | 15 |
| Oct.20-22,1983 | ~36 | 2.0 | 4.0 | -- |
| Nov.10,1983 | ~4 | 1.0 | 2.5-3.0 | 25 |
| Nov.15,1983 | ~6 | 1.0 | 2.0-2.2 | 25 |
| Dec.28,1983 | ~12 | 1.2 | 1.5-2.0 | 25 |
| Jan.17-18,1984 | ~30 | <1.0 | 2.0 | 20 |
| Feb.3,1984 | ~8 | 2.5 | 2.0-2.5 | 25 |
| Feb.22-23,1984 | ~48 | 3.0 | 3.8-4.0 | 45 |
| Feb.27-28,1984 | ~48 | 2.5 | 3.0 | 45 |
| Mar.20,1984 | ~6 | <1.0 | 2.0 | 15 |
| Jun.22,1984 | ~6 | --- | --- | 15 |
| Sep.11-14,1984 | ~96 | 1.0 | 2.5 | 25 |
| Sep.26-28,1985 | ~72 | 2.5 | 3.0 | 60 |
| Nov.1-4,1985 | ~96 | 3.0 | 3.5-4.0 | 60 |

February 22-23, 1984

The February 22-23 event, while largely unpredicted, provided the first opportunity for wave attack to rework sediments of the upper beach and berm area, following completion of the renovation in the Fall of 1983.

Northeast winds dominated on February 22, but by late afternoon had shifted to south-southeast (Figure 15). Wind speeds remained 16-24 km/h for most of February 22. By February 23, winds had again shifted to the southeast and then to the southwest as the storm passed from the area.

Wind speeds averaged 32-48 km/h on February 23, with highest gusts associated with the northeast winds. Peak wind velocity occurred at approximately 1600 on February 23, with gusts of 72 km/h. As winds shifted to the south, speeds diminished, but remained constant at 16-24 km/h.

A comparison of measured to predicted tide levels for February 22-24 is presented in Figure 16. The figure indicates that actual tide levels were approximately 12 cm above and 12 cm below predicted values for the high and low tides for February 22. The measured high tide at 1500 on February 23, however, was 0.66 m above the predicted value, and the low tide at 2100 by 0.25 m above predicted levels.

The superelevation of the tides at 1500 occurred relatively "in-phase" with maximum northeast wind speeds at 1600 on February 23. This accentuated the erosion potential by increasing the horizontal area of direct wave attack during this event. Two Marsh-McBirney electromagnetic current sensors were deployed in the vicinity of the oyster pier during this period. Velocity recordings indicated that the peak orbital velocities measured at 20 cm and 70 cm off the bed coincided with the maximum wind velocity at 1600 on February 23. At 70 cm, peaks of greater than 80 cm/sec were measured with a north-south orientation, and nearly 70 cm/sec for this same orientation at 20 cm off the sea bed. The mean average for the 300-second burst recorded during this period indicated the southern component of current velocity was the greatest intensity during the burst sampling at peak conditions on February 23.

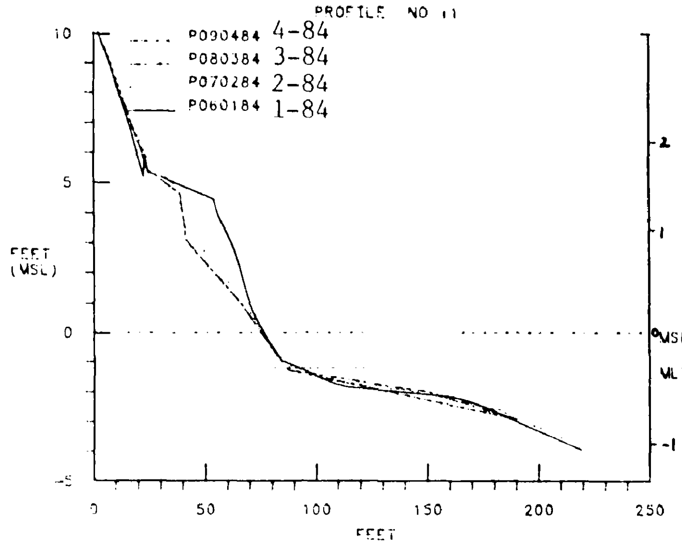
Onshore winds and wave attack, accentuated by higher than predicted tidal water levels on February 23, resulted in the formation of scarps of the recently nourished beach. The northern, more exposed section of shoreline experienced cutting of the beach face and permanent removal of material during this time, as indicated by comparison of beach profiles in Figure 17 for profile 11. Profile changes for profiles 15, 19, and 23 display characteristic erosion of the upper beach and shoreface with the subsequent deposition of material in the zone below MLW. Post-storm recovery was observed following this storm as the return of sediment to the lower beach face from material temporarily stored as an offshore bar during the event.

February 27-28, 1984

The second event with significant erosion potential occurred on February 27-28. East and northeast winds dominated for most of February 27, but shifted to the southwest as the storm diminished on February 28.

Variable winds from 16-40 km/h prevailed on February 27, with gusts of up to 72 km/h. Wind speeds diminished to less than 16 km/h late on the 27th, but increased to 40-48 km/h for most of the 28th, with gusts of up to 64 km/h.

Figure 17. Beach profile changes for profile 11 from January-April 1984.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P080384 3-84
P070284 2-84
P060184 1-84
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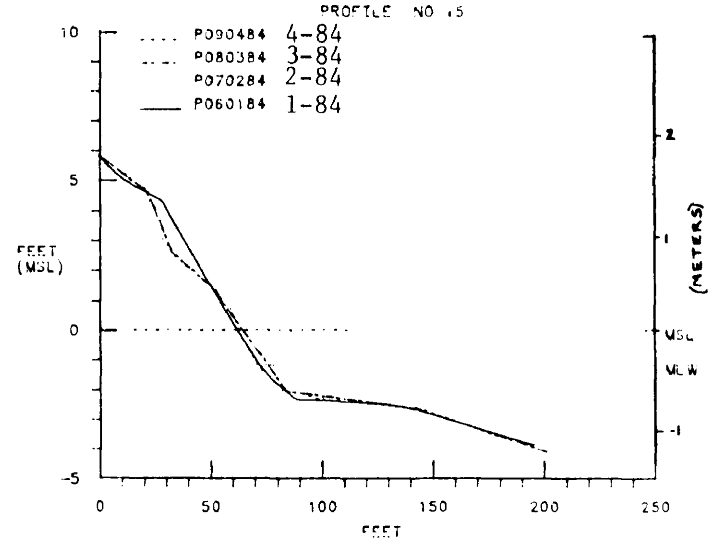
(METERS)
MSL
MLW
FEET


PROFILE NO 15
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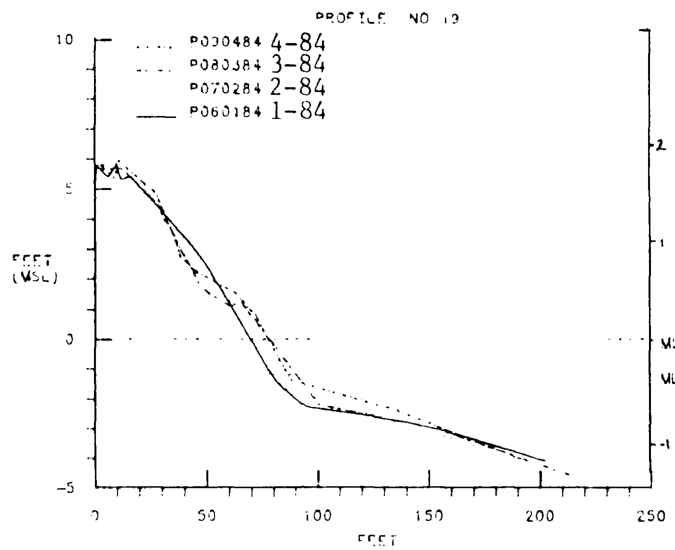
P080384 3-84
P070284 2-84
P060184 1-84
FEET (MSL)
(METERS)
MSL
MLW
FEET


PROFILE NO 19
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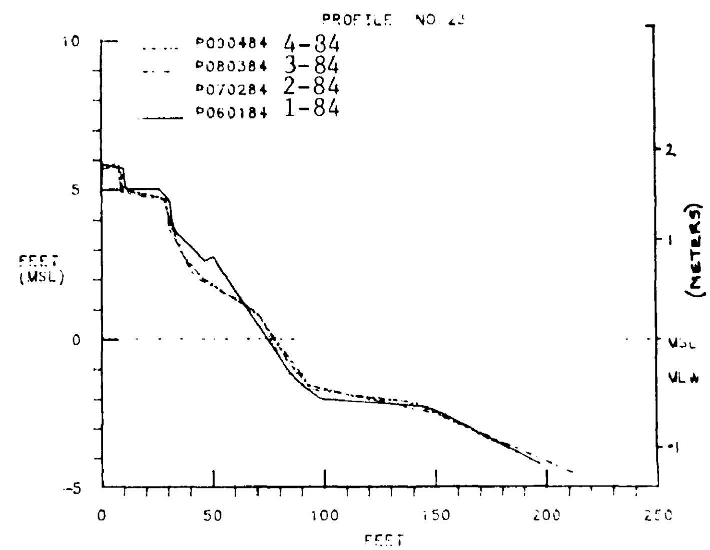
P070284 2-84
P060184 1-84
FEET (MSL)
(METERS)
MSL
MLW
FEET


P090484 4-84
P080384 3-84
P070284 2-84
P060184 1-84
FEET (MSL)
(METERS)
MSL
MLW
FEET

High tides at 1900 on February 27 again coincided with the highest gusting winds for the day. Superelevation of the tide level was 0.46 m at this time (Figure 16). The following low tide achieved its minimum approximately 0.3 m above the predicted level, with a lag of nearly two hours following the predicted time of low tide.

The measured high tide at 0700 hrs on February 28 continued to show an elevation of the actual tide of 0.5 m above predicted levels; however, this difference decreased steadily during the 28th, despite the sharp increase in speeds during much of the afternoon and evening. This decrease can be explained by the concurrent shift in wind direction to the southwest during the afternoon on the 28th. Despite the actual increase in wind velocity, then, further erosion was minimized by the wind switch away from onshore northeast winds and the resultant set-up.

September 11-14, 1984

Hurricane Diana originated as a weak frontal trough, combined with an upper level low-pressure system which formed into a tropical storm off the Florida coast on September 8. Diana organized into a hurricane by September 10, moving north-northeast along the Georgia and South Carolina coasts. The hurricane reached its maximum intensity with 139 km/h winds on September 11 in the vicinity of Wilmington, North Carolina.

The potential for destruction within the Chesapeake Bay was significant for this event; it was fortunate, however, that the path of the storm turned out to sea near Cape Hatteras, North Carolina on September 14, 1984. The effects of Hurricane Diana were evident along the York River shoreline by September 11, with steady easterly winds for the majority of the event. Wind speeds were variable from 8-40 km/h during the four-day period.

The associated tidal record (Figure 16) shows some elevation of the measured tide over the predicted levels during the first 48- hours (approximately 0.15 m), gradually diminishing to levels coincident with predicted levels by September 13. Maximum wave heights during the four days of observation remained less than 0.30 m. These factors accounted for the minimal erosion along the study shoreline during this event. Representative profiles are given in Figure 18; minor movement of sediment occurred from erosion of the beach face and deposition in the zone below MSL. Although the potential was significant for erosion, then, no significant scarping and transport of sediment was observed during the four day event.

