CHAPTER ONE HUNDRED TWELVE

Coastal Changes at Bethany Beach, Delaware

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Introduction

The coastal processes affecting Bethany Beach, Delaware were studied and the short-term and long-term trends in coastal changes were determined in order to develop recommendations for protecting Bethany against coastal erosion (Dick and Dalrymple, 1983). Bethany Beach is located on the Delaware Atlantic coastline which is a wide sandy baymouth barrier beach distinguished by highlands at Rehoboth Beach and Bethany Beach. The shoreline is straight, with only minor bulges and indentations (see Figure 1).

Bethany Beach is a residential and resort community. Privately-owned properties front the publicly-owned beach. Construction of new motels and summer homes is anticipated along with the continued growth of commercial activities to accommodate the increased number of visitors. Bethany is protected by a series of nine groins built between 1934 and 1945. Many of these groins have deteriorated, and are flanked at the landward end. Winter storms severely erode the beach and damage shorefront property. The beach is generally narrow (approximately 45 m wide), especially along the southern portion, and is backed by low dunes (about 15-45 m above NGVD). A timber bulkhead extends along most of the backshore.

Wave Climate

The majority of the waves emanate from the northeast to east; higher waves are from east-northeast during winds of 6.7 m/s or greater. Smaller waves predominate during months of southerly winds with speeds less than 6.7 m/s. Wave heights off the coast of Delaware average 1.2 meters from October to March, and 0.3 meter for the remainder of the year (Polis and Kupferman, 1973). The mean swell direction offshore Delaware Bay is from the southeast during the summer months and from the northeast during the winter (Mauer and Wang, 1973). Ocean waves under severe storm conditions have been estimated to be nine meters high in the surf zone (U.S. Army Corps of Engineers, 1956). The recurrence intervals of extreme waves in the offshore area are summarized below:

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recurrence interval (years)	5	10	25	50
maximum significant wave height (meters)	11	12	14	15
extreme wave height (meters)	18	21	26	29

(Polis and Kupferman, 1973).

Long-Term Trends

The long-term trends in coastal changes were investigated through comparison of a series of historical aerial photographs. Five photographs dating from 1938 to 1977 were selected for study, three from the U.S. Department of Agriculture, one from NASA and one from the Delaware Department of Natural Resources and Environmental Control (DNREC). In

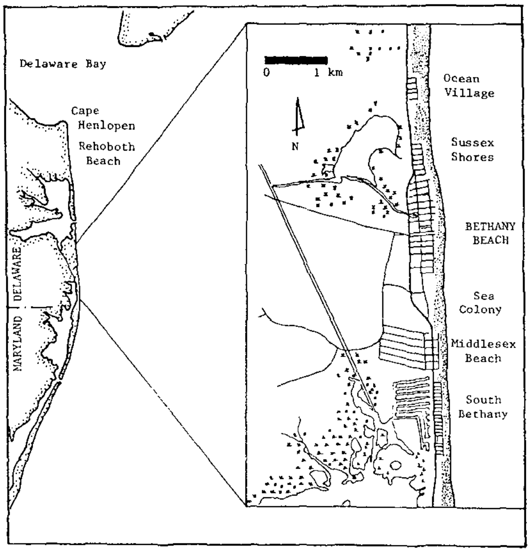


Figure 1: Location Map of Bethany Beach, Delaware.

May, 1938 (the date of the earliest photograph) the groin field had just been enlarged by four groins constructed north and south of the original four groins. Figure 2 clearly illustrates the effects of the groin field on the beach planform. At the time the first photograph was taken the littoral drift was to the north. As the sediment was transported north, the orientation of the shoreline in each groin compartment shifted.

Between May, 1938 and May, 1973, the shoreline straightened out by filling in the groin compartments resulting in slow accretion throughout most of the study area. Before 1968, the rates of change were gradual, in most cases less than a meter horizontally per year. Between 1968 and 1973 the rates increased to between one and five meters per year, averaging about two meters per year.

