COASTAL ENGINEERING STUDY OF BETHANY BEACH, DELAWARE

by
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Research Report No. CE-83-38

Ocean Engineering Program

Department of Civil Engineering
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EXECUTIVE SUMMARY

This study was designed to determine the historical and seasonal changes and to understand the coastal processes at Bethany Beach, Delaware. The beach is protected by a series of nine groins constructed between 1934 and 1945. Many of these groins are corroded, and flanked at the landward end. Winter storms severely erode the beach and damage shorefront property. Bulkheads, constructed to protect the streets and private property, do not provide protection to the beach. The study included field work and data analysis to examine the effectiveness of the groin field and its impact on the neighboring shoreline. A description of each groin with accompanying photographs is located in Chapter Three.

The long-term trends in coastal changes at Bethany Beach were investigated by historical aerial photographs. In 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. Between May 1938 and May 1977, the shoreline had straightened out by filling in the groin compartments, resulted in slow accretion throughout most of the study area. Examination of the aerial photographs and historical profiles reveal that the shoreline has not changed much since the groins were constructed nearly fifty years ago.

Thirteen nearshore profiles, both north and south of Bethany Beach as well as within the town proper were surveyed periodically from May 1982 to May 1983 by the Delaware Department of Natural Resources and Environmental Control. The bathymetric surveys constituted the raw data from which the short-term changes in beach sand volume were examined. The major change identified by the repeated surveys was the transition from the "winter" to the "summer" profile and back again. The summer profile is characterized by a wide berm, a relatively steep foreshore, and a smooth offshore profile. In contrast, the winter profile has almost no berm. The sediment is transported offshore into one or a series of parallel bars. The volume of beach sand varied greatly over the survey area during the study period indicating the sediment was transported either alongshore or further offshore of the seaward limit of the survey area. The volume of sediment in the survey area was nearly equal in May 1982 and May 1983; however, more sand was offshore in May 1983. Because of the severe winter and late spring, the beach in May 1983 was probably seasonally behind the May 1982 beach.

Bethany Beach has long been considered the location of a nodal point (the northward sediment transport equals the southward sediment transport so the resulting net transport is zero). Because knowledge of the magnitude and direction of sediment transport is important to the proper design of coastal structures an estimate of the sediment transport is necessary. With wave height, period, and direction data and frequency of occurrence, a littoral drift rose can be developed that determines the northward and southward littoral drift for various shoreline orientations. The littoral drift rose developed for the Delaware Atlantic coastline identifies the location of the nodal point to be very nearly the orientation of the shoreline at Bethany Beach. However, the nodal point is nonstationary, so its location is uncertain. The northward drift is 14,860 cubic meters/year and the southward drift is 14,290 cubic meters/year, so the resulting net transport is 570 cubic meters/year northward. However, this result should be considered a gross estimate of the actual value.

The groins effectively accumulate sediment during periods of low wave activity and minor storms. However, the occurrence of several storms in rapid succession will result in considerable damage to the protective dunes and shorefront property. Recommendations for increasing the protection to Bethany Beach against storm damage can be found in Chapter Nine.

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ABSTRACT

The effectiveness of the nine groins at Bethany Beach and their impact on the neighboring shoreline has been investigated by field work and data analysis. The field study consisted of 10 six-weekly bathymetric surveys of Bethany Beach. The survey data was examined for variations in beach sand volume, and empirical eigenfunction analyses were performed on the survey data to obtain the beach modes and fluctuations that occurred during the year. Monthly sand samples were analyzed to identify changes in sediment type and size. Wave refraction diagrams were constructed to determine the influence of the offshore topography on the local wave climate. Beach planform change data was obtained from historical aerial photographs. The amount of littoral drift at Bethany Beach was estimated and erosion control measures were proposed.

CHAPTER 1

INTRODUCTION

The shoreline is constantly changing, influenced by short-term seasonal changes and long-term environmental changes. Therefore, data on both long-term and short-term trends in coastal changes are essential to the proper planning and design of coastal management projects. Hundreds of thousands of dollars of state and federal funds are spent every year for coastal management projects designed to protect Atlantic Coast barrier beaches from erosion. Although knowledge of the dynamics of barrier beaches is limited, the beaches are rapidly being developed. Construction policies often ignore the transient nature of the shore by allowing development on and in front of the dune line, destroying the environment's natural protection against the ocean. Not surprisingly, construction so close to the shoreline increases the potential for private and public property to be destroyed by storm damage and long-term erosion. Improperly designed coastal structures can aggravate erosion and multiply expenditures for expensive coastal repairs and protection. Accurate information on coastal changes is necessary and must be used properly if coastal management projects are to be planned, designed, and executed with understanding of the changing shoreline.

Bethany Beach, Delaware is a residential and resort community. Privately-owned properties front the publicly-owned beach. Continued construction of new motels and summer homes is anticipated along with the continued growth of commercial activities to accommodate the increased number of visitors. This study was designed to determine the historical and seasonal changes, and to understand the coastal processes affecting Bethany Beach. This knowledge was used to develop recommendations for protecting Bethany from erosion. Presently, Bethany Beach is protected by a series of nine groins built between 1934 and 1945. Many of these groins are corroded, and flanked at the landward end. Winter storms severely erode the beach and damage shorefront property. Bulkheads have been constructed to protect the streets and private property; however, these bulkheads do not assist in the protection of the beach.

This study investigates the effectiveness of the groin field by field work and data analysis. The results provide a guide as to the advisability of repairing the groins, adding to or removing the groins, or constructing additional erosion control measures. The field study, consisting of eleven bathymetric surveys, provided the data for examining the variations in beach sand volumes. The resulting data was examined by empirical eigenfunction analysis to obtain the various modes and fluctuations which occurred throughout the year. Beach planform change data was obtained by historical aerial photographs. From the field and analytical studies, the magnitude and net direction of littoral drift were estimated. While knowledge of coastal processes cannot eliminate damage or erosion, it can reduce economic losses by assisting in the planning and design of coastal management projects.

CHAPTER 2

BACKGROUND INFORMATION

2.1 GEOMORPHOLOGY

The Delaware coast is located in a low-lying coastal plain which is part of a larger geological structure, the western Atlantic coastal plain-continental shelf geosyncline. This continental shelf province on the northwest margin of the Baltimore Canyon Trough extends seaward to the edge of the continental shelf. The coastal plain-continental shelf of the Atlantic Continental Marine Geosyncline is broad and flat, developing into a steep continental slope and more gradually sloping continental rise. The submerged portion of the coastal plain extends into the ocean for approximately 105 kilometers as the continental shelf, sloping one meter per kilometer southeastwardly (U.S. Army Corps of Engineers, 1956; Kraft et. al., 1976).

The Atlantic shoreline of Delaware can be classified as a lagoon-barrier-marsh shoreline. The barrier beaches, backed by low dunes, are separated from firm ground by marshes and bays. These coastal features are the result of the long- and short-term processes on the landforms that preceeded them (McDonald, 1981). The continental shelf is distinguished by smooth, rounded, northeast-southwest trending bars and depressions of low relief, and infrequent but pronounced terraces with steep seaward sides (U.S. Army Corps of Engineers, 1968).

The Delaware coast is presently undergoing a fairly rapid transgression by the Atlantic Ocean that began approximately 11,000 to 14,000 years ago. Erosion and relative sea level rise is the result of a combination of factors: the effect of wave action and high tidal waters, longer term geological factors such as the compaction of sediment and tectonic subsidence, and eustatic, or actual sea level rise brought about by the melting of Pleistocene ice sheets since the end of the Wisconsin glaciation. Through time, sea level rise effectuates the geomorphic environments of the coastal zone to move upward and landward. Coastal geology of Delaware indicates that the Holocene marine transgression is continuing (Maurmeyer, 1974).

The surface of the Coastal Plain in Delaware is composed of sedimentary formations, Cretaceous and Tertiary in age. These formations outcrop in successive northeast-southwest tending bands: more recent outcrops overlapping the older formations to the west (U.S. Army Corps of Engineers, 1968).

Sediments in the coastal plain include both unconsolidated and semi-consolidated materials. Most of the coastal plain is covered by approximately 30 meters of Pleistocene and Holocene sands and gravels (Maurmeyer, 1974). Sediments of Pleistocene age are mainly comprised of sands and gravels, the debris from continental glaciers transported by melt water down the Delaware River Valley. Three sedimentary formations are exposed at the surface of the coastal plain: the Calvert formation of Miocene age, and the Wicomico and Pamlico formations of Pleistocene age. Sediment from the Calvert formation is mostly siliceous diatomaceous earth and compact calcareous clay and therefore is unlikely to be a significant portion of the beach building material. Due to low stream velocities and the presence of tidal marshes, little material of beach building size from the Pamlico formation reaches the shoreline. Low stream velocities also prevent a substantial amount of material larger than silt of the Wicomico formation from reaching the shoreline. Most of the sediment carried is deposited in the marsh areas (U.S. Army Corps of Engineers, 1968). However, according to Kraft, (1976), the majority of the most recent deposits of beach and dune sands and peat in the marsh areas, are comprised of Pleistocene material.

2.2 DESCRIPTION OF AREA

The Atlantic Coastline of Delaware is on the northeast shore of the Delmarva Peninsula, extending from Cape Henlopen south to the Delaware-Maryland State line at Fenwick Island (see Figure 2-1). The shoreline from Rehoboth Beach to Fenwick Island is a wide sandy baymouth barrier beach distinguished by highlands at Rehoboth Beach and Bethany Beach. The coast is straight, with only minor bulges and indentations. Although the barrier varies in width from 0.3 kilometers to more than 1.4 kilometers, the beach, dune, and washover sands remain rather consistently 0.4 kilometer wide (Kraft et. al., 1976). The incorporated municipality of Bethany Beach, in Sussex County, has about 1.4 kilometers of ocean frontage. The beach is generally narrow, especially along the southern portion, and is backed by very low dunes which lie from 0.3 to 3.0 meters behind the timber boardwalk.

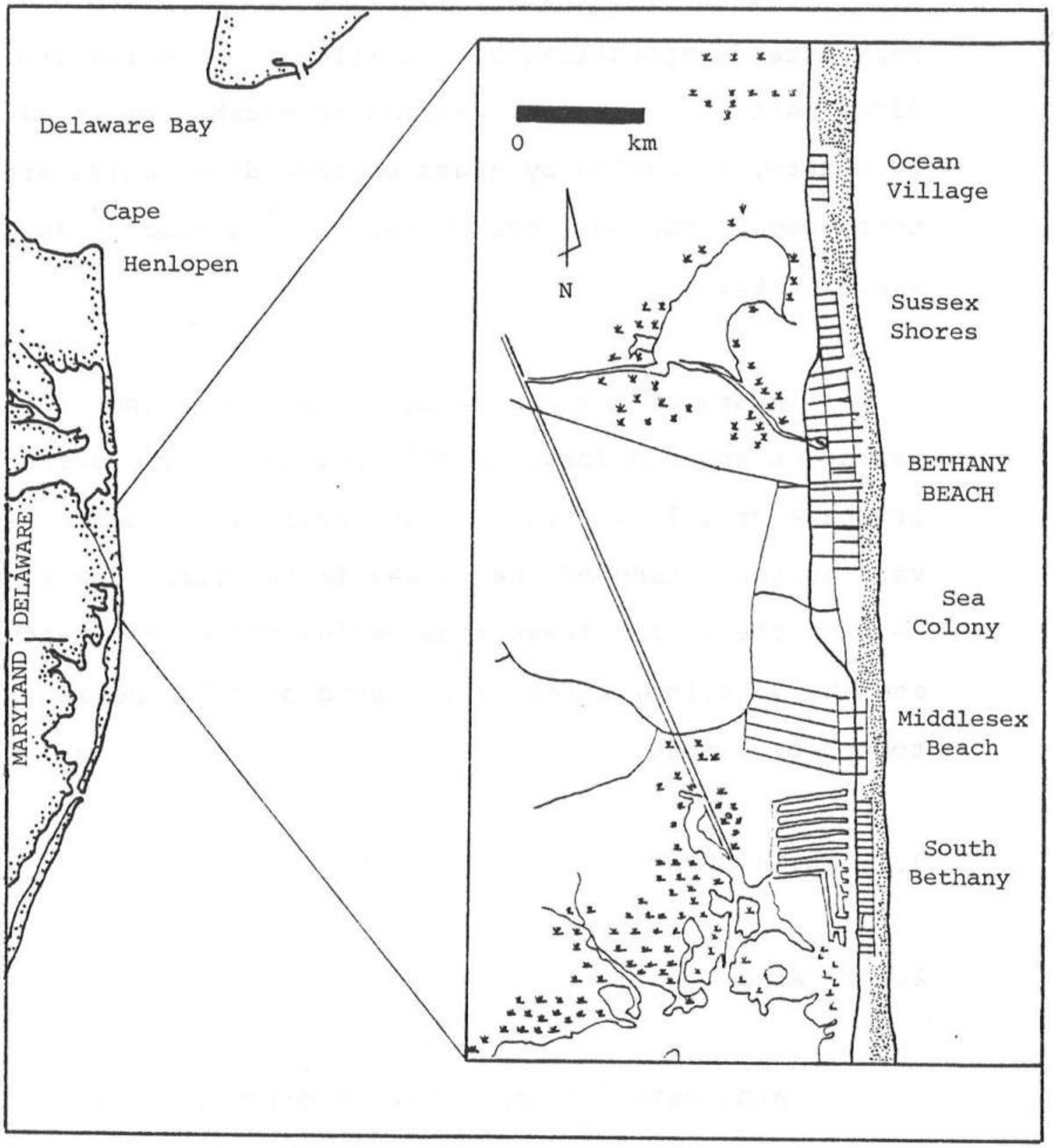


Figure 2-1: Locality map of Bethany Beach, Delaware.

North of Bethany Beach, the Indian River State Park extends approximately two kilometers to the Indian River Inlet. The beach, varying in width from 15 to 60 meters, is backed by grass covered dunes which are preserved by marked cross-overs, planted dune grass, and sand fences.

South of Bethany Beach are the developments of South Bethany and York, which combined, have a ocean frontage of 2.7 kilometers. The beach in this area is very narrow. Many of the houses in the first row in South Bethany are in the swash zone during the winter months, and the duneline, which is landward of these houses, is topped by a road.

2.3 ENVIRONMENT

2.3.1 Winds

Wind data for the Delaware coast has been collected by the U.S. Weather Bureau at Breakwater Harbor, Delaware (just inside the entrance to Delaware Bay), and off Atlantic City, New Jersey (85 kilometers north of Cape Henlopen) (U.S. Army Corps of Engineers, 1968). The Atlantic City yearly averages (see Figure 2-2) indicate

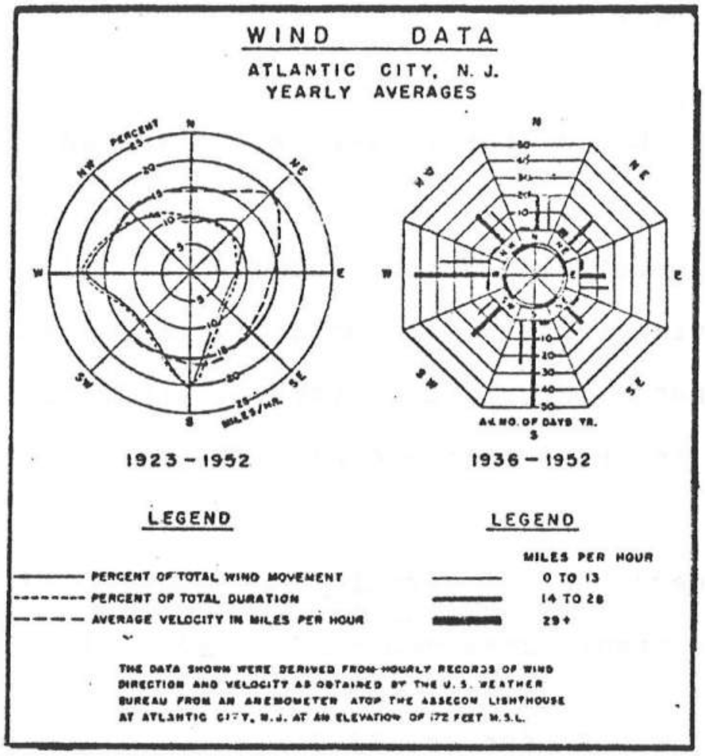


Figure 2-2: Wind data for the Delaware Coast (U.S. Army Corps of Engineers, 1968).

that prevailing winds are from the south and west with average velocities of about 6.7 meters/sec (m/s). Winds with higher velocities more frequently emanate from the northeast.

During the winter, winds are usually westerly to northwesterly, 5.4 to 10.7 m/s. During the summer, winds are generally from the southwest at 2.2 to 5.4 m/s. Wind direction is seldom constant for more than six hours. The recurrence intervals of extreme winds off the coast of Delaware are summarized below:

recurrence interval (years)	5	10	25	50
maximum sustained wind (meters/sec)	37	41	47	51

(Polis and Kupferman, 1973).

2.3.2 Waves

Wave data are available from a number of sources: National Oceanic and Atmospheric Administration, (NOAA), Polis and Kupferman (1973), U.S. Army Corps of Engineers (1968), and U.S. Naval Oceanographic Atlas (1963). Wave height and period data off Ocean City Inlet are available from NOAA for the years 1979 to present. Polis and Kupferman summarize monthly wave height and wave period data at Five Fathom Light Station, Delaware. The U.S. Army Corps of Engineers used three years of synoptic weather charts, (1948-1950), and applied hindcasting methods to generate frequency distributions of waves by direction, height, and period. By interpolating wave data off the New York Harbor and Chesapeake Bay entrances, wave roses were constructed applicable to deep water off the Delaware Bay entrance. Sea and swell data for five degree squares can be found in the U.S. Navy Oceanographic Atlas of the North Atlantic Ocean. As can be determined from the wave roses, (Figure 2-3), the majority of the waves emanate from 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. From October to March wave height off the coast of Delaware averages 1.2 meters, and 0.3 meter for the remainder of the year (Polis and Kupferman, 1973). The mean swell direction offshore from 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

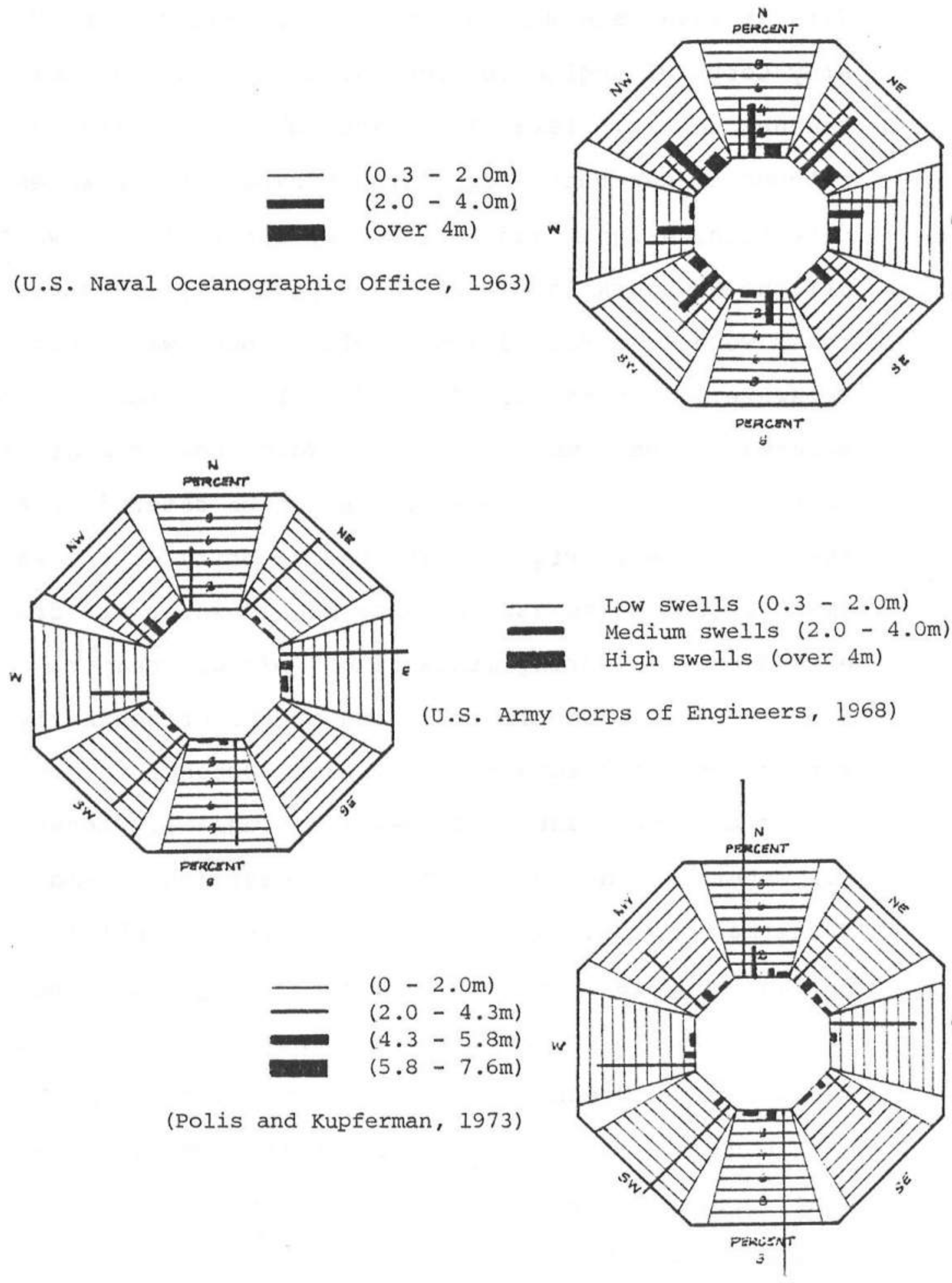


Figure 2-3: Wave data off the Delaware Coast.

waves in the offshore area are summarized below:

recurrence interval (years)	5	10	25	50
maximum significant wave height (meters)	11	12	14	16
extreme wave height (meters)	18	21	26	29

(Polis and Kupferman, 1973).

2.3.3 Currents

Along the Atlantic coast of Delaware, tidal flood currents normally flow toward the northeast. The currents along the southern section of the coast are less influenced by the flows from Delaware Bay than those near the entrance of the bay. The velocity of the ebb currents generally exceed the flood current velocity, ranging from 1.2 m/s, 0.5 kilometers north of Cape Henlopen to 0.2 m/s at the Fenwick Shoals Buoy (NOAA, 1974a).

2.3.4 Storms

The Delaware coast is subject to two major types of storms: tropical and northeasters. Although northeasters are not exclusively cold weather phenomena, they are far more prevalent during the winter months. Tropical storms with wind velocities greater than 33 m/s are considered to be hurricanes. Hurricanes occur mainly in the summer and fall. Since wind data has been recorded, storm centers have passed east and west of the Delaware coastline, but none directly over, although this is a possible occurrence. A detailed description of past hurricanes and other storms was compiled by U.S. Army Corps of Engineers (1968).

The most serious of past storms occurred in March 1962. The combination of persistent, strong onshore winds, spring tides, and wave heights between six and nine meters, resulted in 21.9 million dollars of damage to the Delaware shore from Pickering Beach to Fenwick Island (U.S. Army Corps of Engineers, 1968). Data for other storms are listed in Table 2-1.

2.3.5 Tides

The tides along the Delaware coast are semi-diurnal: two high tides and two low tides in 24 hours 50 minutes. Successive normal high tide elevations differ by less than 0.3 meter, as is true for successive low tide elevations (U.S. Army Corps of Engineers, 1968). The mean tide height variations (in meters) at Rehoboth Beach and

Date	Storm Name	Type of Storm	Maximum Wind Direction	Maximum Wind Velocity (m/s)	Highest Tide Breakwater (m above MSL)
Aug 1933		Tropical	E	34	1.9
Nov 1935		Extra-Tropical	NE	28	-
Sep 1936		Tropical	NE	41	-
Sep 1938		Tropical	W	32	-
Sep 1944		Tropical	NE	41(G)	-
Nov 1950		Extra-Tropical	E	32	2.2
Oct 1953		Extra-Tropical	N	13	1.8
Nov 1953		Extra-Tropical	NE	31(G) 29(V)	1.7
Aug 1954	Carol	Tropical	NE	26	1.1
Sep 1954	Edna	Tropical	NE	29	-
Oct 1954	Hazel	Tropical	SE	36(G)	1.4
Aug 1955	Connie	Tropical	S	29	1.3
Aug 1955	Diane	Tropical	SW	22	1.3
Oct 1955		Tropical	E	27	1.6
Sep 1956	Flossy	Tropical	E	25	1.7
Sep 1960	Donna	Tropical	WNW	37	1.6
Mar 1962		Extra-Tropical	E	26(G)	2.4
Oct 1964	Flossy	Tropical	NE	14	1.2

(G) denotes gust and (V) denotes five-minute value.

Table 2-1: Storm data for the Delaware Coast.
(U.S. Army Corps of Engineers, 1968)

Fenwick Island are:

LOCATION	MEAN TIDE LEVEL	MEAN TIDE RANGE mean	MEAN TIDE RANGE spring
Rehoboth Beach	0.6	1.2	1.4
Fenwick Island Light	0.5	1.1	1.4

(National Oceanographic and Atmospheric Administration, 1974b).

2.4 SHORE HISTORY

Although the littoral transport rate is moderate, because of the nodal point located near Bethany Beach (the northward littoral drift equals the southward littoral drift, so the resulting net transport is zero), the problem of beach erosion is considered to be extremely serious, since the littoral supply is so limited. Shore erosion along the Delaware coast is due primarily to wave action. Obviously, storms cause a large proportion of the erosion because of the greatly increased energy in the wind and waves. Surveys, from earliest record in 1843 until 1964, reveal that the shoreline between Indian River Inlet and the Delaware-Maryland State line has undergone periods of erosion and accretion. Between 1843 and 1929, the shoreline along this entire reach receded landward an average of one to 1.2 meters per year (Kraft et. al., 1976; U.S. Army Corps of Engineers, 1971).

From 1934 to 1943, the State of Delaware constructed nine groins over 1,200 meters at Bethany Beach (Henry, 1980). Between 1921 and 1941, the shoreline accreted seaward an average of over 1.2 meters per year (Kraft, 1976). During the 10-year period 1954-1964, the shoreline experienced a net recession of about two meters per year at the mean high water line, in spite of the placement of artificial beach fill by the State from 1954 to 1961 and the emergency dune and beach fill placed during Operation FIVE-HIGH after the March 1962 storm, which eroded the beach fill placed during the period 1957-1961 and accounted for most of the erosion experienced from 1954 to 1964 (U.S. Army Corps of Engineers, 1971). For the 5-year period, 1968 to 1973, the coast experienced nearly universal retreat (McDonald, 1981).

Although the Bethany groin field accumulates sand and thereby reduces erosion during normal wave activity, severe erosion occurs at Bethany Beach even during moderate storms (U.S. Army Corps of Engineers, 1971). The Army Corps of Engineers, (1956), estimated that Bethany loses on the average 15,000 cubic meters of sand each year; however, in 1971, the Corps estimated the average annual loss of beach material above mean low water (MLW) was 52,000 cubic meters. Between May 1982 and May 1983, this study revealed that Bethany Beach experienced 34,000 cubic meters of erosion above the National Geodetic Vertical Datum over 1800 meters of ocean frontage.

CHAPTER 3

HISTORY OF THE GROINS

3.1 BACKGROUND

In October 1934 the State Highway Department contracted William P. Short of Bethany Beach to construct four groins on Bethany Beach for an estimated cost of $27,960. (Delaware State Highway Dept, 1934a). Originally constructed 68.6 meters long, the groins were quickly shortened by wave action. Subsequently, it was necessary to lengthen the groins in August 1935 (Delaware State Highway Dept., 1934b). Although the beach was considered to be in the best condition since 1925, during 1938 four additional groins were constructed, two north and two south of the four original groins, for a cost of $30,295.50, to provide "proper protection" to the shore and town of Bethany Beach (Delaware State Highway Dept., 1938). By 1941, the seaward ends of some of the groins were disappearing due to the wave action, so in 1943 the State Legislature appropriated funds to "erect, build, rebuild, replace or repair" the groins at Bethany Beach.

The State Highway Department awarded the contract for $10,701. to George E. Shockley and Sons on 7 December 1943 (Delaware State Highway Dept., 1943). In addition to repairs to the existing groins, a ninth groin was constructed at the end of Garfield Parkway, between the two southernmost groins built under the 1934 contract. Figure 3-1 is a map showing the location of the nine groins.

The center of the hurricane of September 1944 passed about 80 kilometers east of the Delaware coast causing considerable damage at Bethany Beach. Approximately 610 meters of the boardwalk were destroyed; artificial and natural sand dunes were broken at several points, and about 60 meters near Fourth Street were completely washed out. Due to the severe hurricane damage, the State Legislature appropriated funds to repair the beach and boardwalk.

In 1950, the State Highway Department awarded George and Lynch of Wilmington, Delaware a contract for $24,450. to repair two of the groins by building a stone-filled timber crib at the ocean end of each (Henry, 1980; Delaware State Highway Dept., 1950). By 1955, the effects of sand and salt water had made most of the nine groins at

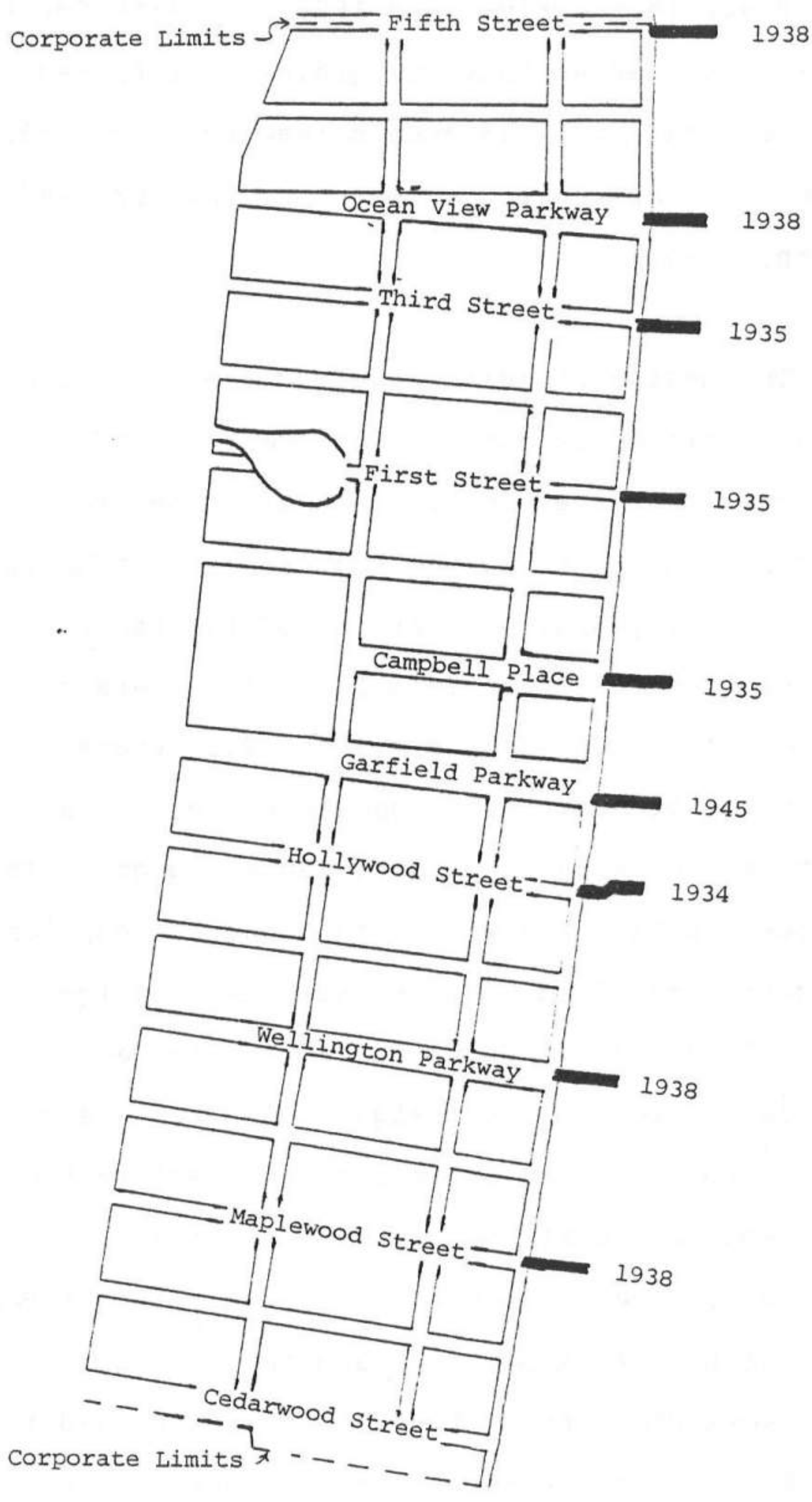


Figure 3-1: Location map for Bethany Beach groins.

Bethany Beach ineffective. In 1956, the Army Corps of Engineers recommended that the groins be repaired and extended approximately 35 meters seaward. In 1958, the State awarded the project to Henry C. Eastburn and Son (Eastburn, 1960).

The design selected required that creosoted timber sheeting be placed immediately adjacent to and parallel to the old corroded steel sheeting on all nine groins. Stone refill was to be added to the timber crib at the seaward end of the 1943 groin. Extensions of the other eight groins, ranging in length from 25 to 45 meters and extending the groins seaward 4.5 to 29.3 meters, were planned to be of heavy stone construction with a core of small stones weighing from 70 to 450 kilograms. The core was to be held in place with large concrete capstones on the landward end of each groin, varying in weight from 1830 to 4270 kilograms each and ranging in length from 17.7 to 38.1 meters. The design called for the groin elevations to vary from 0.6 meter above MSL at the landward end to MSL at the offshore end (Eastburn, 1960; Henry, 1980). Due to cost overruns, only two of the groins, the northernmost groin and the 1943 groin, had the intended work completed. Four groins, shortened in preparation for the stone extensions, were never lengthened, and the three southernmost groins were only slightly altered (Henry, 1980).

In 1961, the State nourished the beach with about 76,500 cubic meters of sand. Much of this was washed away during the March 1962 storm, so during Operation FIVE-HIGH a barrier beach and protective sand dune were constructed, involving a total of 131,390 cubic meters of sand, some of which was obtained by the storm of March 1962. In addition, sand fences were placed from Beach Cove to Bethany Beach and along South Bethany and York Beaches (U.S. Army Corps of Engineers, 1968).

Presently, the groin field is in fair to poor condition. The southernmost groins have large gaps in the timber and steel sheeting. All the groins have been flanked; however, the Town of Bethany Beach constructed bulkheads at the landward end of two of the groins to rectify the problem. In the following section each of the groins are discussed individually.

3.2 HOLLYWOOD STREET GROIN

The first groin, completed 27 December 1934, is located at the end of Hollywood Street (Delaware State Highway Dept., 1933). Although the original specifications were for creosoted piles and lumber, all four groins contracted in 1934 were constructed of steel sheet piling. The steel sheeting, 328 kilograms per square meter of wall, was painted with a bituminous solution before placement. The sheeting was braced by 20.3 cm x 30.5 cm creosoted southern yellow pine wales and nine meter creosoted pine piles (Delaware State Highway Dept., 1934b) The pilings were placed on alternating sides of the steel sheeting 1.8 to 2.0 meters apart (see Figure 3-2).

Fifteen meters of the seaward end of the groin washed out on 9 April 1935. The following day an additional 5.5 meters washed out. This occurred only ten days before the last of the four groins contracted in 1934 was completed (Delaware State Highway Dept., 1933). Although the groin was lengthened in August 1935, by November 1937 wave damage had shortened the groin to a length of 37.8 meters. Plans for repairs in 1958 included concrete capping on 17.7 meters of the nearshore end of

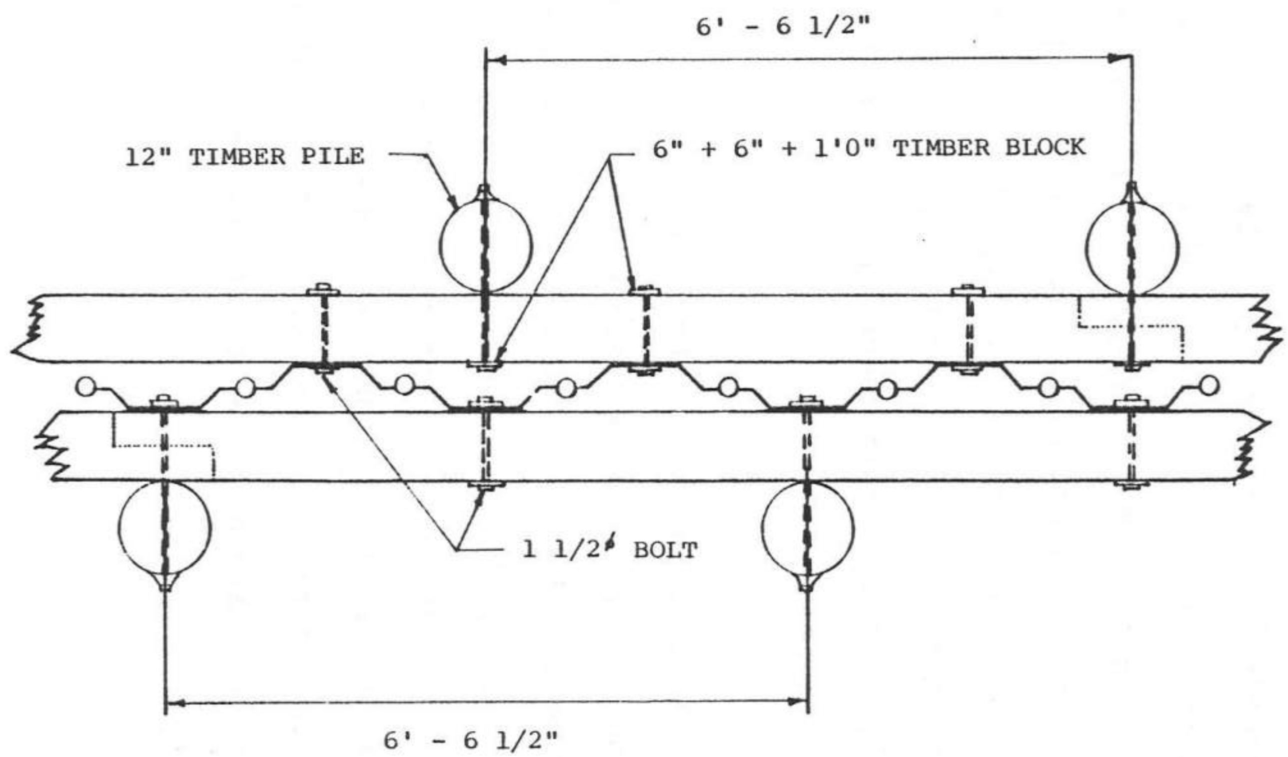


Figure 3-2: Steel sheeting design for the groins under the 1934 contract.

the existing groin and repairs to 18.0 meters of the timber. A new 57.3 meter timber groin was to be overlapped 4.9 meters by a 30 meter stone-filled timber crib (Delaware State Highway Dept., 1957). Due to cost overruns, the work was not completed as specified. The groin was changed from its original design, straight and perpendicular to the beach, to its present shape. The landward end is steel sheeting, perpendicular to the beach, attached to an angled section of wood sheet piling followed by a perpendicular section, also of wood sheeting (see Figure 3-3).

By April 1969, a hole had developed in the groin about 30 meters from the landward end and flanking was occurring behind the groin (Delaware State Highway Dept, 1969). Presently the groin is severely flanked and must be extended 15 meters to be effective. Water breaks through between each plank of the wood sheet piling and through holes in the steel sheeting. The steel sheeting is rusting badly and has been topped by new 7.6 cm x 30.5 cm planks.

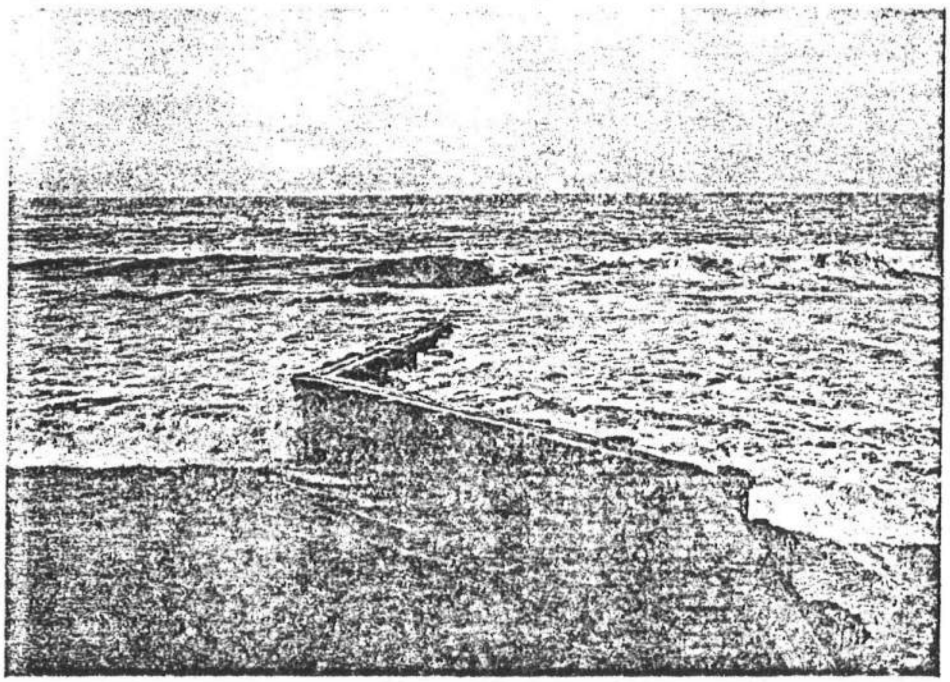


Figure 3-3: Angled design of the Hollywood Street groin. (November 1982)

3.3 CAMPBELL PLACE GROIN

The second groin constructed at Bethany Beach, completed February 1935, is located at the end of Campbell Place. Although it was lengthened in August 1935, by November 1941, the seaward end of the groin was disappearing (Delaware State Highway Dept., 1933). In 1950 the steel sheet pilings were damaged, and the stone crib was designated for repairs. Under the 1958 contract concrete capping was to be placed on 37 meters of the existing groin, 40 meters of stone repairs and reinforcement was to be done on the south side of the groin and 32 meters of stone reinforcement was to be done on the north side. The stone-filled timber crib at the seaward end was to be extended 35 meters and 11 meters of the existing crib was to be refilled with 910 kilogram stone. The groin was shortened in anticipation of the repairs; however, the extension was not made (Delaware State Highway Dept., 1957).