September 26-28, 1985

Hurricane Gloria initiated as a tropical storm near the Cape Verde Islands on September 16, and maintained a west-northwest course across the tropical Atlantic. Hurricane Gloria reached the coast of Cape Hatteras, North Carolina on September 27, crossed over Long Island, New York at mid-day, and became an extratropical storm over England late on the 27th.

Steady northeasterly winds of 16-24 km/h were recorded at the study site for most of September 26; winds shifted to the north at approximately 2000 on the 26th as the storm approached the North Carolina coast (Figure 15). Maximum storm conditions occurred at Gloucester Point at approximately 0500 on September 27, coincident with the storm's closest proximity with the southeastern Virginia's coast.

Winds peaked significantly between 2300 on the 26th and 0500 on the 27th, with maximum gusts of nearly 96 km/h. As the storm continued northward, winds diminished rapidly and shifted to the west.

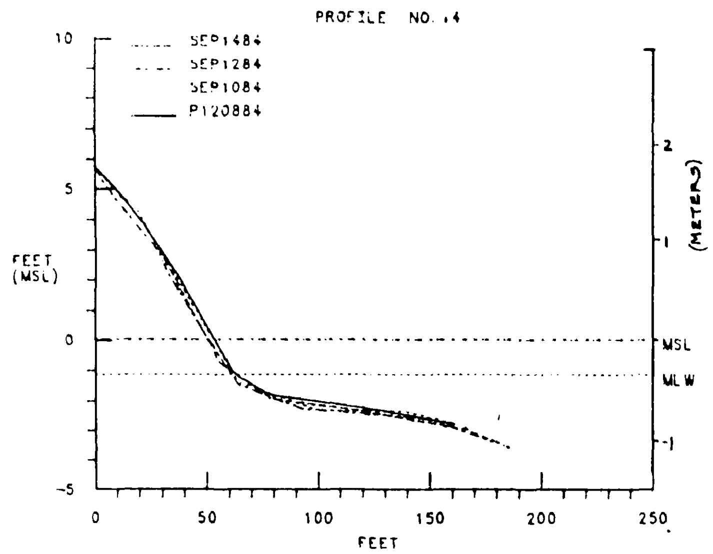
The measured tidal record reflects the extremely high water levels which existed during the passage of Gloria (Figure 16). The last high tide of September 26 occurred at 2000 with a 0.15 m elevation of the predicted high tide. During maximum storm intensity between 2300-0500 hrs on September 27, the ebb cycle was sharply abbreviated, falling only 0.24 m below the last high tide, and nearly 0.6 m above the predicted low tide levels at 0200. In addition, a second peak occurred at 0400, at the time of peak storm conditions and closest proximity of Gloria's passage along the coast. It is interesting to note following the passage of the storm peak that the following 24 hrs were characterized by both high and low tide levels which were lower than the predicted values (0.3-0.5 m).

The extremely high water levels, accompanied by increased wave attack, resulted in significant cutting of the bank and erosion, particularly along the northern segments of the VIMS shoreline. Scarps on the beach face and upper beach were accompanied by the loss of much of the planted and volunteered vegetation which had become established in the berm and upper beach zones.

November 1-4, 1987

Heavy erosion along the study shoreline from November 1-4 resulted from the presence of a stalled low-pressure cell and storm activity in a highly localized path including the study area. Winds maintained an east-northeast direction for approximately 90 hrs. Wind speeds averaged

Figure 18. Beach profile changes during Hurricane Diana, September 10-14, 1984.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SEP1284
SEP1084
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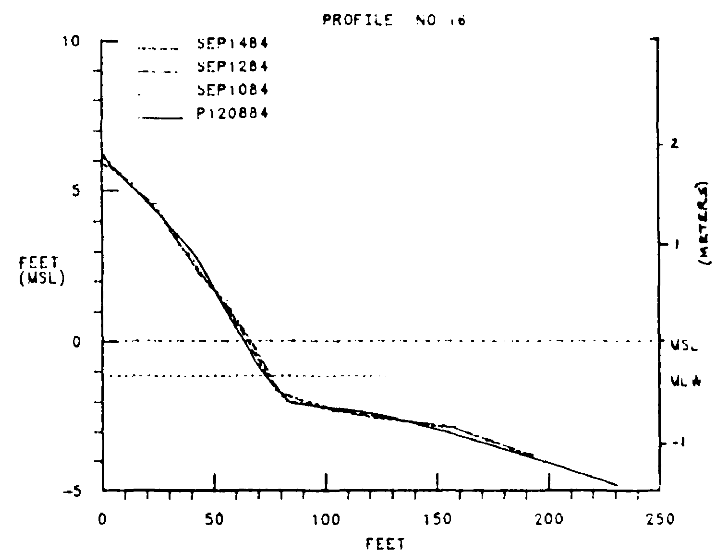
(METERS)
MSL
MLW
FEET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SEP1284
SEP1084
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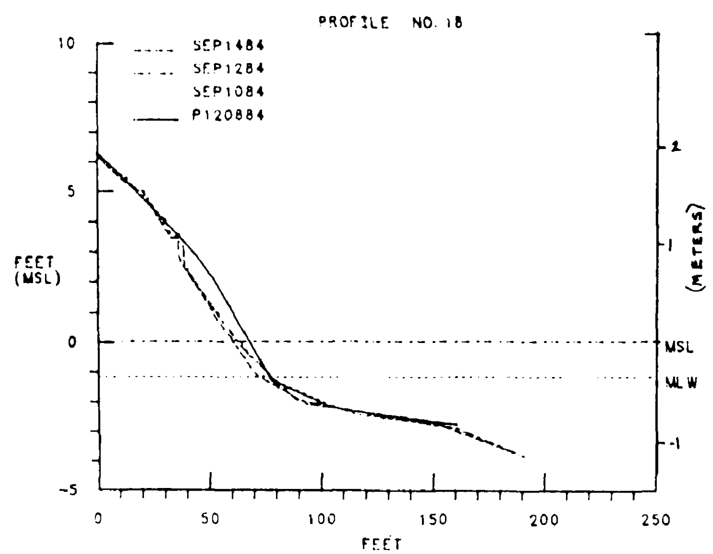
(METERS)
MSL
MLW
FEET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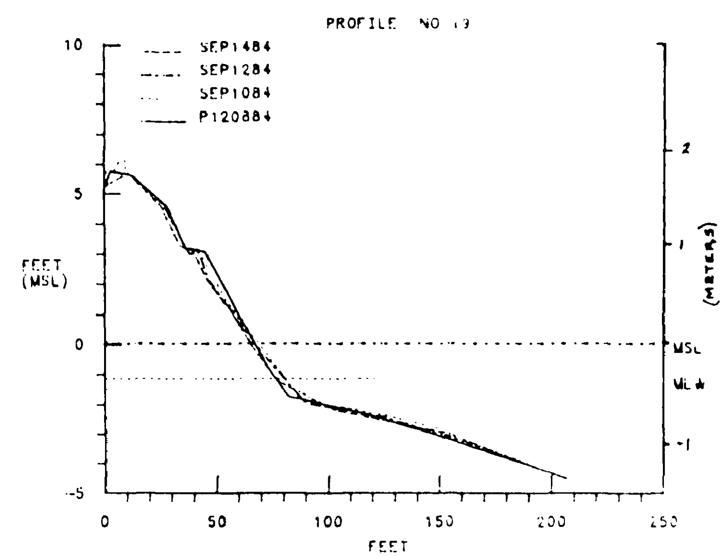
FEET (MSL)
(METERS)
MSL
MLW
FEET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SEP1284
SEP1084
P120884
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(METERS)
MSL
MLW
FEET

24-40 km/h for the event, gusting to 48-96 km/h on November 4 (Figure 15). Maximum observed wave heights were 0.9 m, with periods of 3.5-4.0 seconds.

Maximum storm conditions occurred on November 4, following 3 days of continuous east-northeast winds causing higher than usual water levels at the site. From 1300-1800, winds averaged 40-64 km/h with gusts of 96 km/h during the 5-hour storm peak. The resultant set-up was reflected in the recorded tidal levels, which indicated significant amplification of the tide during this event. Peaks in the maximum observed tidal surge were coincident with peaks in the wind velocity record. The previous 72-hour records were characterized by elevations of approximately 0.3 m of recorded high tides, while lows averaged 0.5 m above predicted values for this time.

On November 4, the predicted high tide (1300) coincided with maximum wind speeds of 96 km/h, resulting in a superelevation of the tide by 0.6 m (Figure 16). Erosional affects of increased storm intensity on November 4 was further amplified by already high water levels during the previous 72 hours.

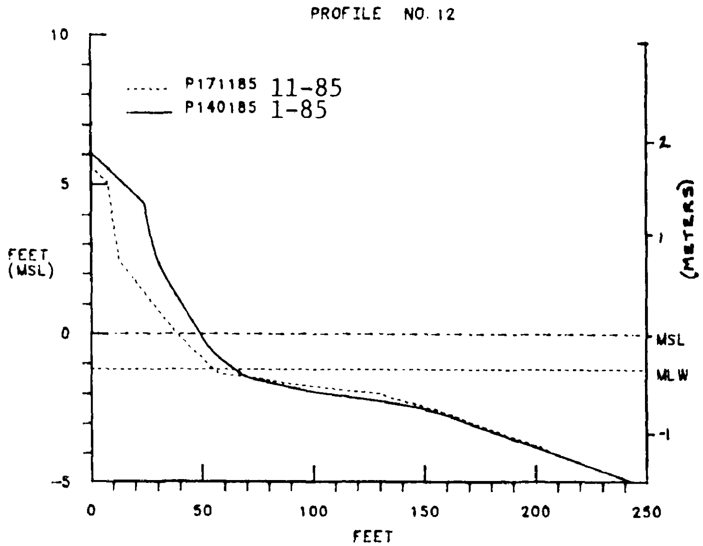
The November 1-4 storm was the most destructive storm to affect the study shoreline over the 26-month period. The combination of elevated water levels and steady east-northeast winds over the 96 hours resulted in erosion along this shoreline of the greatest magnitude of any storm during the study.

Heavy cutting of the upper beach and berm occurred within all segments of the beach; as in previous storms, however, the erosion of the unprotected northern segments was most obvious and significant, some of which resupplied downdrift cells with material eroded upstream.

Undercutting of the rooted vegetation in the upper beach resulted in the loss of nearly two-thirds of the vegetation planted in 1984, and much of the naturally volunteered vegetation from the upper beach.

Beach profiles were not taken immediately prior to the event, however, it was obvious from visual observation that a significant portion of the profile change shown in Figure 19 resulted from this event. In the northern segments, material was most heavily eroded from the upper beach and berm area above MSL. Some of this material was deposited in the nearshore zone below MSL, as shown in Profiles 12 and 20. Most of the sediment, however, was resuspended and transported alongshore to downdrift cells and into the main channel of the York River. From Profile 16 to Profile 30, scarping and resuspension of material was observed in the upper beach areas, however, material was also supplied to these area from the updrift eroding cells. More sediment was deposited temporarily as shallow offshore bars in these protected areas; post-storm observations revealed a fairly rapid (3-4 days) return of the sediment stored in these bars through onshore migration of the bar across the beach face, eventually becoming welded onto the existing beach face. As a result of the intensity and duration of this event, however, a considerable volume of material was transported alongshore and permanently removed from the system into the adjacent channel of the York River in the vicinity of the southernmost point.