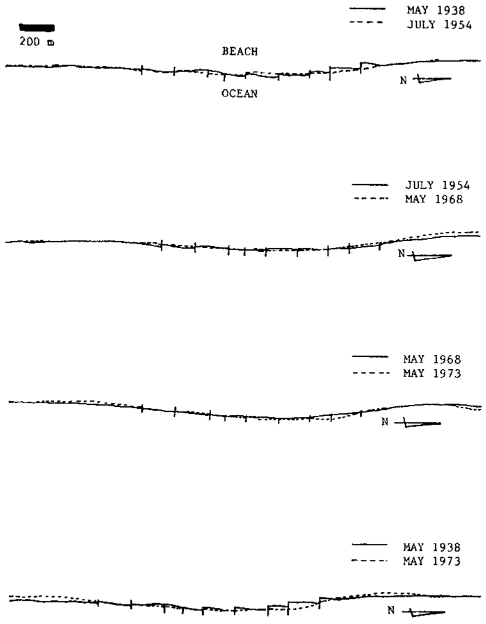


Figure 2: Position of Shoreline at Bethany Between May 1938 and May 1973

The aerial photogrammetric study of Bethany Beach indicates that the historical trend of shoreline change is slow accretion. It is clear from the early photographs that the groins accumulated sediment, thereby widening the beach. The photographs show that the area of the beach protected by the groins has remained relatively constant; however, there is a possibility that the area north and south of the groins (particularly south) have suffered from increased erosion since the construction of the groins. The irregularities in the shoreline at Bethany do not appear to be caused by the groin field. The identation just north of the groins is the relict of an inlet located there around 1690 (Kraft et. al., 1976). The convexity of Bethany Beach is identifiable on U.S.G.S. charts from 1918; however, the bulge has become more prominent to the south since the construction of the groins.

Annual Trends

The short-term changes for one year were determined from periodic surveys of the beach face and coastal zone. Thirteen nearshore profiles, both north and south of Bethany Beach as well as within the town proper were surveyed 11 times from May, 1982 to May, 1983 by the DNREC (dates are shown in Figure 4). The exposed beach was measured using standard surveying techniques and the offshore portion was measured using a tathometer and triangulation. According to the DNREC (Williams, 1983) the dry land elevations were measured to within 3.0 cm and the offshore soundings were measured to 6.0 cm. The bathymetric surveys constituted the raw data from which the changes in beach profiles as well as sand volumes were examined.

The survey location stretched from 110 meters south of Bethany proper to about 152 meters north of the corporate limits (see Figure 3). From a baseline on Bethany Beach 13 profile lines were established, separated by 152.4 meters and extending offshore to the -9-meter contour, which is usually considered the depth of closure.

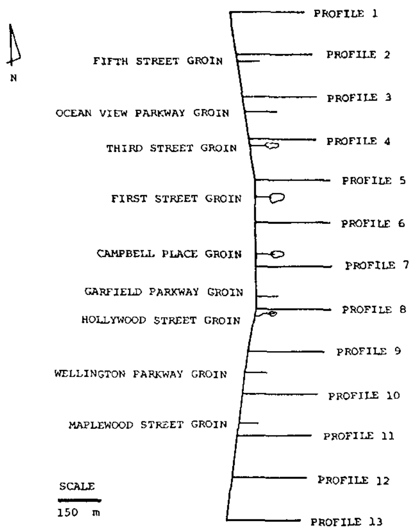


Figure 3: Location of Croins and Profile Lines

Spring to summer profile changes (May 4 - October 18)

It is commonly assumed that sediment shifts seasonally between the berm and the bar so the volume of sand involved remains relatively constant; however, the survey data reveals that the volume of sand did not remain constant at Bethany. Figure 4 illustrates the variations in beach sand volume during the study period. Figure 5 represents the shape of the beach at the time of the first survey. Between May 4 and September 15, 1982, the volume of sand over the survey area increased by 9.7×10^4 cubic meters. The change in beach sand volume between surveys was found by subtracting the elevation of each survey point of the earlier survey from that of the later survey and multiplying by the area between survey points. Between early May and mid-October erosion was generally limited to between the National Geodetic Vertical Datum (NGVD) and the -3-meter contour (see Figure 6). The majority of the survey stations experienced a net accretion of sediment. (The shoreline in Figure 6 has been artificially straightened. This was done so onshore-offshore changes would not be masked by longshore variations due to the convexity of the shoreline at Bethany.) Significant changes in elevation detected offshore could be a result of survey error; however, repetition of the surveys show that survey errors are likely to be smaller than the offshore changes shown in Figure 6. For instance, changes of nearly 55 cm were observed on profile 7 at -9 meters (NGVD).

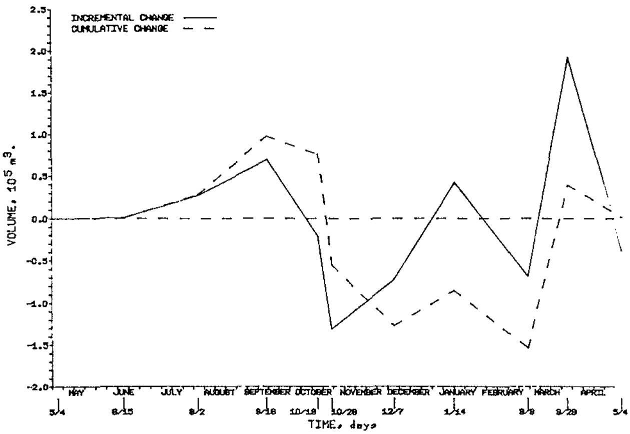


Figure 4: Incremental and Cumulative Change in Volume of Beach Sand over the Survey Area. (Survey Dates Denoted by Vertical Bars on Abscissa.)