Although there was evidence of flanking behind the groin, in April 1969 the groin itself appeared to be in excellent condition. For increased protection to the structures behind the boardwalk, a 18 meter timber bulkhead was constructed between Garfield Parkway and

Campbell Place, and a 65 meter timber bulkhead was erected between Campbell Place and Third Street (Delaware State Highway Dept., 1969). Presently the groin ties into the timber bulkhead which now extends uninterrupted past Third Street. The steel sheet piling section extends 63.1 meters from the bulkhead, the last 38.7 meters reinforced by stones. A 24 meter stone crib extends beyond the steel sheeting section (see Figure 3-4). The wales at the landward end of the groin are in worse condition than those at the seaward end. Some of the bolts holding the stone crib are broken and others have pulled through the wales.

3.4 FIRST STREET GROIN

The third groin built under the 1934 contract is located at the end of First Street. Constructed similarly to the other groins under the contract, it was completed in March 1935. Although it was lengthened in August 1935, by the end of November 1941, the seaward end of the groin, like the Campbell Place groin, was disappearing (Delaware State Highway Dept., 1933). By 1950, the seaward end was destroyed.

Under the 1958 contract, plans for repairs

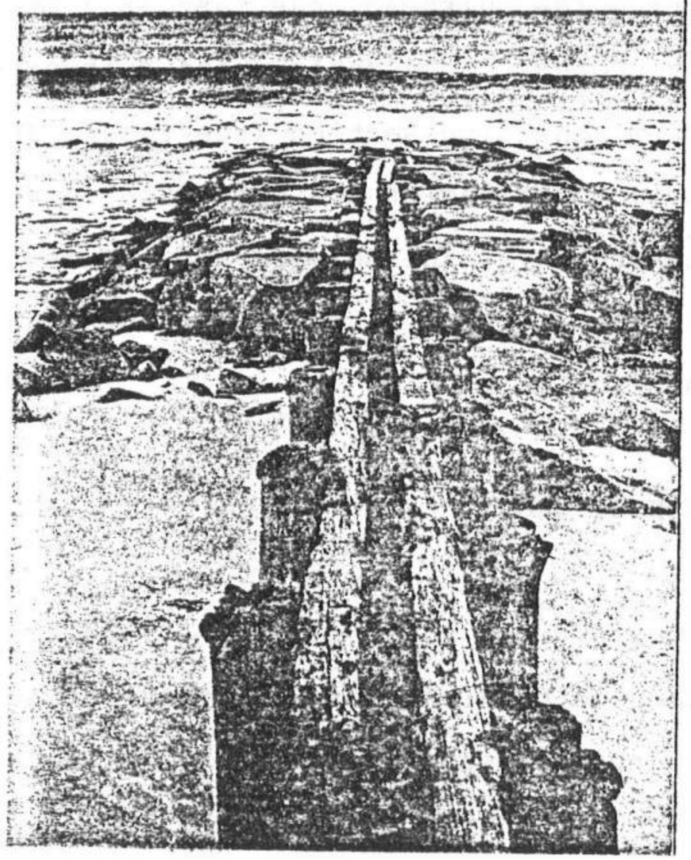


Figure 3-4: Campbell place groin.
(March 1983)

included concrete capping on 23.2 meters of the existing groin and repairs to 29.9 meters of the timber section. A 19.2 meter new timber section was to be overlapped 4.9 meters by a 30.5 meter stone extension. The groin was shortened in preparation for the stone repairs, but the extension was never made (Delaware State Highway Dept., 1957).

In April 1969 there was evidence of flanking behind the groin; however, the groin itself was in excellent condition. Two new timber bulkheads had been constructed between First and Third Streets, and a 65 meter timber bulkhead had been constructed between First Street and Campbell Place (Delaware State Highway Dept., 1969). Presently, the groin abuts a timber bulkhead extending from Garfield Place to north of Third Street. The construction is somewhat different from that of the previous two groins. The steel sheet piling is supported by a double layer of wood sheeting on the north side. Unlike the previous groins, this groin is constructed with two horizontal and one sloping section (see Figure 3-5). Large stones extend seaward at least another 18 meters. In April 1982, the stones of all the groins were so low that sand passed over them. The timber wales are severely deteriorating at the landward end,

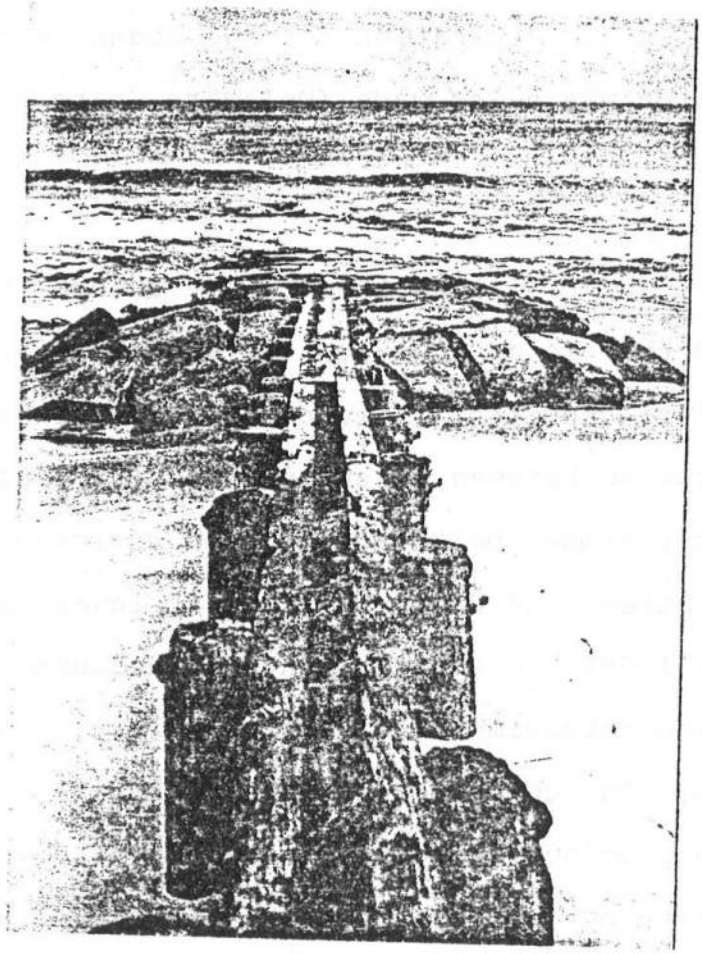


Figure 3-5: First Street groin.
Figure shows steel sheet and timber sheet piling, and stone crib at the seaward end.
(March 1983)

particularly on the south side. Two small holes have rusted through the steel sheeting right below the wales.

3.5 THIRD STREET GROIN

The last groin constructed under the 1934 contract, located at the end of Third Street, was completed the end of April 1935. Although lengthened in August 1937, by 1938 it was in very bad condition (Delaware State Highway Dept., 1933). Repairs planned in 1958 included concrete capping on 24.4 meters of the existing groin and repairs on 18.6 meters of the timber section. A new 21.9 meter timber section was to be overlapped 4.9 meters by a 30.5 meter stone extension. The groin was shortened in anticipation of an extension which was never made (Delaware State Highway Dept., 1957).

By 1969 there was evidence of flanking behind the groin; however, the groin itself was in excellent condition. Two new timber bulkheads had been built between Third and First Streets (Delaware State Highway Dept., 1969). Presently the groin adjoins a timber bulkhead. The groin consists of a horizontal section of steel sheet piling, a sloping section of wood sheeting and seaward section of stone, similar to the First Street

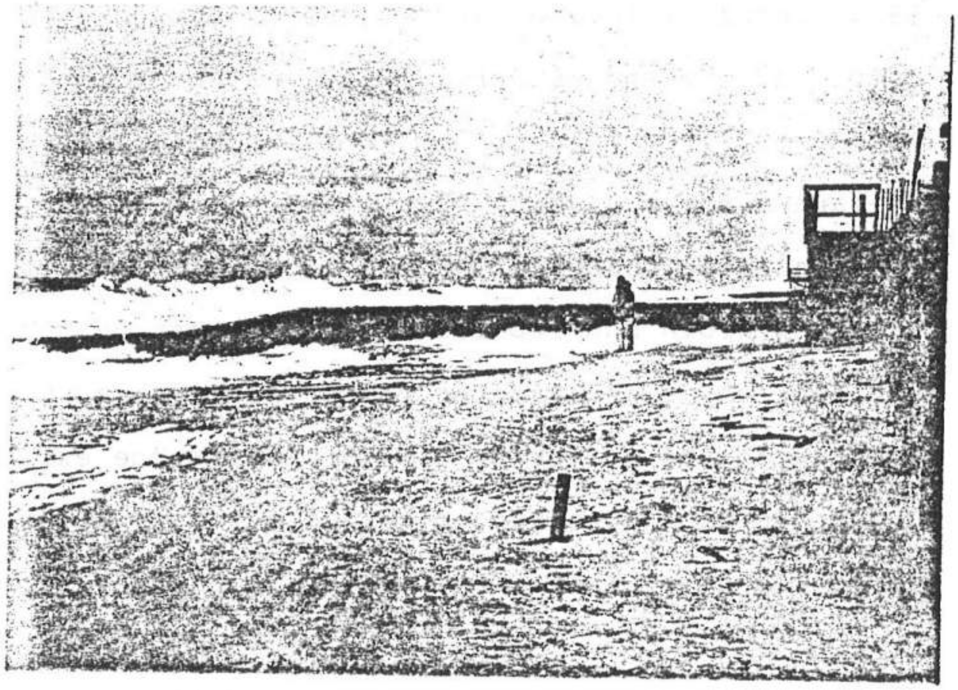


Figure 3-6: Elevation view of the Third Street groin. Design of groin is similar to the First Street groin. (October 1982)

groin (see Figure 3-6). The timber and steel section of the groin extends 37.2 meters seaward; the final 6.7 meters is reinforced by stone (see Figure 3-7).

In November 1982, waves were breaking over the lowest section. A hole (0.3 meter wide) exists at the junction of the wood and steel sheeting causing scouring of the sand on the downdrift side of the groin. The wales appear to have broken off above the hole.

3.6 WELLINGTON PARKWAY GROIN

The Wellington Parkway groin was constructed under the 1938 contract. In 1958 plans for repairs included concrete capping on 30.2 meters of the existing groin and repairs to 33.8 meters of the timber. A new 14.0 meter timber section was to be overlapped 4.9 meters by a 30.5 meter stone extension. However, very little work was done on the groin. As-built plans indicate that the groin was rip-rapped with stone (Delaware State Highway Dept., 1957). By April 1969, there was obvious flanking behind the groin. The groin itself was in very poor condition with several holes in both the timber and steel. For additional protection, a new 82 meter timber bulkhead was constructed between Wellington Parkway and Parkwood Street

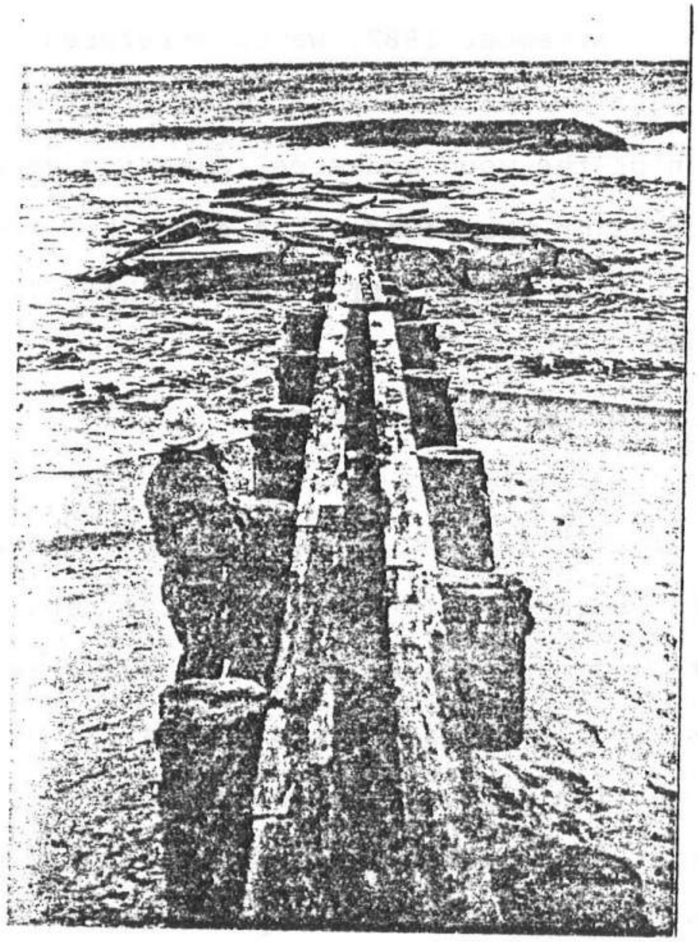


Figure 3-7: Third Street groin.
(March 1983)

(Delaware State Highway Dept., 1969).

Presently, the groin is about 70 meters long, separated into two wood sections divided by a steel section. The steel sheeting is supported by timber piling on both sides of the groin, while the wood sheeting is supported by pilings only on the north (see Figure 3-8). The steel sheeting, of which about 2.7 meters has been ripped out, is covered by new wood capping (see Figure 3-9). The wood sheeting has been destroyed in two locations. In November, the gap in the sheeting measured 5.8 meters. The groin was severely flanked, requiring at least a 8.5 meter extension landward to be effective. In April 1983, private interests had large stones placed at the landward end of the groin. The beach directly north and south of the groin was nourished with sand (see Figures 3-10 and 3-11).

3.7 MAPLEWOOD STREET GROIN

The southernmost groin, located at the end of Maplewood Street, was constructed in 1938. Plans for repairs in 1958 included concrete capping on 22.3 meters of the existing groin and repairs to 21.0 meters of the timber section. A 45.7 meter stone extension was to

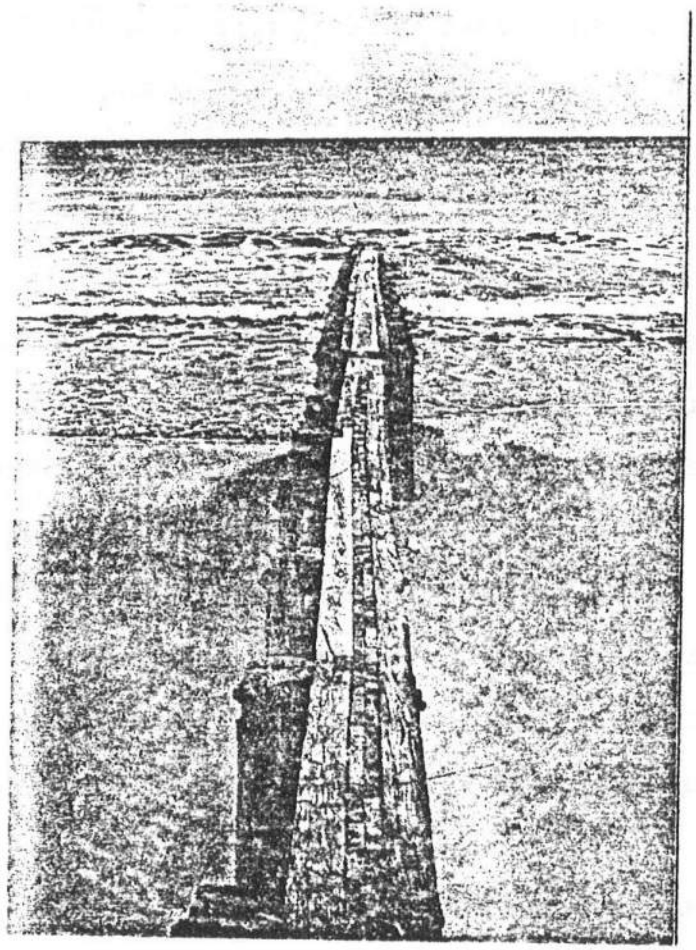


Figure 3-8: Wellington Parkway groin.
Figure shows steel sheeting supported by timber pilings on both sides, while the wood sheeting is supported by pilings only on the north side.
(March 1983)

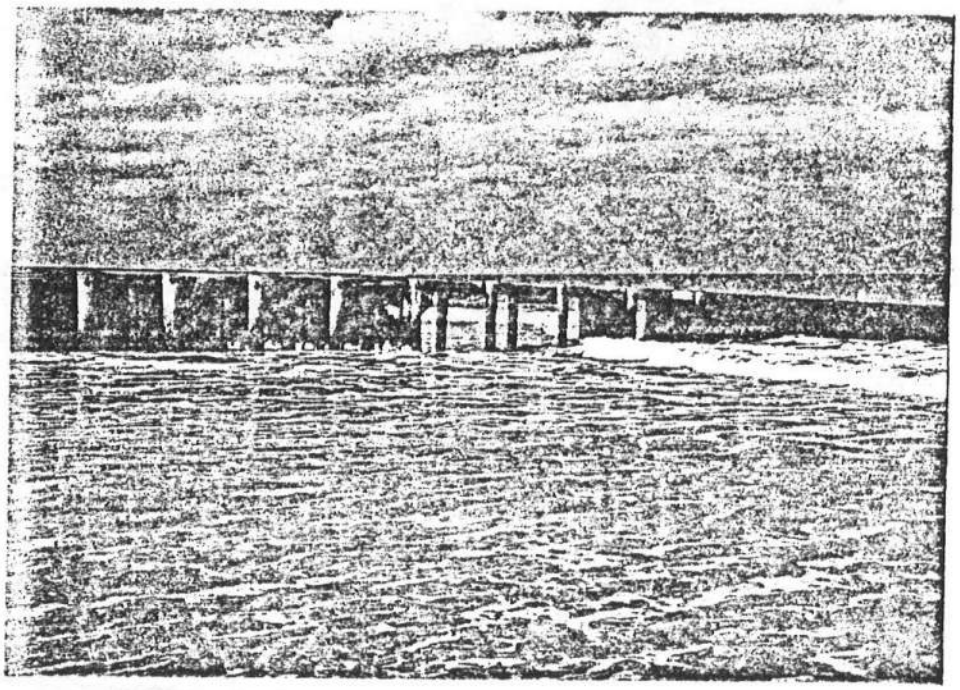


Figure 3-9: Wellington Parkway groin.
The steel sheet piling is corroded and 2.7 meters has been destroyed.
(March 1983)

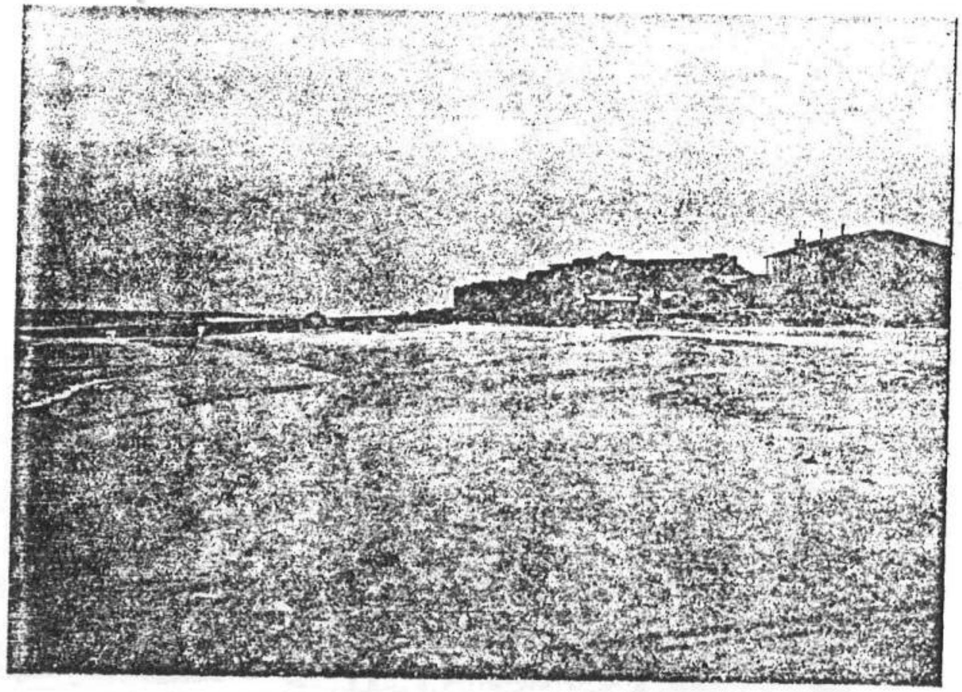


Figure 3-10: Repairs on the Wellington Parkway groin. (May 1983)

Figure 3-11: Detail of repairs. (May 1983)

overlap the timber groin by 4.9 meters. However, very little work was done to the groin (Delaware State Highway Dept., 1957). By April 1969, a three meter long gap had developed in the steel sheeting. There was evidence of flanking behind the groin, and the limit of dune erosion extended about 155 meters south of the groin (see Figure 3-12). A new 20 meter timber bulkhead had been built south of the groin (Delaware State Highway Dept., 1969).

Presently, the 24 meter steel inner section is attached to a 21 meter section of wood sheeting. A three meter hole exists in the steel at the junction of the two sections, and the next three meters landward is rusting through badly (see Figure 3-13). A piece of steel sheeting, connected to the groin by one bolt, flaps violently with each wave.

3.8 OCEAN VIEW PARKWAY GROIN

The Ocean View Parkway groin was constructed under the 1938 contract. As early as April 1938 repairs were made to the groin: a 30.6 meter extension was added to the ocean end (Delaware State Highway Dept., 1937). Under the 1958 contract, concrete capping was to be placed on

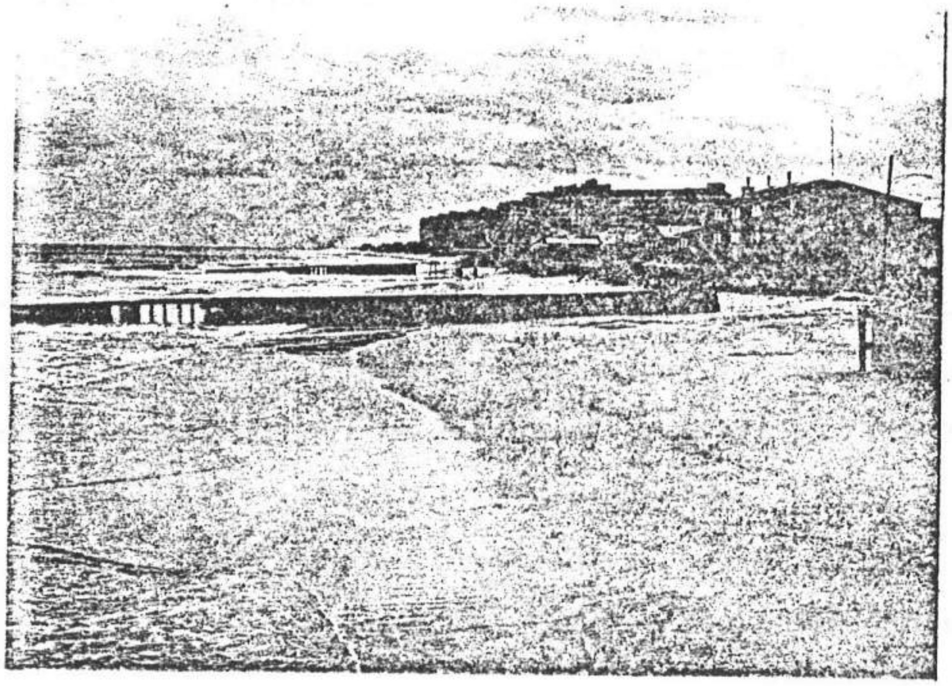


Figure 3-12: Flanking behind the landward end of the Wellington Parkway groin (foreground) and the Maplewood Street groin. (March 1983)

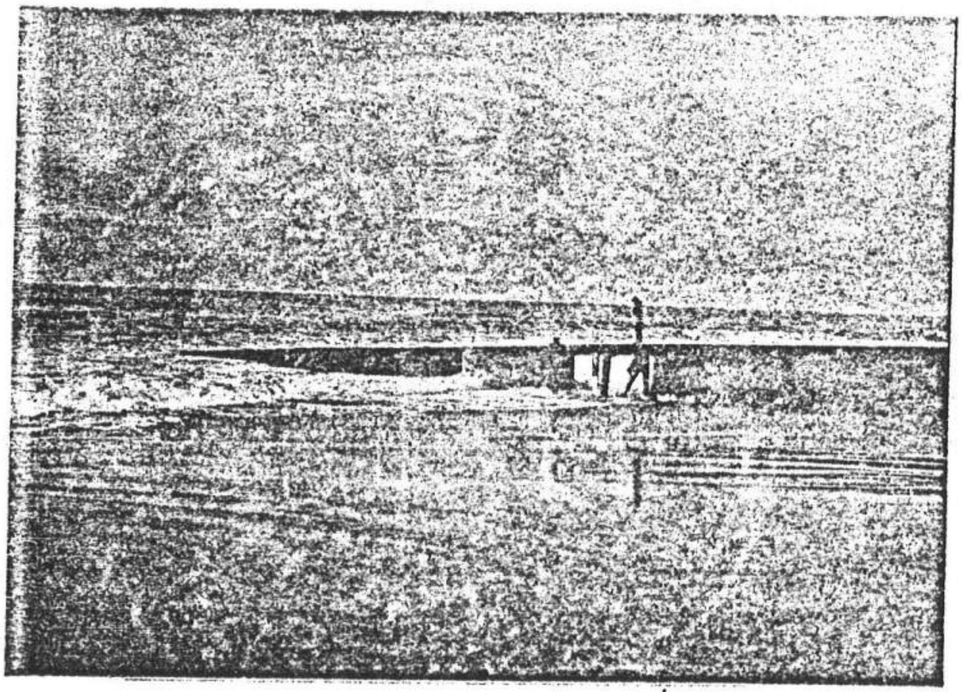


Figure 3-13: Maplewood Street groin.
Water breaks through gaps in the wood planking
and the large holes in corroded steel.
(November 1982)

36.6 meters of the existing groin and repairs were to be made to 29.0 meters of the timber section. A 30.5 meter stone extension with a 4.6 meter overlap between the timber and stone sections was to extend the groin 4.6 meters seaward. Although the groin was shortened in anticipation of the stone repairs, the extension was never made (Delaware State Highway Dept., 1957).

In April 1969, there was evidence of flanking behind the groin, but the groin itself was in excellent condition (Delaware State highway Dept., 1969). Presently, the steel and timber section of the groin measures 70 meters from the toe of the dune; the last 8 meters is reinforced by stone (see Figure 3-14). The bolts and steel sheet piling are rusting; holes have developed under the wales, and the wales and timber pilings are decomposing. In April 1982, the groin was overtopped at the upper beach, and by June it was completely buried. In November the groin was filled nearly to capacity on the north side, especially at the landward end near the high tide level. Due to flanking, a sand scarp developed at the end of the groin during the October 1982 storm.

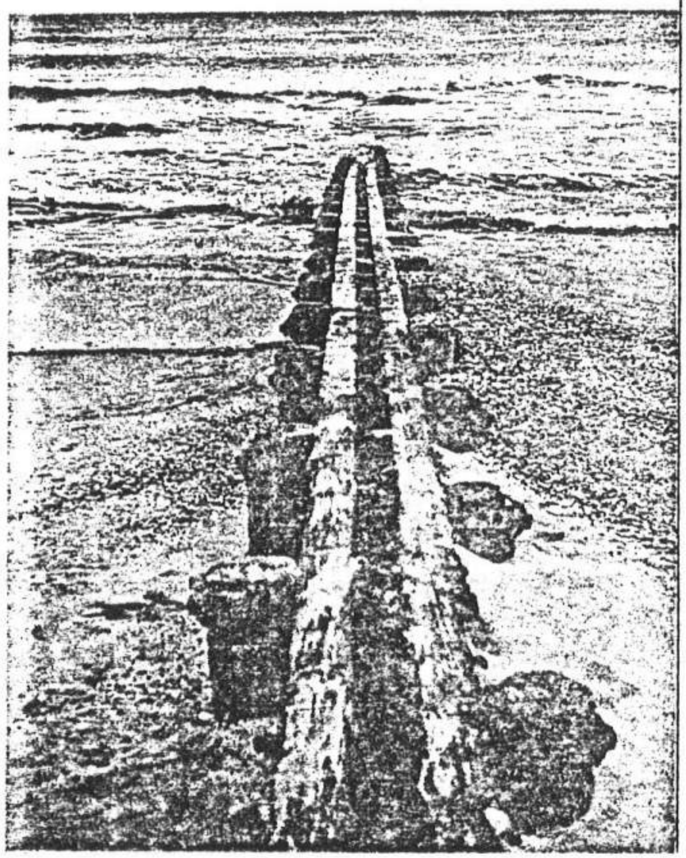


Figure 3-14: Ocean View Parkway groin.
(March 1983)

3.9 FIFTH STREET GROIN

The northernmost groin on Bethany Beach, located at the end of Fifth Street, was finished in May 1938. This is one of two groins that had the repairs contracted in 1958 completed. Concrete capping was placed on 38.1 meters of the existing groin, and repairs were made to 15.2 meters of the timber. The addition of a 27.4 meter stone extension, overlapping the timber section by 6.1 meters, extended the groin 12.2 meters seaward to a final length of 80.8 meters (Delaware State Highway Dept., 1957).

In April 1969, the groin marked the approximate northern limit of dune erosion. Despite evidence of flanking behind the groin, it appeared to be in excellent condition (Delaware State Highway Dept., 1969). Presently, the steel and timber section extends 57.6 meters from the toe of the dune. The last eight meters is reinforced by stone measuring 0.8 m x 1.2 m x 0.5 m (see Figure 3-15). Although in April 1982 the groin was in good condition (no obvious fillet), the offset to the north was evident and the groin was overtopped at high tide. In September, due to flanking, a 0.6 meter scarp developed about 12 meters from

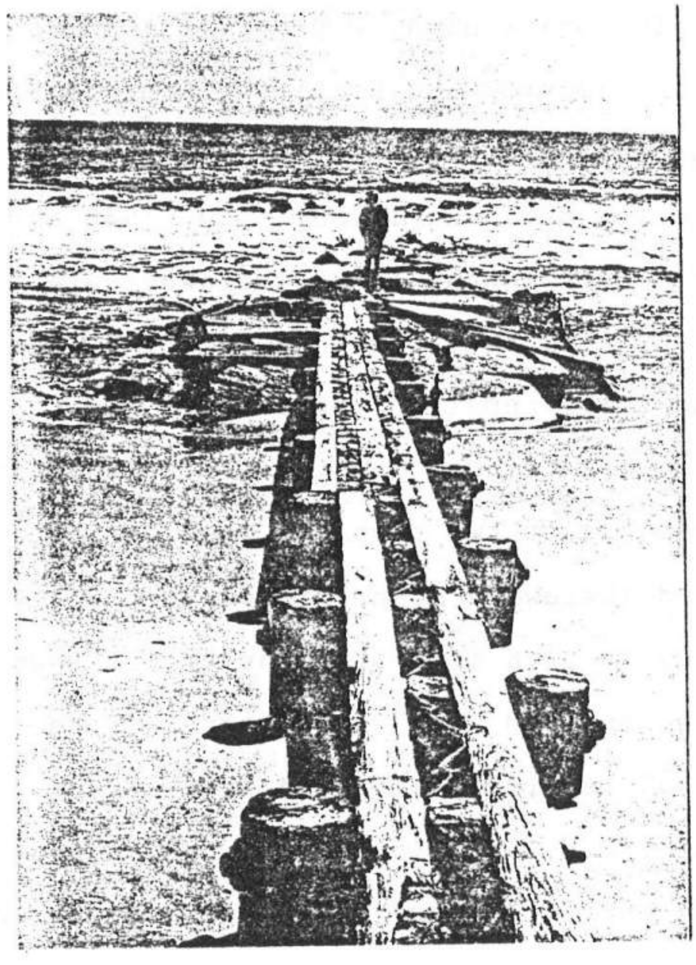


Figure 3-15: Fifth Street groin.
(April 1982)

the south side of the groin.

3.10 GARFIELD PARKWAY GROIN

The State Highway Department awarded a contract to George E. Shockley and Sons on 7 December 1943 to build a ninth groin located at the end of Garfield Parkway. Construction began early September 1945 and was completed two-and-a-half months later (Delaware State Highway Dept., 1937). By 1950 the steel sheet piling was damaged and the crib had to be repaired. The wales and rusted steel sheeting were removed and the groin was straightened. The groin was one of two that had work contracted in 1958 completed (Delaware State Highway Dept., 1957). Repairs were made to 21.6 meters of the timber section, and the crib was refilled with 910 kilogram stone. By April 1969 a hole had developed about 24 meters from the landward end. A new 18 meter timber bulkhead was constructed just north of Garfield Place (Delaware State Highway Dept., 1969).

Due to flanking, a bulkhead was built at the landward end of the groin. Presently, the groin extends 38 meters from the bulkhead to the crib (see Figures 3-16 and 3-17). From the bulkhead to the edge of

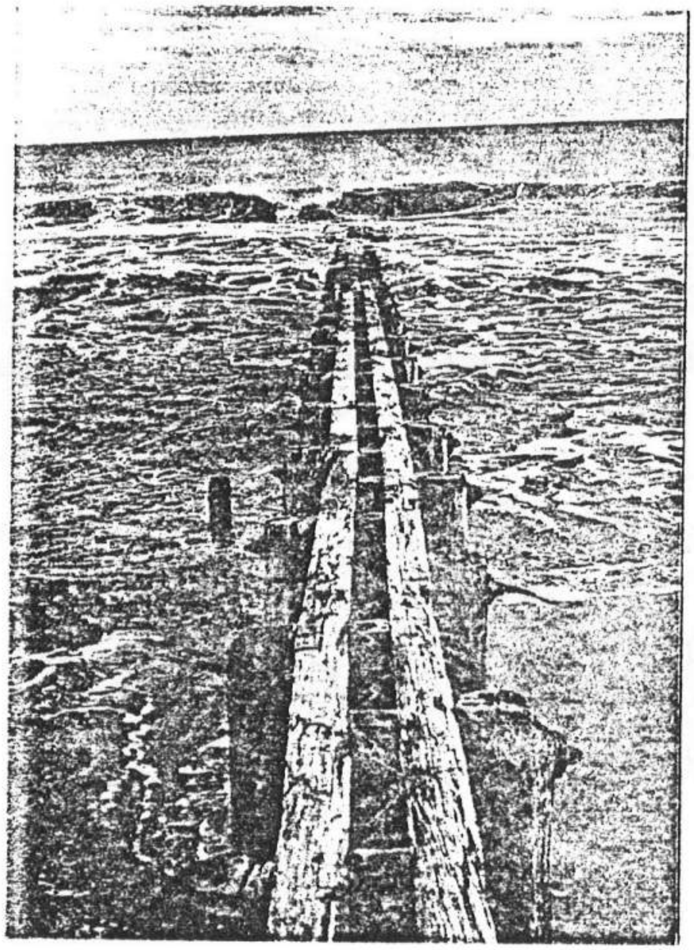


Figure 3-16: Garfield Parkway groin.
(March 1983)

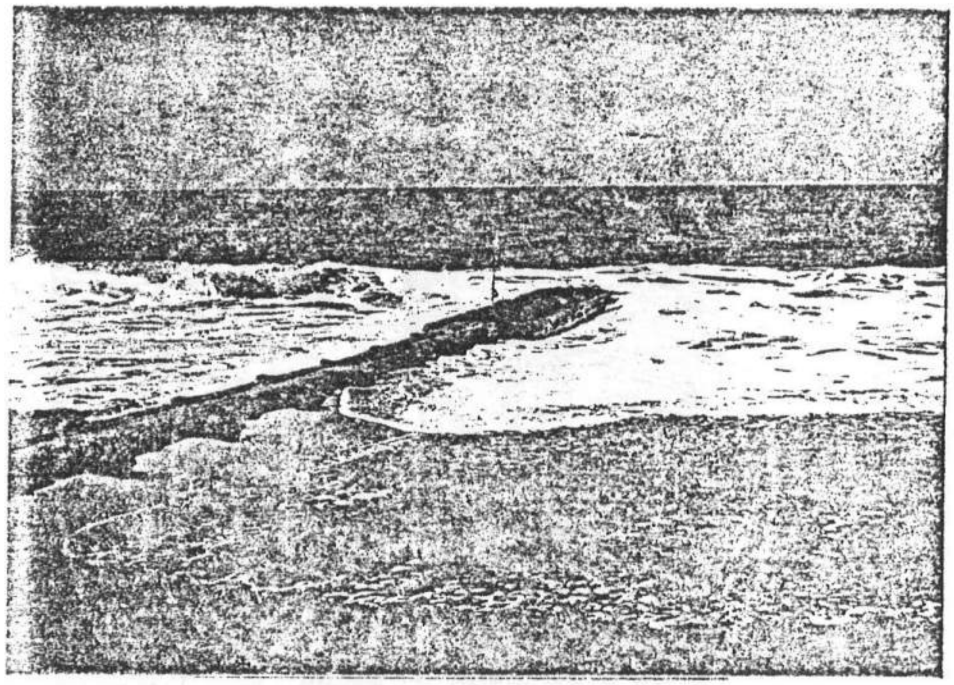


Figure 3-17: Oblique view of the Garfield Parkway groin showing stone and timber crib. (April 1982)

the boardwalk is wood sheeting. The next 24.4 meters seaward is steel sheet piling, followed by wood sheeting. In April 1982, at least eight meters of the groin were buried by sand. In November the groin was overtopped just seaward of the boardwalk.

CHAPTER 4

AERIAL PHOTOGRAMMETRY

4.1 BACKGROUND

There are few systematic data available on the rates and trends of shoreline erosion and accretion. Historical field surveys provide data of the highest resolution; and are ideally suited for detecting coastal trends, but records accurate enough to be used for comparisons are generally unavailable. The need for records of shoreline changes was not recognized in the past, so with the exception of a few scattered sites, shoreline change information is lacking. Moreover, those surveys that were made are of questionable accuracy. Because the generation of extensive new surveys is expensive and time-consuming, contemporary field surveys are best suited for small areas and short time scales. Changes identified by short-term surveys are more likely to be seasonal variances rather than historical changes, and cannot be accurately extrapolated into long-term trends.

Maps and charts, another source of coastal information, frequently date back to the mid-1800's. Unfortunately, they are generally restricted to areas immediately adjacent to major shipping lanes and ports. The accuracy of maps and charts is uncertain. The U.S. Geological Survey standards for horizontal accuracy state that at least 90% of the "well-defined" map points are plotted correctly within 0.5 mm (Tanner, 1978). Which points are well-defined and which 90% of these points meet the required standards are unknown. U.S. Geological Survey maps and U.S. nautical charts have a different zero datum which can incorrectly identify shoreline changes when both these data sources are used. For these reasons, maps and charts should only be used for supplemental information in determining historical trends in shoreline change.

Aerial photographs, however, are a relatively inexpensive and simple way to access long-term trends in shoreline change. Aerial photographs are far less time consuming than beach surveys and are generally more accurate than historical observations. Aerial photographs have the additional advantage of permanently recording the location and appearance of the beach at a particular time. Photographs can record infinitely more detail than a map or chart. Several federal and state agencies have taken aerial photographs for different purposes, providing frequent coverage for a given area.

Aerial photogrammetry, however, has several limitations. Because photographs record only a single point in time, they may depict conditions that are not typical. Beach changes are sensitive to environmental conditions (winds, waves, and tides), so photographs taken immediately after storms represent unusual conditions and therefore are not suitable for determining long-term trends. Changes observed from photographs taken different times of the year may represent seasonal variations. Since photographs are normally taken during the fall or spring (when there is less foliage) and during fair weather, the changes due to seasonal and environmental conditions are not serious. In fact, seasonal changes may be more influential in field surveys where short-term changes are extrapolated to long-term trends (Stafford and Langfelder, 1971).

Another limitation is that aerial photographs can only be used to measure horizontal rather than volumetric changes. In studies of coastal erosion where the volume of material transported is an important characteristic, aerial photogrammetry will not be sufficient. In addition, there are certain inherent flaws in a photographic image; scale variation between photographs due to altitude variation between the photographic aircraft, scale variations within the photograph due to camera tilt, radial scale variations away from the center of the image, and relief distortions caused by elevation differences within the terrain of the area photographed. However, the study procedure for aerial photogrammetry is designed to minimize or eliminate these errors. Therefore, the advantages of using aerial photogrammetry over other possible procedures outweigh the disadvantages.

4.2 METHODOLOGY

4.2.1 Selection of Aerial Photographs

Obviously the first step in analyzing shoreline changes by aerial photogrammetry is the selection of the photographs. Aerial photographs are available from a number of sources: the U.S. Geological Survey; the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Services (ASCS); and the National Aeronautic and the Space Administration (NASA). Photographs are chosen for their scale, frequency of coverage, quality, season, and availability. Larger scales (greater than 1:20,000) are preferred, but not always available. The area in the photographs should overlap to avoid radial distortions that occur on the edges of the prints. Photographs should be clear and distinct, and should be taken the same time of year to avoid seasonal variations.

4.2.2 Selection of Datum Line

Three possibilities exist for the datum line from which to determine shoreline changes: the dune line, the water line, and the high water line (HWL). The dune line is identified as a topographical break or scarp between the wind and wave deposited sand and the sloping beach face. The dune line is an indication of erosion trends because it provides protection against wave damage and storm surge. However, the dune line erodes more easily than it accretes, especially during storms. Waves can quickly erode the dune but accretion from wind and waves is a far slower process, so the dune line is a better reference for erosion than accretion trends. Stereoscopic viewing of photographs is generally necessary to identify the dune line. In many areas the dune line is extremely low or nonexistent, so the dune line cannot be accurately located (Stafford and Langfelder, 1971).

The water line is easy to identify on clear aerial photographs, but a correction must be made to remove the effects of the tidal stage at the time the photograph was taken. Stafford and Langfelder (1971) found that data of shoreline change using the water line for a datum were not consistent with data using the dune line or HWL. Data from the water line exhibited a higher degree of inconsistency because of nonuniform wave run-up and varying beach slope. Stafford and Langfelder felt the additional work correcting for the tidal stage was not justified.

The HWL is easily and consistently recognizable on both black and white and color photographs as a tonal change between moist sand seaward of the HWL and dry sand landward of the line (Stafford and Langfelder, 1971) (see Figure 4-1). The HWL responds quickly to environmental changes and is, therefore, equally accurate for erosion and accretion. Moreover, because it is linearly continuous along the shoreline, the HWL is a better measure of beach change than the dune line in areas where the dune line is difficult to locate.