Figure 19. Beach profile changes from January 1985 to November 1985.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MSL
MLW
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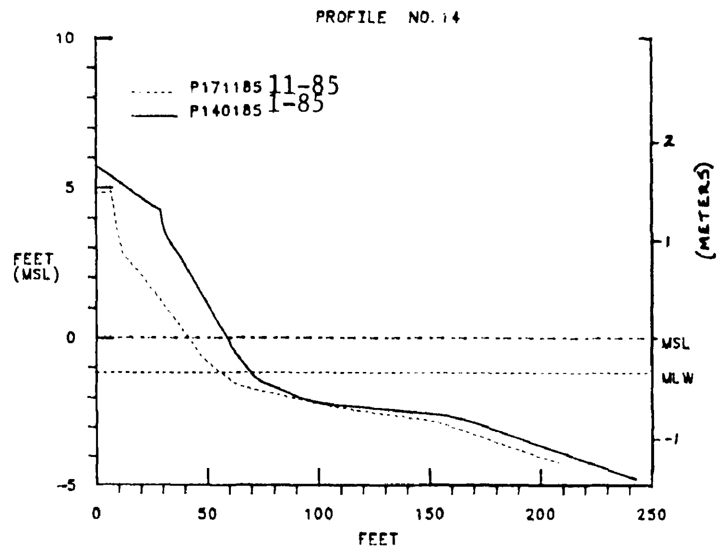
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MSL
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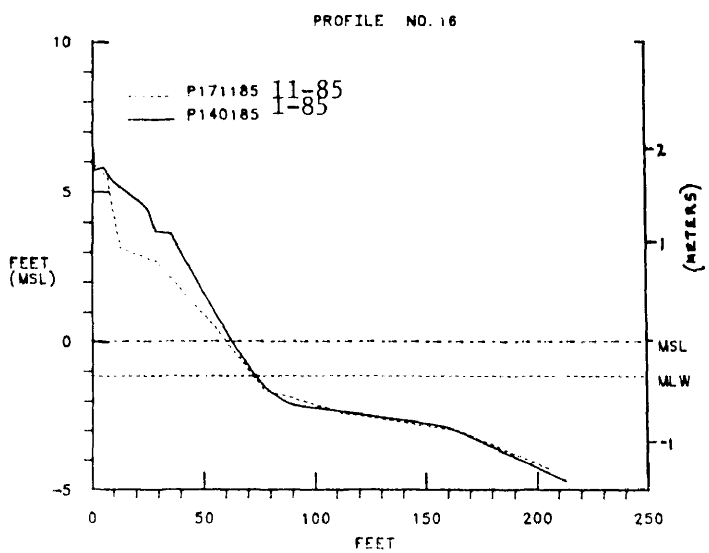
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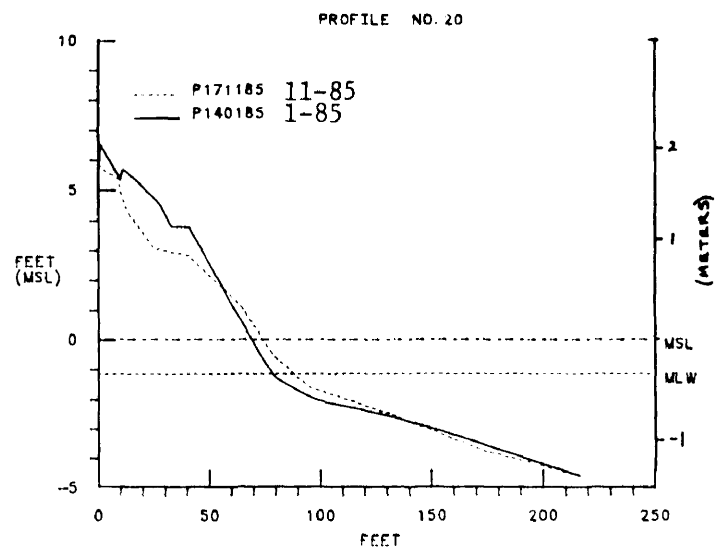
MLW
FEET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(METERS)
MSL
MLW
FEET

4.4 Discussion of Sediment Volume Changes

During the 26-month study, 1,255 $m^3$ (net) of material was lost from the VIMS shoreline (MLW). In terms of gross volume changes, 1,441 $m^3$ of material eroded while 186 $m^3$ accreted, for a total of 1,623 $m^3$ of material transported within the system. This is approximately 16.5% of the fill material emplaced in 1983. With no supplemental nourishment, the shoreline could resume the pre-nourished state of erosion in approximately 13 years from the time of project completion.

Losses of fill were highly variable along the shoreline. The northern, more exposed segments continued to erode rapidly while the more protected downdrift segments appeared stable over time. In addition, intervals of heaviest losses in cells A and B were most often associated with heaviest accretion in the downdrift cells of C and D.

Volume calculations are unavailable from immediately before and after each of the major storm for the 60-profile set. The results of the regular surveys, however, suggest that the intervals which include the seasonal northeast-east storms were associated with periods of highest gross transport. Conversely, the non-storm periods during the spring and summer intervals were characterized by minimal gross transport and net changes in sediment volume. This is particularly evident in the documentation of the interval from January to November 1985. The two major storms which occurred during this period were associated with northeasterly-easterly winds of some duration and with significantly higher than predicted water levels. The net loss of sediment during this 10-month interval was 714 $m^3$, while total net losses for the previous 16-months were 541 $m^3$.

The tidal records indicate that maximum storm wave heights were 1.0 m during the study period. This may be explained by the relatively shallow depths throughout this portion of the bay, which limits the maximum wave heights observed during most storms. Several of the storms had a potential for significant erosion of the shoreline; the greatest losses occurred, however, during periods of steady northeasterly-easterly winds which resulted in higher than average water levels. The combination of elevated water levels with peak storm conditions and predicted high tides resulted in the most damaging condition for cutting and erosion of the backshore area, and transport of sediment to the downdrift segments.

## 5. CONCLUSIONS AND FUTURE RESEARCH CONSIDERATIONS

### 5.1 Conclusions of Study

The present study was designed to investigate the immediate and subsequent response of a nourished estuarine shoreline, emphasizing the small scale systematic analysis of a single reach of shoreline.

It was determined during the 26-month study that the system experienced continuing losses of fill during periods of wind and high water. The 472 meters of shoreline lost 1,255 $m^3$ (net) of sediment from September 1983 to November 1985. This was approximately 16 percent of the fill emplaced in 1983. The changes in sediment volume were spatially variable. Some individual cells within the system appear to have achieved stability after the initial period of redistribution and alteration of the shoreline planform. These segments, however, are isolated areas which are protected by the positioning of the piers and by the groin-like effect of the outfall extensions. In addition, material eroded from the updrift segments is constantly resupplied to these protected sections during storm events.

The northern sections have remained most affected by the lack of updrift supply of sediments due to the presence of adjacent groins and bulkheads. This area has continued to be undercut and eroded during periods of moderate to high wind and wave activity, which has provided a continuous supply of material to downdrift segments of shoreline. The present state of this segment has approached the pre-construction shoreline configuration, although the rip-rap revetment continues to function as the primary line of defense against further erosion of the fastland. The area from Profile 8 to Profile 12 received new fill material during the Spring of 1987. It is not expected that this segment will achieve a stable profile, but will require a schedule of renourishment, or the emplacement of an offshore structure to dissipate wave attack along this exposed region.

Volumetric data from the Gloucester County Public Beach indicated that this downdrift section experienced accretion as a result of losses along the VIMS shoreline. Some of this material was later reworked and eroded from the public beach, although some of the material was permanently gained in the vicinity of the public boat ramp. A net loss of 439 $m^3$ of sediment occurred along this shoreline from September 1983 to November 1985, or approximately 30 percent of the material lost from the VIMS shoreline. Hence, the major benefit to the public beach was in the form of the recipient of the continuous downdrift supply of the VIMS nourishment material during periods of erosion of that shoreline.

Surveys were made during regular intervals to assess long and short-term changes in sediment volumes. The results suggest that intervals which included seasonal northeasterly and easterly storms were the periods of highest gross transport and net losses. Conversely, the non-storm periods during the spring and summer months were characterized by minimal gross transport and net losses of sediment. An examination of major storms which occurred during the study revealed that maximum wave heights during the most severe event was 1.0 meter, due to the relatively shallow nature of this portion of the bay. For this area, which has a relatively narrow mean tide range (0.7 m) the most severe erosion and transport of material out of the system occurred during the storms associated with northeast and east winds. The coincidence of elevated water levels during these events and the occurrence of the normal predicted high tide levels resulted in cutting and erosion of the berm and backshore areas. These events also resulted in transport of sediment into the deep channel adjacent to the southernmost point of the public beach.

A theoretical model curve was also developed from survey data for the natural shoreline. The calculated curve for the natural profile in August 1983 was highly concave, with average m values of 0.17. Fifteen months after nourishment of the shoreline, the calculated profile had steepened, with a mean value of 0.72. This more closely approximated Dean's (1977) predicted value of 0.66. The apparent lack of fit of the profile in August 1983 may be explained by the sediment-starved nature of the site and the presence of the compacted, fossiliferous Yorktown Formation, which truncates the profile near mean low water along much of the VIMS shoreline. Emplacement of a relatively thick wedge of sediment could have provided the unconsolidated layer of material needed to approach the smoothly concave form described by Dean (1977). This may explain the close approximation of the hypothetical form found in January 1985 for VIMS beach and that calculated by Dean for open coast beaches.

The results of the model curve fit were utilized to calculate volume fill requirements for alternative grain sizes of beach fill. These calculations are based on the relationship of grain diameters and the associated scale value A (Moore, 1982). Results suggest the extreme sensitivity of the calculated volumes to the grain size parameter. This indicates the need for highly precise analysis of native sediment samples when developing fill criteria. The results of this analysis also indicate the need for consideration of site-specific conditions, such as the intersection of the Yorktown formation and the natural profile in the nearshore zone at VIMS beach, when developing the criteria for optimal fill design.

The conclusions of this study should be considered in developing a long-range plan of protection of this shoreline. Approximately 16% of the fill emplaced in 1983 has been lost from VIMS beach. The rates of loss, however, vary along the shoreline. The northern segment continues to have the highest rate of sediment loss, and had resumed the pre-nourishment state prior to supplemental nourishment in 1987. It is anticipated that this material will again supply the downdrift segments of VIMS beach and the public beach during periods of high water and wave attack.

### 5.2 Implications for Future Nourishment Projects

With the study conclusions in mind, any supplemental nourishment should be concentrated at the northern sections of VIMS beach, allowing for maximum retention of the fill along VIMS beach. Material emplaced in the more stable, downdrift segments of VIMS beach will be transported downstream into the channel and along the public beach during storms. Based on the state of the northern segment prior to nourishment in 1987, renourishment will likely be necessary on a four to five year cycle, depending on severity of storms which occur during that time.

Retention of the nourishment material has been increased by the groin-like effects of the outfall structures along VIMS shoreline. The emplacement of an offshore, shore-parallel structure could result in longer retention of the fill material in the exposed northern segments, and dissipate wave attack during storms. An additional advantage of a shore-parallel structure is to allow for some alongshore transport of material to downdrift segments, so that complete starvation of sediment does not occur. This structure would be most effective in the northern cell to slow the ongoing process of erosion following nourishment of the beach.