Impact of October storm (October 18 - October 29)

An intense low pressure system moved northeastward from the Virginia Capes to southern New England on October 24-26, 1982. The storm, with steady winds of 18-22 m/s and gusts up to 37 m/s, was one of the worst storms on the Delaware Coast in the past 20 years. Wave heights exceeding six meters were observed off Indian River Inlet (10 km to the north) and tides were 0.5 meters above normal.

The profiles were surveyed one week before and three days after the storm. Comparison of the two surveys indicates that 13 x 10^4 cubic meters of sediment were transported out of the survey area (see Figure 4). The gross sediment transport (the absolute value of the changes between surveys) was over 24 x 10^4 cubic meters. Figure 7

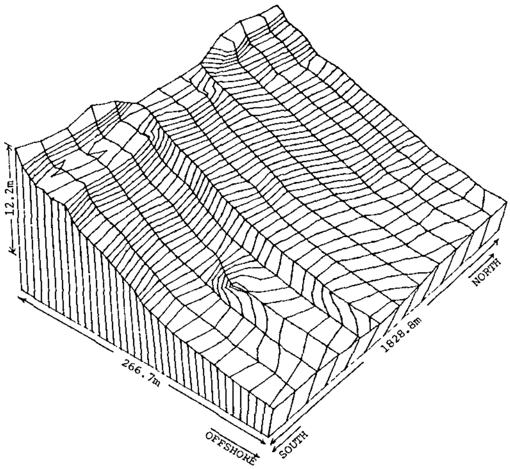


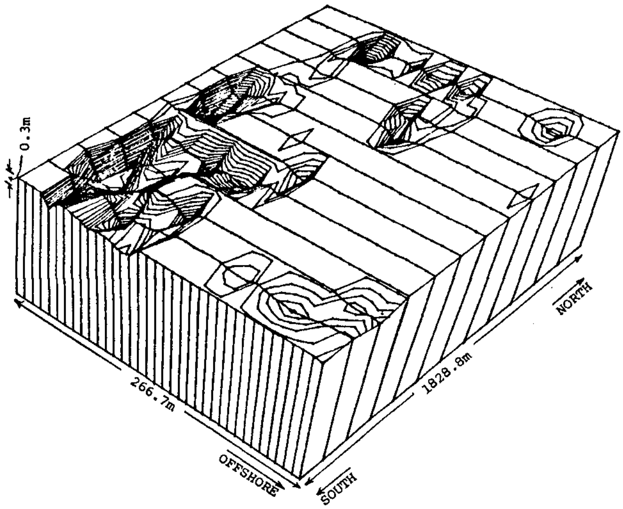
Figure 5: Three-dimensional Representation of Bethany Beach at the Time of the First Survey, May 4, 1982. (Exaggerated Scale)

represents the locations of erosion and accretion due to the storm. All 13 profiles experienced a net loss of sand, transforming the overall shape of the beach from slightly convex to concave. The beach face was severely eroded during the storm. The waterline retreated landward an average of 14.8 meters along the survey reach. The maximum retreat was nearly 28 meters on profile six. Figure 8 illustrates the effects of the storm on the beach profile. (Because of the heavy seas it was impossible to obtain closure between the dry land and the bathymetric surveys, so a gap in the survey data exists. All the data points within this gap were interpolated between known values; therefore, the width of the offshore bars in the surf zone is uncertain.) Significant erosion was observed from the bar region to the seaward limit of the survey area. One profile eroded nearly 52 cm at a depth of 8.3 meters.

Extrapolation of the profile data indicates that the profiles would need to be extended an additional 127 meters seaward to reach the depth of closure which is likely to be -10 m. The volume of sediment that would be accounted for if the profiles had been extended out to this depth is estimated to be one fourth of the volume of sand lost from the survey area during the storm.