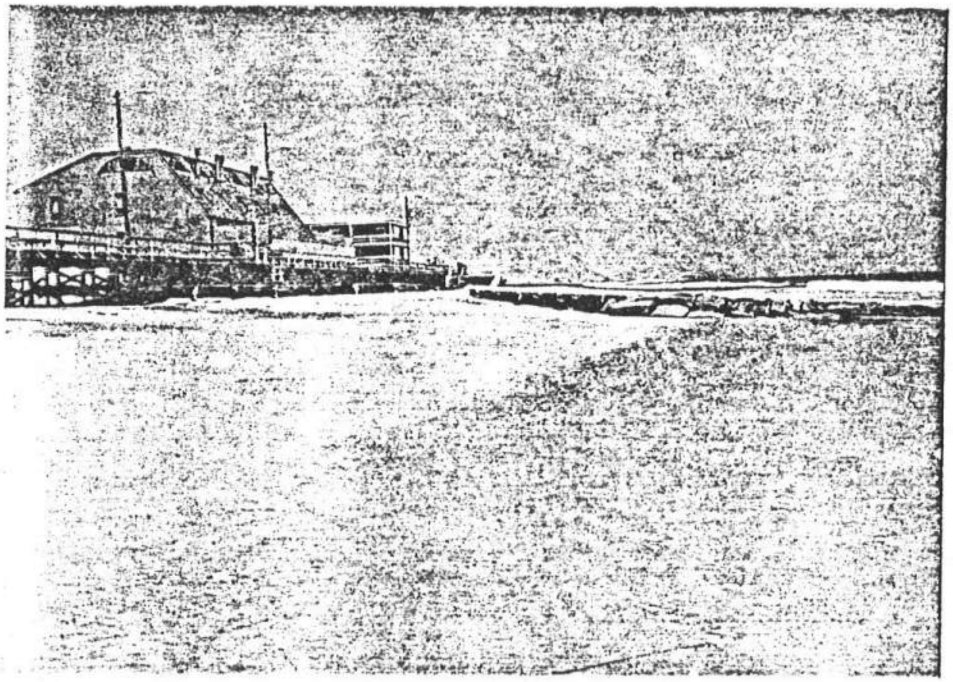


Figure 4-1: The HWL is identified as a tonal change between the moist and the dry sand.

4.2.3 Method of Calculation

The change in the location of the HWL is determined by either tracing the HWL onto a base map or measuring the distance between the HWL and a reference point. The locations of the HWL are then compared between sequential photographic surveys of different dates. For maximum efficiency, the sampling spacing should be increased to just short of the point at which results begin to significantly disagree with those obtained by high density sampling (Hayden et al, 1977). Stafford and Langfelder (1971) suggest 300 meters as an optimum sampling spacing.

4.3 AERIAL PHOTOGRAMMETRIC STUDY OF BETHANY BEACH

Aerial photographs for the study of long-term trends were chosen for the season and year of the photograph, clarity, scale and availability. Three photographs were from the U.S. Department of Agriculture, one from the NASA, and one from the Delaware Department of Natural Resources and Environmental Control (DNREC) (see Table 4-1). The Department of Agriculture and the DNREC photographs were a reasonable scale (1:20,000 and 1:8000, respectively), but the NASA photographs were a

Symbol or Code	Roll Number	Exposures	Scale	Date of Photograph	Source
ANH	21	101-102	1:20,000	5/7/38	Dept. of Agriculture
ANH	3N	86-88	1:20,000	7/20/54	Dept. of Agriculture
ANH	2JJ	140-142	1:20,000	5/2/68	Dept. of Agriculture
238	1	69	1:50,000	5/16/73	NASA
10005	177	11R	1:8,000	5/17/77	DNREC

Table 4-1: Aerial photographs used in study.

considerably smaller scale (1:50,000). Fortunately, the NASA photographs were exceptionally clear.

The HWL was traced directly from each photograph on to transparent film, along with the location of several well-defined reference points. This method proved to be more accurate than enlarging the photograph first with a stereo-zoom transfer scope and then tracing the HWL. Enlarging the photograph directly makes the HWL very difficult to identify. Use of the stereo-zoom transfer scope increases the errors in tracing the HWL to the transparent film. Because the scale of the NASA photographs was so small, it was not possible to directly enlarge them with the stereo-zoom transfer scope to a scale much greater than 1:20,000.

The traced HWL's were then enlarged to a scale of 1:5000 by a Kail autofocus projector. The enlarged HWL's from the projections of the sequence of historical aerial photographs from the five different survey dates constituted the raw data from which the measurements were made. The shoreline was divided into ten sections; one north and one south of the groin field, and the eight groin compartments. The area of erosion and/or accretion for each section was found by using a planimeter. The area was divided by the alongshore length of the section to obtain the average change of the shoreline for a given time interval, and then by the number of years between surveys to derive the annual rate of change.

4.3.1 Results

Between 1938 and 1977 Bethany Beach experienced periods of erosion and accretion. The May 1938 photograph was taken shortly after the completion of the two southernmost and two northernmost groins.

Figure 4-2 clearly illustrates the effects of the groin field on the beach planform. At the time the May 1938 photograph was taken the littoral drift was to the north. As the sediment was transported north, the position of the shoreline in each groin compartment shifted. Sand was deposited on the south side of each groin, resulting in accretion of the shoreline on the south side and causing erosion on the north side of each groin. This phenomenon was observed in all but the two southernmost groin compartments. (The Garfield Parkway groin had yet to be constructed.) In the photograph, the two southernmost compartments appear to be filled with sediment, and the groins appear to be overtopped by sand.

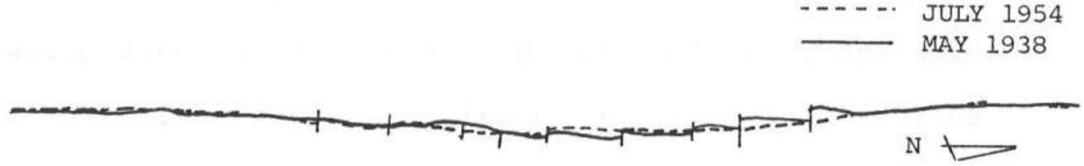


Figure 4-2: Shoreline at Bethany Beach in May 1938 and July 1954.

Figure 4-3: Shoreline in July 1954 and May 1968.

Figure 4-4: Shoreline in May 1968 and May 1973.

Figure 4-5: Shoreline in May 1938 and May 1973.

By 1954, many of the compartments had filled with sand. The shoreline had straightened out, although fillets were obvious on the middle groins (from Hollywood Street to First Street). Slight accretion occurred south of the groin field and erosion occured north of the field. The groin compartments experienced both erosion and accretion. As seen in Figure 4-2, the northern compartments accreted because the sediment transport filled the compartments with sand causing the large setbacks to disappear. Accretion also occurred south of the new Garfield Parkway groin. The shoreline straighted out in the middle three compartments but this resulted in erosion rather than accretion as with the northern compartments. Moody (1964) found that although the groins trapped sediment and thereby caused the barrier between MLW and -3 meters to build seaward, erosion continued offshore at depths of 6 to 7 meters below MLW.

It must be recognized that some of the changes in shoreline may be accounted for by the differences in seasons. Between May and July 1982 the shoreline along Bethany Beach accreted an average of three meters. The shoreline in the middle compartments eroded about three meters while north of Ocean View Parkway and south of Wellington Parkway the shoreline accreted. These changes are similar to those identified in the aerial photographs from May 1938 and July 1954.

Between 1954 and 1961 the State placed artificial beach fill at Bethany Beach. The March 1962 storm eroded this beach fill, so Operation FIVE-HIGH repaired the dunes and replaced the beach fill. Still, the damaged caused by the 1962 storm accounted for most of the erosion experienced from 1954 to 1964 (U.S. Army Corps of Engineers, 1971). Between July 1954 and May 1968 the shoreline experienced erosion north and south of the groin field and nearly universal accretion in the groin field (see Figure 4-3). The largest rates of change were accretion in the middle compartments and erosion south of the field. Many of the northern groins appear to be overtopped at HWL in the May 1968 photograph. While some of the changes may be accounted for by the change in seasons, between July 1982 and May 1983 the shoreline experienced universal erosion of which the highest rates were south of the field.

Between May 1968 and May 1973 there was almost universal accretion (see Figure 4-4). Only the area south of the groin field experienced erosion. However, because of the extremely small scale of the 1973 photographs, details were difficult to identify. Comparison between an enlargement photograph taken in 1968 and the DNREC photograph taken in 1977 also reveals universal accretion of the beach during this period.

Figure 4-5 represents the net change in beach planform between May 1938 and May 1973. The shoreline straightened out be filling in the groin compartments resulting in slow accretion throughout most of the study area. The shoreline changes from 1938 to 1973 are summarized in Table 4-2. Because of the small scale of the 1973 photographs, the change between 1968 and 1977 was determined so the error resulting from the small scale would be eliminated. The results between 1968 and 1973 and between 1968 and 1977 compare reasonably well. The major disagreement is south of the groin field. The 1973 photograph indicates erosion but the 1977 photograph indicates accretion.

The naked eye generally cannot identify distances less than 0.2 mm, so this can be used as a strict limit on the error from the measurement process. For values less than this strict error limit no statement about the beach change can be made. Values within the generous error range (0.5 mm error limit) are in parentheses.

PERIOD	1938 to 1954		1954 to 1968		1968 to 1973		1968 to 1977		1938 to 1973		1938 to 1977	
LOCATION	Total Change	Annual Change	Total Change	Annual Change	Total Change	Annual Change	Total Change	Annual Change	Total Change	Annual Change	Total Change	Annual Change
North of Groin Field	-11.3	-0.7	(-0.8)	(-0.1)	+16.5	+3.3	+18.2	+2.0	(+4.4)	(+0.1)	+6.1	+0.2
Fifth Street to Ocean View Parkway	(+7.3)	(+0.5)	(+2.0)	(+0.1)	+24.0	+4.8	+17.3	+1.9	+33.3	+1.0	+32.0	+0.8
Ocean View Parkway to Third Street	(+2.0)	(+0.1)	(+7.8)	(+0.6)	+14.6	+2.9	+15.3	+1.7	+24.3	+0.7	+23.8	+0.6
Third Street to First Street	-13.9	-0.9	+12.9	+0.9	+16.5	+3.3	+6.1	+0.7	+15.5	+0.4	+12.3	+0.3
First Street to Campbell Place	-21.1	-1.3	+16.1	+1.2	+16.1	+3.2	+10.9	+1.2	(+11.2)	(+0.3)	+10.2	+0.3
Campbell Place to Garfield Parkway	-9.4	-0.6	No Change		(+10.5)	(+2.1)	+21.7	+2.4	No Change		+15.9	+0.4
Garfield Parkway to Hollywood Street	+13.2	+0.8	(-2.4)	(-0.2)	(+7.2)	(+1.4)	+5.7	+0.6	+18.0	+0.5	+19.2	+0.5
Hollywood Street to Wellington Parkway	(-2.5)	(-0.2)	No Change		No Change		-15.3	-1.7	No Change		+14.1	+0.4
Wellington Parkway to Maplewood Street	+8.8	+0.5	-13.0	-0.9	(+4.9)	(+1.0)	+12.3	+1.4	No Change		+7.0	+0.2
South of Groin Field	(+6.9)	(+0.4)	-14.6	-1.0	(-10.9)	(+2.2)	+16.2	+1.8	-18.6	-0.5	+8.9	+0.2

Table 4-2: Historical shoreline changes at Bethany Beach from 1938 to 1973. Distance in meters. Negative value indicates erosion, positive value indicates accretion. Values in parentheses are within the generous error range.

Before 1968 the rates of change were gradual, in most cases less than a meter per year. Between 1968 and 1973 the rates increased to between one and five meters per year.

4.3.2 Discussion

McDonald (1981) discovered nearly universal erosion in her aerial photogrammetric study of beach changes between 1938 and 1973. Two exceptions to this were between 1938 and 1954 in north Bethany and mid-beach between 1960 and 1968. Both were areas found to accrete in this study. The differences between these studies are the result of a number of errors both with the photographic and measurement techniques. The photographs are subject to four kinds of scale errors. Differences in altitude of the photographing aircraft result in differences in scale. This was a slight problem between the 1954 and 1968 photographs and the 1938 photographs. Although all the photographs were supposed to be 1:20,000 the scales were slightly different. Obviously this was a large problem between the Department of Agriculture photographs and the NASA photographs. Since analysis of the changes between 1968 and 1977 through use of larger scaled photographs supports the results found using the small scale NASA photographs, the significance of this error is reduced.

Another source of error is camera tilt. This creates error in scale in the photographs. This problem becomes increasingly evident with the enlargement of the photographs. Thirdly, the photographs exhibit radial distortion around the edges, but this can easily be avoided by only using the center of each photograph for analysis. The fourth source of error, relief distortion, was negligible due to the low relief of the area.

Most of the measurement error is a result of the scale limitations and the distortion from enlarging the photographs. The smallest distance measurable for a 1:20,000 scale photograph is 4-10 meters (Tanner, 1978). For a 1:50,000 scale photograph this distance increases to 10-25 meters. Even the width of the pen used for tracing the HWL (0.3 mm) is equal to a field distance of 6.0 meters on the Department of Agriculture photographs and 15.2 meters on the NASA photographs. The smallest measurable change per year is obtained by dividing the smallest distance measurable by the number of years of the study. For measurements smaller than this there is no detectable change and no statement about erosion or accretion is valid. Because two photographs are necessary to determine change, two different sources of error are introduced. The two limits must be added to obtain the total error. When the base maps were enlarged these errors were reduced but not eliminated. The amount of distortion resulting from enlarging the photographs was small but not negligible. This error was lessened by measuring the distance between known structures and comparing them on the enlarged maps. In this study the distance between groins was used as a basis.

Although aerial photogrammetry has numerous sources of potential errors it is a valid method for identifying trends in shoreline changes. Even with generous error limits, the aerial photogrammetric study of Bethany Beach indicates that the historical trend of shoreline change is slow accretion.

CHAPTER 5

OBSERVED SEASONAL CHANGES

5.1 BEACH PROFILE DATA

Thirteen nearshore profiles, both north and south of Bethany Beach as well as within the town proper were surveyed periodically from May 1982 to May 1983 (see Table 5-1) by the DNREC. The bathymetric surveys constitute the raw data from which the short-term changes in beach sand volume were examined by the empirical orthogonal eigenfunction method to obtain the various beach modes and fluctuations that occurred throughout the year. While a longer survey period would more accurately identify the typical variances in the beach planform, this survey can adequately identify seasonal fluctuations.

The survey locations stretches from 110 meters south of Bethany proper to about 152 meters north of the corporate limits (see Figure 5-1). From a baseline on Bethany Beach, the 13 profile lines were established, separated by 152.4 meters and extending offshore to the

First Survey. . . .	April 30 - May 4
Second Survey . . .	June 14 - June 15
Third Survey. . . .	July 29 - August 2
Fourth Survey . . .	September 15 - September 16
Fifth Survey. . . .	October 18 - October 19
Storm Survey. . . .	October 28
Sixth Survey. . . .	November 30 - December 7
Seventh Survey . . .	January 14
Eighth Survey . . .	March 3
Ninth Survey. . . .	March 28 - March 29
Tenth Survey . . .	May 4

Table 5-1: Survey schedule for Bethany Beach profiles.

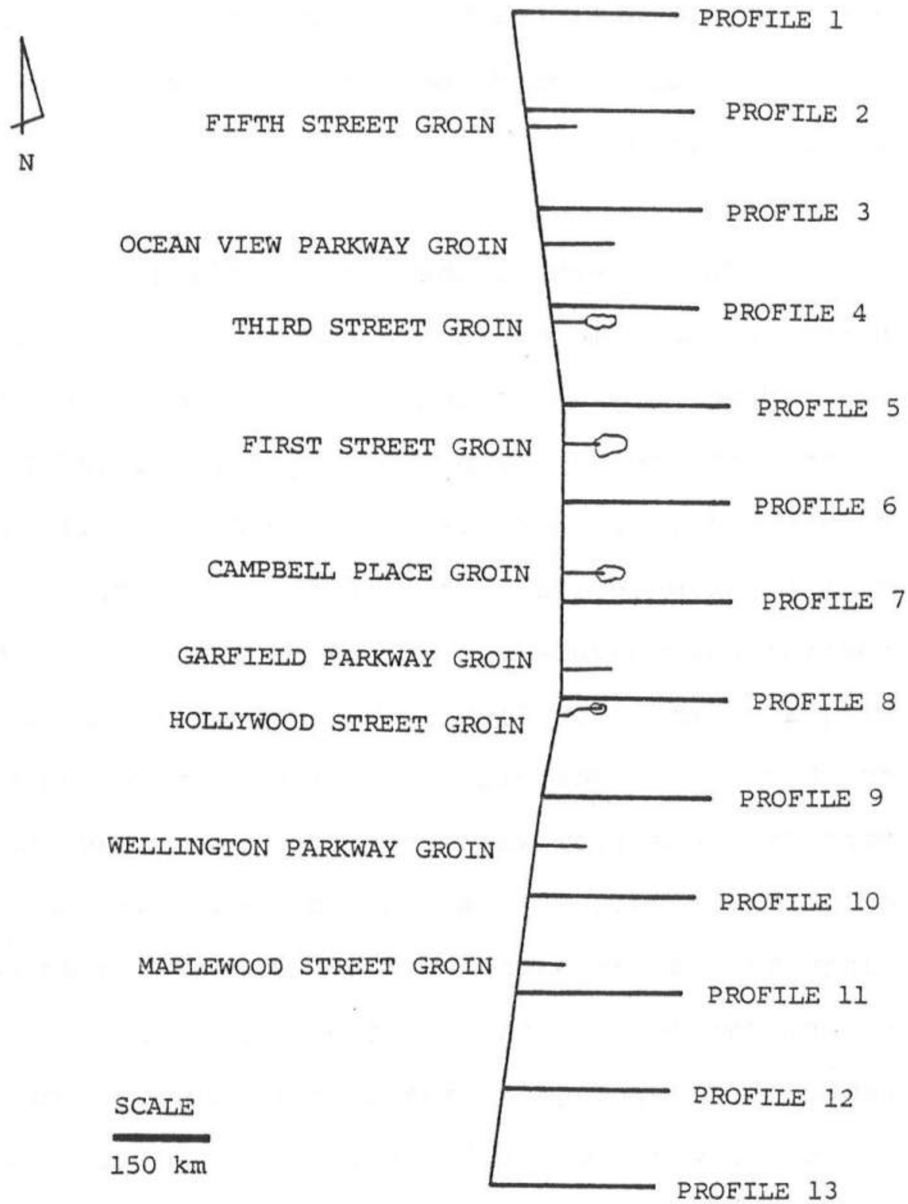


Figure 5-1: Location of groins and profiles at Bethany Beach.

-9-meter contour. Each profile station was marked with a hub and a large board, both of which were painted highly visible orange.

The survey of the beach profile was done in two parts on the same or adjacent days. In the first part the exposed beach was measured at low tide out to wading depth using standard surveying techniques, a theodolite, and a surveyor's rod. According to the DNREC (Williams, 1983), elevations were measured to within 3.0 cm. The offshore portion was measured at high tide to elevations of 6.0 cm with a Raytheon DE-719B fathometer on a boat seaward of the breakers. Positioning of the boat during the offshore part of the survey was determined by a range and horizontal angle system. As the boat advanced along the range toward the shore, the horizontal angles were determined between the range and theodolite on an adjacent range. Survey angles, measured at the time of each depth sounding, were correlated with the time marks on the fathometer record. The distance along the range lines was calculated and then plotted with the appropriate sounding, which had been corrected for tidal and wave effects. During high winds and heavy seas a gap existed between the two surveys. The width of this gap depended on the climate and the tidal range.

The year-long survey of beach profiles at Bethany Beach was designed to examine the short-term changes in beach sand volume. The major change identified by the repeated surveys was the transition from the "winter" to the "summer" profile and back again. The summer (or swell) profile is characterized by a wide berm, a relatively steep foreshore, and a smooth offshore profile, with no longshore bars. In contrast, the winter (or storm) profile has almost no berm. The sand moves offshore to form one or a series of sand bars paralleling the shoreline (see Figure 5-2). The winter profile is developed by large storm waves that erode the berm and deposit the material offshore into sand bars. The gentle swell waves transport the sand onshore through a ridge and runnel system, reshaping the berm into the summer profile. Theoretically, the sediment shifts seasonally from berm to bar so the volume of sand involved remains relatively constant over the profile.

The profiles were extended offshore to a depth of 9.0 meters which was thought to be the depth of closure. The depth of closure is the limiting depth at which no bottom changes occur during the period of study. Hands (1980) defines a "critical depth" at which bottom changes generally do not exceed more than 0.3 meters. He

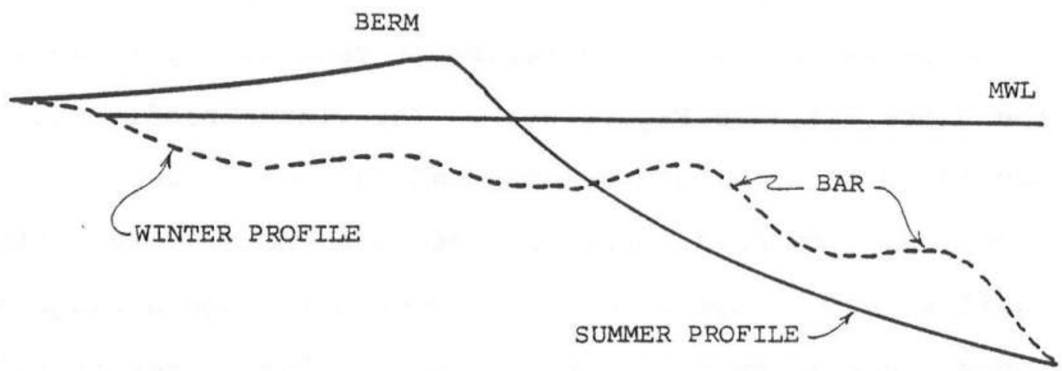


Figure 5-2: The winter profile with alongshore bars and the summer profile with a distinct berm.

states that placement of a bottom structure beyond the critical depth may be sufficient to avoid burial by the normal processes of sedimentation. However, when planning a sediment budget it is necessary to extend the profiles to the absolute depth of closure.

Figure 5-3 represents the shape of the beach at the time of the first survey. The beach profile configuration is fairly uniform over the survey area. Because of the large gap between the dry land and the bathymetric surveys, the survey data does not reveal information concerning the existence of longshore bars.

Between early May and June 15 the volume of material eroded nearly equalled the volume of material accreted. In general, there was a reversal in the sedimentation patterns between the sixth and seventh profiles: the northern section eroded and the southern section accreted. During this period the sediment transport was to the north, as evidenced by the deposition of sand on the south side of the groins. Sand transported north was trapped by the southern groins, consequently the southern profiles accreted. Since the northern compartments were not receiving sediment from the south, the northern profiles eroded. It is probable that on the

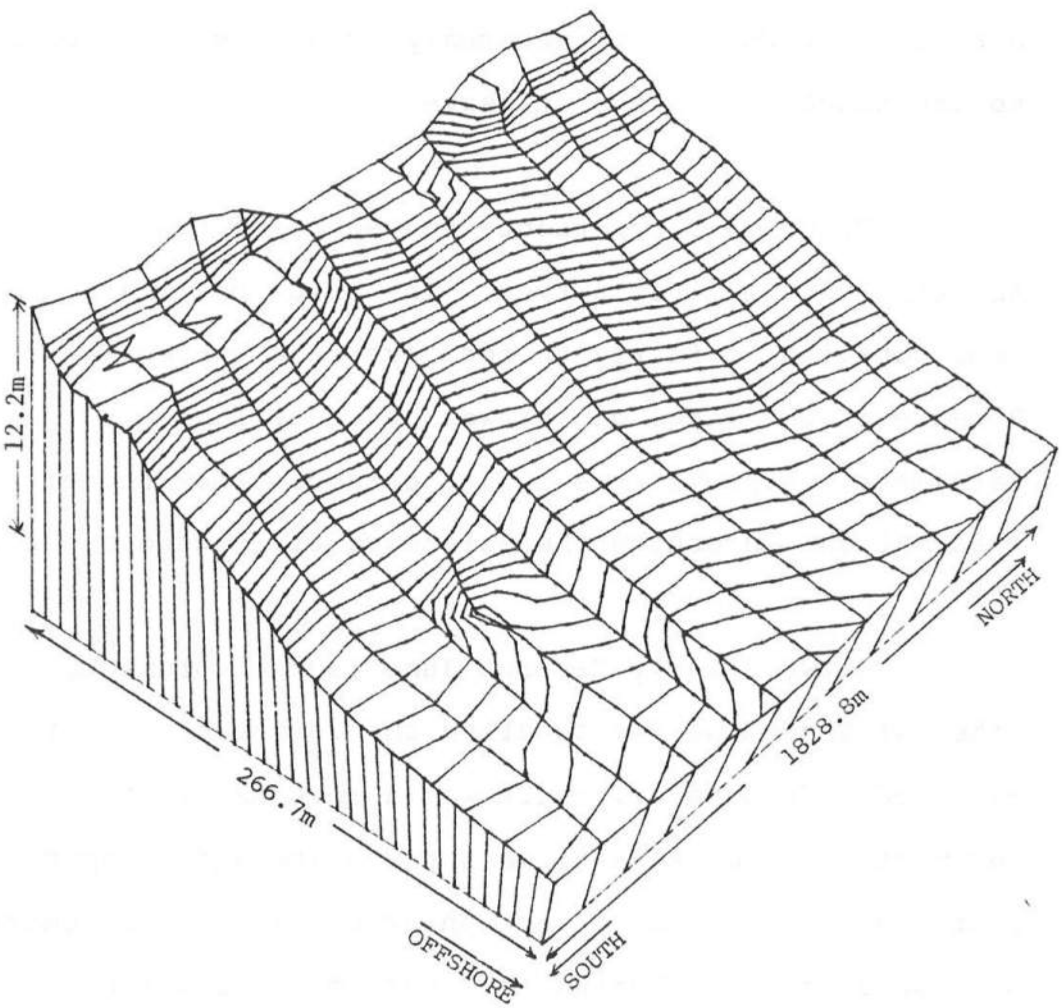


Figure 5-3: Three-dimensional representation of Bethany Beach at the time of the first survey, 4 May 1982. (Exaggerated scale)

southern profiles the material between -2.9 meters to +1.3 meters was transported onshore, because the volume of material eroded from this region equaled the volume of material accreted above +1.3 meters. Seaward of the 3-meter contour, the southern profiles accreted; thus, the material had to be transported from the south or from further offshore.

5.2 WINTER TO SUMMER PROFILE CONFIGURATION CHANGE

The survey data reveals the volume of sand did not remain constant at Bethany. Figure 5-4 illustrates the variations in beach sand volume during the study period. Between May 4 and September 15 the volume of sand along the profiles increased by 9.7×10^4 cubic meters. Although the beach remained in the summer profile configuration, the volume of sand decreased between September 15 and October 18 which was the last survey with the summer profile. 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 5-5). The majority of the survey stations experienced a net accretion of sediment (see Figure 5-6). (The shoreline in Figures 5-5 and 5-6 has been artificially straightened. The shortest distance between

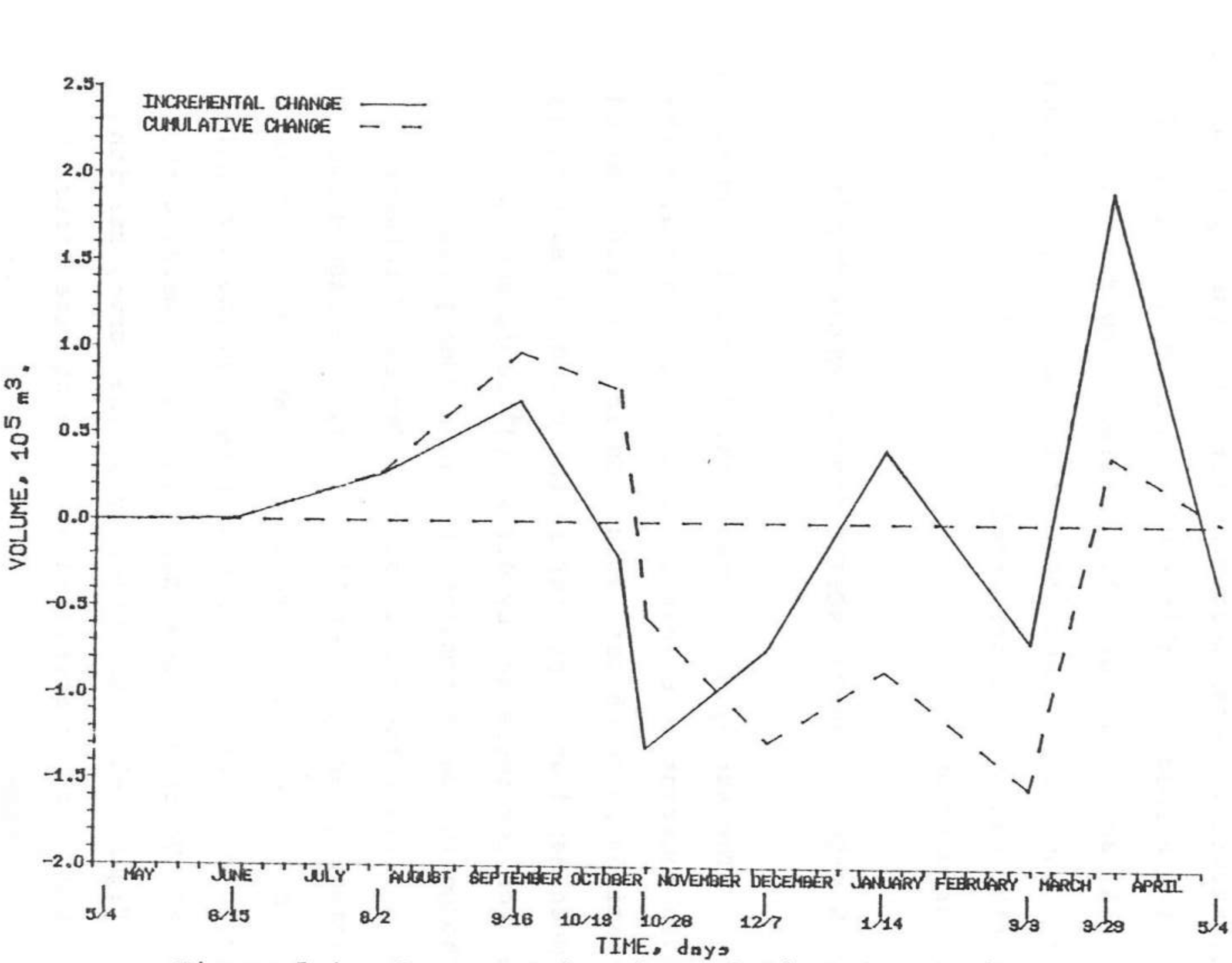


Figure 5-4: Incremental and cumulative changes in volume of beach sand over the survey area.

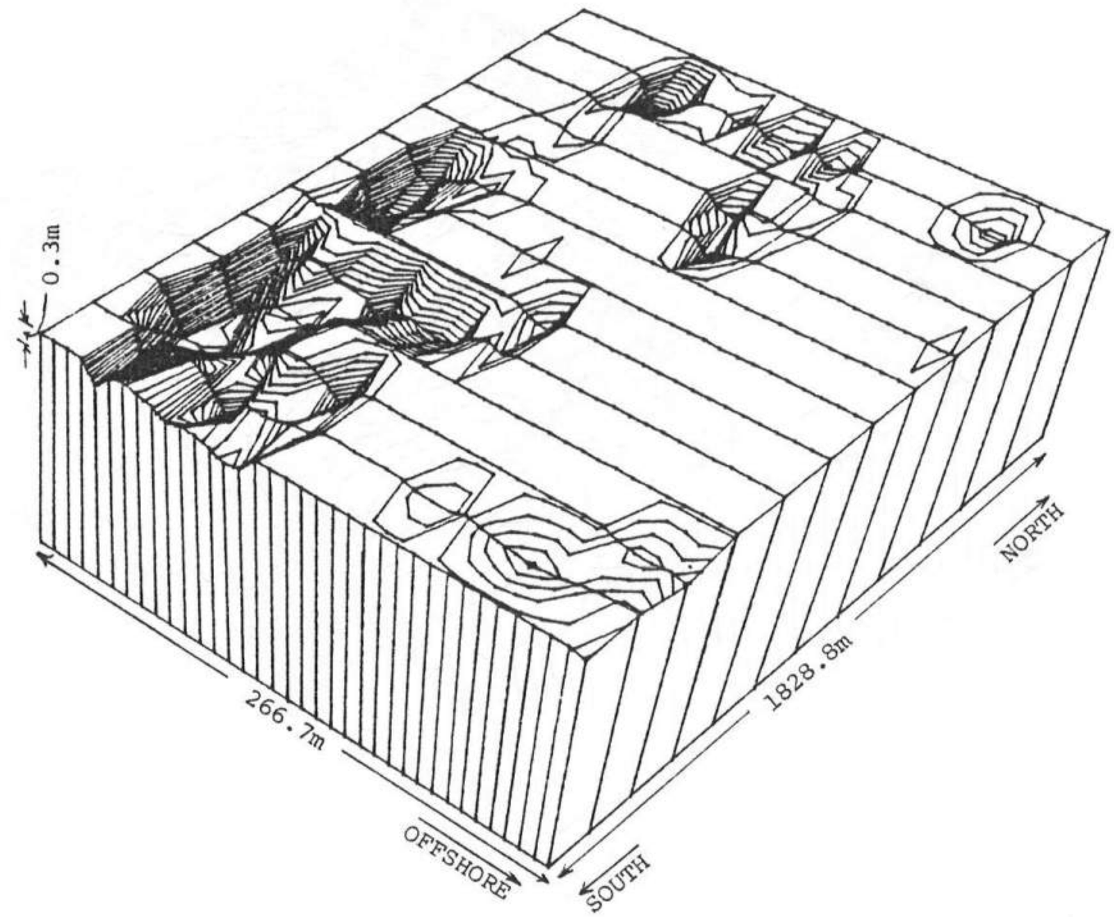


Figure 5-5: Location of the erosion along the profiles at Bethany Beach between May 4 and October 18, 1982. (Straightened waterline, exaggerated scale)

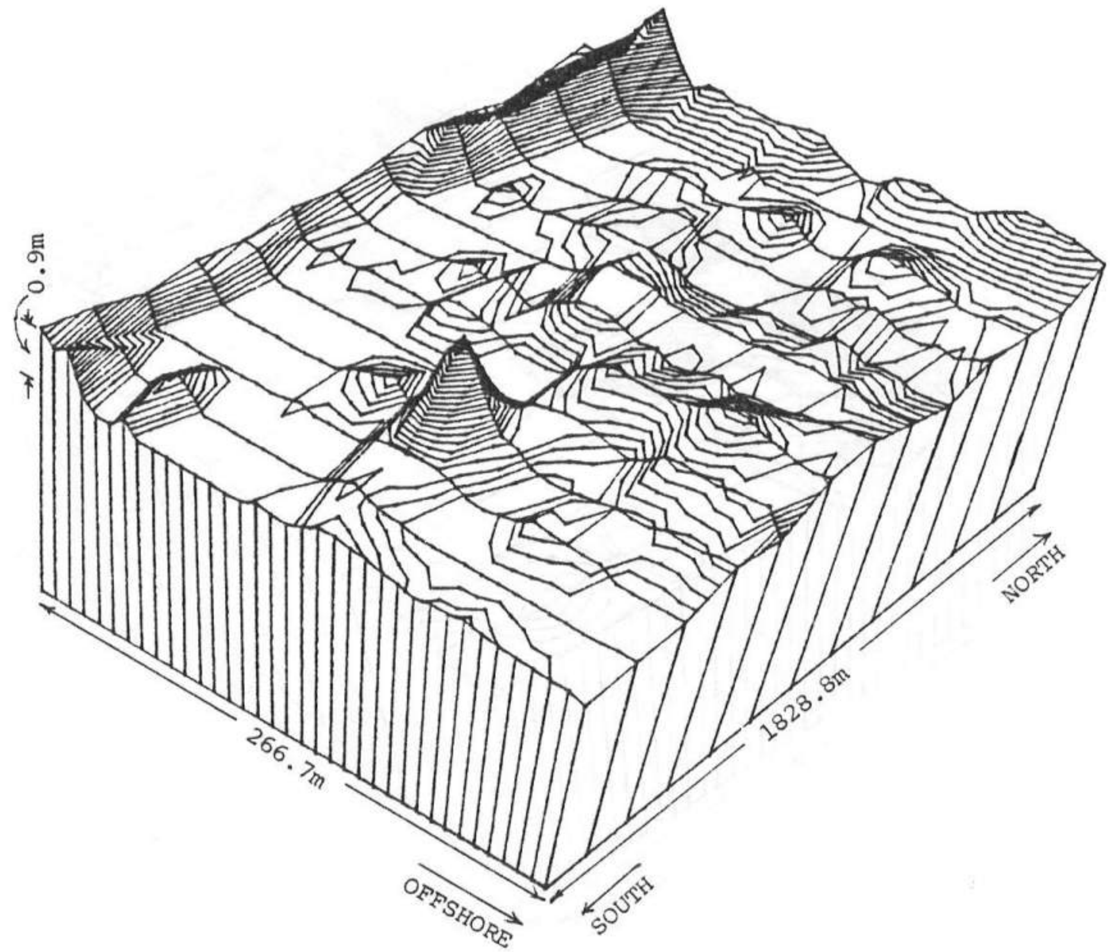


Figure 5-6: Location of accretion at Bethany Beach
between May 4 and October 18, 1982.
(Straightened waterline, exaggerated scale)

the landward end of a profile and the waterline at the time of the first survey was used as a basis. All of the other profiles were shortened from the landward end to match this distance. This was done so onshore-offshore changes would not be masked by longshore variations due to the convexity of the shoreline at Bethany.) In fact, the northernmost profile experienced deposition along the entire length of the profile, accreting 33.5 cm at a depth of 7.9 meters. Even more significant, profile seven accreted 54.9 cm at -9.0 meters.

Between June 15 and August 2 the volume of sediment over the survey area increased. Clearly, there was not a simple transport of sand from the bar to the berm. Whereas the bar region did erode, the profiles experienced significant deposition further offshore. Once again there was a shift between profiles six and seven. From profile six north, the waterline retreated about 7.5 meters landward, while south of profile seven the waterline advanced seaward about 6.7 meters.

The study area experienced almost universal accretion between August 2 and September 15. The waterline moved significantly seaward; moreover, one profile accreted 1.0 meter at a depth of 8.0 meters. By

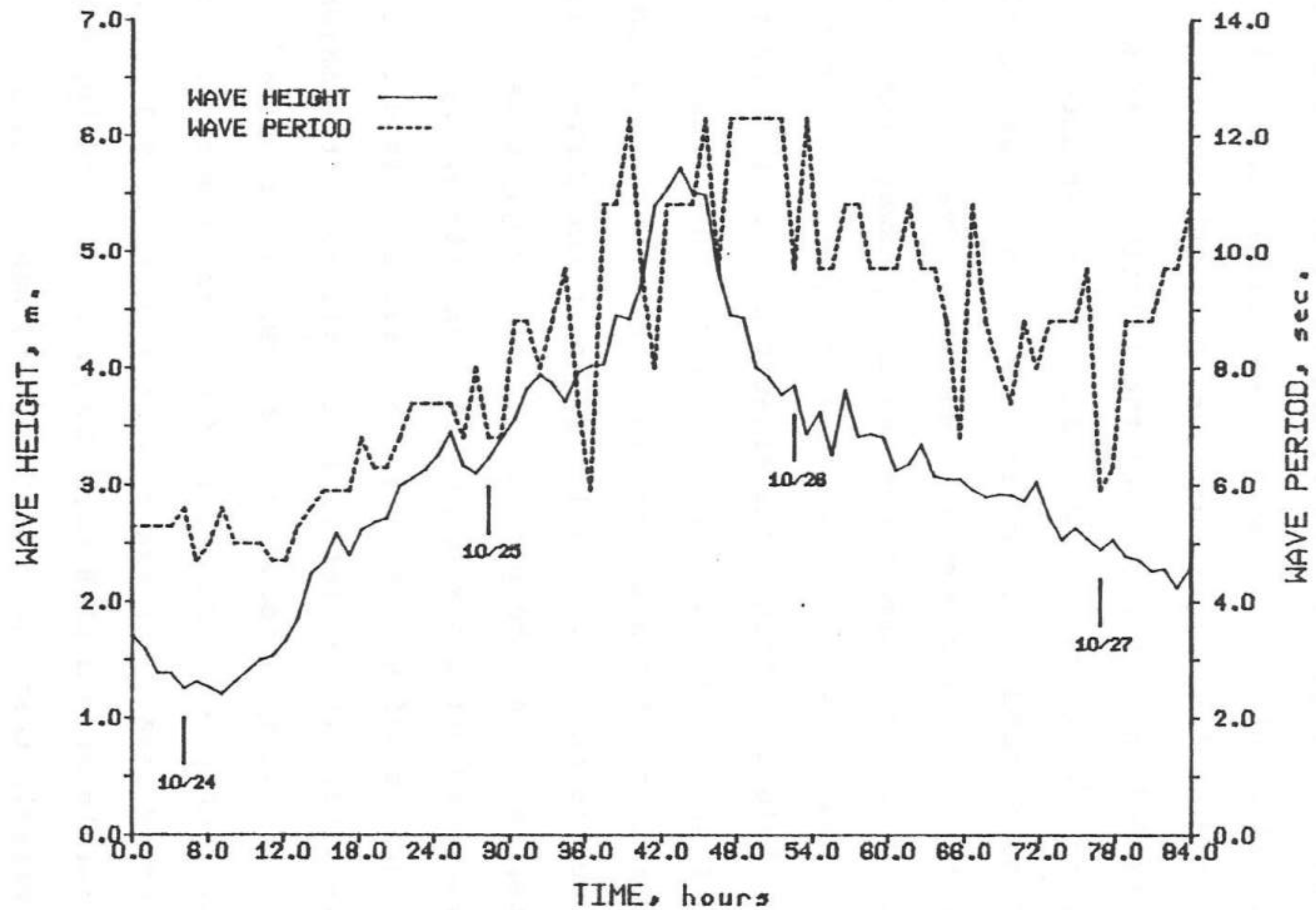
September the beach had developed a distinct berm and the offshore profiles had become much steeper.