Estuarine nourishment projects and responses differ from the open-ocean coasts in that the mechanism of change within these systems occur on comparatively shorter temporal scales. Factors such as individual shoreline reaches and effective fetch are much less important in the understanding of beach response along ocean coasts. As a result, the planning of estuarine projects requires generation of similar but specific data bases before and after project implementation.

Many parameters should be considered in any design and monitoring of a beach renovation project. These factors may be summarized as follows:

1. Detailed analysis of prenourishment conditions to indicate the stable profile for a given site. This information can be used to determine appropriate fill volumes and grain sizes of nourishment material.
2. Monitoring of post-nourishment behavior of beach system to indicate: 1) appropriate schedule and design for subsequent renourishment projects 2) appropriate design and placement of additional defense structures.

One factor not addressed in this study, but of increasing importance in the permitting of beach projects, is a standardized approach for monitoring the biological impact of beach nearshore projects on the biota in the nearshore zone. Guidelines for this type of study are presented by Stauble and Nelson (1985). They suggest determination of the spatial scales of variability for beach organisms, the tolerances for burial of these nearshore organisms, and the impacts of existing projects on these nearshore communities.

Finally, any discussion of shoreline erosion and beach protection should address the effects of sea-level rise. In the planning and development of long-term shoreline stabilization, the economic feasibility of beach nourishment versus the alternative of "rock" approaches involve projections and speculation of rates of sea-level rise. Weggell (1986) presents an interesting analysis of the economics of beach nourishment under the various scenarios of rising sea-level. His paper presents different projections of sea-level rise based on leading studies in this area. Included are discussion of global warming trends, melting of glaciers, the thermal expansion of the earth's oceans, and the resultant widespread increase in erosion along the world's coastlines. Weggell's economic analyses suggest two questions which must be considered in erosion control projects in both ocean and estuarine environments. First, at what rate of sea level rise does the alternative of artificial nourishment become an uneconomic alternative for erosion control? Second, at what point does this rate of rise justify the emplacement of coastal "rock" structures to maximize the residence time of the nourishment material? The implication is that at some point, the increasing costs of perpetual nourishment projects will outweigh the benefits of amelioration of erosion effects.

These considerations are valid for projects currently being considered, as well as for long-term planning and projections. Any responsible beach renovation plan must consider both the economic as well as the functional success of these projects in the contexts of long and short-term scenarios.

## APPENDIX I: SHORT-TERM SEDIMENT VOLUME CHANGES

September 1983- October 1983

The first survey period of the study included the interval from late September to late October, coinciding with the completion of the revetment construction in the vicinity of Byrd Hall. The armourment of the existing outfalls in the vicinity of Profiles 16, 18, 25, and the oyster and ferry piers were completed in mid-October and visibly functioning as barriers to longshore transport by this time.

The first survey interval included three storms which resulted in visible resuspension and alongshore transport of sediment. The events of October 10 and 13 were relatively short-term "northeasters" (duration less than 8 hours) with maximum winds of 16-24 km/h, maximum wave heights of 0.3 m and wave periods of 1-2 seconds.

The October 20-22 storm included periods of northeast winds which later shifted to the southeast as the storm passed from the area. Maximum wave heights of 0.6 m and wave periods of 4.0 seconds were recorded on October 21. Erosion of the nourished beach was further accelerated by higher than average water levels due to spring tides at this time.

228 $m^3$ of material was lost from the segment defined by cells A, B, and C during the initial post-construction period. Of this, approximately 57% was lost from the 46 m segment of cell B. Concurrently, the shoreline section from cells D and E remained relatively unchanged in volume. Calculations of volume change to SLW for

this month indicated net accretion within every cell in the defined zone from MLW to SLW, totaling 65 $m^3$, indicating the redistribution of material in the zone below MLW.

October 1983- November 1983

During the period from late October to late November, two relatively short-term events occurred. The event of November 10, while less than four hours in duration, was intense and erosive. Winds originated from the east-southeast, and shifted to the southeast as the storm passed from the area. Maximum wave heights were 0.3 m, with periods of 2.5-3.0 seconds. Erosional scarps and cuspate features were evident during this brief, but high energy storm event. Entrainment and offshore transport of sediment was also observed.

A second event occurred on November 15 with maximum winds of 40 km/h from the east-southeast for a period of approximately 5 hours. Maximum wave heights were 0.3 m with average periods of 2.0-2.2 seconds. Again, a zone of resuspended sediment resulted from the cutting of the berm and extended along the length of the study shoreline.

This period was one of overall accretion along VIMS beach, although the segment defined by cells A and B lost approximately 57 $m^3$. Cell C accreted 152 $m^3$, while no volume change occurred in cell D, with only minimal accretion in the area of cell E. The interval was one of small net erosion within the zone from MLW-SLW; accretion within this zone from profiles 12-30 was offset by greater losses in the area from profiles 1-11.

November 1983-January 1984

Two storms were recorded during the two-month period from late November through late January. The first event occurred on December 28, 1983. Winds gusting during the morning from the east later shifted to the southeast and finally to the south as the storm passed over the area. Maximum winds of 40 km/h were accompanied by wave heights of 0.4 m and wave periods of 1.5-2.0 seconds.

A second event occurred with steady easterly winds and rains on January 17 and passed out of the area early on January 18. The storm caused resuspension of sediment in a zone approximately 8-15 m from the shoreline, accompanied by cutting of the bank in the northern cells caused by the heavy storm runoff. Wave heights were less than 0.2 m during this event.

This was a period of net erosion. Typical patterns of erosion and accretion within sections were reversed during this time. Approximately 87.4 $m^3$ of material accreted in the cells from cells A and B, primarily due to the existence of two low groins on the property adjacent to VIMS (profiles 1-8), and to the completion of the outfall armourment in the vicinity of profile 9 in late November. Fill material temporarily transported into these cells by southeast and south wind conditions was effectively retained by the structures in this area operating as barriers to the littoral transport along this shoreline.

Cells C, D, and E all eroded during this time, with a cumulative net loss of 365 $m^3$(MLW) for the two-month period. Of this, approximately 284 $m^3$ was lost from cell C. 122 $m^3$ was lost from cell D, and 87.4 $m^3$ was lost from the MLW-SLW zone in cell D.

January 1984- April 1984

This survey interval extended from late January to early April, and included four storms. The first, on February 3, had southeast winds of 24-40 km/h, a duration of approximately six hours, maximum wave heights of 0.75 m and periods of 1.5-2.0 seconds. Entrainment and the transport of material northward (opposite the dominant littoral drift) was visible in the offshore zone as narrow fingers of resupended sediment in the vicinity and northward of profile 1.

The storm of February 23 was considered to be the first major northeast storm to affect the VIMS shoreline since the beach renovation of 1983. Gusting winds of up to 72 km/h were recorded during this two-day event, with erosion compounded by onshore set-up and high tide conditions during the storm. This storm was closely followed by a second storm on February 27-28, associated with easterly winds which shifted to southeast winds on the second day. Wind speeds were highly variable, gusting to 64-72 km/h on February 28. A detailed discussion of these two events is included in a later section.

Observations during the three weeks following the storms of February 22-23 and 27-28 revealed a return of sediment transported offshore during the events, and the subsequent developmment of a ridge-and-runnel topography which migrated landward during the post-storm recovery period. This phenomenon was particularly evident in the segment of shoreline between profile 16-30, while the area from profile 8-16 remained heavily scarped following the storm. The small cells created by the groins within the segment from cell A regained sediment lost as a result of the February 22-23 storm during subsequent periods of southwest winds.

A fourth event occurred during this period on March 20, 1984. Easterly winds of 16-24 km/h were associated with wave heights of 0.2 m and periods of 2.5 seconds. The storm caused resupension of the finer fraction in an alongshore zone for approximately eight hours.

Nearly 108 $m^3$ of material was lost during this period, however, the loss was only 30 $m^3$ when calculated to the SLW datum. More notable was the gross volume of sediment transport during this period. Approximately 593 $m^3$ of material was transported within the system during this two-month period (737 $m^3$ calculated to SLW).

A closer examination of these findings revealed that 23 $m^3$ eroded from cell A, while cell B lost 274 $m^3$, or approximately 6.0 $m^3$/m. Another 70 $m^3$ eroded from the zone below MLW. While the area from profile 12-15 visibly lost material, much of the sediment eroded from cells A and B accumulated along the downdrift section from profile 16-21. As a result, only 30.4 $m^3$ of net erosion occurred in this section, and a gain of 18 $m^3$ was calculated for the SLW datum. Downdrift of the oyster pier (cell D) accreted by 242 $m^3$, or approximately 79% of the sediment eroded from the northern segments of the beach. The section south of the ferry pier (cell E) lost a small volume of material during this time.

April 1984- May 1984

This period encompassed the interval from early April to mid-May. No storms were recorded during this interval.

A continuing trend of erosion of the northern section was noted during this time, with losses of 152 $m^3$ recorded from profile 1-21. Most of this (133 $m^3$) eroded from the cell from cell B. The section of shoreline from cell D again accreted by 139 $m^3$, and 13 $m^3$ was gained in the cell from cell E.

Comparisons of volume change from MLW to SLW indicated a period of net erosion within this zone from April- May, primarily resulting from the significant losses across the profile in the northern segments.

June 1984- August 1984

This survey interval extended from late June to late August. One event was recorded during this time on June 22. Easterly winds averaged 16-24 km/h for approximately four hours, resulting in wave activity and resuspension of material. Wave action during this time was amplified by higher tides of this period.

No significant net volume changes were recorded during this interval, as calculated to the MLW datum. Interestingly, the net erosion of 65 $m^3$ from the zone from MLW-SLW was evidenced by losses in every segment of the shoreline, with the exception of the cell from cell C, which experienced minimal accretion for the two-month period.

August 1984- January 1985

This survey interval includes the period from late August to early January. One significant storm, Hurricane Diana, was documented from September 11-14. Easterly winds continued steadily for the majority of the event, averaging 16-32 km/h, and gusting to 40 km/h. Steady easterly winds of 16 km/h which persisted for more than several hours effected the entrainment of sediment along this shoreline, as was confirmed during this event. Further documentation and discussion of this storm is included in a later section.

Volume changes during this period were similar to post- storm findings of the February 22-23 event. Losses of approximately 23 $m^3$ were calculated to MLW, whereas the net volume change, as calculated to SLW, indicated the accretion of 57 $m^3$. These findings suggested a significant deposition of material within all cells below the MLW zone. Again, it is notable that approximately 546 $m^3$ of material was transported within the system during this four-month period. Losses of 95 $m^3$ from cell A and 273 $m^3$ from cells B and C were offset by the accretion of 220 $m^3$ from the zone of cell D, or approximately 60% of the net loss for this interval. Cell E remained relatively unchanged from August 1984 to January 1985.