Winter profile changes (October 29 - March 3)

The October storm began the transformation of the beach into the winter profile configuration. By early December, the beach showed signs of recovery from the storm, but remained in the winter



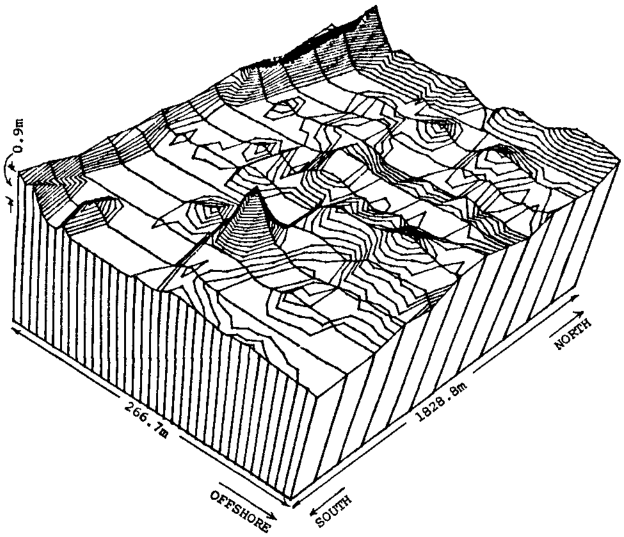


Figure 6: Location of Erosion and Accretion Along the Profiles Between May 4 and October 18, 1962. (Straightened Waterline, Exaggerated Scale)

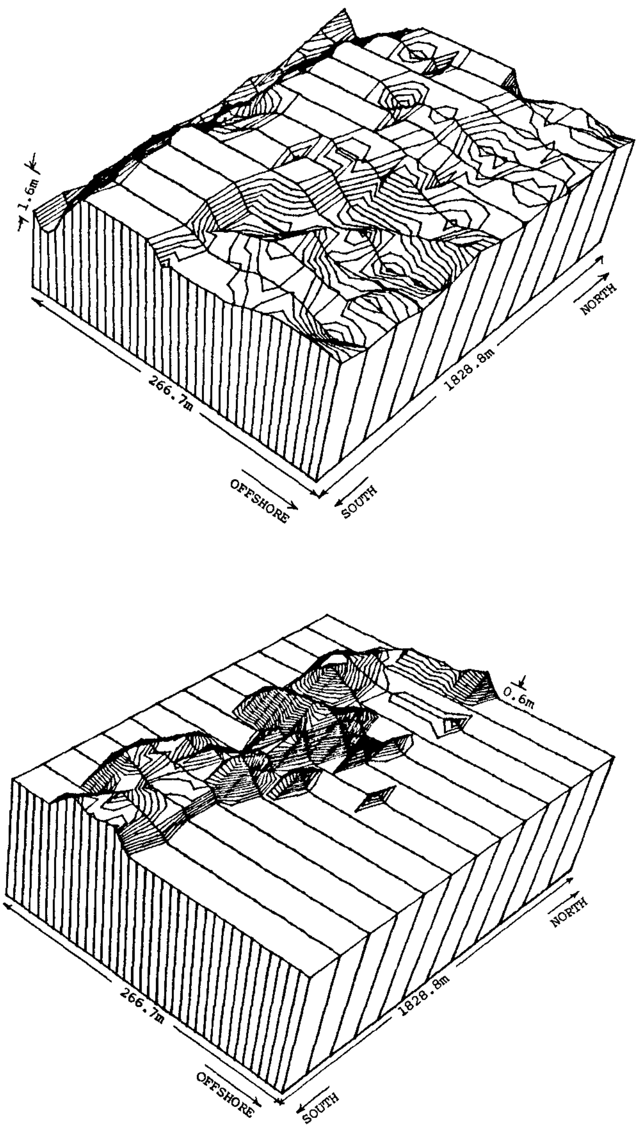


Figure 7: Location of Erosion and Accretion due to October Storm. (Straightened Shoreline, Exaggerated Scale)

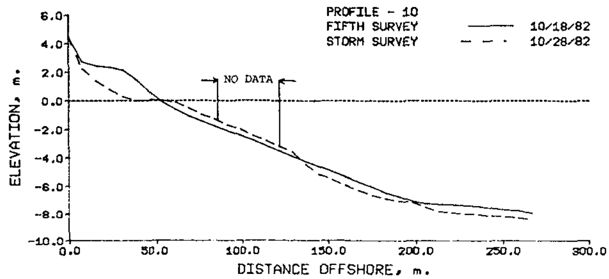


Figure 8: Profile 10 Before and After October Storm

configuration. The area between the landward limit of the survey and the NGVD which was severely eroded during the storm, experienced universal aggradation during the recovery; however, the foreshore did not return to its pre-storm profile. Although the foreshore accreted, the berm remained lower and narrower than it was prior to the October storm.

Bethany Beach suffered a severe winter in 1983, especially during February when a series of storms occurred. The direction of sediment transport is toward the south during the winter, so the northern seven profiles accreted. By trapping the sediment transported from the north, the northern groin compartments starved the south end of Bethany, causing the southern profiles to erode. This erosion/accretion pattern caused a rotation of the waterline about the middle of the groin field. The waterline moved seaward in the northern half of the study area and landward in the southern half.