In mid-October the beach was beginning the transition from the summer to the winter profile configuration. Erosion was prevalent, especially at depths greater than 4.5 meters. Between profiles 5 and 11, the waterline retreated about 4.5 meters. North and south of this region the waterline advanced seaward.

5.3 IMPACT OF OCTOBER STORM ON BETHANY BEACH

An intense low pressure system moved northeastward from the Virginia Capes to southern New England on 24-26 October 1982. The storm, with steady winds of 18-22 m/s and gusts up to 37 m/s, has been called 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 and tides were 0.5 meters above normal. The largest significant wave height for the storm was recorded at the afternoon high tide on October 25. Figure 5-7 presents the wave height and wave period data off Ocean City, Maryland during the storm.

The profiles were surveyed one week before and



STORM DATA, OCTOBER 24-27,1983

Figure 5-7: Wave height and wave period data off Ocean City, Maryland during October storm. Approximate water depth is 20 meters. (NOAA, 1982).

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 5-4). The gross sediment transport was over 24 x 10^4 cubic meters. Figures 5-8 and 5-9 represent 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. Over half of the total volume of sediment between the landward limit of the survey and the NGVD was eroded away during the storm. Figure 5-10 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 large gap in the survey data exists. All the data points within this gap were interpolated between known values; therefore, the existence of offshore bars in the surf zone is uncertain. However, definite accretion is identified on the majority of the profiles to about -4.5 meters. The profiles eroded significantly from the bar region to the seaward limit of the survey area. For example, at a depth of 8.3 meters, one profile eroded 51.8 cm. Examination of the profile data reveals that the profiles would need to be extended seaward an additional 127 meters to reach the depth of closure. The volume of sediment that would be accounted

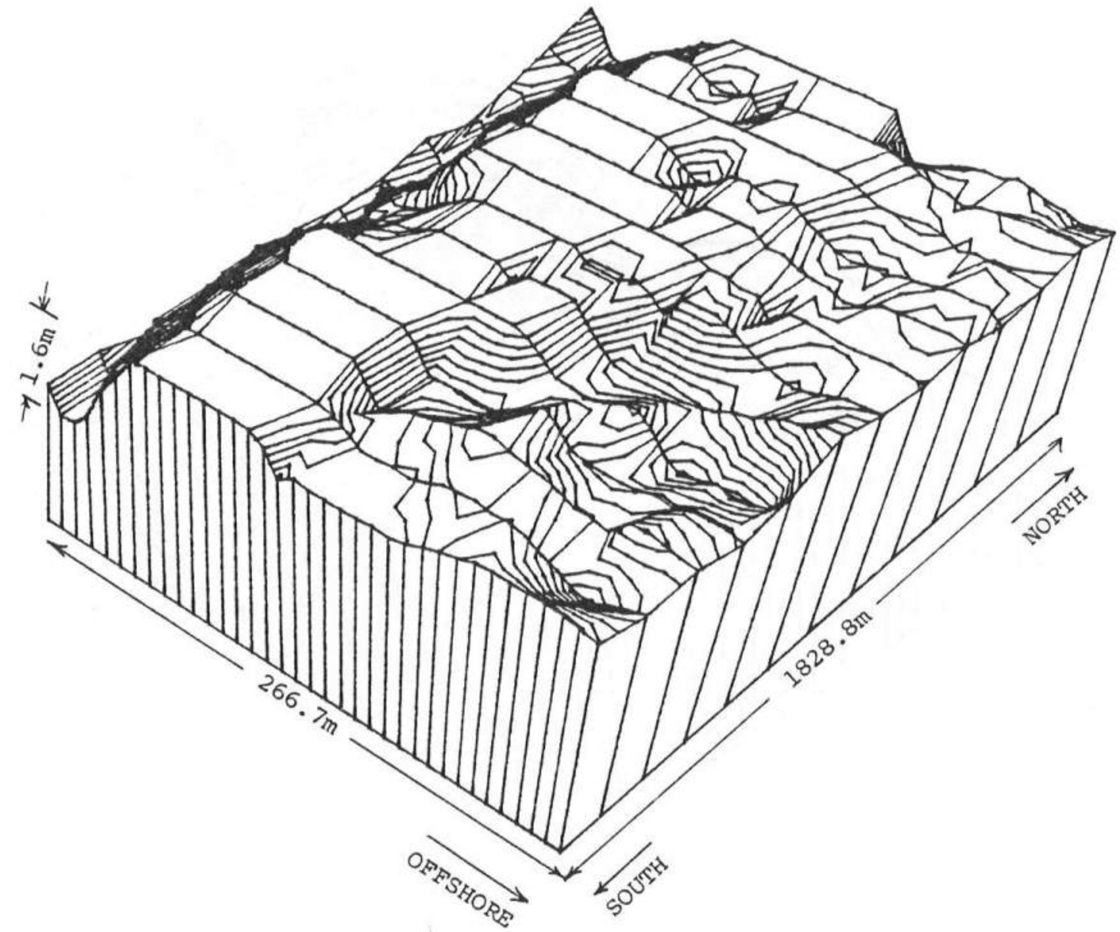


Figure 5-8: Location of erosion at Bethany Beach
due to October storm.
(Straightened waterline, exaggerated scale)

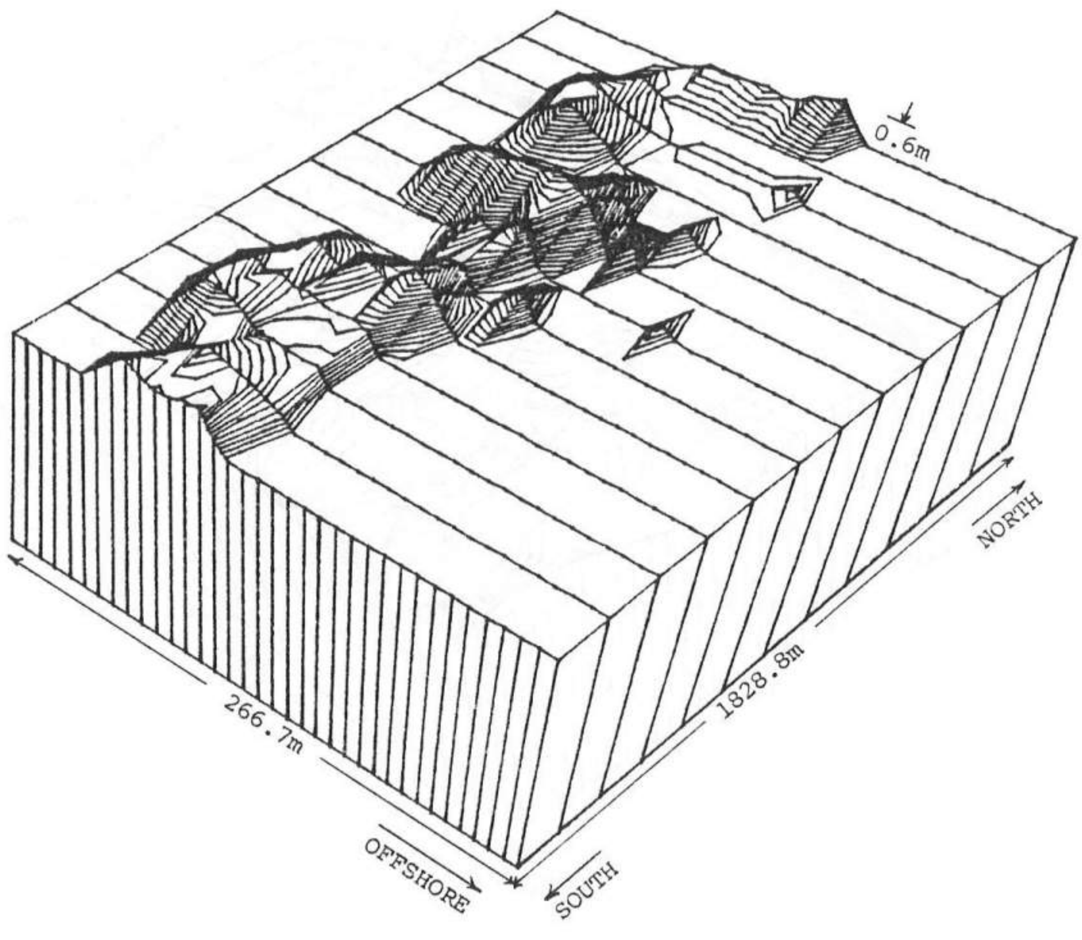


Figure 5-9: Location of accretion at Bethany Beach due to October storm. (Straightened waterline, exaggerated scale)

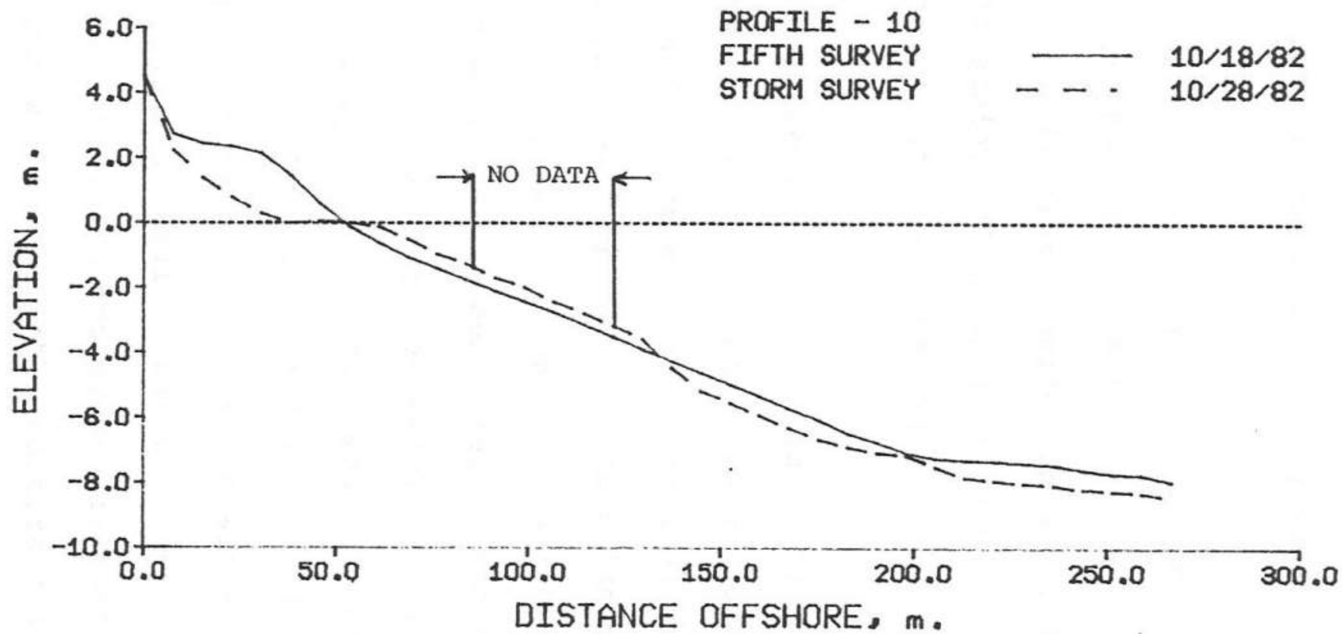


Figure 5-10: Profile ten before and after October storm.

for if the profiles had been extended out to the estimated depth of closure is about one fourth of the volume of sand lost from the survey area during the storm.

The storm waves caused the waterline to retreat landward an average of 14.8 meters along the survey reach. Interestingly, the shoreline retreated the most at profile six (nearly 28 meters) although the volume of sediment along this profile increased more than any other profile.

The October storm quickly transformed the beach into the winter profile configuration. By early December, the beach had recovered from the storm, but remained in the winter configuration. The area between the landward limit of the survey and the NGVD, which eroded universally during the storm, experienced universal aggradation during the recovery. The foreshore, however, did not return to its pre-storm profile. Although it experienced vertical and horizontal accretion above the NGVD, the foreshore and berm did not achieve the pre-storm sand volume and its location remained landward of its pre-storm location. Despite the recovery above the NGVD, the survey area experienced net erosion. In fact, below the NGVD the profiles underwent nearly universal erosion.

5.4 CHANGES IN BEACH CONFIGURATION DURING WINTER MONTHS

Bethany Beach suffered a severe winter, especially in February 1983 when several storms, separated by short intervals, hit Bethany. The survey data reveals that the beach underwent periods of erosion and deposition until early May when the last survey was made (see Figure 5-4).

Although the volume of sand in the study area increased between December and the end of January, it was still less than the volume immediately after the storm. Since the direction of sediment transport was toward the south during the winter, 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. Most of the accretion along the beach occurred about six meters below the NGVD. Seaward of this region the pattern of deposition differed between the northern and southern sections of the study area. The northern section accreted from just below the NGVD to the seaward limit of the profile. One of the northern profiles accreted 60 cm at a depth of 8.7 meters. In contrast, the southern profiles developed an offshore sand bar which was located increasingly close to shore towards the south. During this period the waterline advanced seaward from the second to the seventh profiles but retreated landward south of profile nine.

As mentioned above, several storms struck Bethany Beach during February. The berm and foreshore were eroded and the sediment moved offshore to form longshore bars. Erosion was prevalent offshore of the bars. During this period, the sediment volume reached its lowest point for the year. Since early May 1982, 15.4 x 10^4 cubic meters of sediment had been transported out of the survey area. By early March the winter profile was fully developed.

At the end of March the volume of beach sand had risen above the August 1982 level. In one month the sand level increased by 19.3 x 10^4 cubic meters. Whereas the waterline retreated landward universally, the two northernmost and the two southernmost profiles retreated the most, an average of 18.2 meters. Moreover, the waterline was landward of the October storm waterline on half of the profiles.

It appears that the volume of 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. The foreshore advanced seaward over the study area creating a wider berm, which on one profile, accreted nearly two meters vertically. Below the NGVD, the beach eroded.

A full year passed between the first and last survey, but the beach profile configuration was not the same. Two (or more) years of profile data would better represent a typical full year cycle. The volume of sand was 1150 cubic meters greater in May 1983 than May 1982; however, most of the difference was offshore. Because of the severe winter and late spring, the beach in May 1983 was probably seasonally behind the May 1982 beach. The foreshore and berm had not yet developed. The May 1982 profile had been reshaped more into the summer profile. With the exception of the two northernmost profiles, the 1983 waterline was landward of the 1982 waterline. It is probable that another survey taken later in May would be further along seasonally so its shape would more closely resemble the May 1982 profile. It must be noted that the beach had more sand than in May 1982, but less above the NGVD. Figures 5-11 and 5-12 show the volumetric sand changes over the survey period above and below the NGVD. These figures confirm the conjecture that the beach in May 1983 was behind the beach in May 1982 seasonally. The

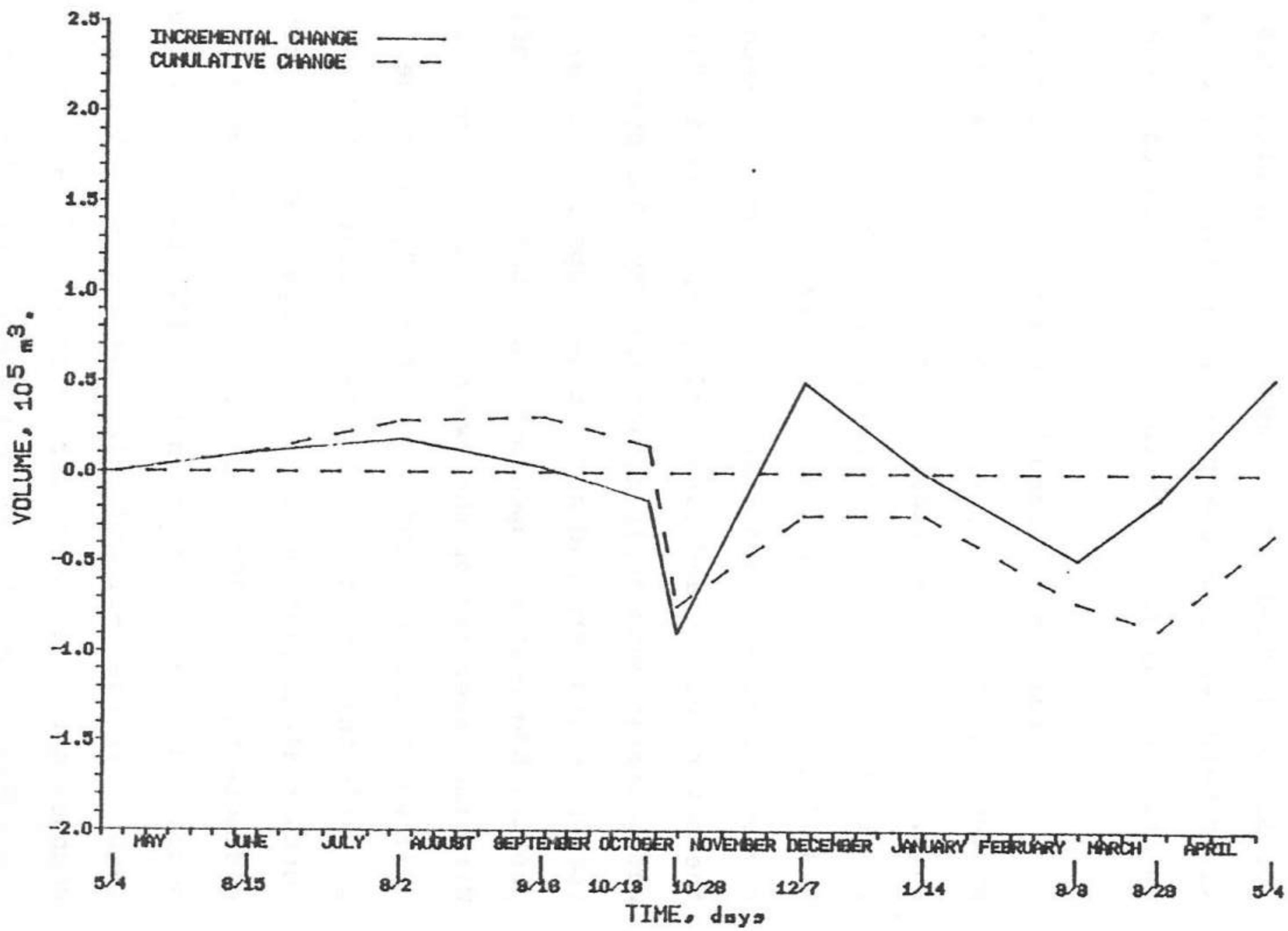


Figure 5-11: The incremental and cumulative changes in volume of beach sand above the NGVD.

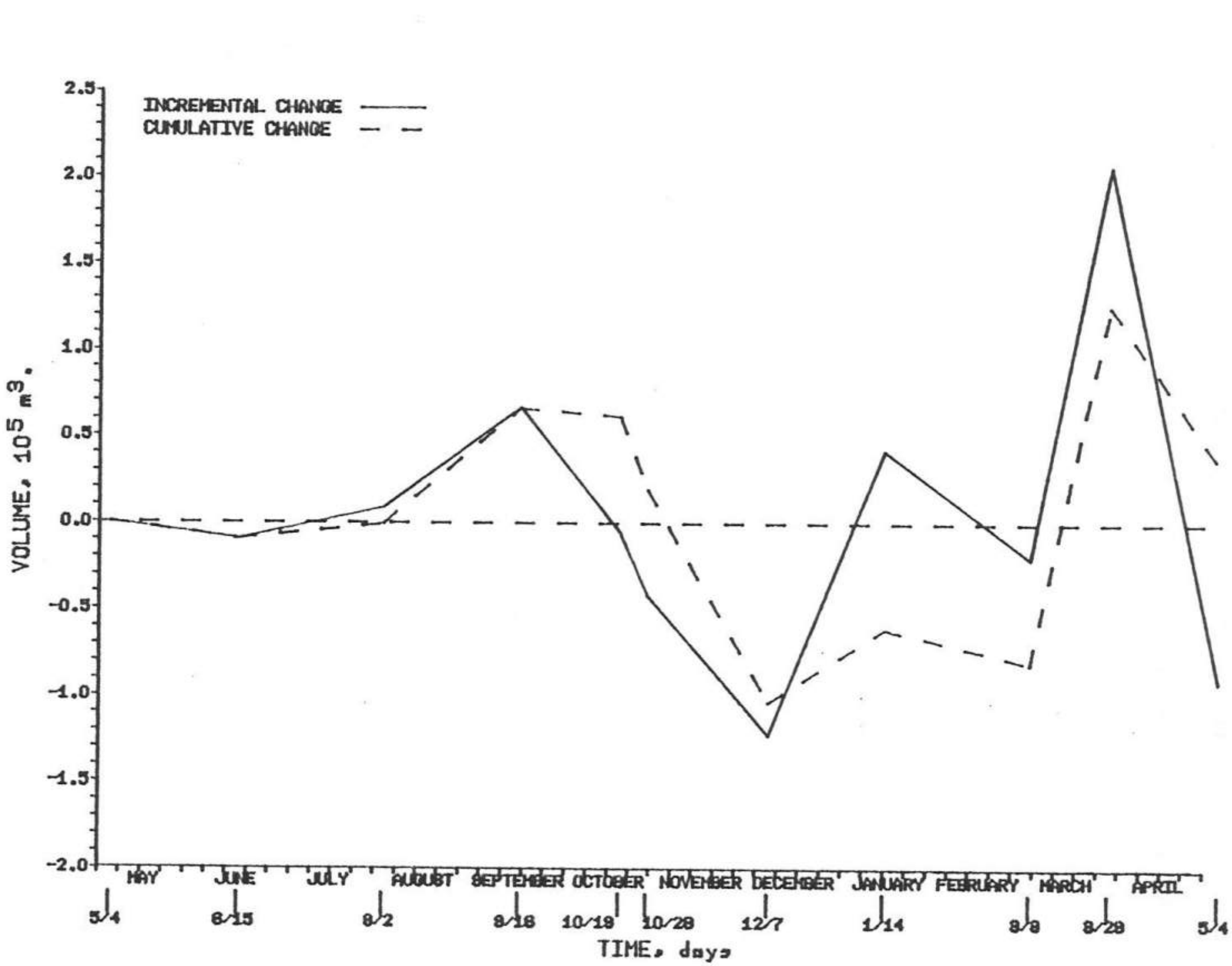


Figure 5-12: The incremental and cumulative changes in volume of beach sand below the NGVD.

results from the aerial photogrammetry are supported by the profile data, indicating that Bethany Beach is undergoing slow accretion.

CHAPTER 6

EMPIRICAL ORTHOGONAL EIGENFUNCTION METHOD

6.1 BACKGROUND

Changes in beach profiles are caused by onshore-offshore sediment transport and by the longshore transport gradient. These coastal processes are often investigated through repeated surveys of the beach topography. In the future, predictions of beach change will be possible using profile data in conjunction with wind, wave, and other data. Presently, however, our knowledge of beach processes is limited, so statistical analysis is necessary to describe beach change.

Previous studies of beach changes and other phenomenon have been conducted using the empirical orthogonal function (EOF) method. In 1967, Stidd described annual precipitation patterns in Nevada through the use of eigenvectors. Winant (1975) used empirical eigenfunctions to describe seasonal beach changes, and Aubrey (1979) detected "pivot points" for seasonal onshore-offshore sediment movement through empirical eigenfunction analysis.

The empirical orthogonal function 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.

Orthogonal functions are needed to describe a composite process composed of several primary processes. Unless the functions used to represent the primary processes are orthogonal, changing the influence or proportion of one function to the composite function, will change the proportions of the other primary functions, and thereby incorrectly represent the influence of the other primary processes on the composite process. With orthogonal functions the correlation between any two functions is zero, so altering the influence of one primary process will not affect the influence of the other primary processes.

The process of fitting orthogonal functions to observed data is equivalent to simple correlation. Since the functions serve as the independent variables, the correlation between functions is zero. But if the simple correlation between an observed pattern and each of the functions is not substantial, then a relatively large number of functions will be necessary to adequately represent the data. However, a set of orthogonals can be derived from the data itself such that the orthogonals are the eigenvectors of the data (Stidd, 1967). Eigenvectors have the the advantage over orthogonal polynominals of resembling the important characteristics of the data so that a higher percentage of the variance in profile configuration can be represented by fewer eigenvectors than orthogonal polynominals, thereby reducing the number of functions necessary to represent a specified data set. The eigenfunctions associated with the eigenvectors are orthogonal, each representing a certain amount of the mean square value of the data. The eigenfunction associated with the largest eigenvalue represents the data best, in a least squares sense, while the second function describes the residual mean square data best. Consequently a large number of data variables is efficiently represented by a few empirical functions, describing most of the mean square value of the data (Aubrey, 1979).

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.

6.2 STATISTICAL METHOD

Beach profile data is used to generated sets of empirical eigenfunctions. Since the structure of the functions is defined by the actual profile data, it does not assume a priori a particular functional form as does a Fourier representation (Aubrey, 1979). The EOF method assumes beach profile data can be represented by a set of functions h_{ik} (i=1,I; k=1,K) where the elevation h is measured at the same I locations equidistant along the profile, for a total of K surveys. An attempt is made to find a function ϕ_{ni} which statistically best approximates the functions. Since beach profile data consists of discrete point values the correlation is written as the scalar product of the two K-dimensional vectors

$$r_{nk} = \frac{\overline{h_{ik}} \cdot \overline{\phi_{ni}}}{|\overline{\phi_{ni}}|} = \frac{\sum h_{ij}\phi_{ni}}{\left[\sum \phi_{ni}^2\right]^{1/2}} \tag{6.1}$$

Thus r_{nk} is a measurement of how successfully the function ϕ_{ni} describes the kth member of the functions, or in other words, how parallel the two vectors are. If $(r_{nk}/|\overline{h_{ik}}|)=1$, the vectors are parallel; if $(r_{nk}/|\overline{h_{ik}}|)=-1$, they are parallel, and opposite; and if $(r_{nk}/|\overline{h_{ik}}|)=0$, they are orthogonal.

The expectance of r_{nk}^2 is chosen as a measure of the resemblance of ϕ_{ni} to the profile functions

$$\lambda = \frac{1}{IK} \sum_{k=1}^{K} \frac{\left\{\sum_{i=1}^{I} h_{ik}\phi_{ni}\right\}^2}{\left\{\sum_{i=1}^{I} \phi_{ni}^2\right\}} \tag{6.2}$$

If $h_{ik} = c_{nk}g_{ni}$ where g_{ni} is a known function, then λ will be a maximum and equal to

$$\frac{1}{IK} \sum_{k=1}^{K} c_{nk}$$

if and only if $\phi_{ni} = \pm g_{ni}$. So the problem is formulated: given a set of evenly weighted functions, h_{ik}; find the function ϕ_{ni} which maximizes λ.

To determine ϕ_{ni}, let's assume we have a function ϕ_{ni}. An increment $\varepsilon\phi_{ni}$ to ϕ_{ni}, where ϕ_{ni} is an arbitrary but fixed function of i, would then change λ such that $\varepsilon=0(\varepsilon^{\lambda})$ with $\lambda>1$.

$$\lambda(\varepsilon) = \frac{1}{IK}\sum_{k=1}^{K}\frac{\left\{\sum_{i=1}^{I} h_{ik}(\phi_{ni}+\varepsilon\phi_{ni})\right\}^2}{\sum_{i=1}^{I}\phi_{ni}^2} \tag{6.3}$$

Differentiation of $\lambda(\varepsilon)$ with respect to ε yields

$$\left.\frac{d\lambda(\varepsilon)}{d(\varepsilon)}\right|_{\varepsilon=0} = \frac{1}{IK}\sum_{k=1}^{K}\sum_{j=1}^{I}\left\{\sum_{i=1}^{I}(h_{ik}\phi_{nk}h_{jk})-r_{nk}^{2}\phi_{nj}\right\}\frac{\phi_{nj}}{\sum_{i=1}^{I}\phi_{ni}^2} \tag{6.4}$$

Introducing the notation

$$a_{ij} = \frac{1}{IK}\sum_{k=1}^{K} h_{ik}h_{jk} \tag{6.5}$$

and noting

$$\lambda = \frac{1}{IK}\sum_{k=1}^{K} r_{nk}^2 \tag{6.6}$$

equation (6.4) can be rewritten

$$\left.\frac{d\lambda(\varepsilon)}{d(\varepsilon)}\right|_{\varepsilon=0} = 2\sum_{j=1}^{I}\left\{\sum_{i=1}^{I} a_{ij}\phi_{nj} - \lambda\phi_{nj}\right\}\frac{\phi_{nj}}{\sum_{i=1}^{I}\phi_{ni}^2} \tag{6.7}$$

If λ has an extremum for ϕ_{ni},

$$\sum_{i=1}^{I} a_{ij}\phi_{nj} = \lambda\phi_{ni} \tag{6.8}$$

Therefore the function ϕ_{ni} will be a solution to equation (6.8).

It may be shown the equation (6.8) has the following properties:

1) It has at least one solution and at the most an infinite but enumerable number of solutions.
2) All the eigenvalues λ are real and non-negative.
3) $\lambda=0$ is not an eigenvalue.
4) The order of multiple eigenvalues is limited.
5) The eigenvalues are real and orthogonal.

Suppose that the individual functions h_{ik} can be represented by

$$h_{ik} = \sum_{n=1}^{N} c_{nk}\phi_{ni} \tag{6.9}$$

where the expansion coefficients c_{nk} are random variables. It follows that

$$a_{ij} = \sum_{k=1}^{K} \frac{1}{IK} \sum_{n=1}^{N} c_{nk}\phi_{ni} \sum_{m=1}^{N} c_{mk}\phi_{mj} \tag{6.10}$$

which leads to

$$\frac{1}{IK} \sum_{k=1}^{K} c_{nk}c_{mk} = \frac{1}{IK} \sum_{k=1}^{K} c_{nk}^{2}\delta_{nm} = \lambda\delta_{nm} \tag{6.11}$$

by using the orthogonality property below

$$\sum_{i=1}^{I} \phi_{ni}\phi_{mi} = \delta_{nm} \tag{6.12}$$

in which δ_{nm} is the usual Kronecker delta. Only if equation (6.11) is statisfied, and thus the expansion coefficients are uncorrelated, is an expansion in the eigenfunctions possible (Busch and Petersen, 1971).

The coefficient c_{ik} is found by minimizing the error in the fit to h_{ik}

$$h_{ik} = \sum_{n=1}^{N} c_{nk}\phi_{ni} = \varepsilon_{ik} \tag{6.13}$$

where ε_{ik} is the error at each realization. The mean square error for each survey is minimized with respect to c_{nk} which results in

$$2 \sum_{i=1}^{I} (h_{ik} - \sum_{n=1}^{N} c_{nk}\phi_{ni})\phi_{mi} = 0$$

By using the Kronecker delta, the weights of the coefficient c_{nk} can be found

$$\sum_{i=1}^{I} h_{ik}\phi_{mi} = c_{mk} \tag{6.14}$$

Defining the total mean square variance of the data,

$$\sigma^2 = \frac{1}{IK} \sum_{k=1}^{K} \sum_{i=1}^{I} h_{ik}^2 = \frac{1}{IK} \sum_{k=1}^{K} \sum_{i=1}^{I} \left(\sum_{n=1}^{N} c_{nk}\phi_{ni}\right)\left(\sum_{n=1}^{N} c_{mk}\phi_{mi}\right)$$

$$= \frac{1}{IK} \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{m=1}^{N} c_{nk}c_{mk} \sum_{i=1}^{I} \phi_{ni}\phi_{mi} = \frac{1}{IK} \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{m=1}^{N} c_{nk}^2$$

a relationship between σ^2 and c_{nk} can be found

$$\sigma^2 = \frac{1}{IK} \sum_{k=1}^{K} \sum_{n=1}^{N} c_{nk}^2 \tag{6.15}$$

The contribution of c_{nk} to σ^2 is maximized so that the weights are as large as possible. However ϕ_{ni} must be constrained to make the solution unique. Therefore, the eigenfunctions are normalized such that

$$\sum_{i=1}^{I} \phi_{ni}^{2} = 1 \tag{6.16}$$

The maximum contribution to the variance is then

$$\max \left\{ \frac{1}{IK} \sum_{k=1}^{K} c_{nk}^{2} - \lambda \left[\sum_{i=1}^{I} \phi_{ni}^{2} - 1 \right] \right. \tag{6.17}$$

where λ is the Lagrange multiplier. The maximum is found by differentiating with respect to ϕ_{nj}

$$\frac{\partial}{\partial \phi_{nj}} \left[\frac{1}{IK} \sum_{k=1}^{K} \left(\sum_{i=1}^{I} h_{ik}\phi_{ni} \right) \left(\sum_{m=1}^{I} h_{mk}\phi_{nm} \right) - \lambda \left(\sum_{i=1}^{I} \phi_{ni}^{2} - 1 \right) \right] = 0$$

$$\sum_{k=1}^{K} \frac{1}{IK} \sum_{i=1}^{I} h_{ik}h_{jk}\phi_{ni} = \lambda \phi_{nj}$$

$$\sum_{i=1}^{I} \phi_{ni} \left(\frac{1}{IK} \sum_{k=1}^{K} h_{ik}h_{jk} \right) = \lambda \phi_{nj}$$

Since by definition the symmetric correlation matrix is

$$a_{ij} = \frac{1}{IK} \sum_{k=1}^{K} h_{ik}h_{jk} \tag{6.5}$$

there is now one equation for I unknowns,

$$\sum_{i=1}^{I} a_{ij}\phi_{ni} = \lambda \phi_{nj} \tag{6.18}$$

From matrix theory, it can be shown shown that there is a total of J eigenvalues and eigenfunctions.

This technique is similar to a Fourier Series analysis, in which the eigenvalues are analogous to the amplitude of a given Fourier term, but since the data is discrete, summation is used instead of integration to obtain the correlation matrix (Winant et. al., 1975).

Thus the proper orthogonal decomposition theorem has been proved: A random function h_{ik} which is mean-square continuous on a closed interval [A,B] has a decomposition

$$h_{ik} = \sum_{n=1}^{N} c_{nk}\phi_{ni} \qquad (6.19)$$

with

$$\frac{1}{IK} c_{nk}c_{mk} = \frac{1}{IK} \sum_{k=1}^{K} c_{nk}{}^{2}\delta_{nm}$$

$$= \lambda\delta_{nm}$$

if and only if λ are the eigenvalues and ϕ_{nj} are the orthonormal eigenfunctions belonging to the correlation function a_{ij}. The series will then converge uniformly in quadratic mean (Busch and Petersen, 1971).

6.3 EXAMPLE

A simple example will be illustrative. Profile data consists of K surveys of a beach profile with I points. The correlation matrix is calculated by

$$a_{ij} = \frac{1}{IK} \sum_{k=1}^{K} \sum_{i=1}^{I} h_{ik} h_{jk}^{T}$$

where T denotes the transpose of the matrix. The sum of the diagonal terms in a_{ij} is equal to the mean square of all the measurements. The eigenvalues are found by solving the determinant

$$\begin{vmatrix} \lambda - a_{11} & -a_{12} & -a_{13} \\ -a_{22} & \lambda - a_{22} & -a_{23} \\ -a_{31} & -a_{32} & \lambda - a_{33} \end{vmatrix} = 0 \quad .$$

associated with the simultaneous equations

$$(A - I\lambda)\phi = 0$$

in which I is the identity matrix. Note that the coefficient of λ^2 is the negative of the mean square of the data. The sum of the eigenvalues is equal to the trace of the matrix, or in this case, the mean squáre value of the data. The eigenfunctions are then determined from the eigenvalues and normalized. It is useful to calculate the coefficients c_{nk} to determine how well the data are represented by the series:

$$c_{nk} = \sum_{j=1}^{J} \phi_{nj}^{T} h_{jk}$$

The calculated elevations can be determined from

$$h_{jk} = \sum_{n=1}^{N} \phi_{nk} c_{nk}^{T}$$

and compared to the actual profile data.

Figure 6-1 illustrates the eigenfunction decomposition of the beach profiles.

6.4 STATISTICAL RESULTS

Empirical eigenfunction analysis has been performed in several different ways by the method described above on the 13 profiles at Bethany Beach. Eigenfunctions were calculated for the spatial variations along the beach at the time of each survey, for the temporal variations throughout the year-long survey for each of the profiles, and for the spatial variations along the beach for the change between two surveys. Eigenfunctions have also been computed for the results of the sediment analysis of samples acquired at the time of each survey.

The eigenfunctions were first computed for the 13 profiles at the time of each survey. This identified the variations along the beach at a particular time. As expected, the eigenfunction associated with the largest

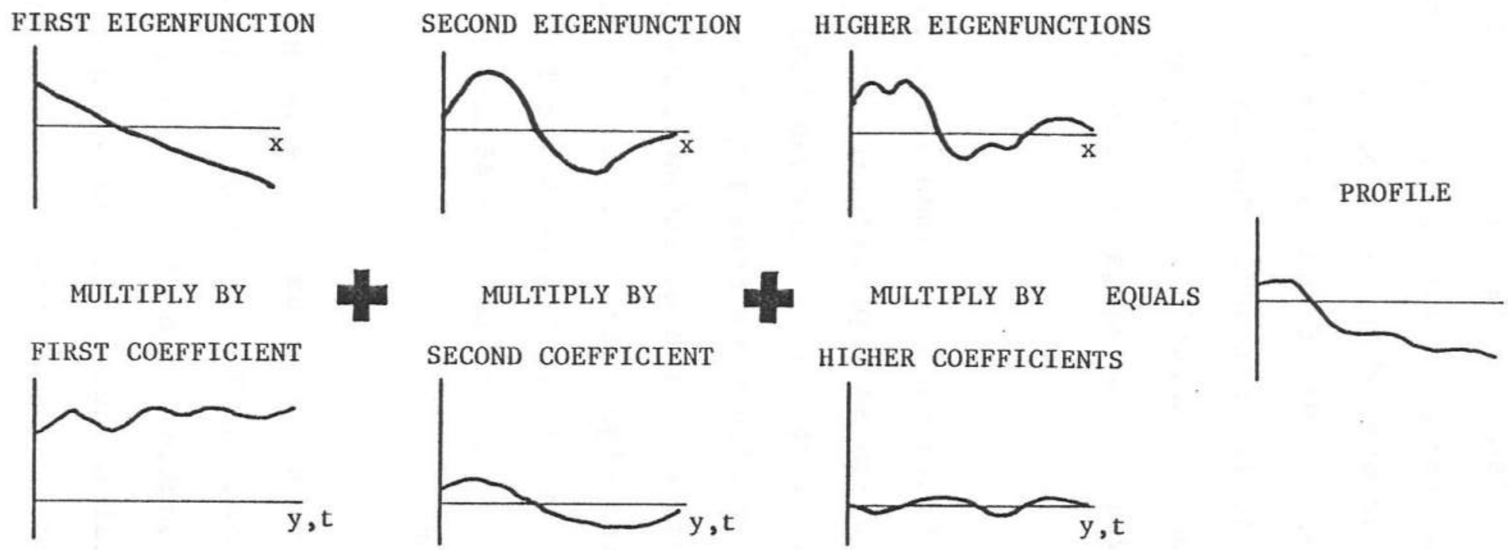


Figure 6-1: Eigenfunction decomposition of the profiles.

eigenvalue represented the mean profile, accounting for about 99.6% of the total variance. The second largest function usually accounted for 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 largest function 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 6-2 is the first three eigenfunctions computed for the straightened profile data from 3 March 1983, which is fairly representative of the eigenfunctions for all the surveys. The first eigenfunction indicates the mean beach was in the winter profile. The berm was indistinct and a small bar can be identified between 45 meters and 120 meters offshore.

The maximum and minimum of the second eigenfunction denote the locations of the greatest change. The second eigenfunction identifies the bar region as an area of substantial change along the beach. The eigenfunction also indicates that the berm and seaward limit of the survey area are locations with considerable

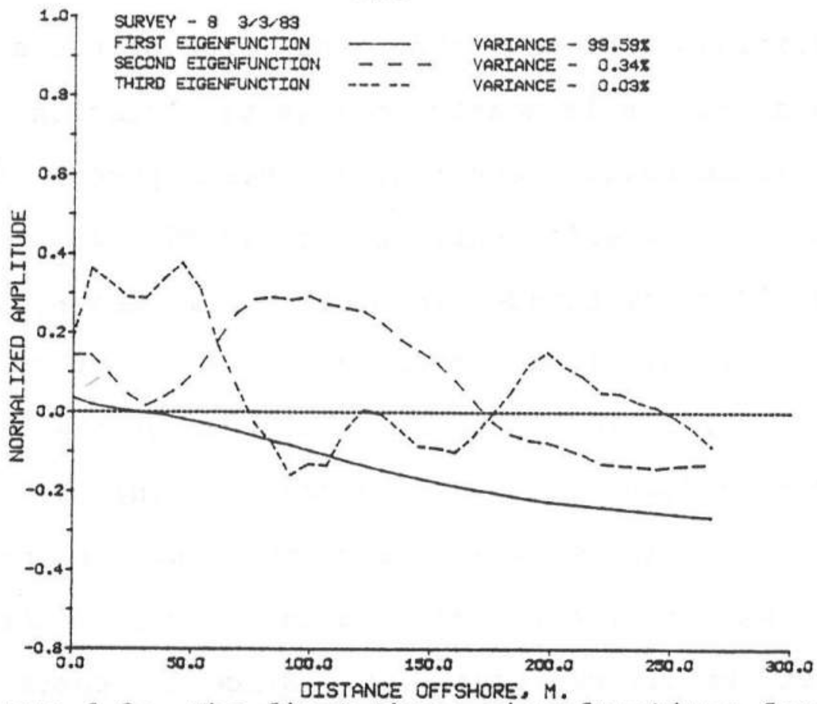


Figure 6-2: The first three eigenfunctions for the profile data from March 3.