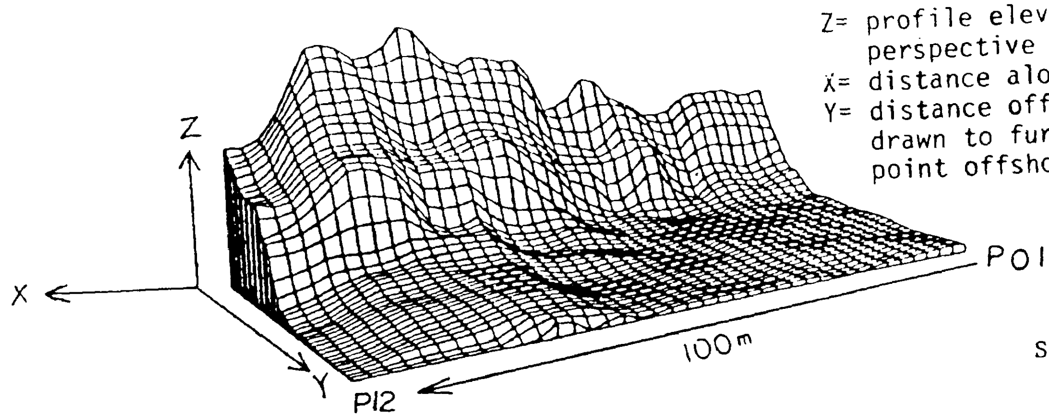
January, 1985- November, 1985

The final study interval included the period from early January to mid November. No documentation exists for this interval of relatively short-term events, two significant storms were recorded during this eleven-month period. The first storm occurred from September 26-28, and resulted from the passage of Hurricane Gloria along this coast. The second, largely unpredicted storm event, occurred from November 1-4 and was responsible for the greatest damages and losses of sediment of any storm recorded during the two year study period. Both storms were associated with east and northeast winds during most of the storm period, with gusts of 88-100 km/h. Wave conditions during Hurricane Gloria were choppy and confused, with maximum heights of 0.75 m. Maximum wave heights of 0.9 m were recorded for the November 1-4 storm, with periods of 3.5-4.0 seconds. Both storms of this period are further discussed in the following chapter.

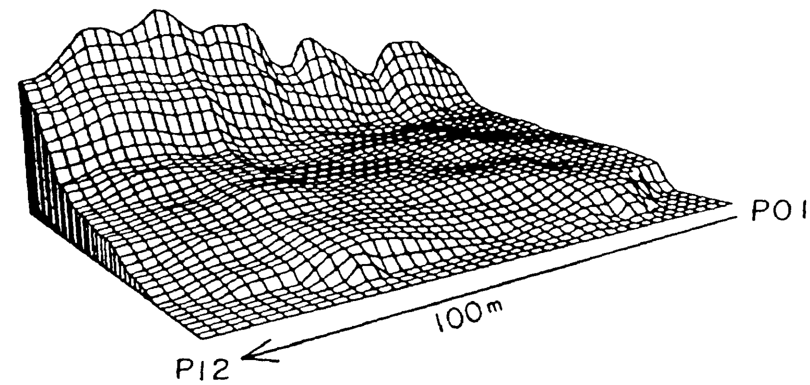
Net losses of 714 $m^3$ (MLW) occurred during this period. This loss represents 57% of the total net erosion for the two-year study period. The loss of 630 $m^3$, calculated to SLW, indicates some transport of material within the zone of MLW-SLW. Heavy losses occurred along the northern, exposed segments of VIMS beach. From cells A, B, and C, erosion of 1,002 $m^3$ of material was offset by accretion in cells D and E of 288 $m^3$, and another 57 $m^3$ within the zone below MLW.

APPENDIX II: Two- and three- dimensional Surface II plots of profile cells and changes in profile elevation contours

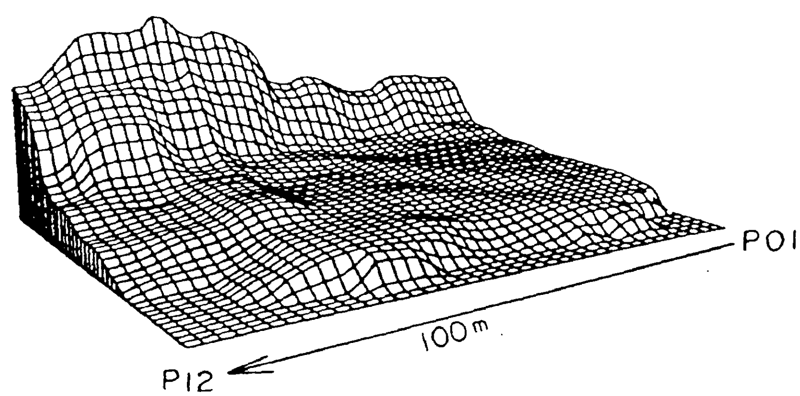
Figure 1 of Appendix II. Surface II plots of beach and nearshore contours for profiles 1-12 from September 1983-November 1985.



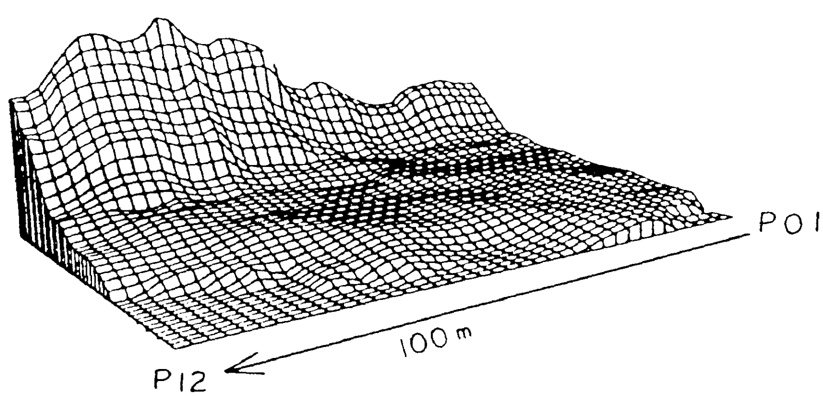

September 1983



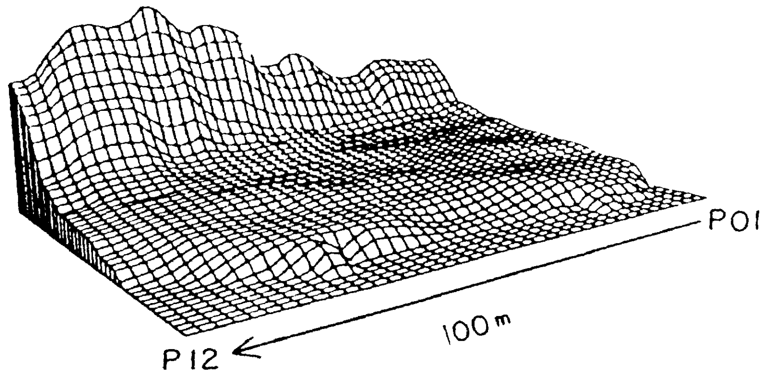

October 1983



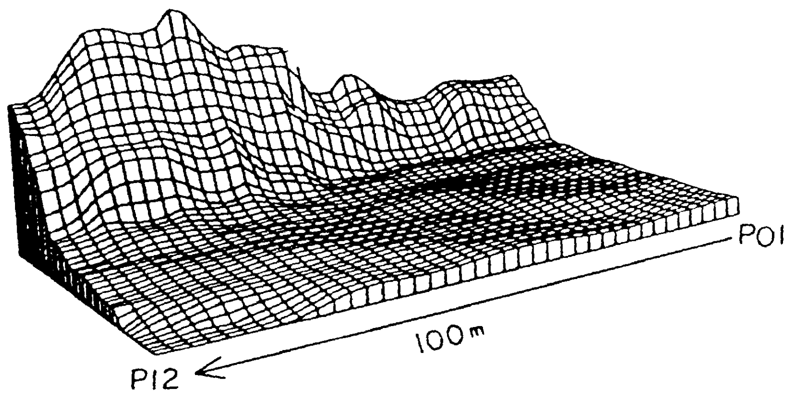

January 1984



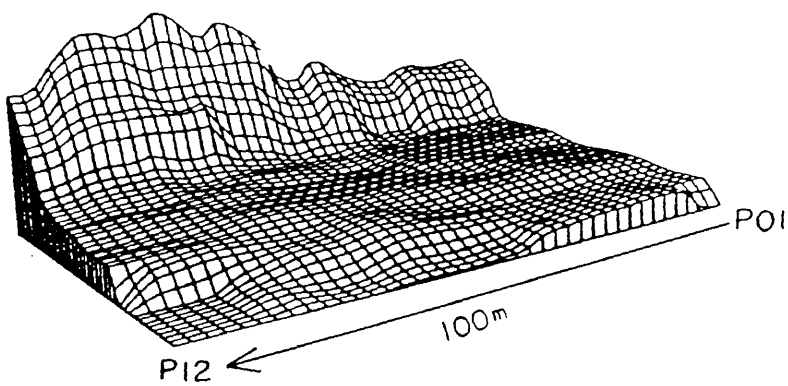

April 1984



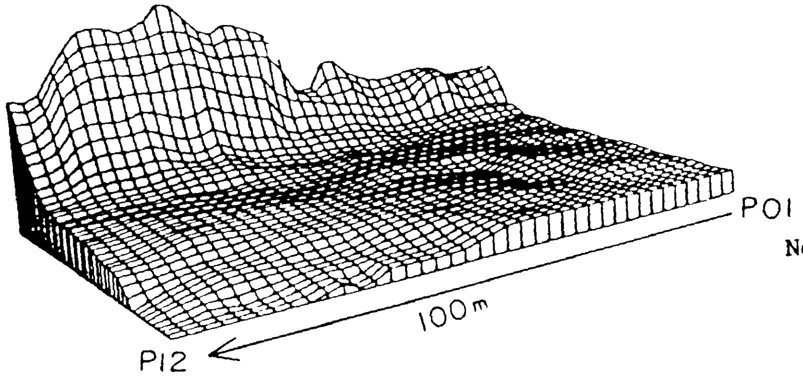

May 1984




August 1984

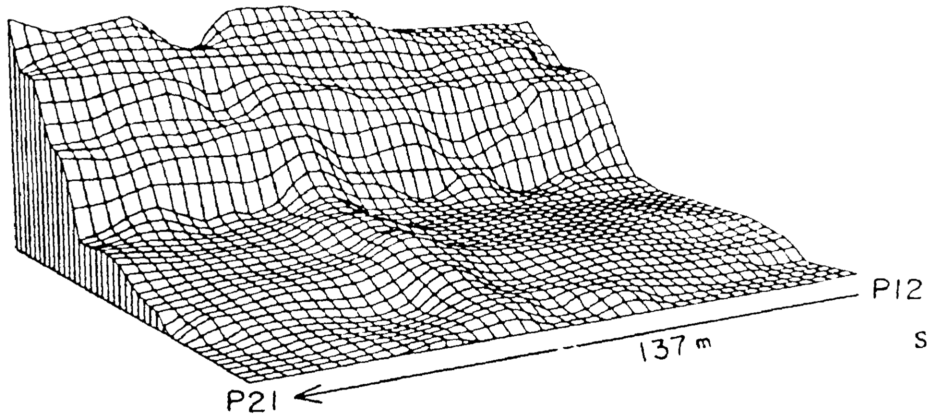



January 1985

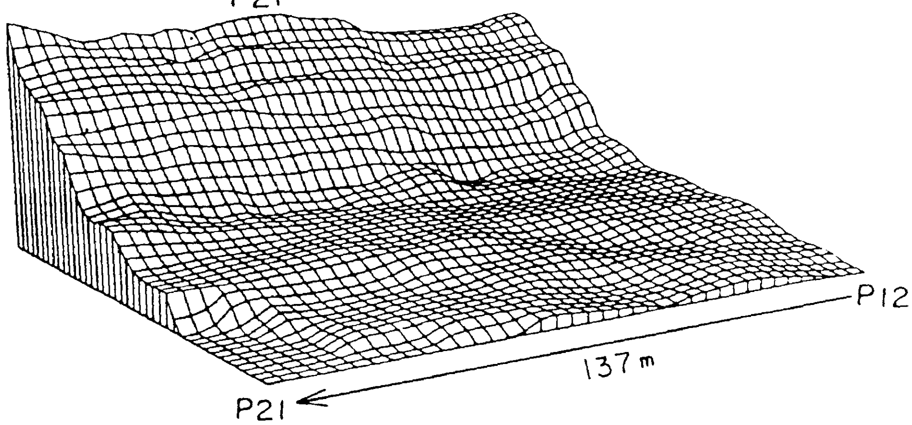



November 1985

Figure 2 of Appendix II. Surface II plots of beach and nearshore contours for profiles 12-21 from September 1983- November 1985.