During February, the berm and foreshore were eroded and the sediment moved offshore to form longshore bars. Since early May 1982, 15.4×10^4 cubic meters of sediment had been transported out of the survey area reducing the volume of sand on the beach to its lowest point for the year. By early March the winter profile was fully developed.

Changes in profiles during spring (March 3 - May 5)

At the end of March the volume of beach sand had increased significantly. In one month the volume of sand increased by 19.3×10^4 cubic meters, most of which was deposited in the offshore region. It appears that the sand accreted offshore and then moved landward between the end of March and early May, when the beach was beginning the transition from the winter to the summer profile configuration. Material from below the NGVD was transported shoreward creating a higher and wider berm. Increases in berm elevation of nearly two meters were recorded.

A full year passed between the first and last survey. The volume of sand was only slightly greater in May 1983 than in May 1982, of which most of the difference was offshore. Because of the severe winter and late spring, the beach in May 1983 was seasonally behind the May 1982 beach. The foreshore and berm had not yet developed in May 1983.

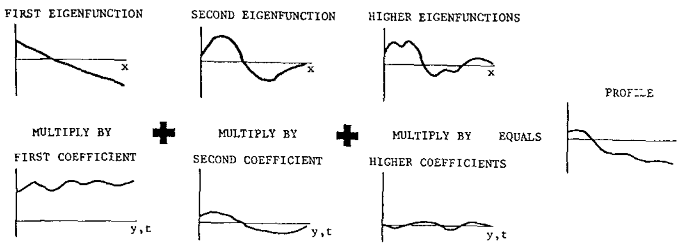
Eigenfunction Analysis

Previous studies of beach changes and other phenomenon have been conducted using the empirical orthogonal function (EOF) method. The EOF method is an efficient way to describe beach profile changes; however, it should be emphasized that it is a descriptive process and therefore does not reveal any information regarding the governing processes. The reader is referred to Winant et. el. (1975) for a derivation of the technique.

Winant et. al. (1975) has shown that when the EOF method is applied to beach profile data, the eigenfunctions have a physical interpretation. The first eigenfunction, corresponding to the largest eigenvalue is called the "mean beach function" and represents the average profile. The second eigenfunction, termed "berm-bar function", has a large maximum at the location of the summer berm and a minimum at the location of the winter bar. The third eigenfunction, the "terrace function", has a maximum at the location of the low tide terrace. Higher order eigenfunctions account for a very small percentage of the variance of the profile configuration.

Figure 9 is a schematic representation of the decomposition of a beach profile by the empirical eigenfunction method. The original profile can be described by the summation of each eigenfunction multiplied by its corresponding coefficient. The weight of the coefficient defines the degree of variation from the statistical mean.

Three types of eigenfunctions were calculated on the profile data: the "usual" temporal analysis (Winant et. al., 1975; Aubrey, 1979); spatial analysis of the variations along the beach during each survey; and spatial analysis of the variations along the beach for the changes between surveys.



$$h_{i_k} = \sum_{n=1}^{N} c_{n_k} e_{n_i}$$

Figure 9: Eigenfunction Decomposition of the Profiles

Temporal Analysis

Temporal eigenfunction analysis of beach profile data identifies the seasonal variations along a particular profile during the survey period. The first eigenfunction described the mean profile, accounting for about 99.7% of the variance. The second largest eigenfunction accounted for about 0.2% of the mean square value of the data, or about 70% of the variance with the mean beach function removed. The third largest eigenfunction accounted for less than 0.1% of the mean square value of the data.

The maximum and minimum of the second eigenfunction denote the locations of the greatest change. Figure 10 shows the first three eigenfunctions and the corresponding coefficients for the temporal analysis of profile 2. As expected, the second eigenfunction identified the berm and bar as regions with the most deviation from the mean. The coefficients for the second eigenfunction are consistent for all of the profiles, which indicates that the seasonal variations are described well by the temporal eigenfunction analysis. In Figure 10 the large positive eigenvalue at the berm means that the berm was enlarging during the summer and early fall. The negative second coefficient (see Figure 11) during the winter months indicates that the berm was eroding and the bar region accreting. Temporal analysis revealed berm changes extended from the landward end of the survey about 55 m to just seaward of mean sea level. A bar region about 100 m wide was also identified. Significant values at the offshore end of the second eigenfunctions for all of the profiles signifies that this is an area of considerable change rather than the depth of closure. It is unlikely that survey error would result in such consistent values.

Since the third function identifies the location of the low-tide terrace, it is probable that significant changes in the level of the low-tide terrace can take place in only a few days. This would cause aliasing in data from six-weekly surveys (Winant et. al., 1975).