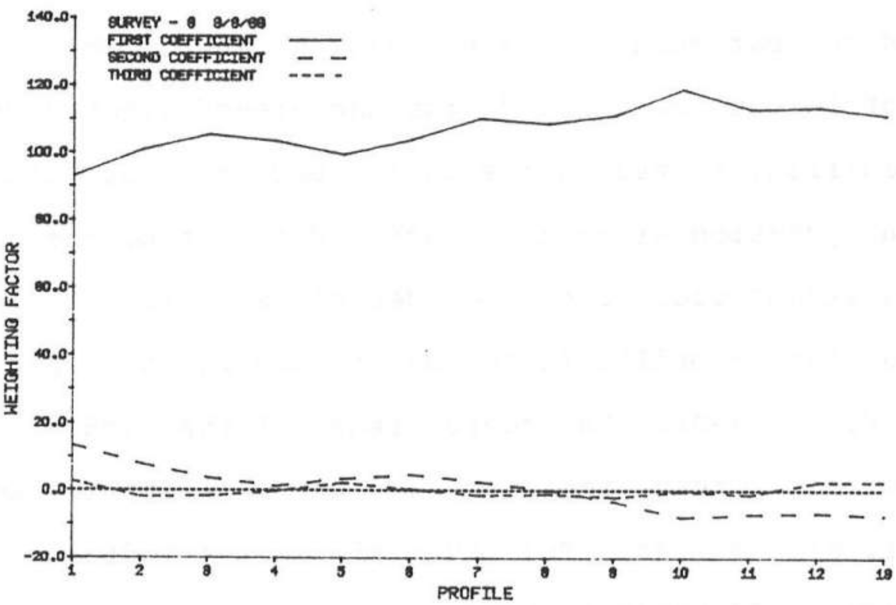


Figure 6-3: The coefficients corresponding to the eigenfunctions obtained from March 3rd data.

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. The coefficients of the second eigenfunction explain these changes in more detail (see Figure 6-3). The coefficients are positive for the northern four profiles, so in the northern section of the beach the berm was more developed than the mean and the bar was less distinct. The middle five coefficients are nearly zero. For this area, the mean function closely describes the beach profile configuration. Since the coefficients corresponding to the southern profiles are negative, the berm in the south end of the study area was less distinct and the bar more developed than the mean. The coefficients associated with the second eigenfunction identified shifts in the deviations from the mean profile configuration along the beach. For most of the surveys, the second coefficient changed signs between the eighth and tenth profiles (seen just to the right of profile nine in Figure 6-2). The coefficients of the middle region are frequently zero, implying that the profiles are described well by the mean. The reversal in sign indicates that the beach is "rotating" about the middle or mean region. The northern section is accreting at the same distance offshore that the southern section is eroding and vice versa. For this reason, the second eigenfunction for the spatial variations along the beach will be called the rotation function.

Whereas the configurations of the second eigenfunctions were fairly consistent for all the surveys, the second coefficients were not. Thus, the coefficients are important in identifying the location of the variations along the beach.

In Figure 6-3 the shape of the third eigenfunction is very similar to the shape of the second. The third coefficients also resemble the second coefficients; however, this was not true 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.

Empirical eigenfunctions were also calculated for each profile through time. The first eigenfunction describes the mean beach configuration at a given location. The coefficients describing the time variations of the second eigenfunctions are strikingly consistent for all the profiles. This signifies that the eigenfunction analysis describes the seasonal changes very well. In Figure 6-4 the second eigenfunction clearly identifies the location of the berm and the bar. Large positive values for the bar-berm function at the location of the berm implies that the berm is widening and that the beach is changing into the summer profile configuration. Large negative values in the bar region implies the opposite. The berm is eroding (also indicated by large negative values of the second eigenfunction at the berm) and the bar is developing. The positive value of the second eigenfunction at the offshore end of the profile means that this is an area of considerable change rather than the depth of closure. Figure 6-5 indicates that the berm was widening and the bar eroding from June to October. The storm (survey "s") eroded the berm and developed the bar. The recovery period reversed this trend, but the winter profile configuration continued to develop through the end of March. The upward direction of the second coefficient at the time of the last survey signifies that the transition from the winter to the summer profile was about to take place. Probably within the six weeks after the last survey the change to the summer profile began.

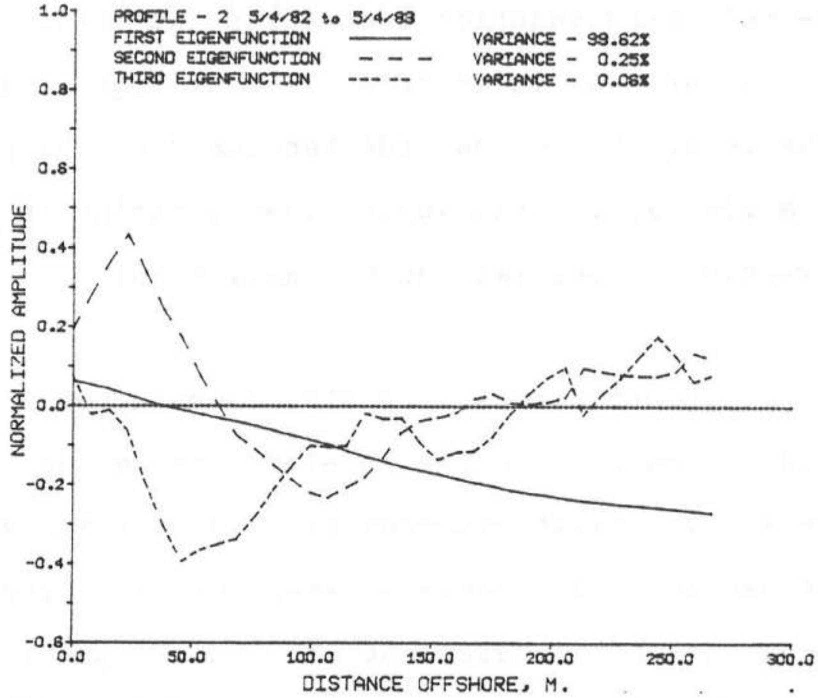


Figure 6-4: The first three eigenfunctions for the profile data for profile 2.

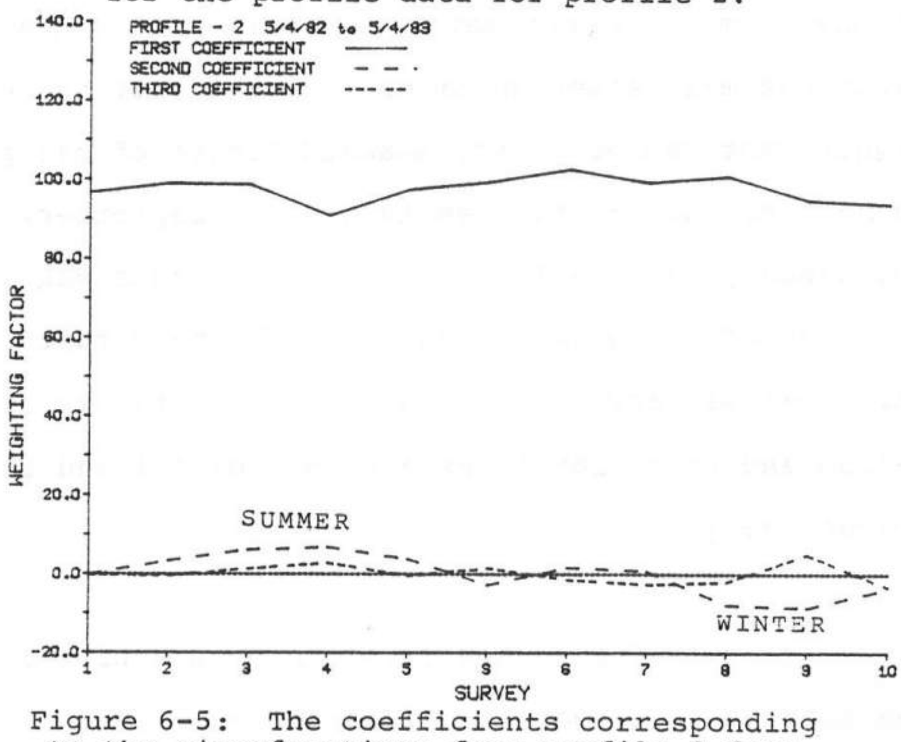


Figure 6-5: The coefficients corresponding to the eigenfunctions from profile 2 data.

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).

Eigenfunctions were also computed on matrices formed of the differences in elevation between two surveys. The first eigenfunction in this analysis describes the mean change between the two surveys. The development of the beach into the summer profile is described by the first eigenfunction with a large maximum at the berm and a minimum at the bar. Between August and March the mean eigenfunctions indicate that there was significant change at the seaward limits of the 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. The mean function in this analysis accounts for about 60% of the variance. The second and third functions account for 15% and 10%, respectively.

Figure 6-6 is the first three eigenfunctions for the changes in elevation before and after the October storm. As expected, the berm and bar are identified as areas of considerable variations. Significant change also occurred at the seaward limit of the profiles. In Figure 6-7, the coefficient associated with the first eigenfunction is increasingly negative toward the right indicating that the southern section of the survey area experienced more erosion of the berm and offshore region than the northern section.

The coefficients associated with the mean beach function of the difference matrix reversed sign between the fifth and seventh profiles on several of the analyses. Since the waterline also shifts about the same location it is probable that the sand was transported from the northern section to the southern section or vice versa. 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. Not surprisingly, the mean accounted for a greater percent of the variance during the months with the worst storms, October and February.

Eigenfunctions were computed for the size variation in monthly sand samples. The mean accounted for about 98.6% of the variance. The shape of the mean is

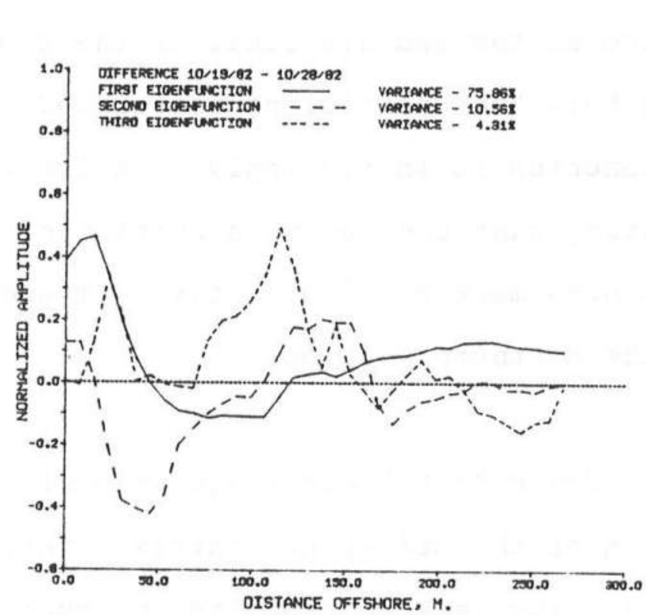


Figure 6-6: The first three eigenfunctions for the difference matrix for October 19 and October 28.

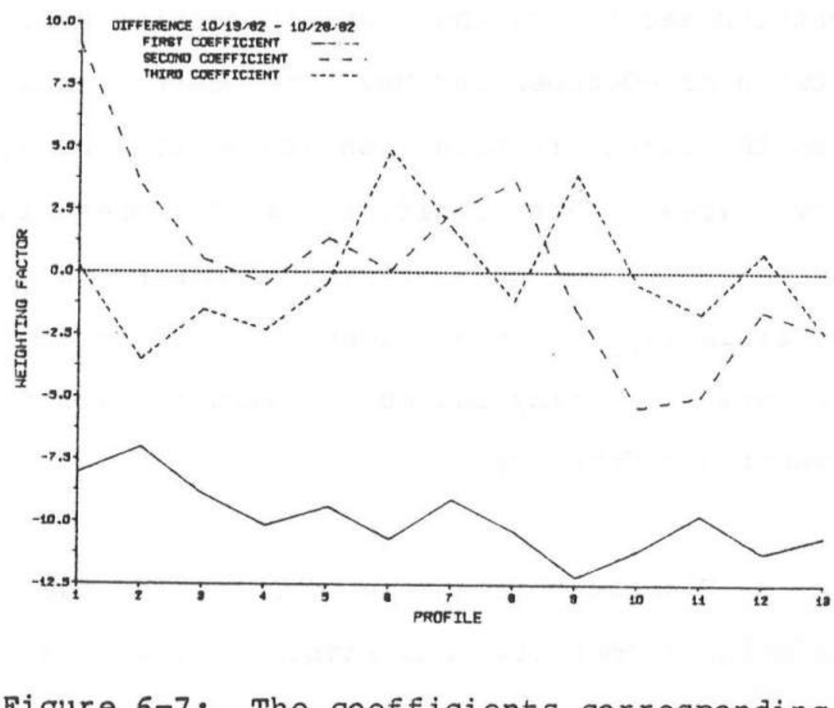


Figure 6-7: The coefficients corresponding to the eigenfunctions above.

similar for all the surveys. As the summer profile developed, the mean sediment size became finer. According to the first eigenfunction, the sand was the most fine at the end of the summer. As the beach profile began its seasonal shift to the winter profile, the sand became slightly coarser. The storms and winter conditions brought even coarser sand, which remained through the winter. The mean diameter varied by 0.05 mm, or about 12% over the study period. During the storm, the sand was sampled further landward. One thought is that the sand should have been finer since it was further landward. On the other hand, it was in the surf zone so it should have been coarser. No significant pattern for the coefficients associated with the first eigenfunction was identifiable.

The second eigenfunctions are very similar throughout the surveys. Figure 6-8 is representative of the first three eigenfunctions of the sediment analysis. The third eigenfunctions are also quite similar. In general, there was a large negative at 0.42 mm and a large positive at 0.3 mm (see Figure 6-9).

The empirical orthogonal function method efficiently produced quantitative results describing the changes in the beach profiles both spatially and

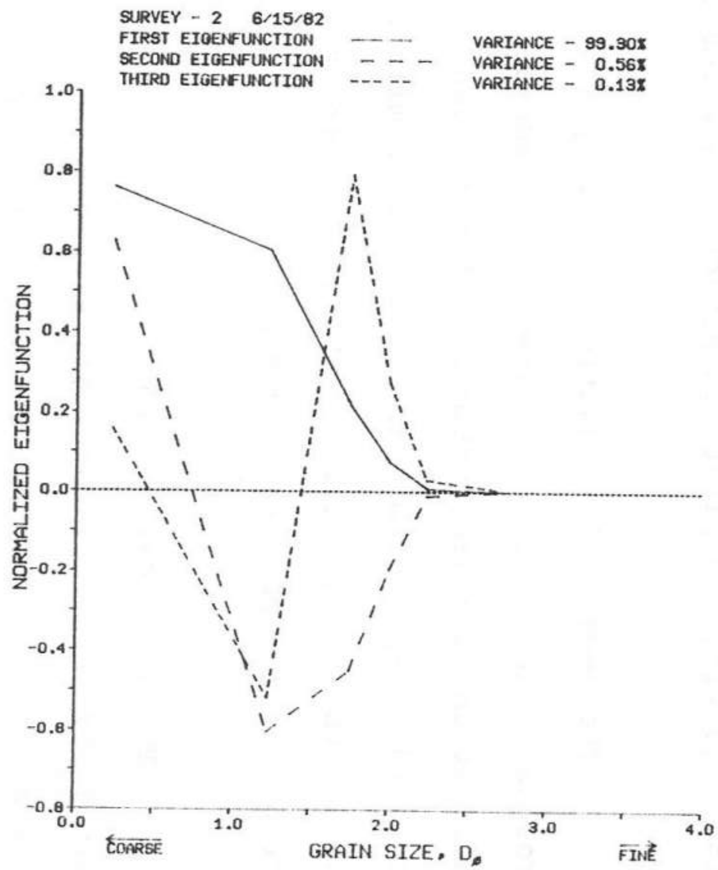


Figure 6-8: The first three eigenfunctions of the sediment data.

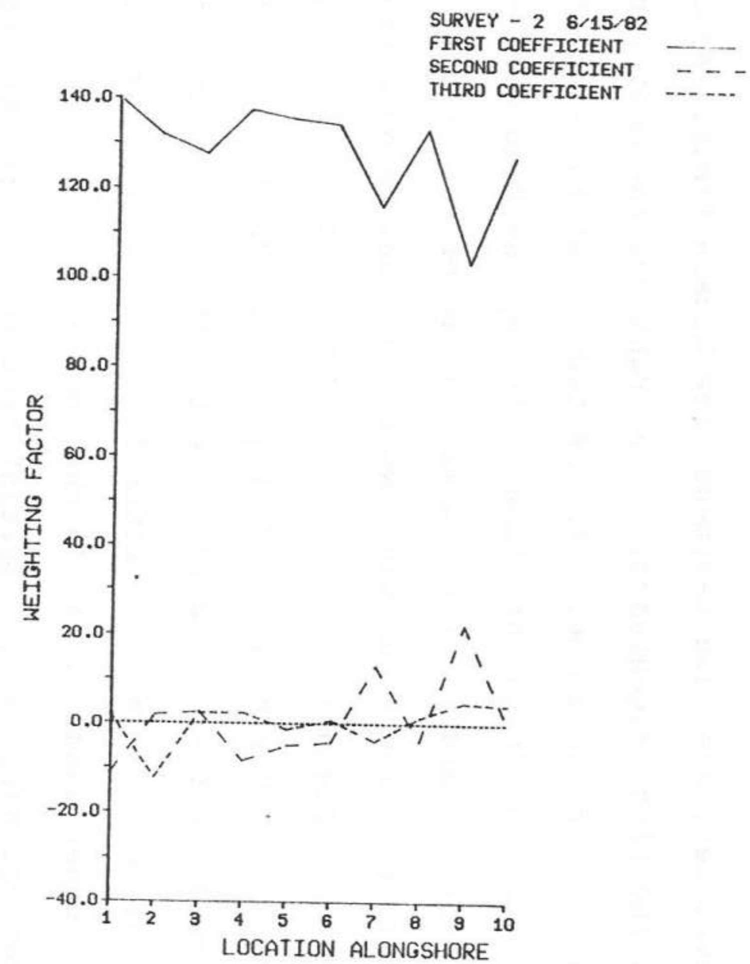


Figure 6-9: The coefficients corresponding to the eigenfunctions above.

temporally. The results of the temporal eigenfunction analyses indicate that although the predominant process affecting Bethany Beach is the seasonal transition between the summer and winter profiles, there are considerable changes occurring at depths previously thought to be stable. The spatial eigenfunction analyses identified a rotation of the beach profiles about the mean profile.

CHAPTER 7

SEDIMENT MOVEMENT

For many years Bethany Beach has been assumed to be the location of a sediment transport nodal point. This hypothesis is based on the knowledge that the net littoral drift is to the north at Indian River Inlet and to the south at Ocean City, Maryland. Because the magnitude and direction of littoral drift is crucial to the design of most coastal engineering projects, and the retention of sediment by groins and jetties on the Delaware Atlantic coast indicates that longshore transport is an important process of sediment redistribution, a more accurate assessment of the sediment transport at Bethany Beach is necessary. Obviously, the changes in elevation of the profiles between surveys is a reliable estimate of the volume change, but it reveals no information pertaining to the direction of sediment transport.

7.1 SEDIMENT TRANSPORT

As waves approach the shoreline obliquely, a longshore current is generated in the direction of wave propagation. Sediment, suspended by breaking wave action, is carried and distributed along the shore by this current. Littoral drift and longshore transport are often thought to be synonymous; however, littoral drift is actually the sediment moved by waves and currents in the littoral zone, and the longshore transport rate is the rate at which littoral drift is moved parallel to the shoreline. Longshore transport rates are usually given in units of volume per time. The volume transported is typically 40% voids and 60% solids (Shore Protection Manual, 1977). Presently, there are four major methods for determining longshore transport. The best method is to modify the longshore transport rate known at a nearby site to local conditions. However, this is not always possible. The next best method is to calculate the longshore transport from historical data showing changes in topography in the littoral zone. If neither of these methods is feasible, it is also possible to calculate a longshore component of "wave energy flux" which is related through an empirical curve to the longshore transport rate. The fourth procedure, developed by Galvin (1972), is an empirical procedure to estimate gross transport rate from mean annual nearshore breaker height. The computed gross rate can then be used as an upper limit of net longshore transport rate (Shore Protection Manual, 1977).

Each of these methods has advantages and disadvantages. The first technique depends on the accuracy of local data and engineering judgment. The second method depends on the reliability and availability of historical data. The third procedure may be less involved than the second if only a few representative wave directions and magnitudes are used, but is accordingly less accurate. The last method requires either calculated or measured nearshore breaking wave height. Because calculation of wave energy flux is often easier and more consistent than researching hydrographic records and estimating changes between local conditions, the third technique is frequently used (Shore Protection Manual, 1977).

The wave energy flux method is based on the assumption that the longshore transport rate is dependent on the longshore component of energy flux in the surf zone, which is approximated by assuming conservation of energy of shoaling waves and evaluating the energy flux relation at the breaker position. The energy flux per unit length of wave crest, or, equivalently, the rate at which energy is transmitted across a plane of unit width perpendicular to the direction of wave advance for a given wave height, H, and wave group celerity, C_g, is

$$\overline{P} = \overline{E}\ C_g = \frac{\rho g}{8} H^2 C_g \tag{7.1}$$

If the waves approach the shoreline at an angle, α, (see Figure 7-1) the energy flux in the direction of wave advance per unit length of beach is

$$\overline{P} \cos\alpha = \frac{\rho g}{8} H^2 C_g \cos\alpha \tag{7.2}$$

and the corresponding longshore component of energy flux is

$$P_{\ell} = P \cos\alpha \sin\alpha = \frac{\rho g}{8} H^2 C_g \cos\alpha \sin\alpha \tag{7.3}$$

Using the trigonometric expression,

$$\cos\alpha \sin\alpha = \frac{1}{2} \sin\alpha \tag{7.4}$$

equation (7.4) can be rewritten

$$P_{\ell} = \frac{\rho g}{16} H^2 C_g \sin 2\alpha \tag{7.5}$$

of which the surf-zone approximation is

$$P_{\ell s} = \frac{\rho g}{16} H_b C_g \sin 2\alpha_b \tag{7.6}$$

where the subscript b indicates conditions at breaking. Since the group celerity is approximately equal to the wave celerity, C, for linear theory in shallow water,

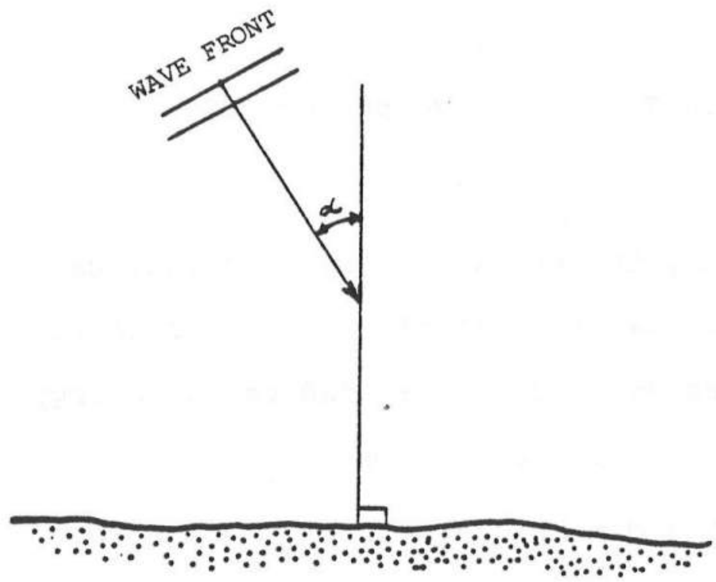


Figure 7-1: Waves approach shoreline at angle α.

$$P_{\ell s} = \frac{\rho g}{16} H_b \, C \sin 2\alpha_b \tag{7.7}$$

where the wave celerity is calculated from

$$C = \frac{gT}{2\pi} \tanh\left(\frac{2\pi}{L}\right) \approx (gd)^{1/2} \tag{7.8}$$

and $d=1.28H_b$.

For deep water the group celerity is equal to half the deep wave celerity, C_o, where

$$C_o = \frac{g}{2\pi} T \tag{7.9}$$

in which T is the wave period. So

$$P_{\ell s} = \frac{\rho g}{64\pi} T (K_r H_o)^2 \sin 2\alpha_b \tag{7.10}$$

where K_r, the refraction coefficient, can be found from Snell's Law of Refraction. The longshore transport rate has been empirically related to the energy flux by

$$Q = 12.6 \times 10^3 \, P_{\ell s} \tag{7.11}$$

where the dimensional empirical constant (12.6×10^3 m^3/year) was determined from field data. This equation tends to overestimate the longshore transport rate for higher values of the energy flux (Shore Protection Manual, 1977). Walton (1973) uses a slightly different empirical constant of about 11,250 cubic meters/year for the longshore transport rate.

As can be seen from the above relationships, deep water wave height and breaking wave angle are important parameters in determining sediment transport. Increased wave heights cause increased sediment transport. The volume of material transported varies with the breaking angle from a maximum at 45° to a minimum at 0° and 90°. However, it is the shoreline orientation that causes different transport rates at closely spaced locations with different shoreline orientations.

Walton (1973) described a method employing offshore wave data to evaluate littoral drift rates for various shoreline orientations. For a specific shoreline, the longshore energy flux and corresponding littoral drift can be calculated from the available wave data. For a selected shoreline orientation, the littoral drift is the summation of each wave condition, (wave height, period, and direction), multiplied by its frequency of occurrence. Shoreline orientation is defined as the azimuth of the outward normal to the shoreline. Waves approaching the shoreline with angles greater than 90° are neglected. The shoreline is rotated through small increments to determine the littoral drift for various orientations. Resulting longshore transport rates are expressed either as positive (sediment movement to the right looking offshore) or negative (sediment movement to the left looking offshore).

The result, a littoral drift "rose" is the representation of the gross and net littoral drift for various shoreline orientations.

7.2 LITTORAL DRIFT ROSE

Using the wave energy flux method, a littoral drift rose was developed for Bethany Beach. Wave data from several sources (Goldsmith et al, 1974; U.S. Naval Oceanographic Office, 1963; Moody, 1964) were combined to reduce the possibility of bias. From this synthesized data wave height and wave period roses were constructed (see Figure 7-2). Frequency of occurrence was then calculated for each wave condition. The breaking wave depth was calculated by linear theory from

$$h_b = \frac{1}{g^{1/5}\kappa^{4/5}}\left(\frac{H_o{}^2 C_o \cos\alpha_o}{2}\right)^{2/5} \quad (7.12)$$

where h_b is the water depth at breaking, g is the gravitational acceleration, and $\kappa=0.8$. From this the breaking wave angle was found by

$$\sin\alpha_b = \frac{\sqrt{gd}\,\sin\alpha_o}{gT/2\pi} \quad (7.13)$$

Due to sheltering from Cape May and deviations from the assumption of straight and parallel contours, a sheltering-refraction coefficient was determined from wave

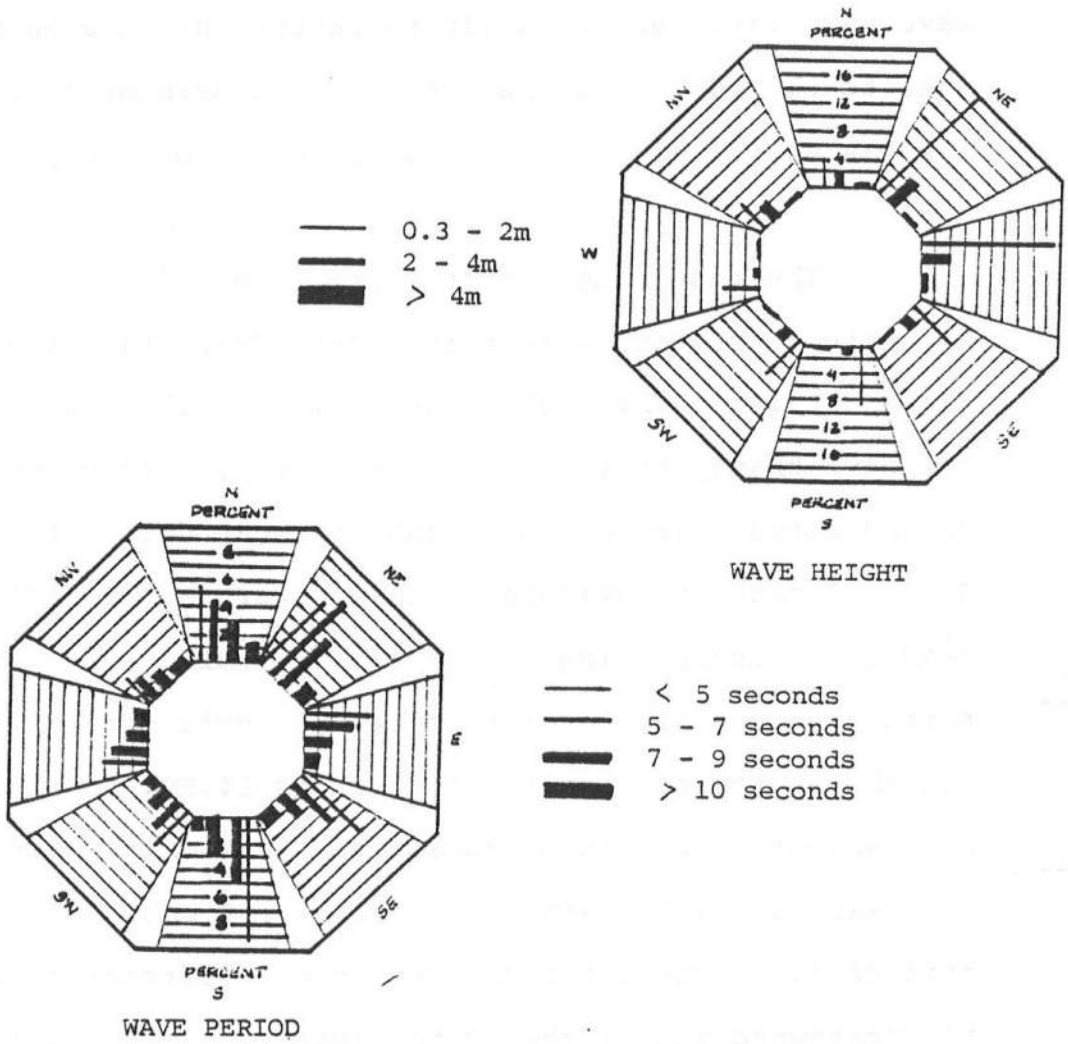


Figure 7-2: Wave height and wave period data used for littoral drift at Bethany Beach.

refraction diagrams (Poole, 1976). The coefficients, shown in Figure 7-3, were computed as the ratio of the wave rays that were actually refracted into the Bethany area to the wave rays that would reach Bethany if Snell's law was valid and Cape May had no effect of the rays.

The resulting littoral drift rose for the Delaware Atlantic coast can be seen in Figure 7-4. Positive transport is to the south, shown by the solid curve, negative transport is to the north, indicated by the dashed curve. To determine the littoral drift at Bethany Beach, locate the azimuth to the outward normal (85°) and read the corresponding values of littoral drift. The northward (negative) drift is 14,860 cubic meters/year, and the southward (positive) drift is 14,290 cubic meters/year. The gross transport, the summation of the northward and southward drift, is 29,150 cubic meters/year. The net transport, the difference between the northward and southward transport, is 570 cubic meters/year, northward; however, this difference is an estimate rather than an exact value.

The location where the two curves intersect is called the "null" point. It indicates the shoreline orientation of the nodal point, where the northward

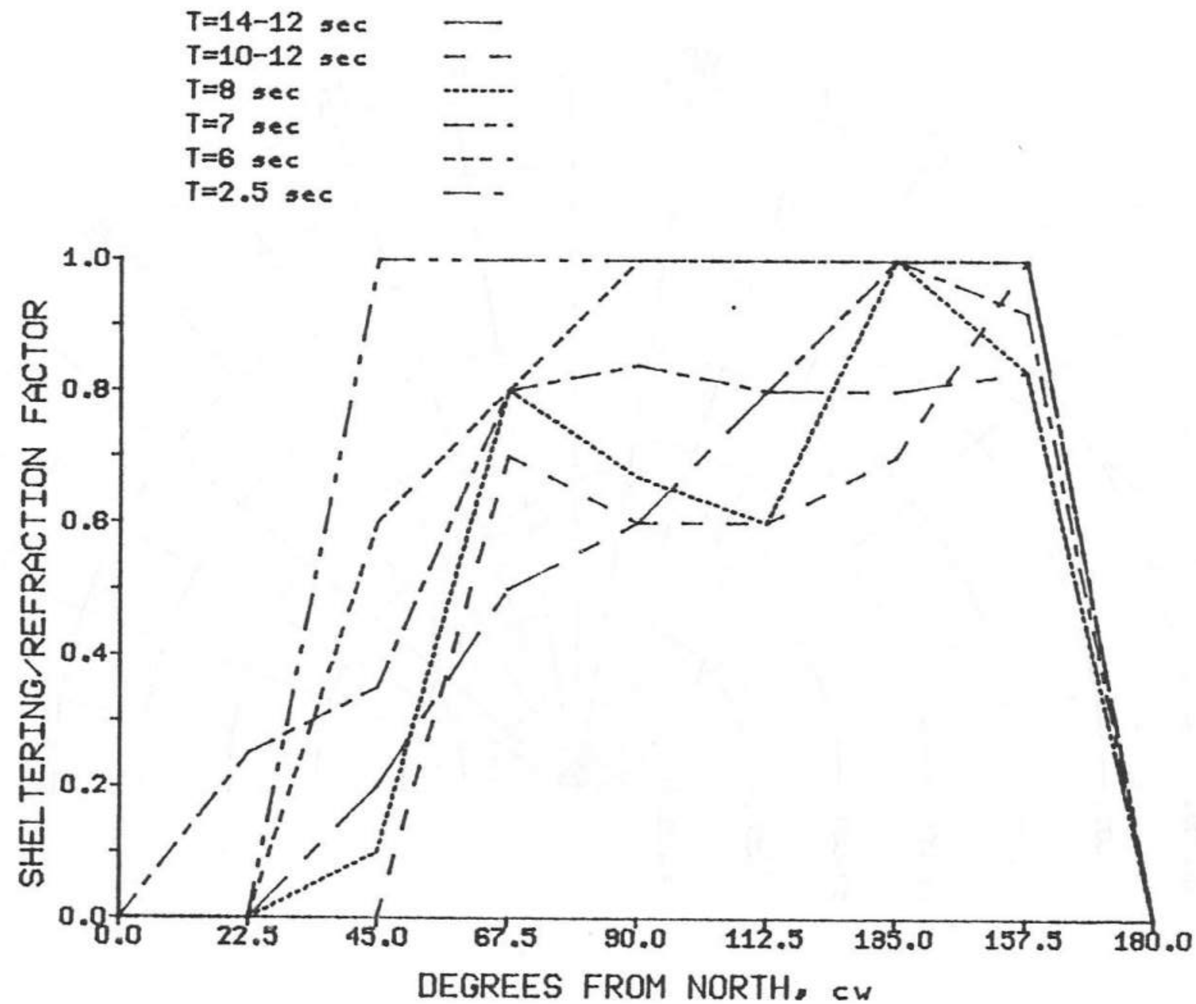


Figure 7-3: Sheltering/Refraction coefficient for Bethany Beach.

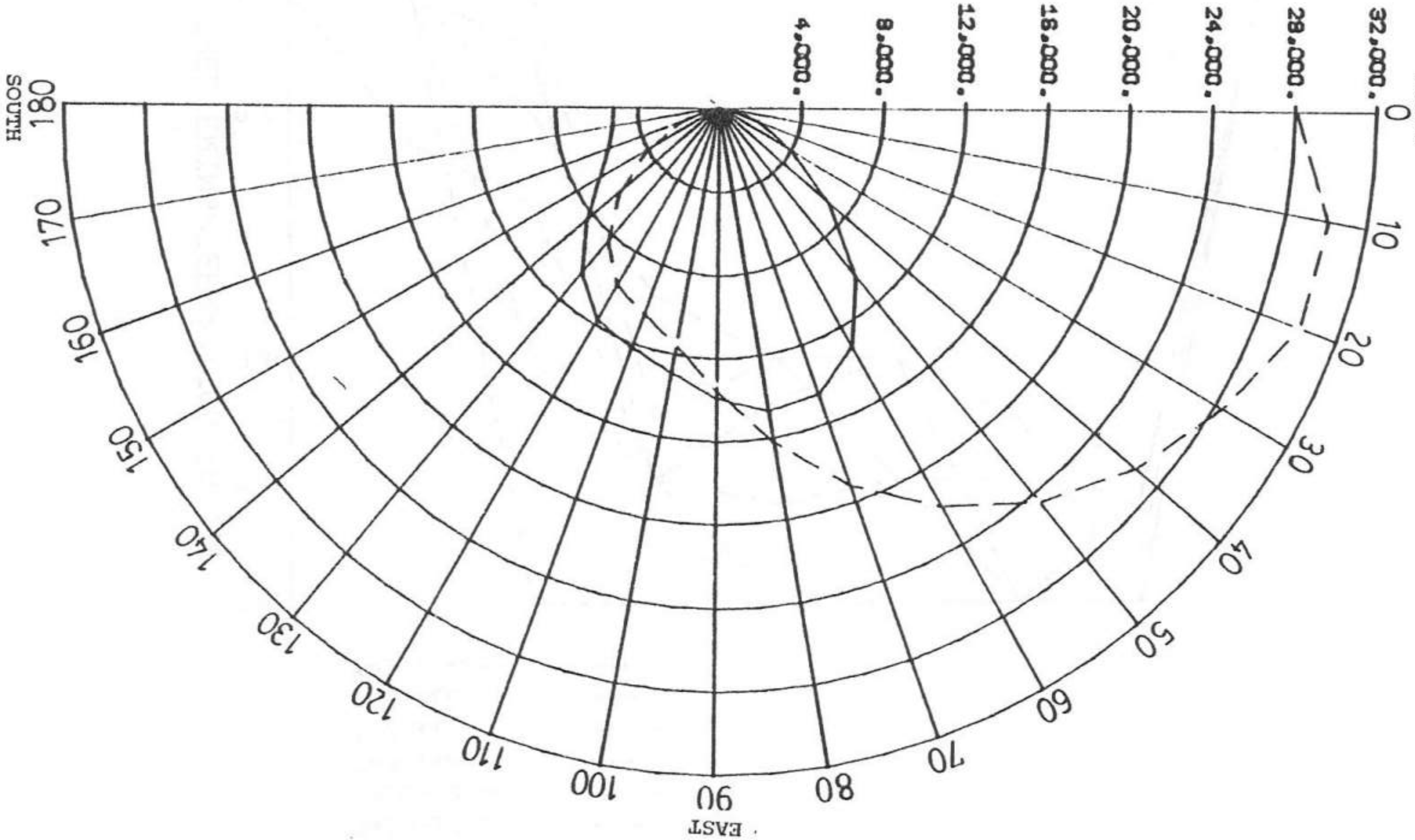


Figure 7-4: Littoral drift rose for the Delaware Atlantic Coast.

littoral drift equals the southward littoral drift and the resulting net sediment transport is zero. The azimuth to the outward normal at the nodal point is about 85°, which is very nearly the orientation of Bethany Beach.

Since the deep water wave conditions vary throughout the year, the littoral drift will also vary. Figure 7-5 through Figure 7-8 represent the littoral drift roses for spring (March-May), summer (June-August), autumn (September-November), and winter (December-February) calculated from seasonal wave data (U.S. Naval Oceanographic Office, 1963). Different wave data had to be used for the seasonal analysis because some of the data used in the annual drift rose represented annual rather than seasonal wave conditions. The greatest rate of gross littoral drift occurs during autumn. The wave heights, and therefore the wave energy, are the greatest during autumn. The net littoral drift at this time is strongly to the south. By winter, the frequency of occurrence of the larger wave heights (greater than 4.5 meters) has decreased. The net littoral drift is still southward, but not as great as in autumn. During the fall-winter period the north sides of the groins show accretion, another indication of net southward transport. In spring, the dominate wave direction is from the south. The gross

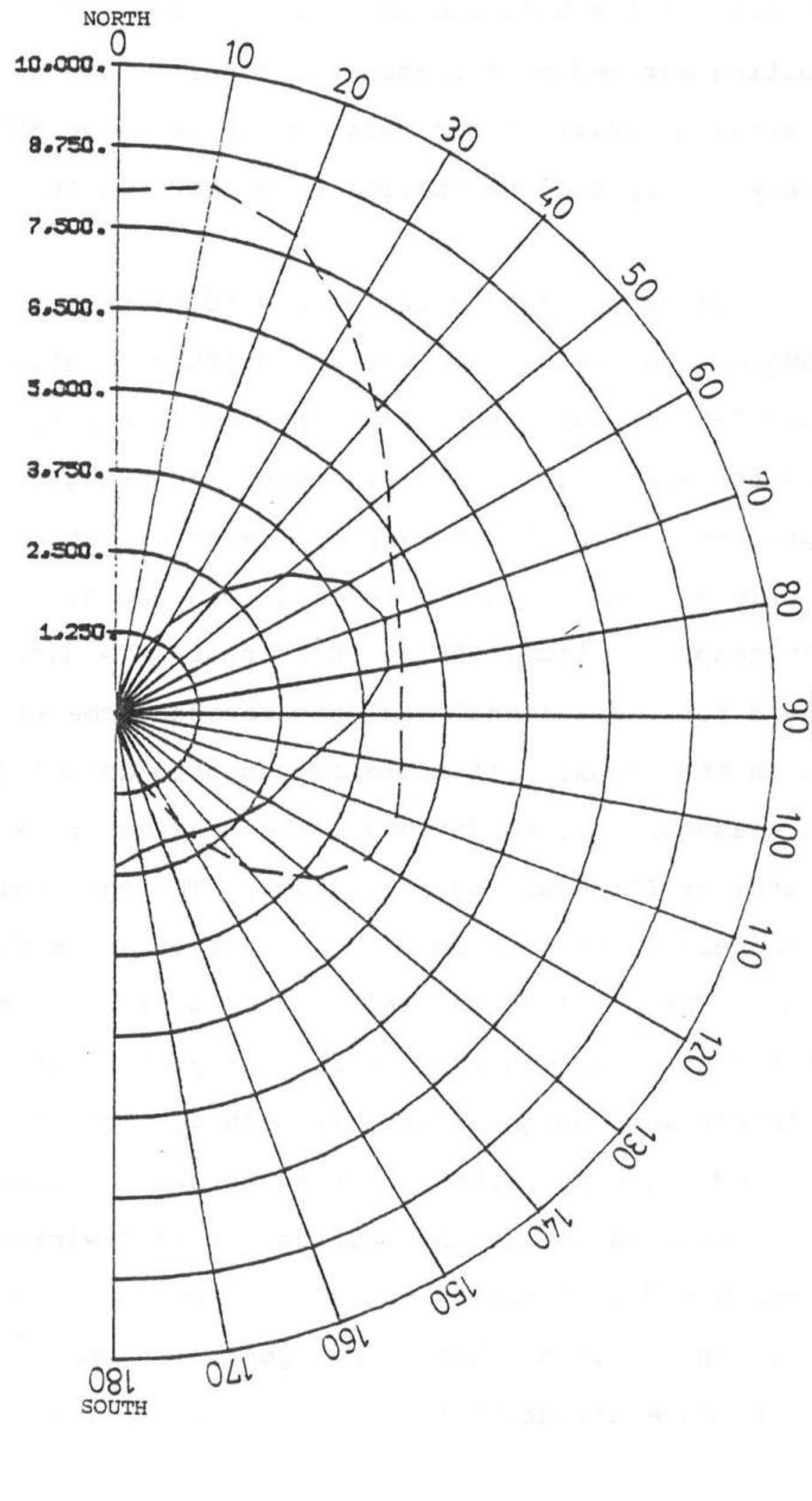


Figure 7-5: Spring littoral drift rose.