September 1983

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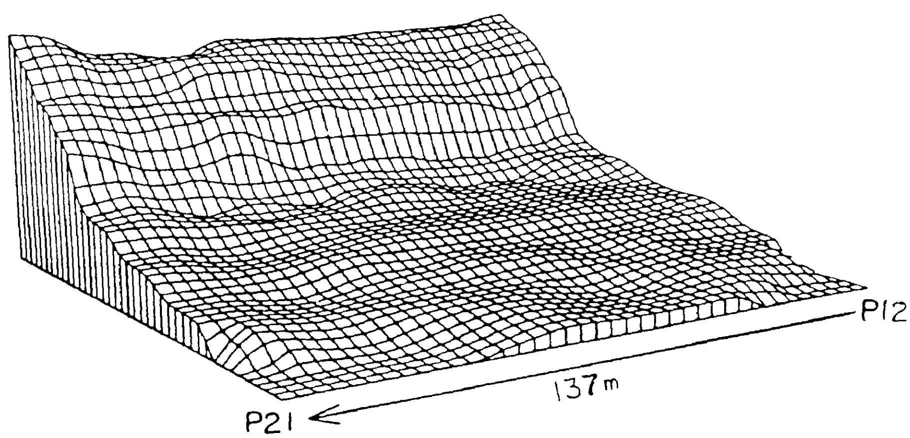
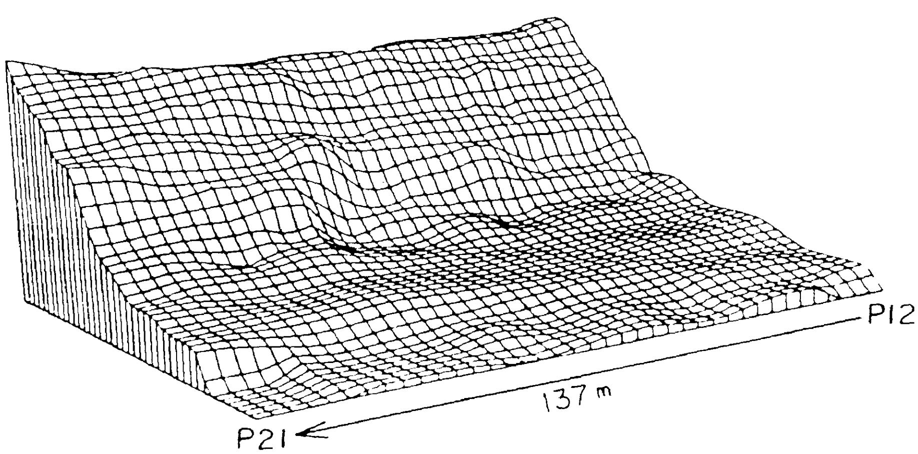
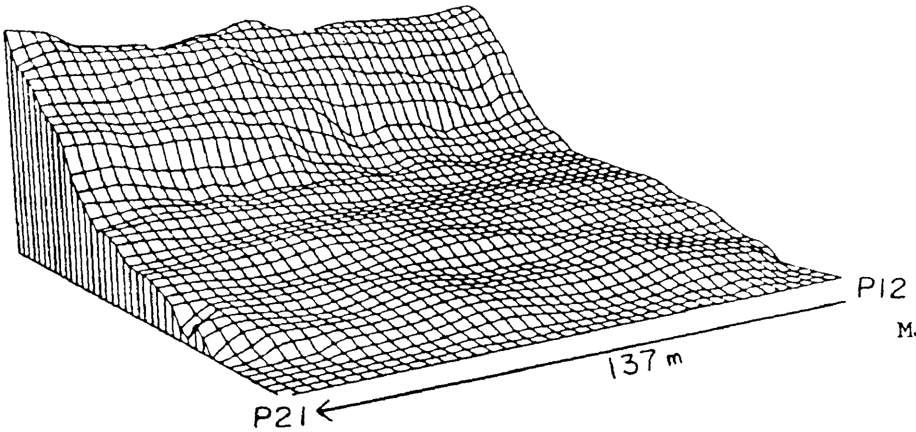


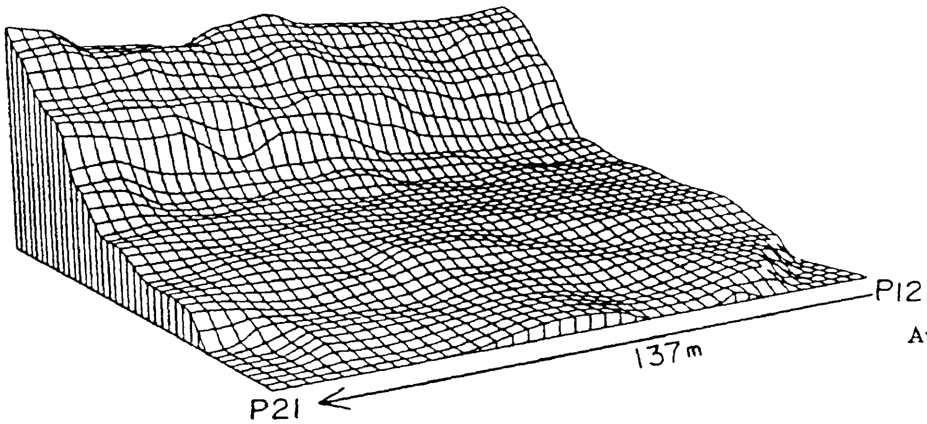

January 1984



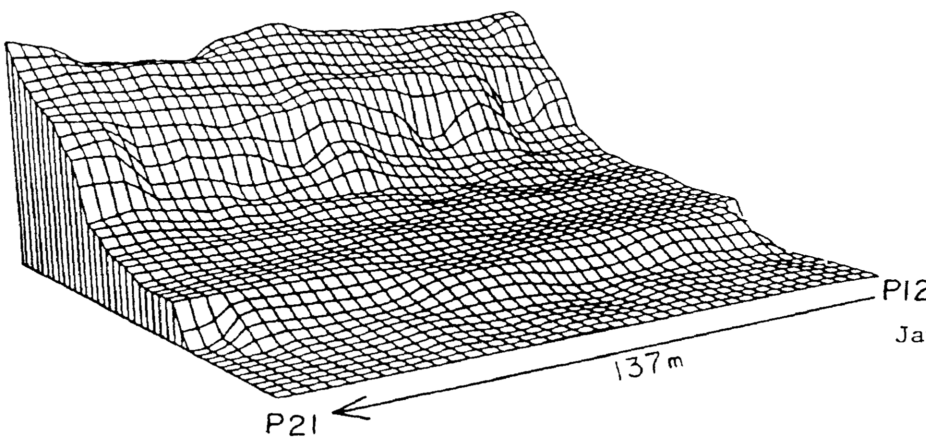

April 1984



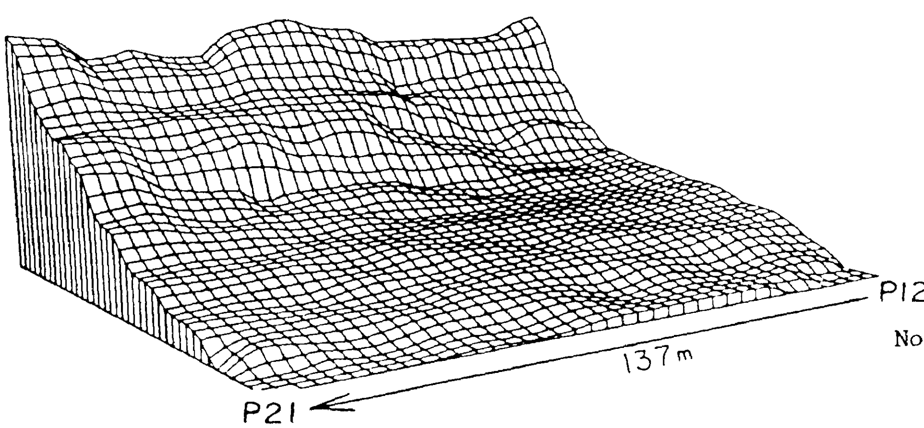
May 1984



August 1984

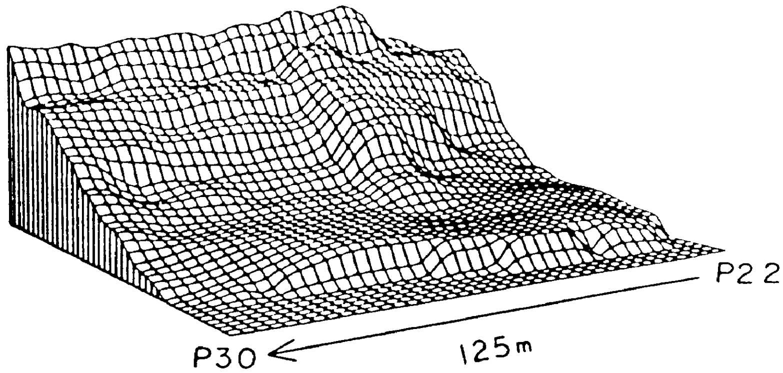


January 1985

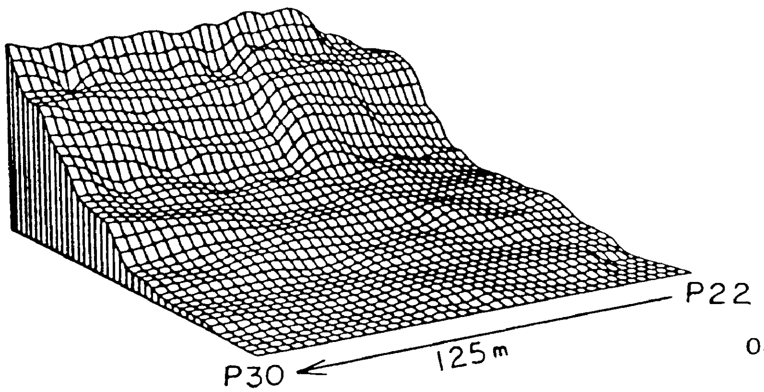


November 1985

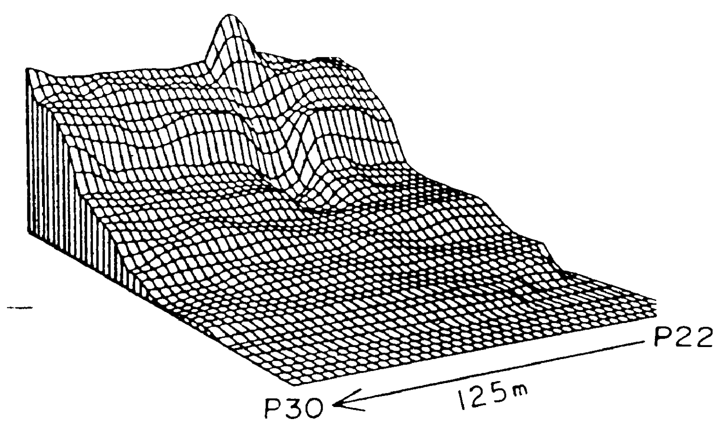
Figure 3 of Appendix II. Surface II plots of beach and nearshore contours for profiles 22-30 from September 1983- November 1985.