Spatial Analysis

Spatial eigenfunctions identified the variations along the beach at a particular time. As expected, the eigenfunction associated with the largest eigenvalues represented the mean profile, accounting for about 99.6% of the total variance. The second eigenfunction usually accounted for about 0.3% of the mean square value of the data, or 70% of the variance of the data with the mean beach function removed. The third eigenfunction accounted for about 0.1% of the mean square value of the data, or 20% of the variance with the mean beach function removed.

The mean beach function identified the major trends along the beach at a particular time. Figure 12 shows the first three eigenfunctions computed for the straightened profile data from 3 March 1983. The mean beach function revealed that the beach was in the winter profile. The berm was indistinct and a small bar can be identified between 45 m and 120 m offshore.

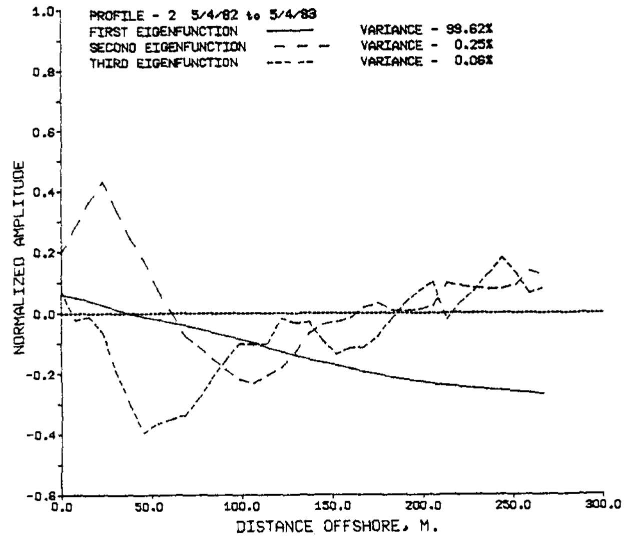


Figure 10: The First Three Eigenfunctions for the Profile Data for Profile 2

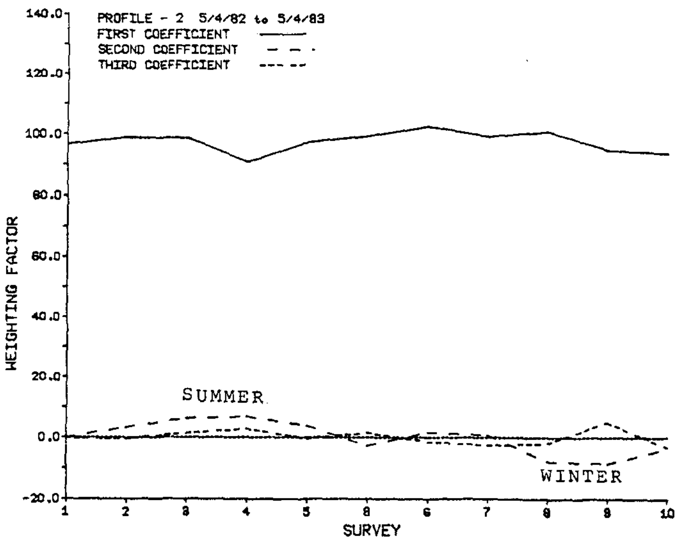


Figure 11: The Coefficients Corresponding to the Eigenfunctions from Profile 2 Data

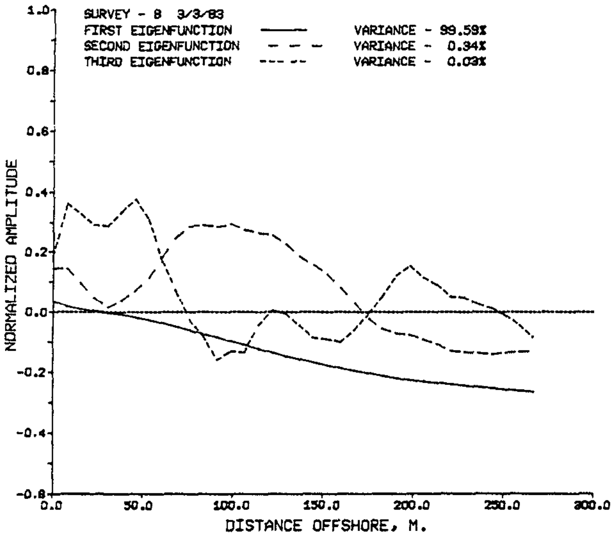


Figure 12: The First Three Eigenfunctions for Profile Data from March 3

The second eigenfunction identified the bar region as an area of substantial variation along the beach. The eigenfunction also described the berm and seaward limit of the survey area as locations with considerable deviations from the mean. The value of the second eigenfunction is nearly zero at the location of the waterline because straightened beach profile data was used. In Figure 13, the coefficients of the second function are positive for the northern four profiles, so in the northern section of the beach the berm and bar were more developed than the mean. The coefficients for the middle five profiles are nearly zero. For this area, the mean function closely described the beach profile configuration. Since the coefficients corresponding to the southern profiles are negative, the berm and bar in the south end of the study area were less distinct.