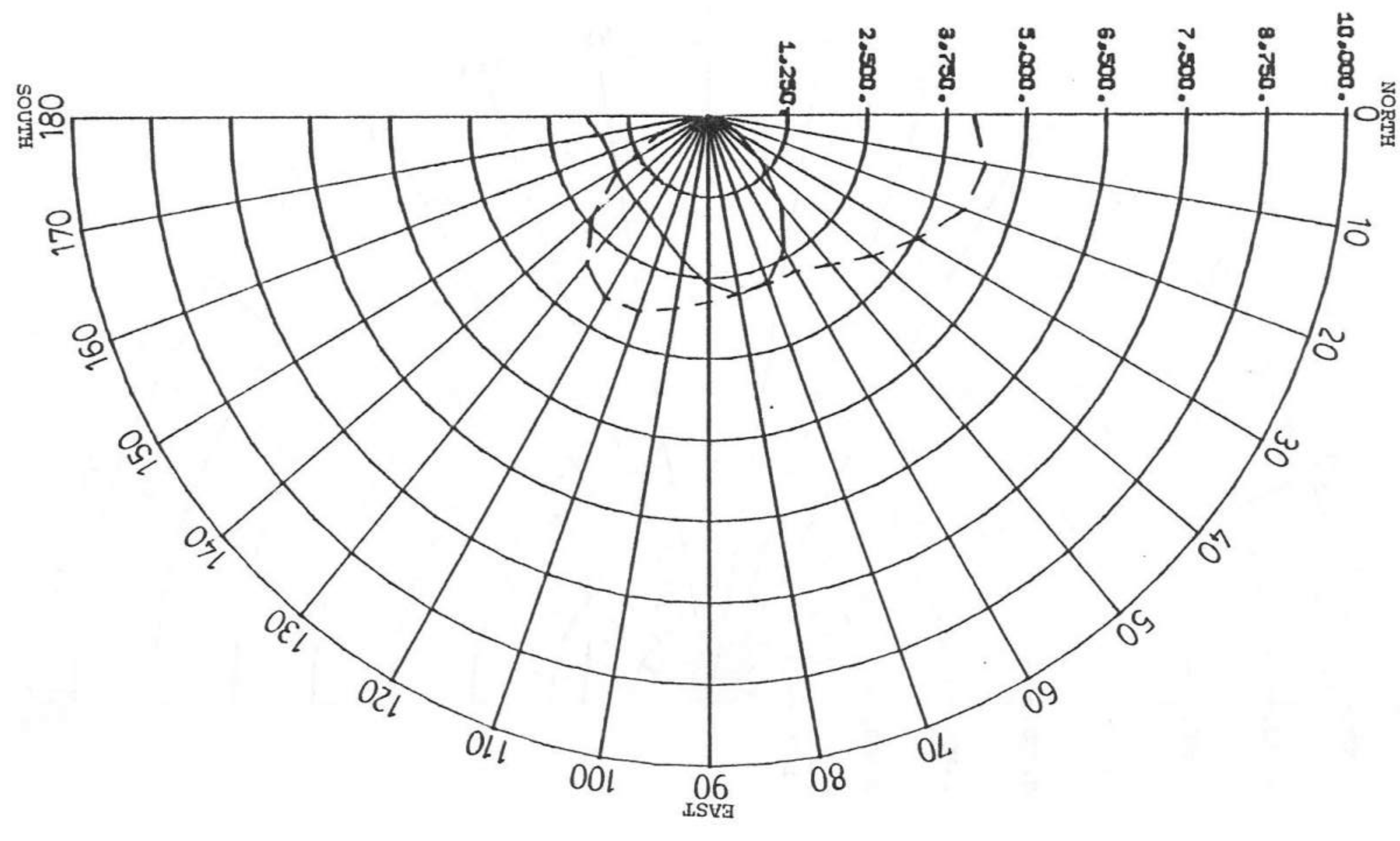


Figure 7-6: Summer littoral drift rose.

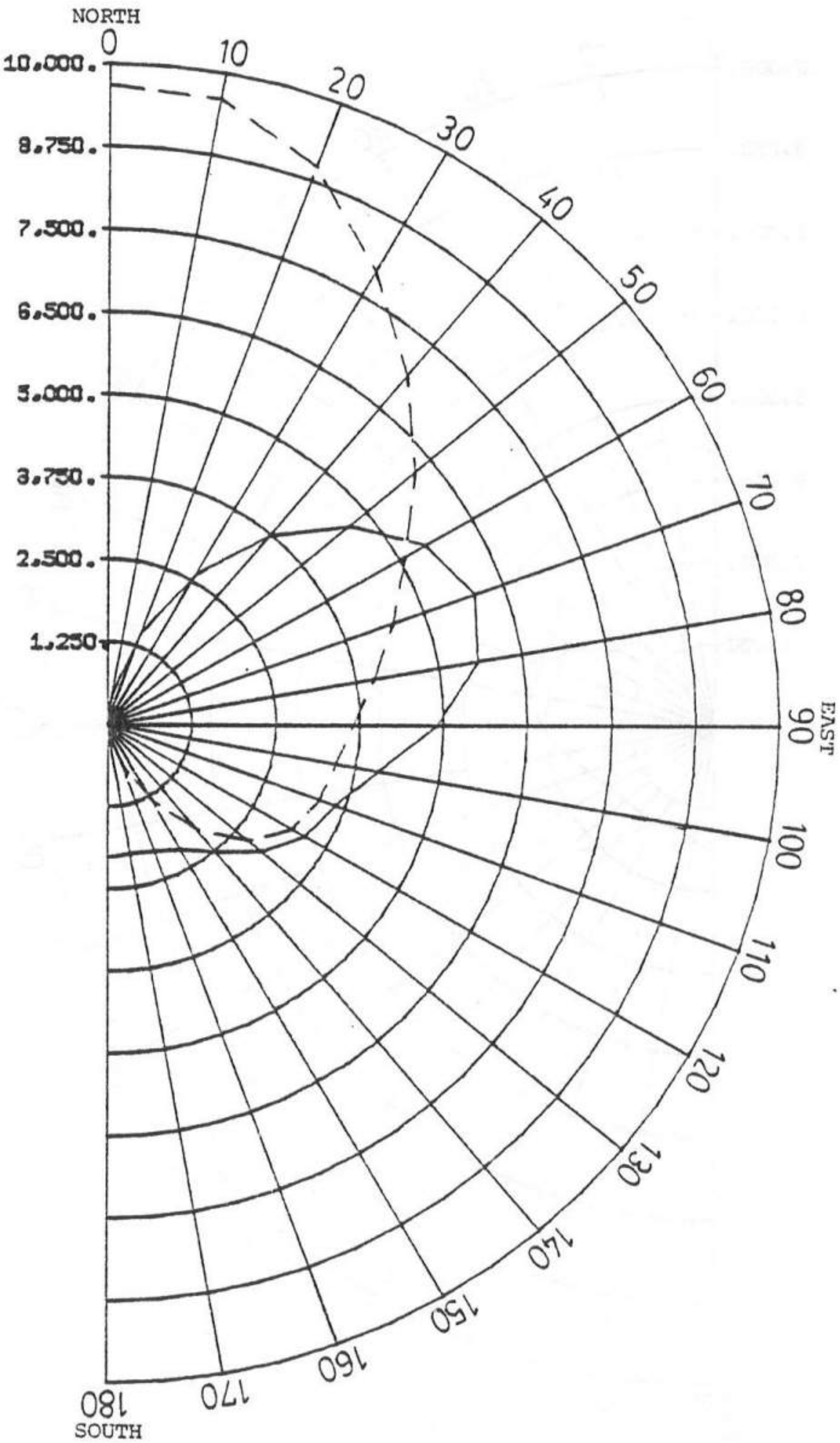


Figure 7-7: Autumn littoral drift rose.

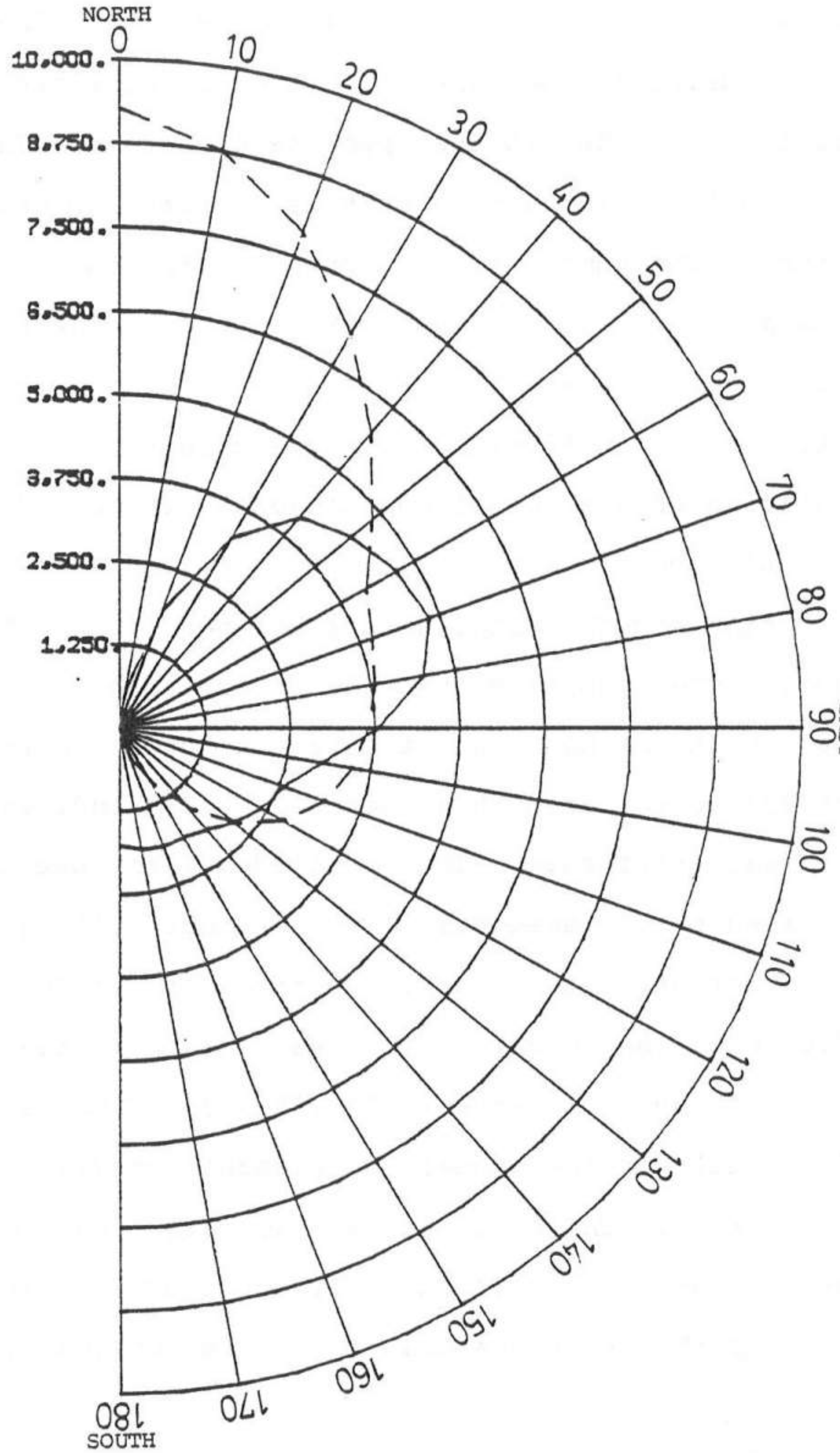


Figure 7-8: Winter littoral drift rose.

littoral drift is greater than in the winter. The net littoral drift is the same magnitude as the winter net littoral drift, but in the opposite direction. The small wave heights during summer mean less energy to transport sediment. The summer gross littoral drift is approximately half the autumn gross drift. The net littoral drift is about ten times less than the autumn net drift. Because different data were used for the calculation of the annual and seasonal littoral drifts, the results do not agree exactly on the location of the nodal point and the magnitude of the net drift. The seasonal roses indicate that the orientation of the shoreline at the nodal point is at an outward normal of about 90^{o} to the azimuth as opposed to 85^{o} indicated by the annual drift rose. The magnitude of the net drift as determined by the seasonal roses is about 1600 cubic meters/year which is about three times larger than that predicted by the annual drift rose. However, the rates of gross drift only differed by 5% (29,150 m^3/year and $30{,}700^3$/year for the annual and seasonal gross drifts, respectively). The seasonal representation can be used to determine the general trend of littoral drift throughout the year rather than the exact magnitude of the drift.

Several assumptions must be made to use the littoral drift rose:

1) Littoral drift is dependent on wave action (rather than on tidal currents or wind-driven transport).
2) Linear wave theory is valid.
3) The bottom topography is relatively straight with parallel contours (Snell's law is valid).
4) There are no drastic changes in the bottom profile.
5) There is an adequate supply of sand available for transport.

Because extreme storm activity is an important factor in determining the magnitude and net direction of littoral drift, especially in low energy areas where the normal wave climate has little influence on shoreline processes, the results of this study should be used with caution and the littoral drift rates should be considered as a gross estimate to the actual littoral drift rates (Walton, 1976).

The northward net littoral drift at Bethany Beach indicated by the annual littoral drift rose is supported by the Army Corps of Engineers (1968). Both sources also agree that there is a nodal point in the vicinity of Bethany, in that, north of Bethany the net drift is to the north, while south of Bethany Beach the net drift is to the south. The location of the nodal point is dependent on the magnitude and direction of the wave climate as well as the orientation of the shoreline. Considering the shoreline configuration, a net northward drift at Bethany is more plausible. The orientation of the coast is fairly consistent from Cape Henlopen to Fenwick Island, so neglecting the sheltering effects of Cape May and the irregular offshore contours, the littoral drift should be the same along this reach. At Fenwick Island, the shoreline orientation changes to a southwestward direction. Because of this change in orientation, Fenwick Island is a probable location for the nodal point.

7.3 HISTORICAL PROFILES

Since 1843 the Army Corps of Engineers (1968) has sporadically surveyed beach profiles along the Delaware Atlantic coast. From 1843 to 1929, Indian River Inlet to Fenwick Island experienced net erosion (see Table 7-1). Erosion was nearly 35% greater at Indian River Inlet than between Indian River Inlet to Bethany, and it was twice as great at Bethany as between Bethany and Fenwick Island. Between 1929 and 1954, the reach from Indian River Inlet to south of Bethany Beach accreted. It was during this 25-year period that the groin field was built at Bethany and Indian River Inlet was stabilized. Bethany Beach accreted twice as much as the area between Indian River Inlet and Bethany, while the region from Bethany to the

PERIOD / LOCATION	1843 - 1929 (86 years)	1929 - 1954 (25 years)	1954 - 1964 (10 years)	1964 - 1982 (18 years)	1843 - 1964 (121 years)
Indian River Inlet to Bethany Beach (6.8 km)					
Volume	-7,170,000	+8,490,000	-417,000		-6,740,000
Annual Rate	-830,000	+34,000	-42,000		-56,000
Annual Rate/km	-12,200	+5,000	-6,000		-8,000
Bethany Beach (1.4 km)					
Volume	-1,943,000	+352,000	+16,000	-4,497,000	-1,574,000
Annual Rate	-23,000	+14,000	+1,500	-25,000	-13,000
Annual Rate/km	-17,000	+10,000	+1,100	-18,000	-9,300
South Bethany to Fenwick Island (9.3 km)					
Volume	-6,290,000	-1,020,000	-1,923,000		-9,245,000
Annual Rate	-73,000	-41,000	-191,000		-76,000
Annual Rate/km	-7,800	-4,400	-20,500		-8,200

Table 7-1: Changes in volume from Indian River Inlet to Fenwick Island for the period 1843 to 1982. (U.S. Army Corps of Engineers, 1968).

State Line eroded at about half the rate as it did between 1843 and 1929. Bethany Beach was the only area that experienced net accretion between 1954 and 1964. (Adjustments were made to account for the beach and dune fill placed after 1954.) The entire reach south of Bethany eroded at a rate over 4.5 times larger than between 1929 and 1954. During this period, Bethany eroded above MLW, but accreted below, resulting in a net annual accretion for that area. Between 1964 and 1982, Bethany Beach accreted above MLW; however, below MLW the profiles steepened, resulting in net erosion during this period. These profiles were not extended to the depth of closure. In fact, at -7.5 meters, the 1964 and 1982 profiles were diverging, so these values are only indications of the trends in the volumetric change.

7.4 DISCUSSION

At this point it would be interesting to construct a sediment budget for the Bethany Beach area; however, this is not feasible because of the lack of data, but a discussion of the sources and sinks is possible. Sources for sediment are limited on the Delaware Coast. McDonald (1981) states that the rivers of the coastal plain do not supply sand directly to the beaches and that biological material supplies very little sediment. Kraft (1983) believes that the sediment forming the barriers and beaches is "totally provided" by severe storm wave action eroding the Pleistocene stratigraphic units that are comprised of sand. Both Kraft and Moody (1964) feel that the sand from the barrier moves offshore rather than the reverse. The profiles at Bethany clearly indicate that sediment from outside the survey area was deposited offshore and subsequently moved landward. Whether this sediment was transported from alongshore, was deposited further offshore during the winter, or was transported from the shelf is uncertain.

The sinks along the Delaware coast are easy to identify. The net littoral drift north of Bethany transports sand to Cape Henlopen. Some of this is moved offshore to the Hen and Chicken shoal. In the Bethany area the major sink is south of the southern jetty at Indian River Inlet and the ebb-tidal shoal off of the inlet. The importance of sediment transport to the shelf is unknown.

CHAPTER 8

CONCLUSIONS

Although erosion has long been considered a serious problem at Bethany Beach, the shoreline has not changed much since the groins were constructed nearly fifty years ago. The groins appear to effectively accumulate sediment during periods of normal wave activity and minor storms. However, severe storms temporarily remove large volumes of sand. If several storms occur in rapid succession, the beach will not recover between them, so the damage to the protective dunes and beach-front property could be considerable. Presently, the dunes are narrow and discontinuous, furnishing minimal protection against wave action. In all probability, the next major storm or hurricane will incur damage similar to that caused by the March 1962 storm. The bulkheads fronting Bethany Beach aid in the protection of the streets, utilities, and private property, but do not protect the area seaward of the bulkheads. The groins would be far more effective if they were not damaged and flanked at the landward end.

Aerial photogrammetry provides information about the historical changes in the shoreline at Bethany Beach. 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 areas 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 groins. The indentation just north of the groin field 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.

The survey data reveal interesting information about the seasonal changes the beach undergoes. Theoretically, the sand is transported throughout the year between the berm and the bar. The profiles were thought to be extended beyond the depth of closure; however, the volume of beach sand in the survey area varied considerably during the year, indicating that the sediment was either transported alongshore or further offshore.

The empirical eigenfunction analyses revealed the modes and fluctuations that occurred during the year. The predominate process identified by the temporal analyses was the transition between the winter and the summer profiles, although the analysis on the difference between two surveys disclosed significant changes offshore of the bars. The spatial eigenfunction analyses identified the rotation of the beach profiles about the mean beach. A longer study period would provide more accurate results.

The littoral drift rose explains the variations in sediment transport along Delaware's Atlantic Coast; moreover, it confirms the existence of a nonstationary nodal point near Bethany Beach. The seasonal roses describe the fluctuations in sediment transport that occur throughout the year, providing a mechanism for the movement of the nodal point. These results should be considered to be a gross estimate of the actual littoral drift at Bethany.

The results of the long-term trends and short-term fluctuations in the shoreline are essential to the proper planning and design of a coastal management project to protect Bethany Beach from erosion. Under normal wave conditions, erosion at Bethany should not be a problem;

however, without further protection to the beach, the next major storm could cause severe damage to the beach and the town, which will result in considerable financial loss.

CHAPTER 9

RECOMMENDATIONS

On the basis of the findings of this study, several improvements are suggested which, if implemented, would increase Bethany's defenses against storm wave action. The groins have proved to be effective in maintaining the beach during normal wave conditions and protecting the town against minor storms; however, several groins are presently in very poor condition, which greatly reduces their effectiveness.

The Fifth Street groin is in fair condition, but because of the location of the dune at the end of Fifth Street, the groin is flanked certain times of the year. To prevent this, the groin should be extended landward into the dune.

The wales and timber pilings on the Ocean View Parkway groin are decomposing, causing holes to develop under the wales. The decayed timber, and the bolts and steel sheeting that are corroded should be replaced. To prevent flanking, which occurred around the landward end of the groin during the October 1982 storm, the groin should be extended into the dune.

The hole at the junction of the wood and steel sheet piling which causes scouring on the downdrift side of the Third Street groin, needs to be repaired.

The timber wales at the landward end of the First Street groin are severely deteriorating (particularly on the south side) and should be replaced. Two small holes have rusted through the sheet piling right below the wales. These holes could enlarge if they are not repaired.

The wales at the landward end of the Campbell Place groin are also in poor condition and should be repaired. Some of the bolts in the stone crib are broken, so they should be replaced with new ones.

The Hollywood Street groin is severely flanked and must be extended 15 meters to be effective. The corroded steel sheeting needs to be replaced and the holes between the wood planks need to be patched.

The Wellington Parkway groin is in very poor condition. The steel sheeting, of which 5.8 meters has been ripped out, must be replaced. The wood sheeting has been destroyed in two places and needs to be repaired. This groin is also badly flanked. To be effective, it should be extended at least 8.5 meters landward.

The Maplewood Street groin is in very poor condition. The steel sheeting has rusted through and must be replaced. Because flanking occurs around this groin all winter, it also needs to be extended. Unfortunately, the dune is low or non-existent in the south, so extending the groins into the dune is not a viable solution as it is with the northern groins. Continuing the bulkhead or constructing a sand dune to the corporate limits would solve this problem.

The bulkheads are vitally important to the protection of the streets and private property against heavy wave action since the dunes are virtually non-existent along the front of the center of Bethany. The dune line is also low and narrow south of the bulkhead. By extending the bulkhead to the corporate limits, the town would be protected by the bulkhead from Third Street south. As mentioned above, this extension would have the additional benefit of preventing flanking around the landward ends of the three southernmost groins (currently, a severe problem) by providing a stable location to tie back the groins. If bulkheads are to be constructed, they need to be designed to provide substantial protection against wave action. They must extend far enough below the sand level to prevent scouring beneath them. The bulkheads must be firmly tied-back, and extended landward at both ends to prevent flanking. Stone revetment placed in front of the bulkheads will help prevent scouring from wave reflection and enable sand to be trapped between the stones.

Alternatively, a dune could be built extending from the present bulkhead south. If designed and maintained properly, the dune can protect the town against wave action without the scouring of the beach face which can occur with a bulkhead. Another option is to construct a stone revetment south from the present bulkhead. Although the dune line at the northern end of Bethany was damaged by the October storm, it probably is not necessary to extend the bulkhead or stone revetment to the northern town limits at this time because the beach is wider in this area and the dune is more pronounced.

The dunes north and south of Bethany are presently narrow and discontinuous which means they provide little protection against a major storm. It is advisable to repair the dune line and enlarge the dunes.

A tenth groin constructed at the end of Cedarwood Street would complete the groin field so the entire Bethany ocean front would be protected. The additional groin would also prevent downdrift erosion south of Maplewood Street. Although the distance between Maplewood and Cedarwood Streets is about the same as the distance between the other groins, a short groin may be sufficient because of the location. Downdrift erosion could also be reduced if a short groin was constructed.

It is expedient to remember the disastrous effects of the last major storm. Figures 9-1 and 9-2 are views of Bethany Beach before and after the March 1962 storm. Many of the beach-front houses were totally destroyed and others were severely damaged. The areas of overwash and flooding are still obvious seven months later by their lack of vegetation. It must be noted that by the time the second photograph was taken the beach and boardwalk had already been repaired by Operation FIVE-HIGH. While the shoreline has remained relatively stable over the last

Figure 9-1: Bethany Beach before the March 1962 storm.

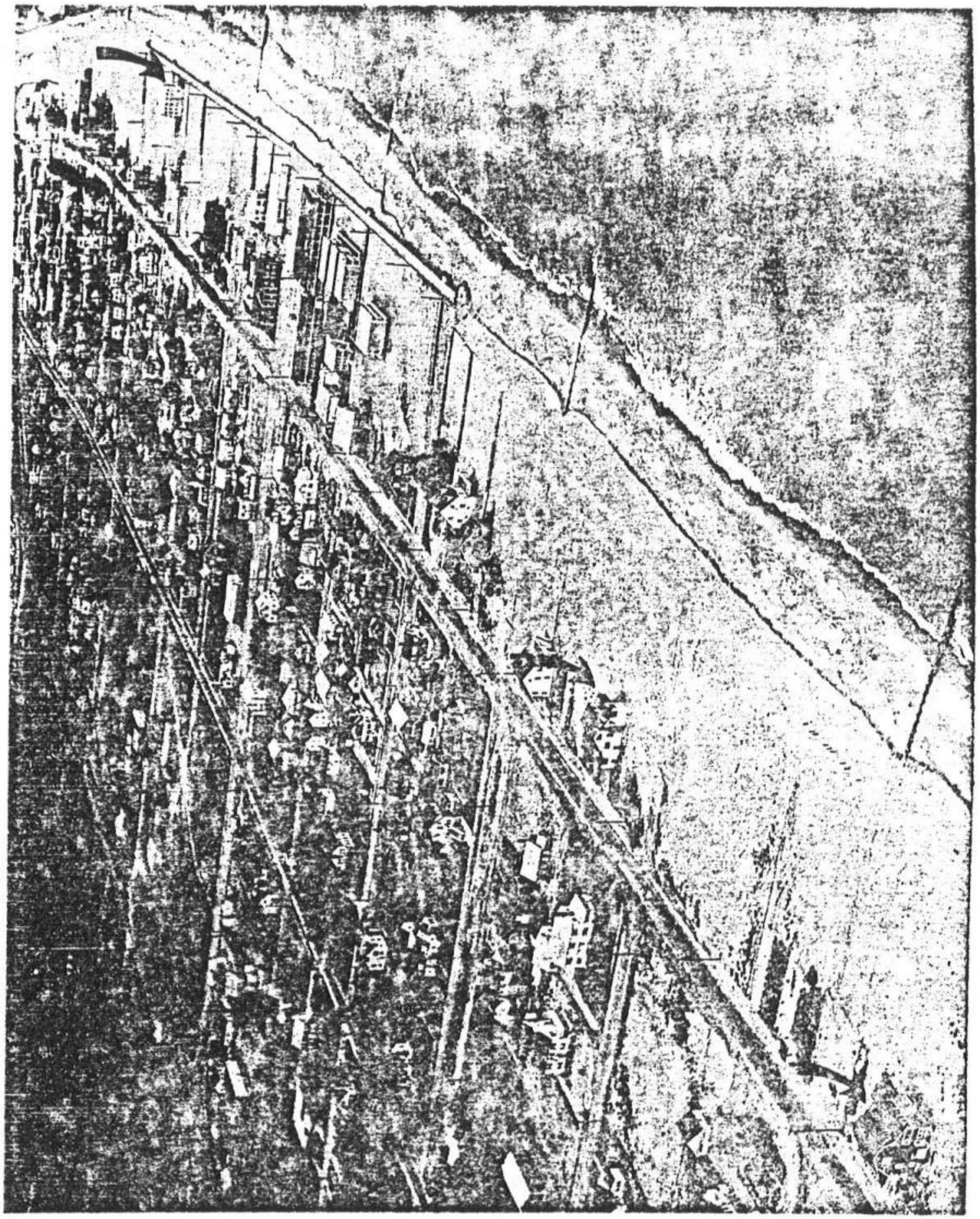


Figure 9-2: Bethany Beach in October 1962. Note the disappearance of several houses and the areas that were affected by flooding and washover. The arrows help identify the houses.

twenty years, the repairs necessary to protect Bethany Beach need to be made before the next hurricane.

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APPENDIX A

BEACH PROFILE DATA

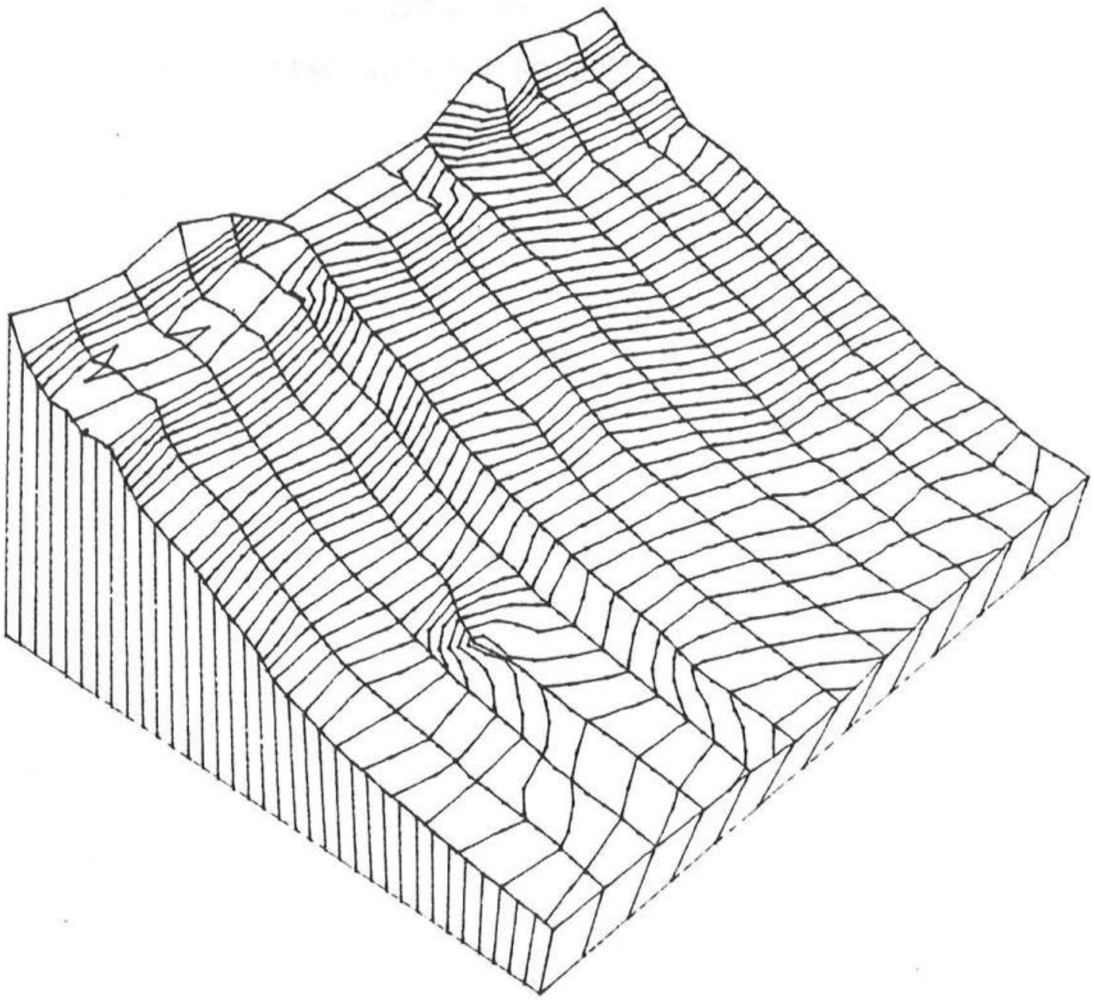

Figure A-1: Beach profile 4 May 1982.

P1		P3		P5		P7		P9		P11		P13
11.50	11.90	13.80	12.70	6.80	6.60	6.55	6.00	11.70	14.60	11.80	12.60	14.75
10.30	11.80	10.60	12.50	5.20	6.20	6.20	6.25	5.80	8.00	9.40	7.90	10.00
7.40	8.20	7.30	12.40	3.65	6.00	6.00	5.50	6.00	5.60	6.70	5.50	7.40
6.40	6.75	6.45	6.00	2.50	4.50	4.60	3.40	5.60	5.90	6.00	6.20	5.70
5.60	5.90	5.40	4.50	1.90	4.45	4.60	1.50	4.45	5.75	6.30	5.80	5.70
4.30	4.30	3.10	3.40	0.90	2.50	2.65	-0.10	4.45	4.60	5.50	4.90	3.90
2.00	2.10	1.10	2.20	-0.45	0.00	0.20	-1.80	2.20	4.80	4.80	4.90	4.20
-0.30	0.35	0.80	1.00	-1.70	-1.70	-1.60	-3.15	-0.40	1.80	2.40	0.80	3.90
-0.80	0.00	0.20	0.00	-2.80	-3.40	-3.20	-4.30	-2.20	-0.40	0.45	-1.55	0.90
-1.45	-0.50	-1.00	-1.10	-3.40	-4.65	-5.15	-5.60	-3.40	-2.40	-1.75	-2.70	-2.00
-2.10	-1.70	-2.10	-2.40	-4.60	-6.00	-6.40	-6.80	-4.40	-3.40	-3.60	-3.60	-3.00
-3.10	-2.40	-3.20	-3.20	-6.00	-7.30	-8.00	-8.70	-5.40	-4.40	-5.40	-4.60	-4.00
-4.20	-3.60	-4.30	-4.40	-7.20	-8.80	-8.70	-10.40	-7.30	-5.90	-7.10	-5.85	-4.85
-5.30	-4.80	-5.30	-5.80	-8.80	-10.20	-10.50	-11.70	-9.50	-7.85	-9.00	-8.40	-6.40
-6.40	-6.00	-6.45	-7.00	-10.20	-11.40	-11.15	-13.00	-10.90	-9.50	-10.75	-9.65	-8.00
-7.40	-7.10	-7.50	-8.35	-11.35	-12.90	-12.00	-14.20	-12.20	-11.00	-11.80	-11.20	-9.60
-8.50	-8.40	-8.60	-9.50	-12.40	-14.40	-14.00	-15.25	-13.60	-12.50	-12.80	-12.80	-11.00
-9.70	-9.50	-9.60	-10.70	-13.60	-16.00	-15.50	-16.40	-15.00	-14.00	-13.90	-14.20	-12.35
-10.90	-10.70	-10.70	-12.00	-14.70	-16.90	-17.00	-17.40	-16.20	-14.40	-14.80	-15.60	-15.00
-12.00	-12.00	-12.00	-13.00	-15.90	-17.75	-18.00	-18.30	-16.90	-16.40	-15.80	-16.80	-16.10
-13.00	-13.20	-13.40	-14.00	-17.00	-18.60	-18.80	-19.20	-17.50	-20.20	-16.80	-17.80	-17.00
-14.10	-14.45	-14.80	-15.20	-18.20	-19.25	-19.60	-20.15	-18.70	-22.60	-17.70	-18.30	-18.00
-15.20	-16.30	-16.30	-16.65	-19.10	-20.00	-20.40	-21.00	-19.75	-22.35	-18.70	-18.85	-19.00
-16.30	-16.70	-18.00	-18.15	-19.80	-20.50	-21.40	-21.60	-20.30	-22.10	-19.60	-19.30	-19.65
-17.70	-17.60	-18.75	-19.20	-20.50	-21.20	-22.00	-22.20	-21.00	-22.30	-20.20	-19.75	-20.20
-18.70	-19.10	-19.20	-20.00	-21.10	-21.80	-22.70	-22.80	-21.45	-22.95	-20.80	-20.30	-20.80
-19.60	-20.00	-19.75	-20.40	-21.40	-22.35	-23.50	-23.50	-22.10	-23.40	-21.30	-20.90	-21.20
-20.20	-20.75	-20.75	-21.20	-21.75	-23.00	-24.20	-24.30	-22.70	-23.80	-22.00	-21.90	-21.80
-20.80	-21.30	-21.70	-22.00	-22.20	-23.55	-24.60	-25.30	-23.30	-24.00	-22.80	-22.20	-22.20
-21.40	-21.90	-22.40	-22.60	-23.00	-24.10	-25.20	-26.20	-23.85	-24.35	-23.70	-22.50	-22.80
-22.30	-22.50	-23.20	-23.00	-23.60	-24.60	-25.70	-26.75	-24.40	-24.60	-24.00	-22.90	-23.20
-23.20	-22.90	-23.50	-23.90	-24.20	-25.10	-26.20	-27.00	-24.90	-25.00	-24.30	-23.20	-23.70
-24.00	-23.30	-23.80	-24.40	-24.60	-25.60	-26.80	-27.40	-25.50	-25.40	-24.60	-23.75	-24.00
-24.30	-23.70	-24.10	-24.60	-25.00	-26.00	-27.40	-27.60	-26.10	-25.80	-25.00	-24.40	-24.40
-24.60	-24.10	-24.25	-25.00	-25.10	-26.45	-28.00	-28.15	-26.60	-26.20	-25.50	-25.10	-24.80
-25.00	-24.90	-24.80	-25.80	-25.40	-27.00	-28.50	-28.70	-27.20	-26.75	-26.00	-25.80	-25.20

Table A-1: Beach profile data 4 May 1982.

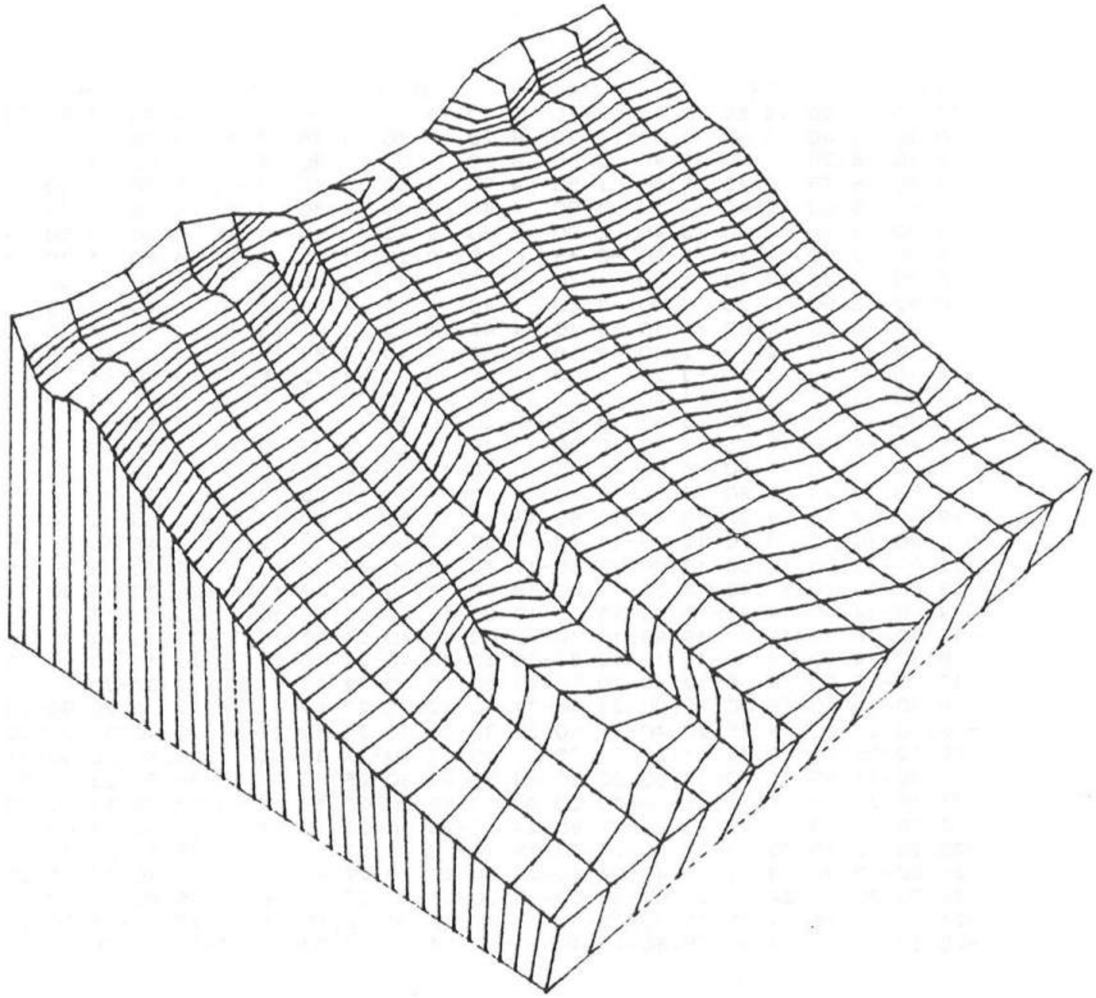

Figure A-2: Beach profile 15 June 1982.