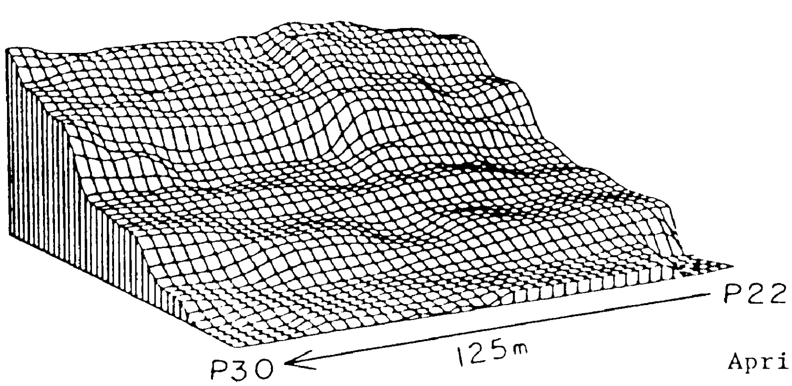

September 1983



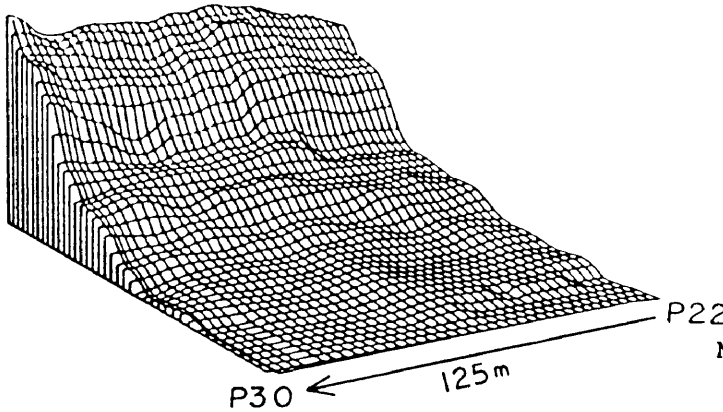

October 1983



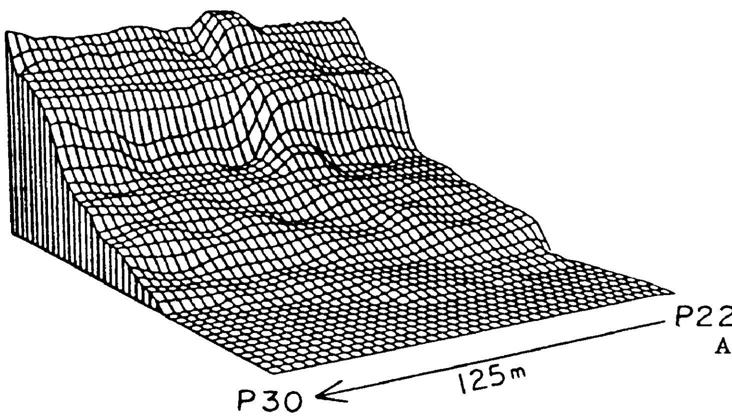

January 1984



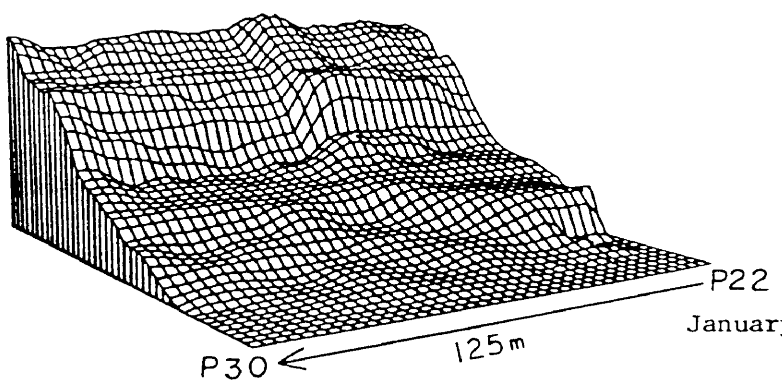

April 1984



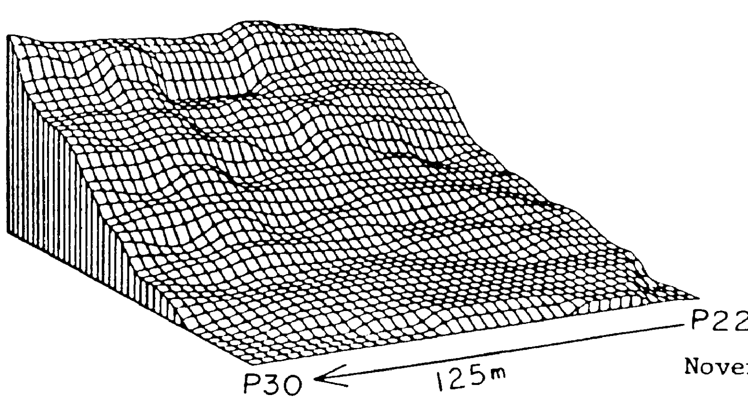
May 1984



August 1984

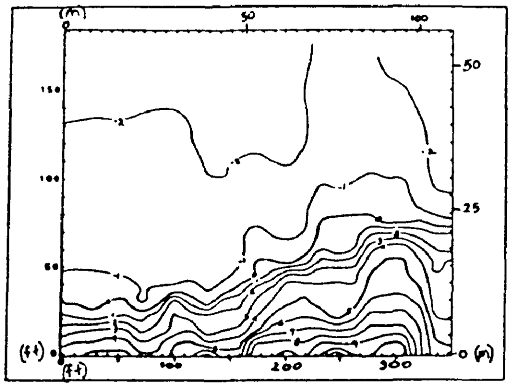


January 1985

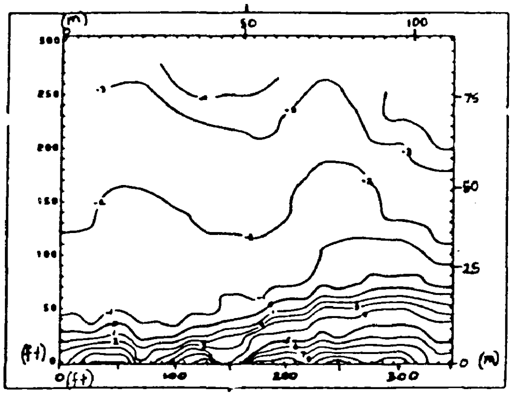


November 1985

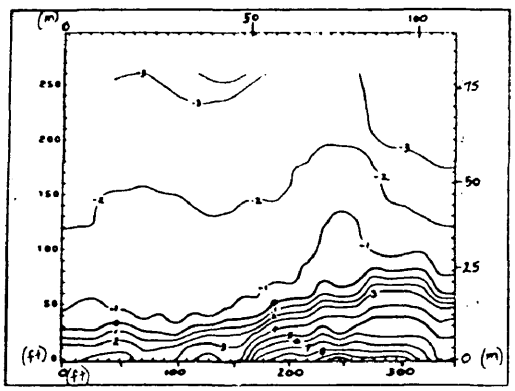
Figure 4 of Appendix II. Surface II two-dimensional plots of elevation contours for beach and nearshore zones for profiles 1-12 from September 1983-November 1985.