For most of the surveys, the second coefficient changed signs between the eighth and tenth profiles. The coefficients of the middle region are frequently zero, implying that these profiles are shaped similar to the mean. The reversal in sign indicates that the beach is "rotating" about the middle or mean region. The beach face in the southern end of the survey is steeper with more sediment deposited offshore of the bar region than at the northern end. More sediment is deposited in the berm and bar regions on the northern profiles resulting in a steeper offshore profile. For this reason, the second eigenfunction for the spatial variations along the beach will be called the rotation function.

Although in Figure 12 the shapes of the second and third eigenfunctions are very similar, and in Figure 13 the third

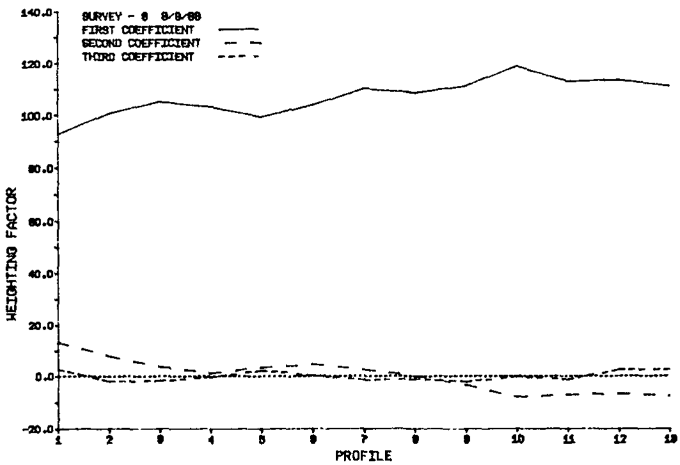


Figure 13: The Coefficients Corresponding to the Eigenfunctions Obtained from March 3rd Data

coefficients resemble the second coefficients, this was not typical for all of the surveys. Because the third eigenfunction accounts for such a small percent of the total variance, it describes weaker deviations from the mean so the configurations of the third eigenfunction and the corresponding coefficients are, in general, less consistent along the beach than the configurations of the second eigenfunctions and coefficients.

Difference Eigenfunctions

Spatial eigenfunctions were also computed on matrices formed of the differences in elevation between two surveys. The first eigenfunction in this analysis describes the mean changes along the beach between two surveys. The development of the beach into the summer profile is described by the first eigenfunction with a large maximum at the term and a minimum at the bar. Because the storm altered the beach profile from its summer to winter configuration, in specifying the areas of greatest change between surveys, the eigenfunction analysis of the difference matrix identified the seasonal variations along the beach which are represented by a maximum at the berm and a minimum at the location of the bar. This describes the same variation as the berm-bar function of the temporal analysis. Therefore, the first eigenfunction of the difference matrix between a summer and a winter survey represents the seasonal changes in the profile, and in fact, it is really the berm-bar function of the temporal analysis. Comparison of the second eigenfunction in Figure 10 and the first eigenfunction in Figure 14 confirms this finding.

Between August 1982 and March 1983 the mean eigenfunctions indicate that there was significant change at the seaward limits of the

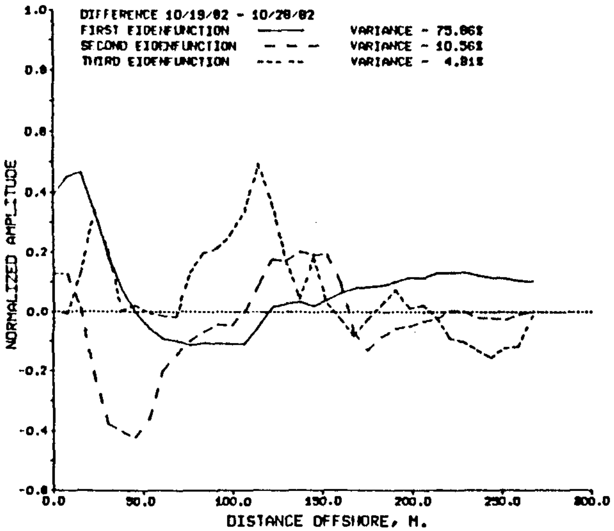


Figure 14: The First Three Eigenfunctions for the Difference Matrix for October 19 and October 28