11.40	11.80	13.75	12.75	6.80	6.80	7.00	7.20	11.60	14.60	12.00	12.30	14.60
10.15	11.80	11.20	12.45	6.50	6.65	7.60	7.45	6.20	8.00	9.55	7.55	10.60
7.50	7.60	7.30	12.40	5.85	5.60	7.00	5.75	7.40	6.80	6.75	6.20	7.00
7.00	7.00	6.90	6.90	4.50	4.45	4.00	2.70	7.40	7.30	7.20	7.20	6.50
6.40	6.10	6.90	6.40	2.80	3.00	1.65	1.00	5.20	7.00	7.00	7.70	7.30
5.65	4.70	4.90	4.65	1.70	1.60	0.15	0.00	2.80	4.60	4.20	5.90	7.40
4.30	3.15	3.00	2.20	0.60	0.25	-0.75	-1.30	1.00	2.00	2.10	3.00	6.00
2.45	2.00	1.10	1.40	-0.75	-1.00	-2.30	-3.00	-0.70	-0.10	0.00	0.70	3.60
1.20	1.25	0.50	0.60	-2.20	-2.00	-3.80	-4.50	-1.85	-1.80	-1.60	-1.00	1.40
0.80	0.50	-0.10	-0.90	-3.90	-3.80	-6.30	-6.10	-3.40	-3.20	-3.00	-2.60	-0.20
-0.25	-1.35	-1.80	-2.55	-5.60	-5.60	-6.75	-7.60	-4.90	-4.50	-4.40	-4.10	-1.90
-1.80	-2.75	-3.60	-4.20	-7.20	-5.70	-8.20	-8.90	-6.40	-5.80	-5.80	-5.60	-3.50
-3.50	-4.15	-5.50	-5.20	-8.20	-9.10	-9.70	-10.00	-7.85	-7.00	-7.30	-7.00	-5.50
-5.20	-5.60	-7.40	-6.75	-9.10	-10.20	-11.00	-11.60	-9.10	-8.35	-8.90	-8.40	-7.00
-6.95	-6.95	-9.20	-8.75	-10.50	-11.50	-11.40	-12.70	-10.60	-9.55	-10.00	-9.60	-7.40
-8.60	-8.40	-10.55	-10.00	-11.85	-12.60	-12.80	-13.55	-12.20	-11.00	-11.00	-10.90	-9.50
-10.15	-10.00	-11.15	-11.10	-13.20	-13.40	-14.15	-14.75	-13.20	-12.60	-12.15	-12.00	-11.30
-11.20	-11.15	-11.80	-11.90	-14.05	-15.50	-15.15	-16.00	-13.75	-13.30	-13.45	-13.05	-12.70
-12.30	-12.35	-13.00	-12.20	-14.80	-15.80	-16.20	-17.30	-14.60	-14.30	-14.80	-14.20	-14.20
-13.35	-13.55	-14.30	-13.40	-16.00	-17.40	-17.20	-18.50	-16.00	-16.15	-16.00	-15.40	-15.40
-14.25	-14.25	-15.40	-14.50	-17.10	-18.20	-18.20	-18.80	-17.00	-18.40	-16.90	-16.60	-16.40
-15.15	-15.00	-16.45	-15.95	-18.30	-18.80	-19.15	-20.00	-17.75	-21.00	-17.90	-17.40	-17.40
-16.00	-15.80	-17.40	-17.30	-19.00	-20.00	-20.00	-20.60	-18.60	-21.50	-18.75	-18.20	-18.15
-16.90	-17.20	-17.80	-18.60	-19.80	-20.75	-20.60	-21.10	-19.80	-21.50	-19.50	-19.00	-19.00
-18.00	-18.65	-19.00	-19.10	-20.60	-20.80	-21.60	-21.70	-21.00	-22.00	-20.40	-19.80	-19.80
-18.80	-18.70	-19.80	-20.00	-21.10	-21.80	-22.70	-22.20	-21.20	-22.45	-21.10	-20.60	-20.55
-19.80	-18.80	-20.50	-20.70	-21.50	-22.35	-23.50	-22.90	-21.50	-23.00	-21.75	-21.10	-21.00
-20.50	-20.80	-21.10	-21.40	-22.00	-23.00	-24.20	-23.80	-21.90	-23.40	-22.40	-21.80	-21.45
-21.20	-21.50	-22.00	-22.00	-22.20	-23.55	-24.60	-24.80	-22.50	-23.80	-23.00	-22.30	-22.00
-22.00	-22.45	-23.00	-22.65	-23.00	-24.10	-25.20	-25.65	-23.15	-24.00	-23.30	-23.00	-22.45
-22.30	-23.35	-23.70	-23.00	-23.60	-24.60	-25.70	-26.20	-23.80	-24.40	-23.75	-23.40	-23.00
-23.20	-23.90	-24.00	-23.90	-24.20	-25.10	-26.20	-26.80	-24.50	-24.60	-24.30	-23.75	-23.45
-24.00	-24.20	-24.40	-24.40	-24.60	-25.60	-26.80	-27.20	-25.50	-25.40	-24.60	-24.10	-23.90
-24.30	-24.50	-24.60	-24.60	-25.00	-26.00	-27.40	-27.60	-26.10	-25.80	-25.00	-24.50	-24.35
-24.60	-24.80	-25.00	-25.00	-25.10	-26.45	-28.00	-28.15	-26.60	-26.20	-25.50	-25.10	-24.80
-25.00	-25.00	-25.20	-25.80	-25.40	-27.00	-28.50	-28.70	-27.20	-26.75	-26.00	-25.80	-25.20

Table A-2: Beach profile data 15 June 1982.

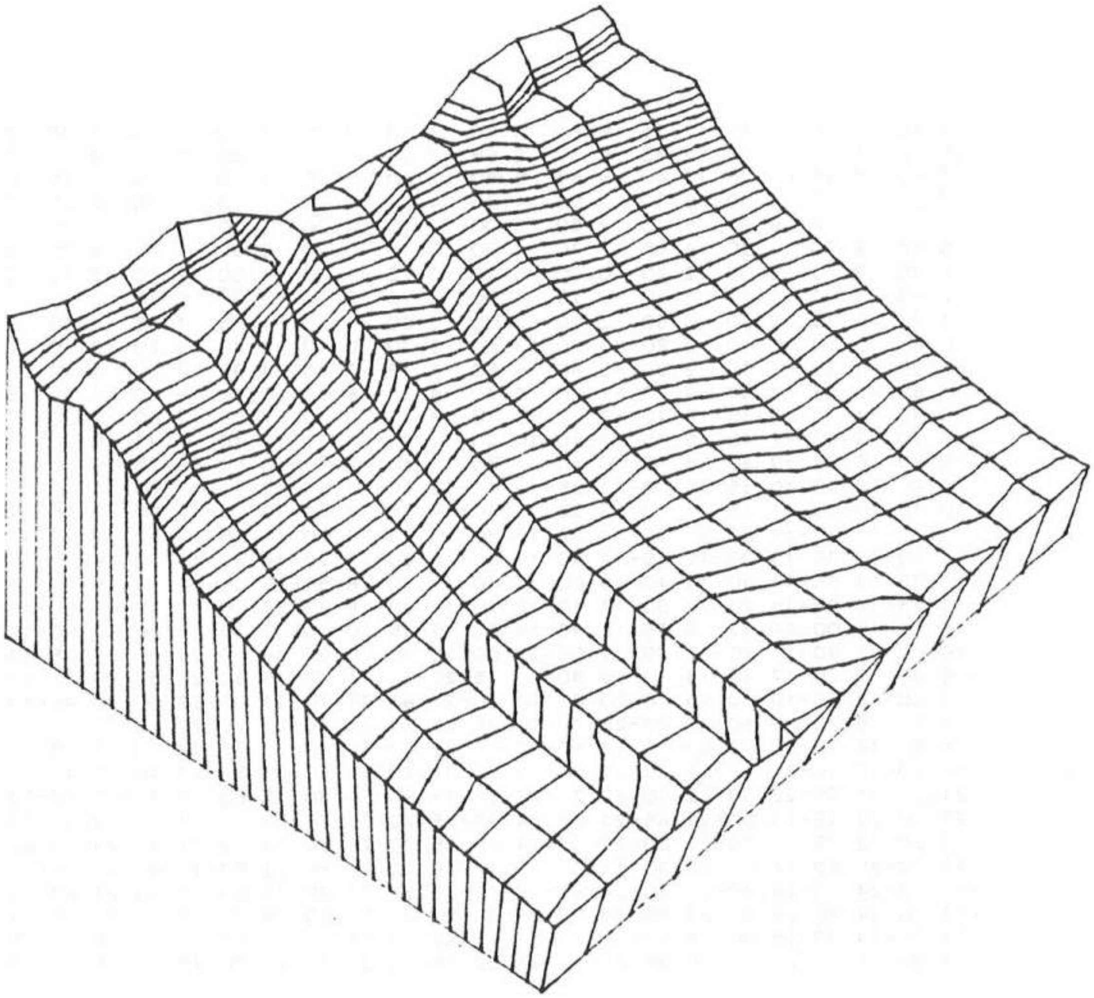

Figure A-3: Beach profile 2 August 1982.

11.40	11.90	13.80	12.70	6.80	7.45	7.20	6.50	11.70	14.60	12.00	12.30	14.60
10.30	11.80	11.00	12.50	6.80	6.80	7.60	6.50	7.10	8.00	9.40	7.90	9.70
7.40	8.00	7.40	12.40	6.60	6.40	7.20	5.90	7.40	7.20	6.70	6.60	7.40
7.10	7.10	7.30	7.10	4.00	3.20	6.00	3.80	7.60	7.70	7.20	7.30	6.40
6.50	6.80	7.00	6.70	1.90	1.50	3.65	2.00	5.10	7.20	7.40	7.70	7.10
6.40	6.20	6.40	6.00	0.20	0.20	2.00	0.20	1.00	5.20	7.15	6.90	7.60
6.45	6.20	4.00	2.90	-1.00	-1.10	0.65	-2.60	0.10	3.60	6.70	6.00	6.60
6.50	4.00	1.65	0.50	-2.00	-2.10	-0.40	-3.70	-0.40	2.00	5.10	4.80	5.30
3.80	1.00	-0.70	-1.00	-4.00	-4.00	-1.80	-5.00	-1.50	0.00	2.90	1.90	3.10
0.80	-1.00	-2.10	-2.20	-5.20	-5.75	-3.40	-6.20	-2.80	-1.50	0.60	-2.40	0.80
-1.00	-2.60	-3.60	-4.00	-6.60	-7.15	-5.35	-7.50	-4.35	-3.20	-1.60	-3.80	-2.00
-2.70	-3.85	-5.00	-5.80	-7.60	-8.30	-7.30	-9.00	-6.10	-5.20	-4.40	-5.00	-4.10
-4.00	-5.00	-6.20	-7.60	-8.60	-9.40	-9.20	-10.10	-8.00	-7.40	-7.20	-6.80	-6.50
-5.50	-6.00	-7.20	-8.40	-9.70	-10.55	-10.50	-11.35	-9.50	-8.60	-9.00	-8.30	-8.60
-6.70	-7.40	-8.20	-9.30	-10.90	-11.70	-11.70	-12.60	-11.00	-10.00	-10.00	-10.00	-9.75
-7.80	-8.60	-9.20	-10.20	-12.00	-12.90	-12.80	-13.80	-12.70	-11.40	-11.20	-11.70	-10.90
-8.80	-10.00	-10.20	-11.20	-12.90	-14.10	-13.90	-15.00	-14.10	-12.50	-12.50	-13.40	-12.00
-9.85	-11.10	-11.20	-12.00	-14.00	-15.20	-14.90	-16.20	-15.55	-14.10	-13.70	-14.50	-13.00
-10.90	-12.30	-12.20	-12.90	-15.00	-16.20	-16.00	-17.50	-16.40	-15.40	-15.00	-15.30	-14.10
-11.90	-13.60	-13.20	-13.70	-16.00	-17.35	-17.10	-18.70	-17.10	-16.60	-16.00	-16.10	-15.20
-13.00	-14.60	-14.20	-14.70	-17.00	-18.35	-18.10	-19.30	-18.00	-17.90	-17.00	-16.90	-16.20
-14.10	-15.20	-15.30	-15.50	-18.10	-19.30	-19.35	-20.10	-19.00	-19.40	-17.40	-17.70	-17.30
-15.20	-16.40	-16.40	-16.50	-19.00	-20.00	-20.30	-20.80	-19.70	-20.20	-18.00	-18.40	-18.20
-16.30	-17.20	-17.10	-17.40	-20.00	-20.50	-21.40	-21.45	-20.30	-20.80	-18.70	-19.20	-18.80
-17.10	-18.00	-18.00	-18.20	-20.80	-21.20	-22.00	-22.20	-21.00	-21.30	-19.30	-20.00	-19.45
-18.10	-19.00	-18.80	-19.10	-21.10	-21.60	-22.70	-23.00	-21.40	-22.10	-20.00	-20.80	-20.00
-18.90	-19.90	-19.60	-20.00	-21.70	-22.20	-23.30	-23.60	-22.00	-22.50	-20.70	-21.40	-20.60
-19.70	-20.75	-20.40	-20.85	-22.20	-22.80	-24.10	-24.10	-22.50	-23.00	-21.40	-21.90	-21.20
-20.40	-21.30	-21.20	-21.80	-22.60	-23.40	-24.60	-24.60	-23.10	-23.60	-22.00	-22.20	-21.80
-21.20	-21.90	-22.00	-22.60	-23.10	-24.00	-25.20	-25.10	-23.85	-24.35	-22.60	-22.80	-22.70
-22.00	-22.50	-22.50	-23.20	-23.50	-24.40	-25.70	-25.70	-24.20	-24.60	-23.10	-23.30	-23.10
-22.70	-22.90	-23.00	-23.60	-24.00	-24.80	-26.10	-26.20	-24.70	-25.00	-23.70	-23.60	-23.50
-23.40	-23.45	-23.40	-24.00	-24.20	-25.30	-26.60	-26.80	-25.20	-25.40	-24.20	-24.10	-24.00
-23.70	-24.00	-23.80	-24.60	-24.60	-25.90	-27.00	-27.25	-25.70	-25.60	-24.80	-24.40	-24.40
-24.10	-24.60	-24.30	-25.00	-24.90	-26.45	-27.45	-27.85	-26.20	-26.10	-25.30	-25.10	-24.80
-24.40	-25.00	-24.70	-25.80	-25.20	-27.00	-28.00	-28.70	-26.70	-26.40	-25.80	-25.70	-25.20

Table A-3: Beach profile data 2 August 1982.

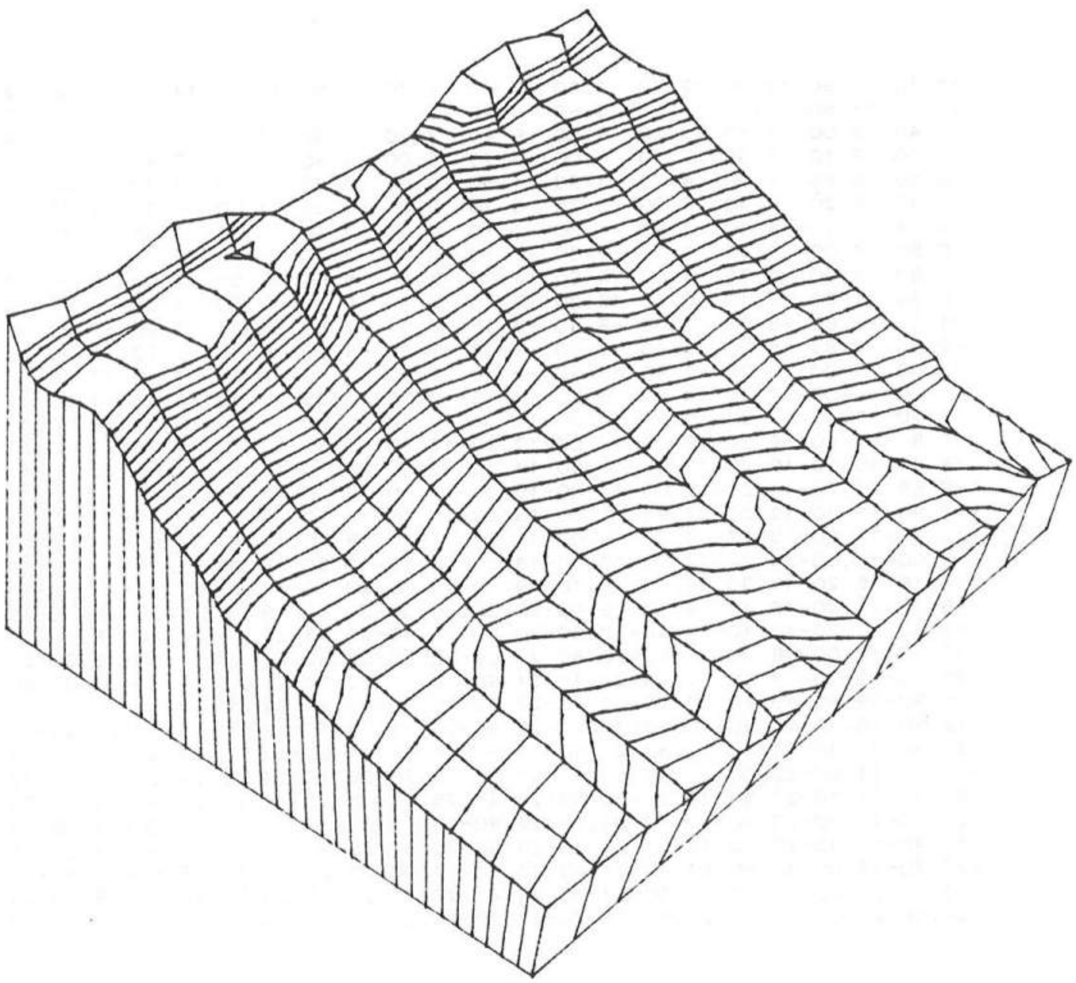

Figure A-4: Beach profile 16 September 1982.

11.40	11.60	13.80	13.00	6.80	7.10	7.30	7.40	11.60	14.70	12.00	12.30	14.60
9.50	12.00	11.00	12.50	6.30	6.40	7.40	7.50	6.75	8.00	8.90	7.80	9.70
7.60	8.00	7.80	12.40	6.20	5.90	7.30	7.30	7.00	7.20	7.00	6.60	7.00
7.00	7.20	6.80	7.00	3.50	4.40	6.40	5.30	7.30	7.60	7.10	7.60	6.80
6.50	6.50	6.65	6.70	1.30	2.45	4.30	2.60	6.80	7.40	7.40	7.80	7.40
6.40	6.60	5.60	3.80	0.10	0.00	2.00	0.40	5.50	6.80	7.60	7.80	7.80
6.60	5.30	2.70	1.00	-1.00	-1.10	-0.20	-1.60	2.60	4.60	7.60	6.10	7.80
4.20	2.20	2.00	0.00	-2.20	-2.20	-2.00	-2.60	0.05	1.50	4.40	3.50	6.40
2.10	0.50	1.10	-1.00	-3.20	-3.00	-3.00	-3.50	-2.05	-0.60	0.70	1.30	4.00
0.40	-1.00	-0.70	-2.10	-4.20	-4.40	-4.20	-4.30	-3.50	-2.20	-2.30	-0.95	1.30
-0.80	-2.20	-2.30	-3.40	-5.80	-5.70	-5.20	-6.10	-5.00	-3.60	-4.00	-3.00	-2.10
-1.90	-3.40	-3.30	-4.30	-7.20	-8.40	-6.70	-8.10	-6.40	-5.20	-6.00	-4.60	-3.45
-3.30	-4.70	-6.00	-5.20	-9.20	-9.80	-7.90	-9.40	-9.20	-7.20	-7.80	-6.30	-4.90
-4.50	-6.00	-6.40	-6.30	-10.20	-10.70	-9.30	-10.20	-10.60	-8.80	-9.60	-8.55	-6.20
-5.50	-7.20	-8.10	-7.90	-10.40	-11.55	-10.70	-12.00	-11.75	-11.00	-10.40	-10.90	-8.60
-7.00	-8.30	-10.00	-9.50	-11.40	-12.40	-12.20	-14.00	-13.00	-11.80	-11.20	-12.40	-11.60
-8.60	-9.10	-11.80	-10.50	-12.50	-13.20	-13.20	-14.90	-14.10	-12.80	-12.20	-13.20	-12.10
-10.10	-10.60	-11.80	-11.50	-13.50	-13.30	-13.60	-16.00	-15.20	-13.80	-13.50	-14.00	-12.70
-11.00	-12.50	-12.50	-12.50	-14.60	-14.00	-14.80	-17.00	-16.00	-14.60	-14.75	-15.10	-13.60
-11.80	-13.10	-13.60	-13.60	-15.70	-15.00	-16.00	-18.00	-17.00	-15.80	-15.80	-16.20	-14.60
-12.60	-13.50	-14.80	-14.50	-16.70	-15.90	-17.20	-19.00	-17.80	-16.90	-16.90	-17.30	-15.40
-13.50	-14.80	-16.00	-15.40	-17.80	-16.80	-18.40	-19.40	-18.40	-18.40	-17.75	-17.90	-16.20
-14.60	-15.20	-17.10	-16.40	-18.60	-17.80	-19.60	-20.00	-18.60	-20.00	-18.40	-18.45	-17.00
-16.00	-16.00	-18.10	-17.30	-19.30	-18.00	-20.10	-20.35	-20.10	-21.00	-19.00	-19.00	-17.90
-16.70	-17.00	-19.10	-18.20	-20.10	-19.20	-20.70	-21.20	-20.40	-21.40	-19.70	-19.70	-18.80
-16.80	-18.00	-20.20	-18.90	-20.90	-19.70	-21.20	-22.00	-20.60	-22.00	-20.30	-20.20	-19.50
-18.00	-19.10	-20.80	-19.50	-21.50	-20.20	-22.00	-22.70	-21.10	-22.40	-21.00	-20.80	-20.40
-20.40	-20.10	-21.30	-20.30	-21.40	-20.70	-22.40	-23.40	-21.70	-23.00	-21.40	-21.20	-21.00
-21.00	-20.70	-21.90	-21.00	-21.40	-21.20	-23.00	-24.00	-22.30	-23.50	-22.00	-21.80	-21.40
-21.40	-20.90	-22.10	-21.70	-22.00	-22.00	-23.40	-24.40	-22.90	-24.20	-22.40	-22.20	-21.85
-21.90	-21.00	-22.20	-22.40	-22.60	-22.70	-24.10	-24.80	-23.50	-24.60	-23.00	-22.80	-22.20
-22.20	-21.20	-22.40	-23.20	-23.15	-23.20	-24.80	-25.20	-24.10	-25.00	-23.40	-23.20	-22.65
-22.80	-21.40	-23.00	-23.90	-23.75	-23.20	-25.20	-25.80	-24.80	-25.40	-24.00	-23.60	-23.05
-23.20	-21.70	-23.90	-24.60	-24.10	-23.30	-25.80	-26.60	-25.40	-26.00	-24.60	-24.00	-23.50
-23.60	-21.80	-24.80	-25.00	-24.40	-24.00	-26.40	-27.40	-26.00	-26.60	-25.10	-24.40	-24.00
-24.10	-22.00	-25.20	-25.20	-24.90	-24.70	-26.60	-28.80	-26.60	-27.30	-25.60	-25.05	-24.50

Table A-4: Beach profile data 16 September 1982.

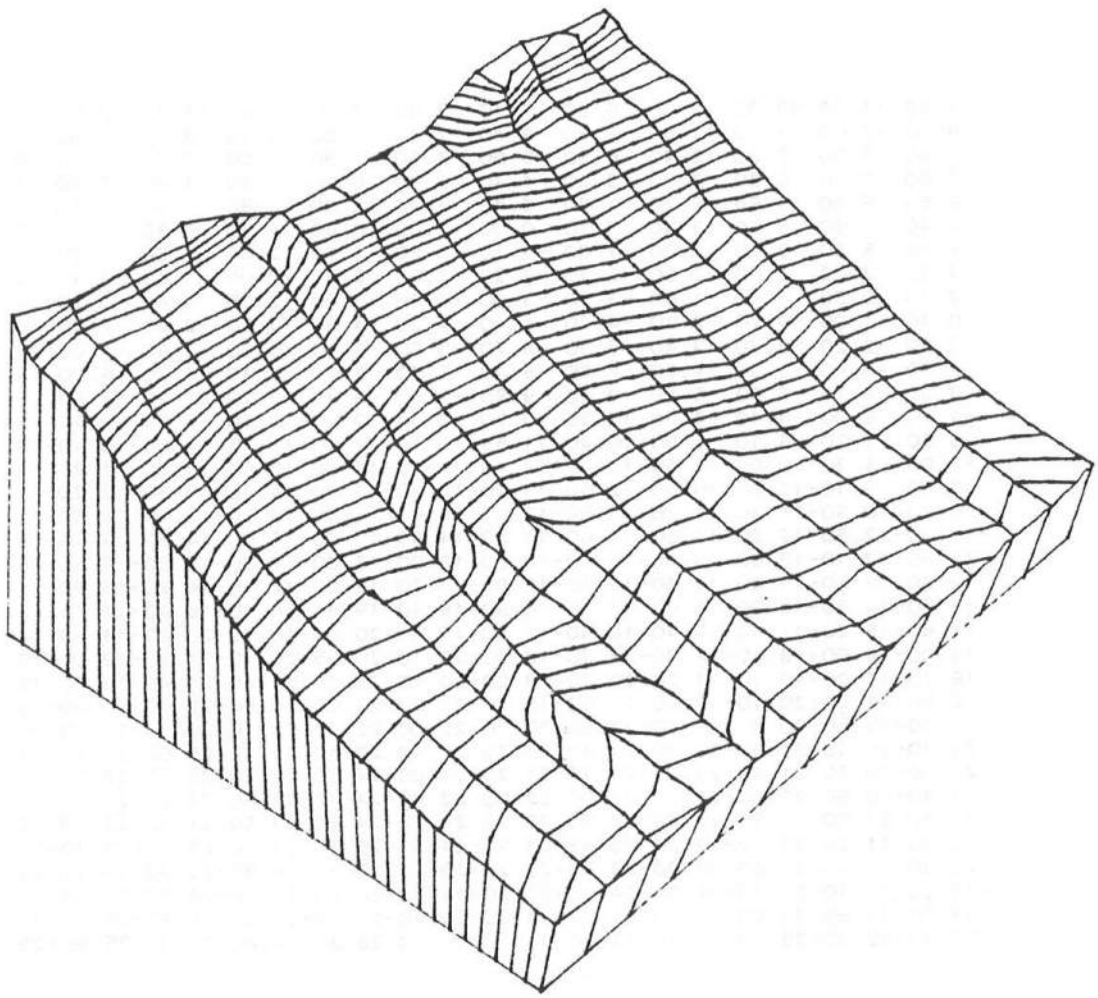

Figure A-5: Beach profile 19 October 1982.

11.40	11.60	13.80	13.00	7.60	8.15	7.40	7.60	11.60	14.70	12.00	12.30	14.60
10.50	12.00	11.50	12.50	6.90	7.60	7.30	6.50	7.95	9.00	9.90	8.80	10.80
8.50	8.90	8.20	12.40	6.00	6.40	6.60	5.20	7.45	8.00	8.50	8.00	9.00
7.40	7.50	6.80	7.20	5.50	4.60	4.90	3.80	6.80	7.70	7.60	7.40	8.70
6.80	6.20	5.60	5.50	3.40	3.10	1.50	1.60	4.70	7.00	6.30	6.90	8.00
6.00	5.60	5.50	5.40	0.90	0.80	-0.20	0.10	2.90	4.80	4.55	5.10	6.60
5.70	5.10	4.20	3.60	-0.60	-0.90	-1.30	-1.40	1.20	2.00	2.40	2.50	4.90
4.40	3.60	2.30	1.50	-1.00	-2.30	-2.20	-2.80	-0.80	-0.40	0.00	1.70	2.90
2.60	1.70	0.80	0.00	-2.20	-3.60	-3.60	-4.00	-2.60	-2.00	-2.25	-0.10	0.70
0.60	-0.10	-1.00	-1.20	-3.30	-5.00	-4.80	-5.30	-4.35	-3.50	-3.85	-1.90	-1.20
-0.90	-1.80	-2.50	-2.50	-4.40	-6.15	-5.90	-6.60	-5.40	-4.65	-5.20	-4.00	-3.20
-1.40	-3.70	-3.35	-3.50	-5.60	-7.40	-7.20	-7.80	-6.50	-5.80	-6.50	-6.00	-4.40
-2.60	-5.00	-4.20	-4.60	-6.80	-8.75	-8.40	-9.40	-9.40	-6.90	-7.70	-8.00	-5.70
-4.00	-5.85	-5.00	-5.80	-8.10	-10.00	-9.60	-10.80	-10.60	-8.00	-8.90	-9.20	-6.90
-5.00	-6.20	-6.00	-6.80	-9.30	-11.20	-10.80	-12.30	-11.80	-9.10	-10.50	-10.55	-8.60
-6.10	-7.20	-6.90	-7.90	-10.45	-12.50	-12.10	-13.80	-13.30	-10.30	-12.00	-11.90	-10.40
-7.20	-8.55	-8.00	-8.90	-11.60	-13.50	-13.40	-15.40	-14.80	-11.60	-13.50	-13.20	-12.10
-8.30	-9.90	-9.10	-10.00	-12.80	-14.40	-14.40	-16.90	-16.10	-12.80	-15.20	-14.60	-13.30
-9.30	-10.20	-10.50	-11.00	-14.00	-15.40	-15.50	-18.10	-16.50	-14.00	-15.00	-15.40	-14.60
-10.40	-12.50	-11.70	-12.10	-15.40	-16.20	-16.40	-18.20	-16.90	-15.10	-15.20	-16.10	-15.80
-12.00	-13.70	-13.00	-13.90	-17.20	-17.20	-17.30	-18.35	-17.80	-16.30	-16.10	-16.90	-16.80
-13.50	-15.10	-14.20	-15.80	-19.10	-18.20	-18.40	-18.75	-18.65	-17.50	-17.00	-17.80	-17.40
-15.00	-16.20	-15.40	-17.40	-19.50	-19.00	-19.50	-19.30	-19.10	-18.70	-17.90	-18.50	-18.00
-16.00	-17.30	-16.90	-18.20	-20.00	-19.60	-20.40	-20.00	-19.50	-19.90	-18.80	-19.10	-18.70
-16.65	-18.10	-18.20	-19.10	-20.20	-20.20	-21.40	-20.60	-20.00	-21.20	-19.70	-19.90	-19.30
-17.50	-19.00	-19.55	-20.20	-20.70	-20.80	-22.00	-21.20	-20.40	-22.10	-20.70	-20.60	-20.00
-18.30	-19.80	-20.00	-20.55	-21.10	-21.40	-22.50	-21.80	-21.25	-23.10	-21.30	-21.25	-20.60
-19.10	-20.60	-20.40	-21.00	-21.50	-21.90	-23.00	-22.40	-22.10	-23.70	-21.80	-21.90	-21.30
-19.90	-21.10	-20.85	-21.40	-21.90	-22.40	-23.80	-23.00	-22.90	-23.90	-22.40	-22.40	-21.90
-20.50	-21.70	-21.20	-21.90	-22.20	-23.00	-24.25	-23.70	-23.00	-24.00	-22.90	-22.90	-22.30
-21.00	-22.40	-21.90	-22.60	-23.00	-23.40	-24.70	-24.20	-23.00	-24.20	-23.35	-23.40	-22.70
-21.50	-23.00	-22.45	-23.20	-24.00	-24.00	-25.10	-24.90	-23.40	-24.40	-23.70	-23.80	-23.00
-22.00	-23.60	-23.00	-24.00	-24.30	-24.40	-25.50	-25.50	-24.10	-24.90	-24.10	-24.30	-23.50
-22.40	-24.20	-23.40	-24.60	-24.70	-25.00	-26.00	-26.00	-24.80	-25.30	-24.50	-24.80	-24.00
-22.90	-24.60	-24.00	-25.00	-25.10	-25.60	-26.40	-26.70	-25.10	-25.40	-25.80	-25.30	-24.50
-23.30	-25.00	-24.50	-25.50	-25.50	-26.10	-26.80	-27.00	-25.70	-26.05	-26.45	-25.90	-24.90

Table A-5: Beach profile data 19 October 1982.

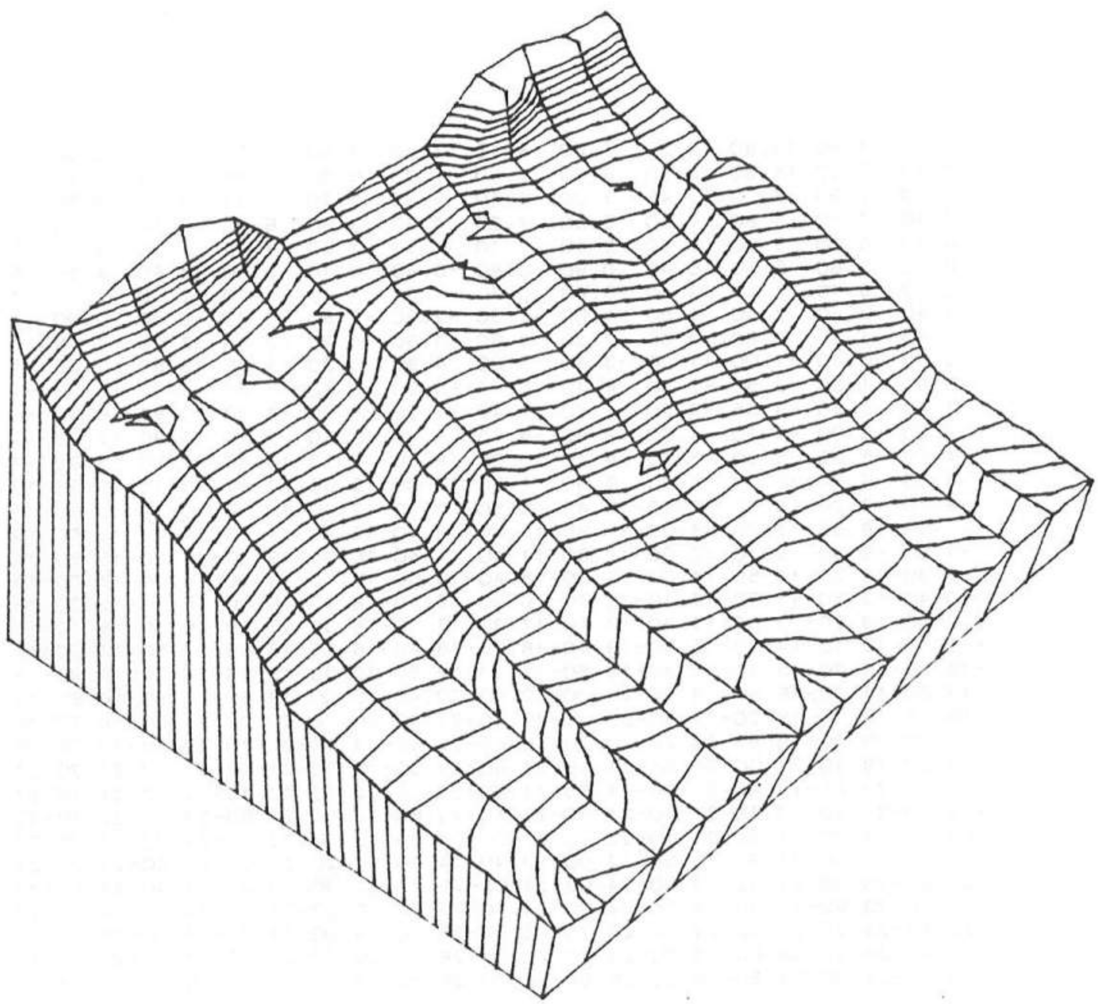

Figure A-6: Beach profile 28 October 1982.

11.40	11.60	13.80	13.00	5.70	5.80	4.80	3.70	11.60	14.70	12.00	8.60	14.60
10.50	11.40	9.60	12.50	3.50	3.40	3.00	2.00	4.80	7.30	7.40	6.00	9.60
7.00	7.10	6.20	12.40	1.90	1.90	1.75	0.60	2.80	4.50	4.80	4.00	6.60
5.00	5.10	3.50	3.10	0.35	1.00	0.70	-0.40	1.40	2.60	2.80	2.00	4.70
3.10	3.30	2.30	2.00	-1.80	-0.50	-0.40	-1.40	-0.40	1.00	0.90	0.50	2.60
2.10	2.60	1.00	0.40	-0.80	-1.20	-2.80	-1.40	1.00	0.00	-0.20	2.20	1.30
1.00	0.40	-0.40	-0.20	-0.80	-2.20	-3.60	-2.80	0.40	0.20	-0.40	2.00	0.50
0.30	-0.10	-1.00	-0.80	-1.20	-1.50	-4.20	-3.60	-0.80	0.00	-0.40	0.90	0.50
-1.30	-1.00	0.20	-0.85	-1.90	-1.80	-4.90	-4.70	-1.70	-0.40	-0.40	-0.20	0.00
-3.00	-1.70	-0.25	-1.10	-2.90	-2.70	-5.60	-5.60	-2.90	-1.60	-1.70	-1.70	-0.10
-1.70	-2.10	-0.90	-1.45	-4.00	-3.60	-6.20	-6.60	-4.40	-3.20	-3.00	-3.00	-1.20
-2.00	-3.25	-1.90	-2.00	-5.30	-4.80	-7.00	-7.70	-5.95	-4.20	-4.60	-4.50	-2.40
-2.40	-4.30	-3.00	-2.50	-6.40	-6.00	-7.60	-8.60	-7.50	-5.60	-6.20	-6.00	-4.00
-3.30	-5.55	-4.20	-4.05	-7.70	-7.00	-8.20	-9.60	-9.00	-6.60	-8.00	-7.50	-5.50
-4.30	-6.70	-5.40	-5.60	-9.00	-8.20	-9.90	-11.00	-10.60	-8.00	-9.50	-9.00	-7.10
-5.40	-7.90	-6.60	-7.00	-9.70	-9.30	-10.30	-14.40	-11.20	-9.20	-11.10	-10.60	-8.70
-6.40	-9.10	-7.80	-8.70	-9.70	-10.60	-11.00	-15.40	-12.40	-10.40	-12.70	-12.30	-10.30
-7.40	-10.10	-9.00	-10.30	-11.85	-12.00	-14.00	-15.90	-14.20	-11.80	-14.30	-14.00	-12.60
-8.60	-11.60	-10.30	-11.90	-14.00	-14.00	-16.10	-16.70	-15.80	-14.70	-16.00	-15.60	-15.10
-9.60	-12.70	-11.50	-13.50	-16.00	-16.20	-17.00	-18.00	-16.90	-17.00	-17.10	-16.80	-17.50
-10.60	-13.70	-12.80	-14.90	-17.10	-15.00	-17.90	-19.20	-17.80	-18.10	-17.50	-18.10	-18.00
-11.90	-15.10	-14.00	-16.10	-18.10	-18.20	-18.60	-20.40	-19.00	-19.40	-18.10	-19.00	-18.70
-13.10	-16.20	-15.20	-17.60	-19.20	-19.20	-20.00	-21.60	-20.00	-20.60	-18.80	-19.60	-19.30
-15.20	-17.30	-16.70	-18.60	-20.00	-20.10	-21.60	-22.40	-21.10	-21.80	-19.40	-20.30	-20.00
-18.20	-18.10	-17.90	-19.60	-20.80	-20.75	-21.40	-23.00	-21.60	-22.60	-20.10	-20.80	-20.60
-20.00	-19.00	-19.00	-20.40	-21.30	-21.45	-21.40	-23.60	-22.10	-23.10	-20.70	-21.20	-21.20
-20.40	-19.80	-20.10	-21.30	-22.10	-22.10	-22.40	-24.10	-22.70	-23.40	-21.30	-21.70	-21.90
-20.80	-20.80	-20.90	-22.20	-22.60	-23.60	-23.40	-24.60	-23.20	-24.60	-22.10	-22.30	-22.40
-21.30	-21.60	-21.60	-23.05	-23.10	-23.20	-24.60	-25.00	-23.90	-25.60	-22.90	-23.00	-22.70
-21.70	-22.50	-22.00	-23.70	-23.70	-23.80	-25.40	-25.30	-24.70	-25.90	-23.50	-23.40	-22.80
-22.20	-23.35	-22.60	-24.20	-24.30	-24.30	-26.20	-25.60	-25.60	-26.20	-24.20	-24.10	-23.00
-22.40	-24.20	-23.10	-24.90	-24.80	-25.00	-26.80	-25.90	-26.40	-26.40	-25.00	-25.00	-23.00
-23.10	-24.50	-23.80	-25.40	-25.10	-25.40	-27.00	-26.10	-26.95	-26.80	-25.40	-25.80	-23.50
-23.80	-25.00	-24.60	-25.90	-25.40	-26.00	-27.20	-26.50	-27.40	-27.00	-26.00	-26.80	-24.00
-24.40	-25.30	-25.00	-26.10	-25.80	-26.50	-27.30	-26.70	-27.90	-27.20	-26.40	-27.50	-24.50
-25.10	-25.60	-25.60	-26.40	-26.10	-27.10	-27.70	-27.00	-28.40	-27.60	-27.00	-27.70	-24.90

Table A-6: Beach profile data 28 October 1982.

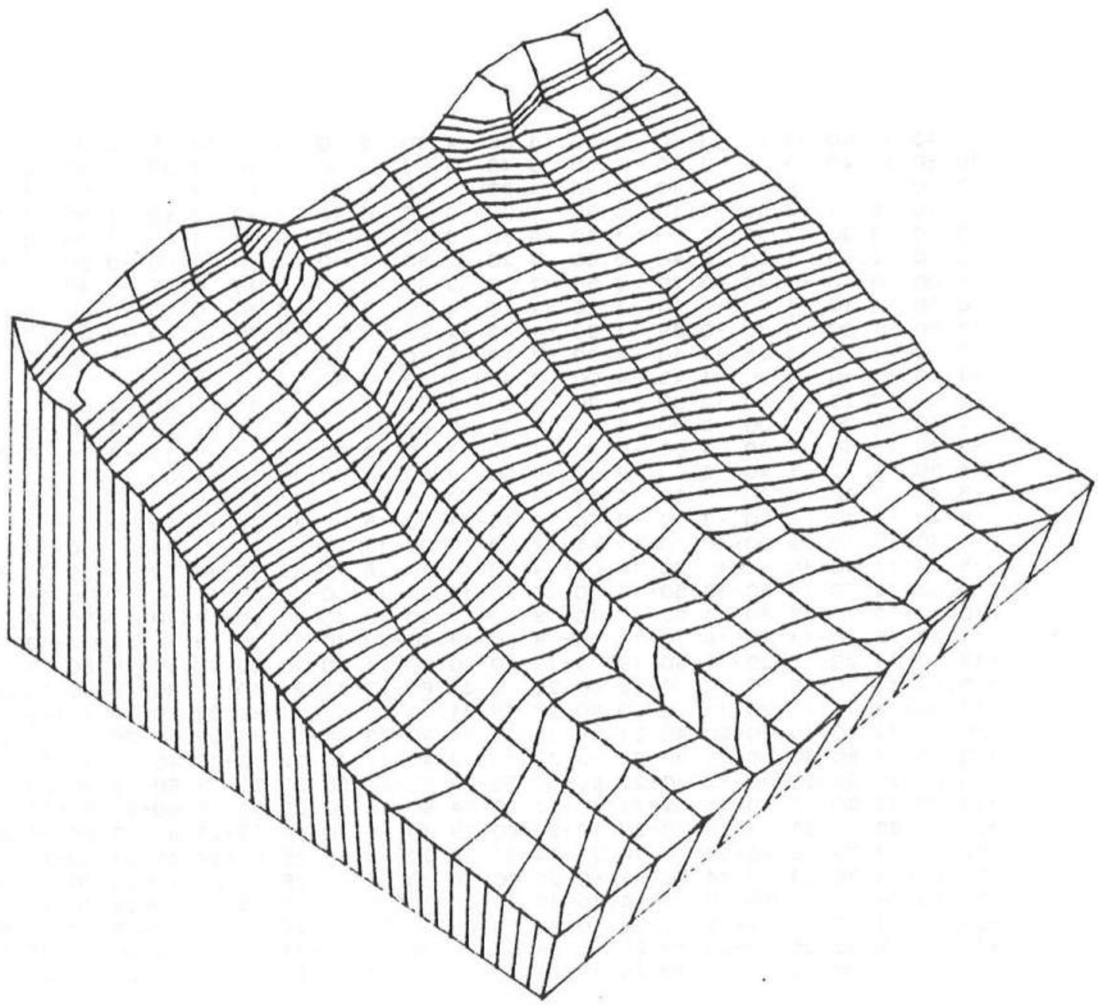

Figure A-7: Beach profile 7 December 1982.