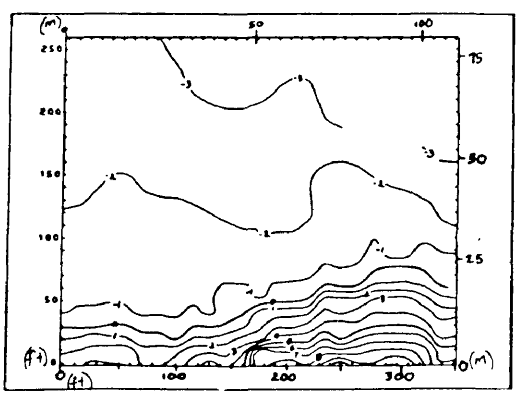
September 1983



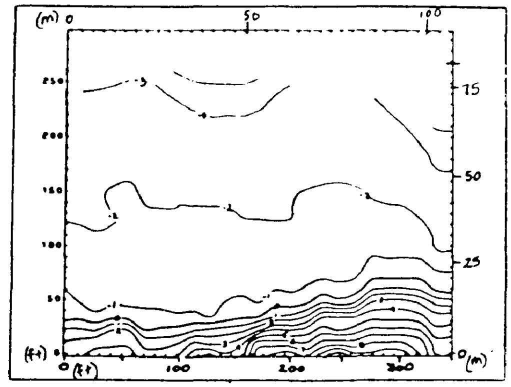
October 1983



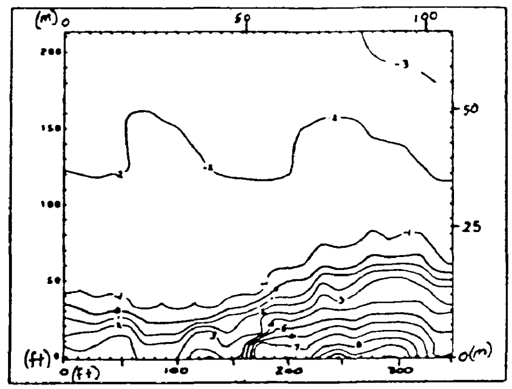
January 1984



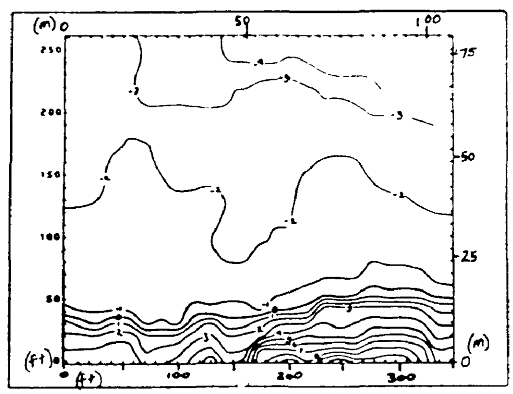
April 1984



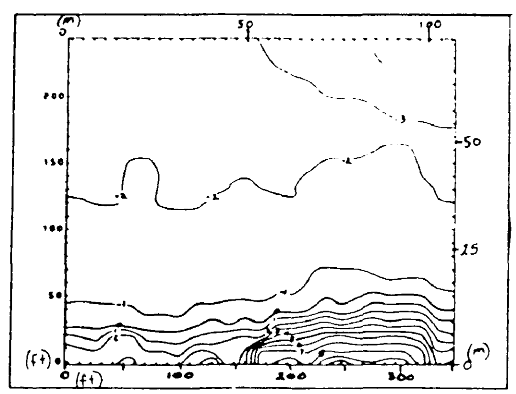
May 1984



August 1984



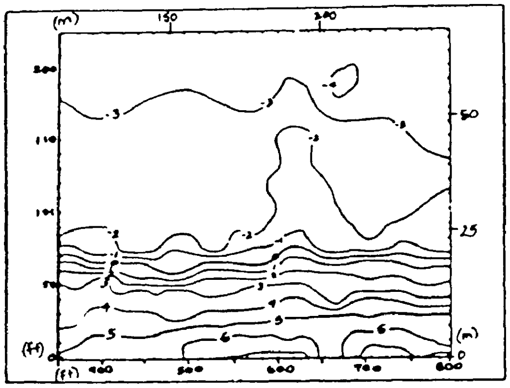
January 1985

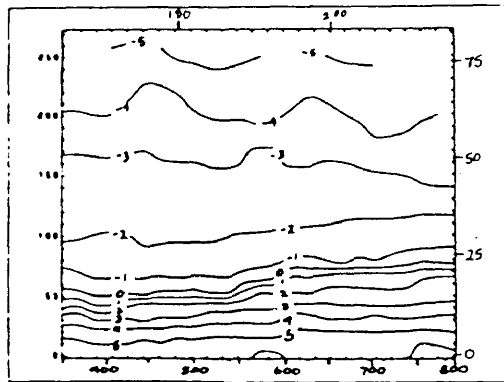


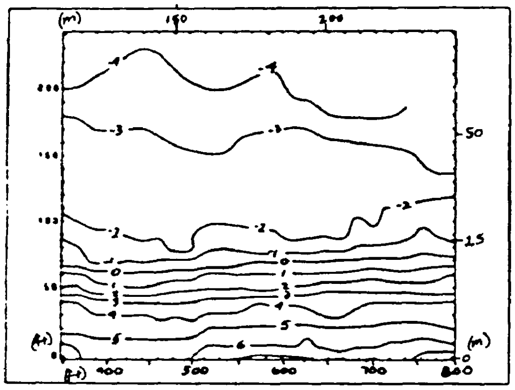
November 1985

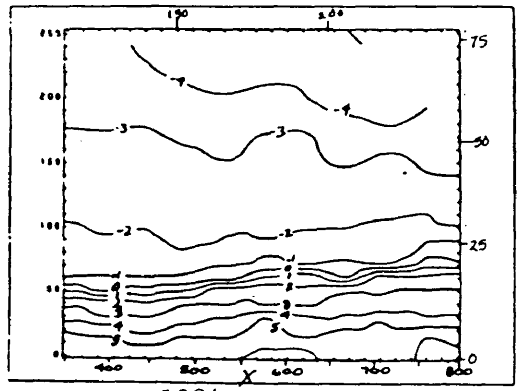
Note: Contours in feet (ft)

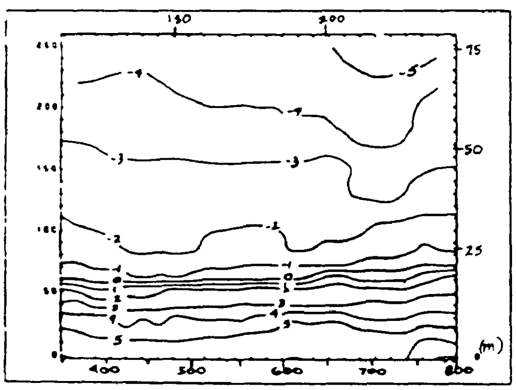
Figure 5 of Appendix II. Surface II two-dimensional plots of elevation contours for beach and nearshore zones for profiles 12-21 from September 1983-November 1985.

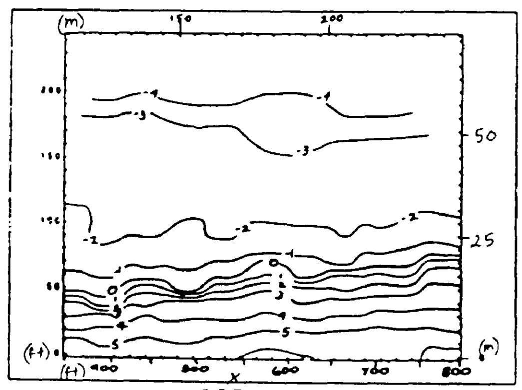

September 1983

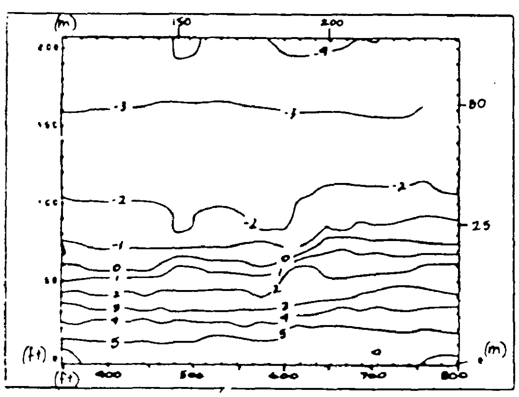

May 1984

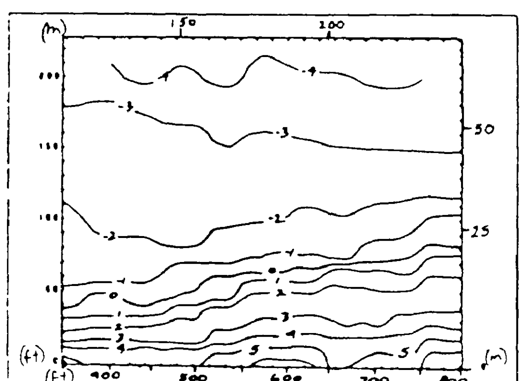

October 1983


August 1984


January 1984

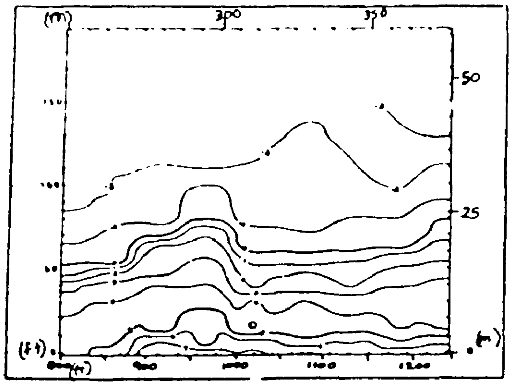

January 1985

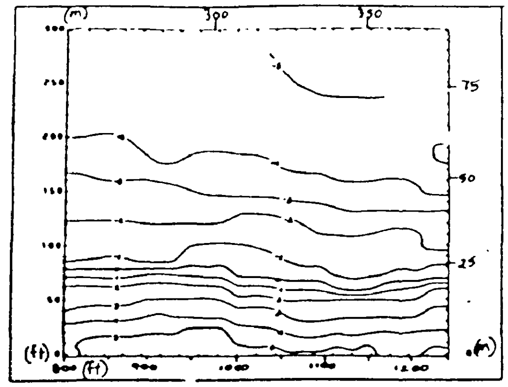

April 1984

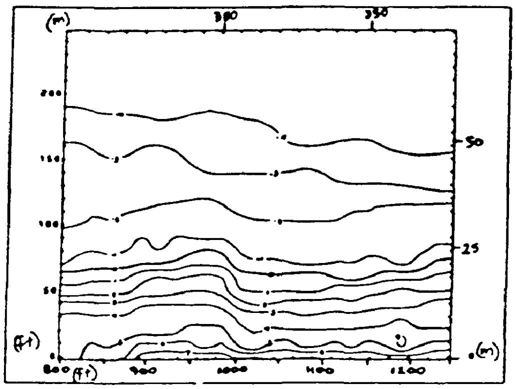

November 1985

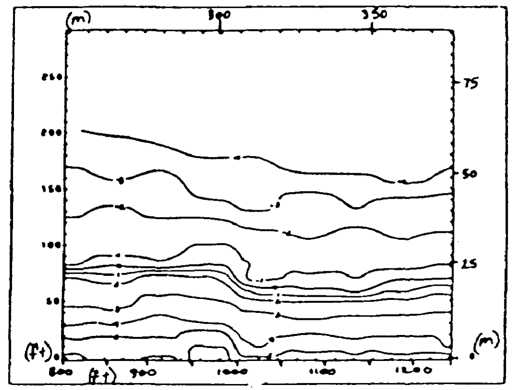
Note: Contours in feet (ft)

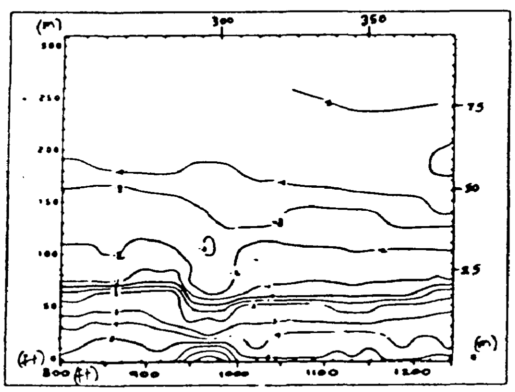
Figure 6 of Appendix II. Surface II two-dimensional plots of elevation contours for beach and nearshore zones for profiles 22-30 from September 1983-November 1985.

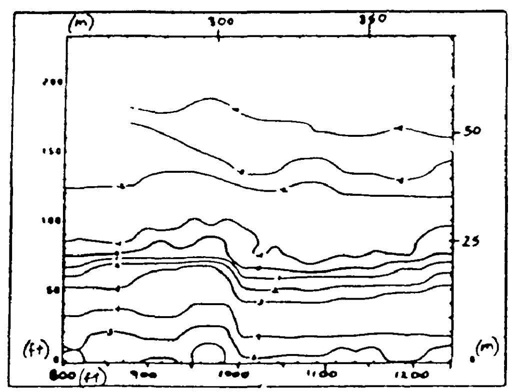

September 1983

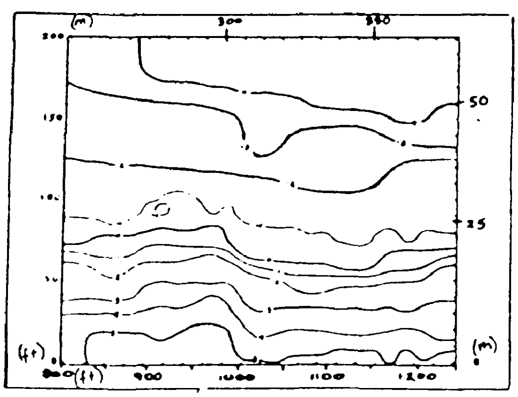

May 1984

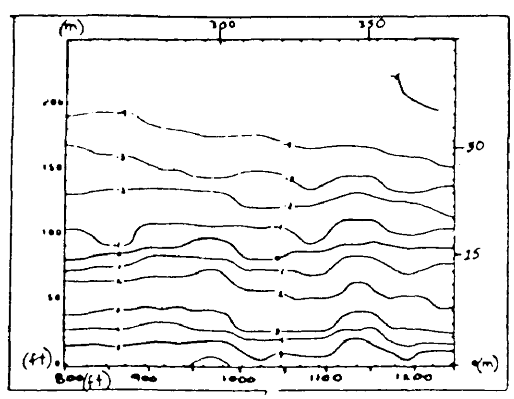

October 1983


August 1984


January 1984


January 1985


April 1984


November 1985

Note: Contours in feet (ft)

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Entered the College of William and Mary, School of Marine Science in January 1983 as a graduate student in the Department of Geological Oceanography.