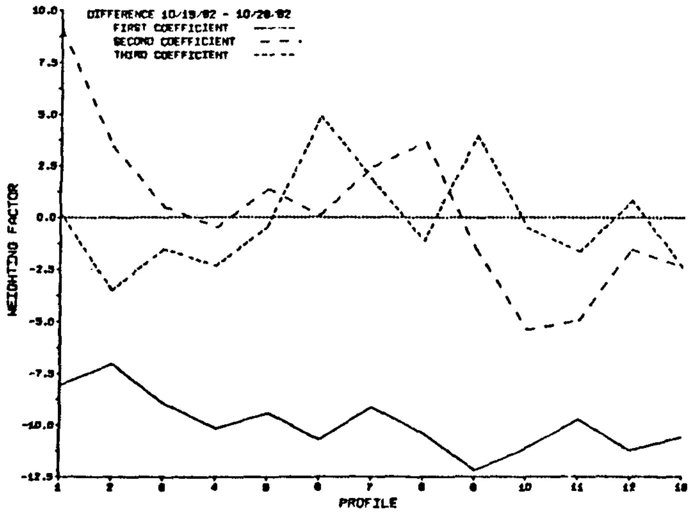


Figure 15: The Coefficients Corresponding to the Eigenfunctions Above

profiles. In half of these: between August and September, December and January, and early and late March, this was the location of the greatest change. Although the mean function accounted for about 60% of the variance, it accounted for a greater percent of the variance during the months with the worst storms, October and February. The second and third functions accounted for 15% and 10%, respectively. Higher order eigenfunctions accounted for a much larger percentage of the variance than in the previous analyses.

The coefficients associated with the mean beach function of the difference matrix reversed sign between the fifth and seventh profiles on several of the surveys. Since the waterline also shifts about the same location it is probable that the sand was transported alongshore between the northern and southern sections. Between mid-October and May, the coefficients associated with the first eigenfunction are consistent along the survey area. This signifies that the predominant process was the same over the survey area during the winter.

Conclusions

Although erosion has long been considered a serious problem at Bethany Beach, the shoreline has not changed significantly since the groins were constructed nearly fifty years ago. Historical aerial photographs show that the groins accumulated sediment, thereby widening the beach. Between 1938 and 1977, the shoreline within the groin field accreted an average of 0.4 meters/year. These rates include the artificial beach fill that the State of Delaware placed on the beach between 1954 and 1961. The fill was eroded by the March 1962 storm but then replaced by the U.S. Army Corps of Engineers (U.S. Army Corps of Engineers, 1971). The areas north and south of the groins (particularly south) may have suffered from a reduced rate of accretion or even erosion since the construction of the groins.

Examination of the survey data revealed that substantial changes in beach sand volume occurred during the year, but the annual change in volume was very small. Between June and September, the volume of beach sand increased gradually. A severe storm in October transported 13×10^4 cubic meters out of the survey area. The total transport, or the absolute value of the volumes of erosion and accretion, was over 24×10^4 cubic meters. In early March, the beach sand volume reached its lowest point for the year. Since early May, 15.4×10^4 cubic meters of sediment had been transported out of the survey area. In 3 1/2 weeks, the volume of beach sand increased by 19.3×10^4 cubic meters, to the highest volume for the year. Despite the large changes that occurred during the year, the net change in volume over the study period was only 1150 cubic meters.

Considerable changes in elevation were observed in depths previously thought to be below the depth of closure. Changes of up to a meter were detected in water depths of 8-9 meters. Because of the experience of the survey crew and the consistent trends between profiles both temporally and spatially, it is assumed that these are actual offshore changes and not a result of survey error.

During the survey period the position of the shoreline varied by around 30 meters. The shoreline and sediment deposition pattern rotated seasonally about the middle profiles. During the summer months when the sediment transport was northward, the southern profiles accreted and the northern profiles eroded. During the winter, the direction of sediment transport reversed causing the northern profiles to accrete and the southern profiles to erode.

The EOF method efficiently produced quantitative results describing changes in the beach profiles. The usual temporal eigenfunction analysis identified the seasonal transition between the summer and winter profiles as the predominant process affecting Bethany. It also revealed the significance of the changes at the offshore end of the profiles. By employing the EOF method spatially to examine the variations along the beach at a particular time, a rotation function was found that identifies the seasonal rotation of the sedimentation patterns about the middle profiles. The first eigenfunction of the spatial analysis of the differences between surveys identifies the same seasonal variations as the berm-bar function of the temporal analysis. The implication of this finding is that the seasonal movement of the beach can be determined from two surveys, one taken of the summer profile and one of the winter, instead of repeated surveys that are necessary for a temporal eigenfunction analysis.

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