11.65	11.65	13.80	13.00	6.80	6.80	6.75	6.00	11.60	14.60	12.20	8.70	14.70
10.00	12.40	10.70	12.40	5.80	5.60	6.50	4.60	6.60	7.20	7.90	6.50	9.70
7.00	7.40	6.80	12.40	4.10	4.45	4.30	2.60	6.10	5.90	6.60	5.70	6.90
6.00	6.10	6.60	5.80	2.40	2.00	2.50	1.60	4.80	5.10	5.70	5.50	6.30
6.00	6.40	6.30	5.00	1.00	0.50	0.60	0.90	2.90	4.20	4.00	5.15	6.30
5.50	5.10	4.10	3.80	0.00	-0.50	-0.60	-0.10	0.85	2.10	2.20	3.20	4.80
4.45	3.50	1.90	1.80	-1.00	-1.60	-1.80	-1.40	-0.40	0.20	1.00	1.30	2.90
2.90	1.70	1.00	0.40	-1.80	-2.25	-2.40	-2.50	-1.60	-0.50	0.00	0.80	1.10
1.10	0.60	0.00	-0.85	-2.65	-2.90	-3.10	-3.40	-2.10	-1.35	-0.90	0.20	0.70
0.00	-0.40	-1.00	-1.45	-3.10	-3.60	-4.10	-4.80	-2.90	-2.35	-1.40	-0.90	-0.30
-0.90	-1.30	-2.20	-2.35	-3.65	-5.60	-5.60	-6.60	-4.00	-3.70	-3.00	-2.50	-1.90
-1.60	-2.20	-3.00	-3.10	-4.60	-7.40	-7.00	-8.30	-5.60	-5.30	-5.50	-4.50	-3.80
-2.40	-3.10	-3.40	-4.00	-6.20	-9.00	-8.30	-10.00	-8.60	-6.80	-7.40	-6.90	-5.90
-3.20	-4.00	-3.80	-5.00	-7.80	-10.60	-9.70	-11.40	-10.50	-8.10	-9.00	-9.10	-8.00
-4.20	-6.30	-6.90	-6.00	-9.40	-12.30	-11.00	-12.70	-11.90	-9.60	-10.95	-11.40	-9.90
-5.35	-7.70	-8.40	-8.60	-11.00	-13.90	-12.30	-13.90	-13.20	-11.00	-13.20	-12.70	-11.50
-6.50	-8.90	-9.90	-10.80	-12.55	-15.20	-13.60	-15.20	-14.40	-12.50	-13.70	-13.90	-12.90
-8.40	-10.40	-11.40	-12.00	-14.10	-16.60	-15.30	-16.40	-15.50	-13.90	-14.10	-15.00	-14.20
-10.10	-11.90	-12.90	-13.15	-15.60	-17.95	-17.10	-17.60	-16.60	-15.40	-14.80	-16.20	-15.60
-11.90	-13.30	-14.40	-14.30	-16.90	-19.40	-18.90	-18.60	-17.60	-16.75	-17.00	-17.40	-17.00
-13.60	-14.90	-14.95	-15.30	-18.00	-20.35	-20.60	-19.80	-18.70	-18.10	-19.20	-18.30	-18.20
-14.50	-16.00	-17.20	-16.40	-19.10	-21.15	-21.20	-20.80	-19.70	-19.60	-20.10	-19.10	-19.40
-15.40	-17.10	-18.50	-17.40	-20.10	-22.00	-21.75	-21.90	-20.10	-21.00	-20.80	-20.40	-20.60
-16.35	-18.20	-19.80	-18.40	-20.80	-22.80	-22.20	-22.75	-20.60	-21.90	-21.40	-21.40	-21.70
-18.50	-19.30	-21.05	-19.50	-21.60	-23.20	-22.80	-23.40	-21.60	-22.40	-22.00	-21.90	-22.60
-20.65	-20.40	-21.90	-20.50	-22.50	-23.60	-23.20	-24.10	-22.90	-23.25	-22.80	-22.30	-22.90
-21.15	-21.30	-22.45	-21.65	-23.90	-24.05	-23.70	-24.80	-23.80	-24.20	-23.30	-22.75	-23.20
-21.60	-22.10	-23.00	-22.60	-24.30	-24.45	-24.50	-25.35	-24.05	-24.90	-23.70	-23.20	-23.50
-22.10	-22.90	-23.50	-23.70	-24.55	-24.90	-25.10	-25.80	-24.50	-25.20	-24.20	-23.60	-23.80
-22.60	-23.30	-24.10	-24.10	-24.90	-25.30	-25.70	-26.10	-24.80	-25.50	-24.80	-24.05	-24.00
-23.10	-23.80	-24.65	-24.65	-25.10	-25.80	-26.20	-26.50	-25.15	-25.90	-25.20	-24.55	-24.40
-23.60	-24.20	-25.20	-25.20	-25.40	-26.10	-26.90	-26.90	-25.60	-26.10	-25.80	-25.00	-24.70
-24.00	-24.70	-25.75	-25.70	-25.70	-26.60	-27.40	-27.25	-26.10	-26.40	-26.30	-25.40	-25.00
-24.50	-25.20	-26.10	-26.30	-25.90	-27.00	-28.00	-27.90	-26.50	-27.00	-26.80	-25.90	-25.30
-24.90	-25.60	-26.40	-26.70	-26.30	-27.40	-28.60	-28.45	-26.90	-27.50	-27.30	-26.50	-25.50
-25.35	-26.10	-26.75	-27.05	-27.45	-27.80	-29.10	-29.00	-27.30	-28.10	-27.75	-27.00	-25.90

Table A-7: Beach profile data 7 December 1982.

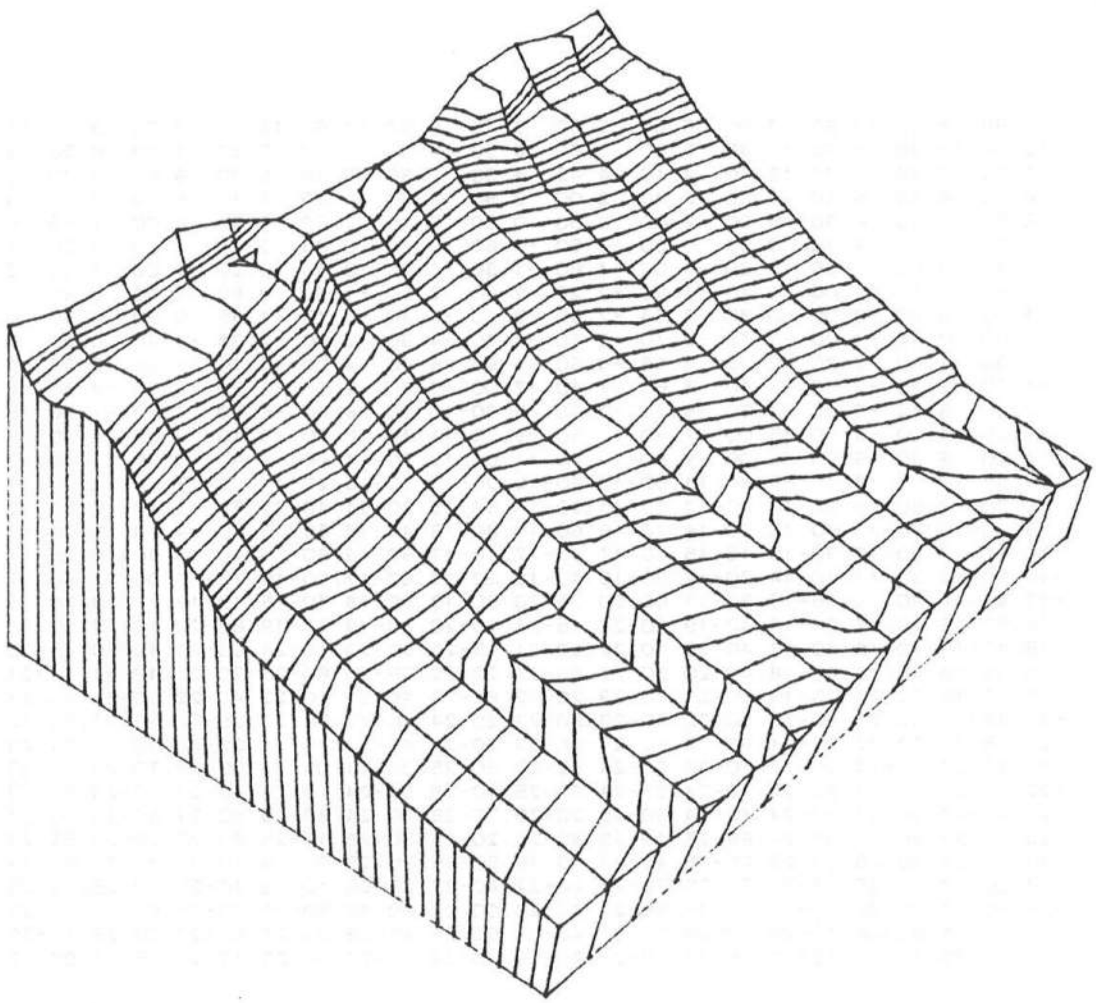

Figure A-8: Beach profile 14 January 1983.

11.65	11.65	13.80	13.00	7.40	7.10	6.75	5.10	11.60	14.60	12.20	8.40	14.70
9.40	12.40	11.70	12.40	5.40	5.40	5.30	4.30	6.00	7.60	7.90	6.20	9.45
7.50	7.40	8.10	12.40	4.00	3.70	3.95	3.60	4.00	5.60	6.70	5.40	7.20
6.50	6.00	7.00	6.10	2.80	2.05	2.80	2.00	3.30	4.90	5.40	4.10	6.60
6.00	5.60	5.60	4.30	1.60	1.10	1.60	0.40	3.50	4.60	5.30	4.10	5.90
4.60	4.70	4.40	2.50	0.80	0.30	0.25	-1.10	-1.65	2.70	4.90	4.60	5.00
2.70	3.30	3.30	1.30	0.00	-0.80	-1.00	-2.20	-0.20	-0.55	2.00	1.60	3.90
1.40	1.70	2.30	0.90	-1.00	-1.85	-2.10	-3.30	-1.60	-1.40	-0.40	-0.20	2.10
0.45	0.60	1.00	-0.10	-2.00	-2.60	-3.10	-4.55	-2.10	-2.20	-0.90	-2.20	0.40
-0.50	-0.40	-0.50	-1.40	-2.70	-3.60	-4.60	-6.00	-3.40	-3.00	-2.00	-4.20	-0.90
-1.55	-1.30	-1.90	-2.00	-3.65	-4.45	-6.00	-7.40	-5.40	-4.30	-3.00	-6.30	-2.15
-2.55	-2.20	-3.00	-3.40	-5.00	-5.35	-7.40	-8.30	-7.40	-5.60	-5.10	-7.40	-3.60
-3.60	-3.10	-3.85	-4.45	-6.10	-6.25	-8.60	-9.55	-8.80	-7.00	-7.30	-8.25	-5.20
-4.00	-4.30	-4.60	-5.85	-7.10	-8.00	-9.70	-10.90	-10.20	-8.00	-8.25	-9.75	-7.80
-5.60	-5.40	-5.45	-7.00	-8.20	-10.00	-10.80	-12.20	-11.60	-9.10	-9.25	-11.20	-8.55
-6.85	-6.50	-6.90	-8.40	-10.20	-12.00	-12.00	-13.50	-13.00	-10.20	-10.60	-14.25	-10.55
-8.20	-7.65	-8.55	-9.65	-12.10	-14.00	-13.00	-14.90	-14.25	-11.55	-12.20	-15.70	-12.70
-9.50	-9.50	-10.20	-10.90	-13.65	-15.00	-14.10	-16.20	-15.50	-13.15	-13.80	-17.20	-14.60
-10.85	-11.90	-11.80	-11.80	-14.60	-15.90	-15.35	-17.50	-16.90	-14.85	-15.10	-17.20	-16.40
-12.20	-14.10	-13.45	-12.10	-15.60	-15.90	-16.60	-18.60	-17.20	-16.40	-16.55	-18.70	-17.20
-15.20	-15.25	-15.10	-13.60	-16.60	-16.60	-19.00	-20.10	-19.55	-18.10	-18.00	-19.70	-18.00
-15.20	-15.40	-16.70	-15.20	-17.55	-17.80	-20.40	-21.50	-20.90	-19.60	-19.25	-20.20	-18.90
-16.70	-15.55	-17.50	-16.80	-18.55	-19.10	-21.60	-22.30	-21.60	-21.00	-19.40	-20.80	-19.75
-18.10	-15.80	-18.30	-18.40	-19.50	-20.45	-21.80	-23.10	-22.00	-22.10	-19.50	-21.40	-20.60
-19.60	-17.10	-19.10	-19.90	-20.00	-21.80	-22.00	-23.75	-22.50	-23.40	-20.60	-21.90	-21.40
-20.65	-18.40	-20.00	-20.00	-20.55	-22.00	-22.30	-24.00	-22.90	-24.40	-22.00	-22.30	-22.00
-21.15	-19.70	-20.75	-20.00	-21.05	-22.00	-23.35	-24.30	-23.25	-24.70	-23.30	-23.00	-22.60
-21.60	-21.00	-21.60	-21.00	-21.60	-22.00	-24.65	-25.10	-23.65	-24.90	-23.90	-23.50	-23.25
-22.10	-22.30	-22.60	-21.95	-22.10	-23.20	-25.50	-26.00	-24.00	-25.20	-24.20	-23.90	-23.80
-22.60	-23.30	-22.70	-22.90	-22.80	-24.20	-26.00	-27.00	-24.40	-25.70	-24.80	-24.20	-24.00
-23.10	-23.70	-22.60	-23.80	-24.00	-24.65	-26.40	-27.90	-25.25	-26.10	-25.20	-24.55	-24.40
-23.60	-24.10	-22.80	-24.55	-25.20	-24.90	-26.90	-28.10	-26.35	-26.50	-25.80	-25.35	-24.70
-24.00	-24.45	-23.35	-24.55	-25.70	-25.45	-27.40	-28.30	-27.30	-27.00	-26.10	-26.95	-25.00
-24.30	-24.80	-23.85	-24.50	-25.90	-26.20	-27.80	-28.50	-27.55	-27.40	-26.55	-26.70	-25.40
-24.60	-25.20	-24.40	-25.00	-26.10	-27.00	-28.20	-28.80	-27.80	-27.80	-26.90	-27.50	-25.80
-24.90	-25.60	-24.95	-25.40	-26.35	-27.20	-28.70	-29.00	-28.05	-28.25	-27.30	-28.20	-26.30

Table A-8: Beach profile data 14 January 1983.

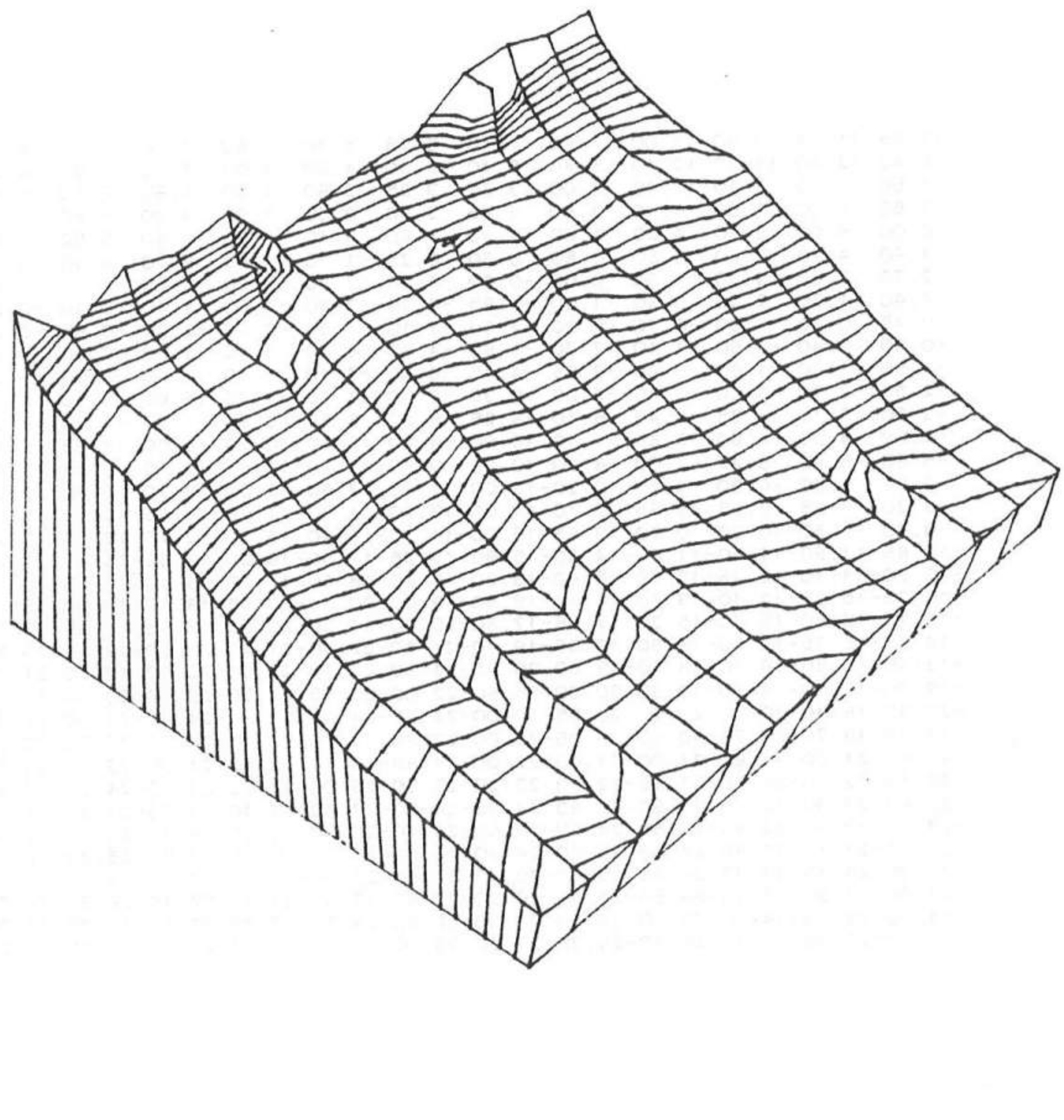

Figure A-9: Beach profile 3 March 1983.

11.65	11.65	13.80	13.00	7.00	6.70	5.00	2.90	11.60	9.60	12.20	6.50	14.70
8.40	8.00	9.30	12.40	4.70	4.00	3.10	1.50	5.00	6.60	6.50	4.80	7.50
6.10	5.90	6.30	12.40	3.20	2.50	1.80	0.30	5.25	4.20	4.60	3.10	5.50
4.50	4.00	3.90	4.10	2.80	1.05	1.00	-0.10	0.50	2.10	2.70	2.00	3.90
3.20	2.50	2.30	2.40	0.75	0.20	0.30	-0.30	0.10	0.60	1.00	0.95	2.50
2.25	0.90	1.00	1.00	0.00	-0.50	-0.40	-1.10	-0.40	0.30	0.70	0.50	1.20
1.25	-0.60	0.30	0.15	-0.60	1.40	-1.30	-1.90	-1.10	0.00	0.00	0.00	0.80
0.50	-1.25	-0.45	-0.65	-0.40	-2.00	-2.10	-2.70	-2.10	-0.25	-0.70	-0.50	0.50
-0.10	-1.50	-1.30	-1.10	-0.90	-2.60	-3.10	-3.80	-3.10	-0.40	-2.10	-0.90	-0.20
-0.80	-1.60	-2.15	-1.60	-2.50	-3.30	-4.10	-4.85	-4.10	-3.00	-3.40	-2.20	-1.50
-0.80	-2.00	-2.90	-2.80	-3.90	-3.60	-5.10	-6.60	-5.10	-4.70	-4.60	-4.50	-3.40
-1.00	-2.30	-3.60	-3.90	-6.40	-4.20	-6.30	-8.40	-6.40	-5.60	-6.30	-6.70	-5.50
-1.50	-2.40	-4.40	-5.70	-7.65	-5.80	-7.30	-8.50	-7.80	-7.00	-7.70	-8.80	-7.10
-2.90	-3.60	-5.40	-6.10	-8.10	-7.50	-8.50	-10.20	-9.10	-8.75	-9.00	-10.20	-8.70
-4.40	-4.80	-6.40	-6.60	-8.80	-9.00	-9.50	-11.95	-10.50	-10.50	-10.50	-11.70	-10.30
-5.80	-6.00	-7.50	-7.30	-10.00	-9.90	-10.80	-13.70	-11.90	-12.30	-10.90	-13.20	-11.85
-7.20	-7.15	-8.50	-9.20	-11.30	-11.20	-12.40	-15.20	-13.15	-13.75	-13.25	-14.80	-13.10
-8.00	-8.50	-10.40	-11.30	-12.50	-12.60	-13.90	-16.00	-14.50	-14.40	-14.50	-16.10	-14.60
-9.00	-10.25	-12.25	-13.00	-13.75	-14.20	-15.50	-16.90	-15.90	-16.20	-15.50	-17.30	-15.80
-10.60	-12.00	-13.80	-13.80	-15.00	-15.70	-16.50	-18.00	-16.90	-18.00	-16.50	-18.50	-17.20
-12.30	-13.70	-14.80	-14.70	-15.90	-17.20	-17.70	-18.90	-17.90	-19.80	-17.60	-19.70	-18.10
-14.00	-15.40	-15.90	-15.50	-16.60	-18.80	-19.35	-20.00	-18.90	-20.90	-18.70	-20.50	-19.00
-15.60	-15.95	-16.90	-17.20	-17.65	-20.05	-21.00	-21.00	-20.00	-21.90	-19.80	-21.10	-20.00
-17.00	-16.40	-17.90	-18.60	-18.90	-20.80	-22.25	-22.00	-20.15	-22.70	-20.90	-21.70	-21.00
-18.00	-17.60	-19.00	-19.40	-20.20	-21.60	-23.05	-23.00	-20.85	-23.60	-21.80	-22.30	-21.80
-19.00	-19.30	-20.00	-20.20	-21.45	-22.30	-23.90	-24.00	-22.00	-24.20	-22.10	-22.90	-22.25
-20.10	-20.90	-21.40	-21.00	-22.05	-23.05	-24.75	-24.90	-23.10	-24.50	-22.40	-23.50	-22.70
-20.90	-22.05	-22.90	-21.75	-22.60	-23.70	-25.50	-25.30	-24.10	-25.10	-23.40	-24.10	-23.20
-21.70	-22.70	-24.40	-22.60	-23.10	-24.35	-25.70	-25.80	-25.00	-25.60	-24.40	-24.80	-23.80
-22.55	-23.25	-25.00	-23.20	-23.70	-25.00	-26.25	-26.20	-25.90	-26.10	-25.50	-25.30	-24.20
-23.30	-23.90	-25.00	-23.80	-24.30	-25.40	-26.80	-26.70	-26.85	-26.50	-25.80	-25.80	-24.70
-24.10	-24.50	-25.20	-24.30	-24.80	-25.60	-27.10	-27.20	-27.10	-27.00	-25.80	-26.35	-25.20
-24.60	-25.00	-25.90	-24.90	-25.40	-26.20	-27.60	-27.60	-27.30	-27.50	-25.95	-26.90	-25.60
-25.00	-25.70	-26.65	-25.40	-26.00	-27.00	-28.10	-28.05	-27.60	-28.00	-26.60	-27.45	-26.10
-25.40	-26.30	-26.90	-26.00	-26.30	-27.40	-28.60	-28.50	-27.80	-28.30	-27.30	-28.00	-26.70
-25.80	-26.90	-27.10	-26.50	-26.70	-27.70	-29.10	-29.00	-28.10	-28.90	-28.00	-28.50	-27.00

Table A-9: Beach profile data 3 March 1983.

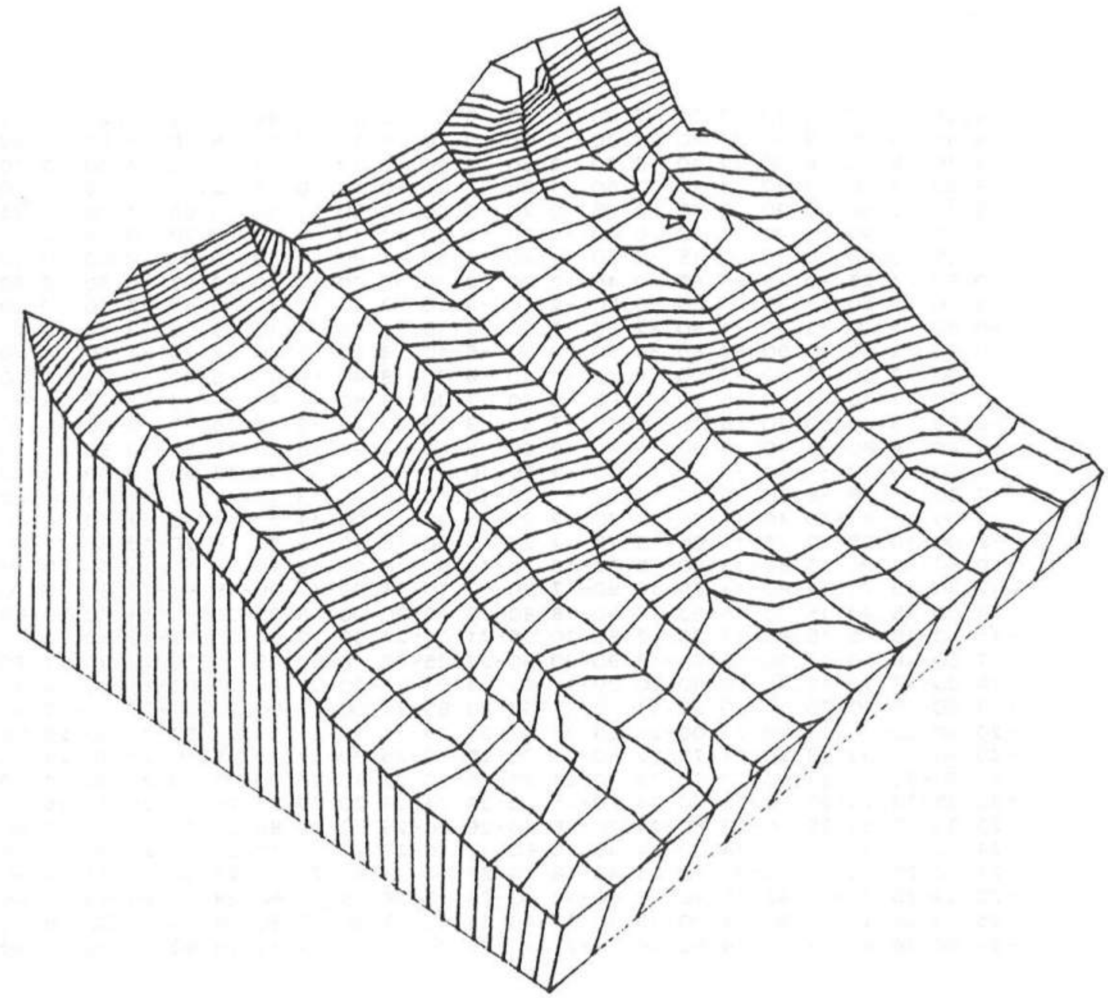

Figure A-10: Beach profile 29 March 1983.

11.40	12.00	13.80	14.00	7.10	7.00	6.70	2.65	10.50	10.40	12.20	6.20	14.50
8.90	8.90	10.30	14.00	4.60	4.80	3.90	1.45	6.70	6.65	6.30	3.20	7.70
7.10	7.00	7.00	14.00	2.65	2.80	1.80	0.40	4.50	4.50	3.90	1.90	4.70
6.90	5.10	4.45	4.30	0.80	1.50	0.70	-0.40	0.65	2.30	2.50	0.65	2.80
3.90	3.20	2.55	0.90	-0.75	0.10	-0.30	-1.00	0.10	1.00	1.20	-0.60	0.80
0.50	1.25	0.70	-1.90	-0.90	-1.40	-1.20	-1.80	-0.40	0.40	0.50	-1.00	-0.05
-2.00	-0.75	0.10	-1.40	-1.40	-2.00	-1.40	-2.45	-1.00	-0.30	-0.50	-1.50	-0.40
-0.80	-2.35	-0.30	-1.60	-2.00	-2.80	-1.60	-3.30	-1.60	-1.00	-0.90	-3.00	-0.70
-1.00	-3.50	-0.80	-2.00	-2.55	-2.00	-1.90	-4.00	-2.10	-1.40	-1.80	-3.80	-1.20
-1.20	-4.70	-3.00	-2.95	-2.90	-2.60	-2.30	-4.90	-2.75	-1.60	-3.00	-4.45	-1.70
-1.90	-4.80	-3.30	-3.90	-3.35	-3.60	-3.20	-5.80	-3.25	-1.80	-3.20	-5.20	-2.20
-2.50	-5.00	-2.60	-4.30	-3.90	-4.95	-4.20	-6.70	-4.30	-2.90	-4.00	-5.90	-2.10
-3.00	-5.10	-4.00	-4.50	-4.55	-6.20	-5.15	-7.50	-5.40	-4.10	-4.60	-6.80	-4.20
-3.60	-5.20	-4.60	-4.60	-6.30	-7.50	-6.00	-8.50	-7.90	-5.20	-5.10	-7.40	-5.30
-4.50	-5.40	-5.30	-4.70	-8.70	-9.00	-7.00	-8.70	-10.60	-6.40	-6.40	-8.30	-6.40
-5.50	-5.60	-5.95	-5.10	-10.90	-9.15	-8.00	-9.90	-11.90	-8.00	-8.20	-9.70	-7.60
-6.20	-6.00	-6.60	-6.70	-11.80	-9.50	-9.60	-11.50	-12.90	-10.60	-10.05	-11.00	-9.10
-7.20	-7.25	-8.05	-8.40	-12.70	-11.25	-11.00	-13.50	-14.00	-10.60	-11.20	-12.40	-11.60
-8.15	-8.90	-10.00	-11.00	-13.70	-13.20	-12.60	-15.50	-15.10	-12.40	-13.00	-14.55	-13.20
-9.00	-10.50	-12.00	-13.60	-15.00	-15.10	-14.10	-15.80	-16.10	-15.00	-14.80	-16.50	-14.80
-10.00	-12.20	-12.50	-13.60	-16.90	-16.05	-15.70	-16.00	-17.10	-17.60	-16.50	-16.70	-15.90
-11.60	-13.80	-14.00	-14.50	-17.90	-16.80	-17.20	-16.30	-19.00	-19.00	-17.30	-17.50	-17.20
-13.40	-15.50	-16.00	-15.90	-18.00	-17.30	-18.00	-20.10	-19.90	-19.50	-17.60	-18.40	-18.10
-15.20	-16.90	-17.90	-17.30	-18.45	-18.40	-18.70	-20.40	-20.30	-20.20	-19.10	-19.20	-18.90
-16.20	-18.10	-19.90	-18.70	-19.20	-19.80	-19.40	-20.60	-20.70	-21.10	-20.00	-20.00	-19.60
-17.20	-19.30	-20.20	-20.20	-21.05	-21.00	-21.40	-21.90	-21.00	-22.50	-20.20	-19.60	-20.40
-18.55	-19.90	-20.50	-20.70	-21.60	-21.35	-24.00	-22.90	-22.30	-23.50	-20.90	-20.30	-21.00
-20.00	-20.30	-22.00	-21.30	-21.55	-21.75	-24.20	-23.50	-22.70	-23.70	-22.05	-21.70	-21.10
-21.00	-20.70	-23.40	-22.60	-21.55	-22.10	-24.50	-24.00	-23.10	-23.90	-22.70	-22.40	-21.30
-21.75	-21.20	-23.40	-22.60	-22.80	-22.50	-24.90	-24.60	-23.90	-24.00	-22.70	-22.50	-22.00
-22.10	-21.70	-23.40	-22.60	-23.25	-24.00	-25.10	-25.20	-24.60	-24.10	-23.50	-22.60	-22.60
-22.50	-23.90	-23.50	-23.20	-23.70	-24.70	-25.50	-25.40	-25.50	-24.30	-23.90	-23.35	-23.20
-22.50	-23.90	-24.20	-24.00	-24.20	-24.90	-25.80	-26.00	-26.00	-24.40	-24.10	-24.20	-23.80
-22.50	-23.90	-25.10	-24.60	-24.70	-24.90	-26.10	-26.80	-26.80	-24.60	-24.40	-25.00	-24.30
-22.50	-23.90	-25.30	-25.00	-25.15	-24.95	-26.40	-26.90	-26.90	-25.50	-25.70	-25.65	-24.80
-24.00	-23.90	-25.50	-25.00	-25.60	-26.20	-26.80	-27.10	-27.10	-26.70	-26.10	-25.90	-25.10

Table A-10: Beach profile data 29 March 1983.

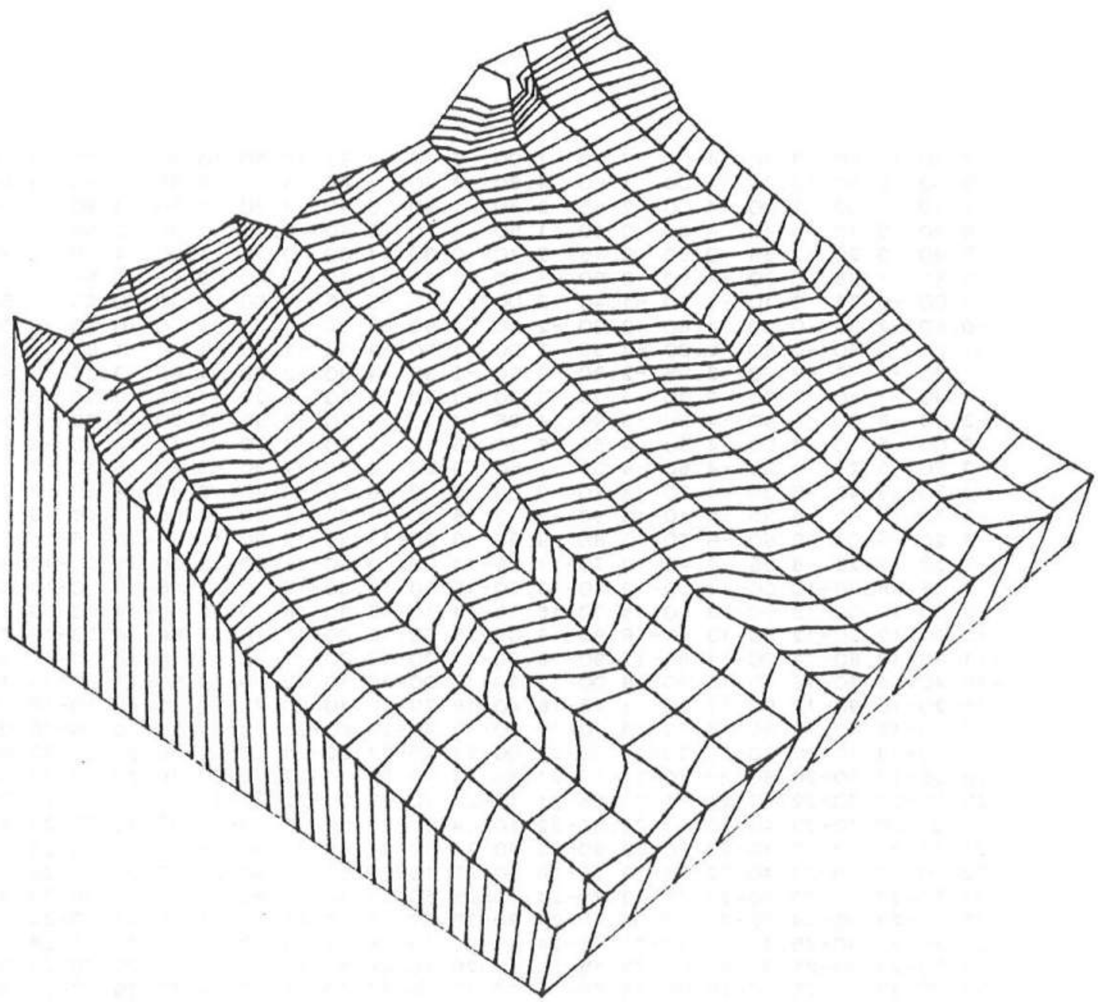

Figure A-11: Beach profile 4 May 1983.

11.40	12.00	13.80	14.00	6.80	7.30	9.00	5.00	11.50	10.40	12.20	6.60	14.50
8.70	9.00	9.10	14.00	5.00	5.20	5.80	4.50	6.10	7.00	6.80	5.10	7.90
8.10	7.00	6.50	14.00	4.10	4.40	4.60	3.50	5.10	5.30	5.30	4.00	6.70
7.10	5.70	5.20	6.00	2.80	2.70	3.90	1.90	4.50	4.70	4.60	4.70	5.50
5.70	4.45	4.20	4.10	1.00	0.10	1.90	0.70	1.25	5.25	5.20	5.20	4.70
4.30	3.40	3.50	2.60	-0.70	-1.30	0.00	-0.70	-0.60	2.50	5.30	2.90	5.70
1.70	2.30	1.90	1.20	-1.80	-2.30	-1.90	-1.30	-0.75	-0.40	2.80	0.50	2.00
0.35	1.40	0.35	0.20	-2.60	-3.40	-1.60	-2.40	-0.75	-0.70	0.40	-1.20	0.05
-0.70	0.45	-0.50	-0.80	-3.40	-4.50	-2.90	-3.80	-1.50	-1.10	-0.90	-3.50	-1.40
-1.50	-0.50	-1.40	-1.75	-4.30	-5.70	-4.50	-5.20	-2.80	-2.10	-1.40	-5.40	-1.70
-2.50	-1.20	-2.40	-2.50	-5.20	-6.70	-5.80	-6.60	-3.90	-3.40	-2.40	-6.60	-3.10
-3.30	-2.10	-3.50	-3.40	-5.90	-7.80	-7 20	-8.00	-5.20	-4.60	-4.50	-7.90	-4.50
-4.20	-2.95	-4.50	-4.20	-6.85	-8.90	-8.50	-9.40	-6.55	-5.90	-6.50	-9.00	-6.30
-5.10	-3.80	-5.50	-5.05	-7.60	-10.00	-9.55	-10.60	-7.90	-7.10	-8.40	-10.20	-8.10
-6.00	-4.60	-6.60	-6.00	-8.40	-11.05	-10.50	-11.80	-9.10	-8.25	-10.00	-11.50	-10.10
-6.90	-5.40	-7.70	-6.80	-9.50	-12.25	-11.60	-12.90	-10.10	-10.30	-11.20	-12.60	-12.20
-7.80	-6.25	-8.70	-7.60	-10.90	-13.20	-12.60	-14.30	-13.00	-12.60	-12.40	-14.00	-14.30
-8.50	-7.00	-9.90	-8.40	-12.35	-14.10	-14.00	-15.80	-14.35	-15.00	-13.65	-15.50	-14.50
-9.80	-8.50	-11.10	-9.30	-13.80	-15.00	-15.00	-17.25	-15.10	-15.70	-14.90	-16.20	-15.40
-10.90	-10.10	-12.20	-11.10	-14.50	-16.00	-16.10	-18.75	-16.10	-16.90	-15.80	-16.90	-16.25
-12.20	-10.70	-13.50	-13.20	-15.30	-16.90	-17.30	-19.50	-17.00	-18.10	-16.40	-17.60	-17.10
-13.50	-13.25	-14.80	-14.70	-16.10	-18.00	-18.40	-20.10	-17.90	-19.30	-17.00	-18.30	-18.00
-14.70	-14.70	-16.00	-16.00	-16.90	-18.90	-19.50	-20.80	-18.70	-20.50	-18.80	-19.00	-18.90
-15.90	-16.25	-17.30	-17.15	-17.60	-19.90	-20.50	-21.30	-19.60	-21.70	-20.05	-19.70	-19.45
-17.05	-17.45	-18.60	-18.05	-18.45	-20.60	-21.90	-21.95	-20.50	-22.90	-20.60	-20.50	-19.95
-18.30	-18.25	-19.90	-19.00	-19.25	-21.00	-23.10	-22.50	-21.40	-23.60	-21.15	-21.10	-20.40
-19.70	-19.00	-20.80	-19.90	-20.05	-21.60	-24.30	-23.10	-22.30	-23.90	-21.75	-21.60	-20.90
-21.00	-19.90	-21.50	-20.80	-20.90	-22.00	-24.70	-23.70	-23.10	-24.00	-22.30	-22.20	-21.40
-21.60	-20.60	-22.20	-21.80	-21.60	-22.60	-25.00	-24.10	-23.90	-24.40	-22.90	-22.70	-21.90
-22.10	-21.40	-22.90	-22.70	-22.40	-23.05	-25.00	-24.50	-24.30	-24.70	-23.40	-23.25	-22.40
-22.60	-22.20	-23.60	-23.60	-22.80	-23.60	-25.20	-24.90	-24.90	-25.00	-23.90	-23.90	-22.90
-23.20	-23.00	-24.40	-24.10	-23.30	-24.10	-25.95	-25.30	-25.30	-25.20	-24.40	-24.50	-23.30
-23.50	-23.60	-24.70	-24.50	-23.90	-24.50	-26.50	-25.70	-25.80	-25.50	-24.90	-25.00	-23.80
-23.80	-24.00	-25.00	-24.70	-24.40	-25.20	-27.10	-26.10	-26.35	-25.80	-25.30	-25.50	-24.30
-24.10	-24.50	-25.30	-25.00	-25.00	-25.70	-27.90	-26.50	-26.80	-26.10	-25.90	-26.10	-24.80
-24.40	-24.90	-25.50	-25.35	-25.40	-26.10	-28.00	-26.95	-27.10	-26.40	-26.40	-26.70	-25.10

Table A-11: Beach profile data 4 May 1983.