The beach water table as a response variable of the beach-ocean-atmosphere system

Leland Edward Fausak
College of William and Mary - Virginia Institute of Marine Science

THE BEACH WATER TABLE AS A RESPONSE VARIABLE
OF THE BEACH-OCEAN-ATMOSPHERE SYSTEM

Leland Edward Fausak
Gloucester Point, Virginia

B.A., University of California, 1968

A thesis presented to the Graduate Faculty
of the University of Virginia
in Candidacy for the degree of
Master of Science

Department of Marine Science
(Virginia Institute of Marine Science)
University of Virginia

August
1970

APPROVAL SHEET

This thesis is submitted in partial fullfillment of
the requirements for the degree of
Master of Science

Author

Approved, August, 1970

Wyman Harrison, Ph.D.

Robert J. Byrne, Ph.D.

John J. Norcross, M.S.

ABSTRACT

Fluctuations of the water table in a marine beach over a rising half-tide cycle were investigated as a function of variations in local still water level, swash runup distance, distance of a sampling station from the shoreline, and atmospheric pressure. The data were taken from a 30-day time series of observations of environmental variables taken at Virginia Beach, Virginia, during August and September, 1969.

Sequential linear multiple regression analyses were used to rank the process variables in order of importance in each of 13 water-table monitoring wells spaced along a transect transverse to the shoreline. Results showed that tidal fluctuations exert the strongest influence in all except the two seawardmost wells and the most landward well. Distance from the shoreline is the most important variable in the seawardmost wells because of the exponential decay of the input wave and the resultant large range of water table fluctuations near the beach face. Atmospheric pressure becomes the dominant variable influencing water-table fluctuations in the most landward well, due to the relatively slight contribution of the tide and wave inputs.

The amplitude of the water table fluctuation decreases exponentially in a landward direction and the lag time of the input tide wave increases linearly with the distance from the shoreline. The time lag is found to be approximately 60 minutes per 18 meters of

THE WATER TABLE CONTINUES TO RISE FOR 1 HOUR, AFTER THE TIDE BEGINS TO EBB AND CONTINUES TO FALL 1 HOUR AFTER THE TIDE BEGINS TO FLOOD beach penetrated. This value is somewhat less than that determined by Emery and Foster (1948), who found a lag time of from one to three hours at distances between 20 and 40 feet (approximately 6 to 13 meters) from the shoreline.

ACKNOWLEDGMENTS

The work described herein is one phase of a broader study which will clarify the action of the beach groundwater table in promoting or inhibiting beach changes. The project is being supported by the Geography Branch of the Office of Naval Research (Project NR 388-097) under contract N00014-70-C-0004 with the Virginia Institute of Marine Science, and is directed by Dr. Wyman Harrison.

The author greatfully acknowledges the courtesy of the commanding officer of the Fort Story Military Reservation in permitting the field party to operate on Cape Henry. The author is also indebted to the following people, without whose help the study would have been made far more difficult: Dr. David DeVries, for his help in emplacing the wells; John D. Boon, III, for the design and construction of the water table monitoring devices; and Dr. Wm. G. MacIntyre, for his valuable aid with the often uncooperative electronics.

Special thanks are extended to Dr. Wyman Harrison and Dr. Robert J. Byrne, for the direction and assistance which they freely gave throughout the study. Thanks is also given to John M. Norcross and Dr. Wm. G. MacIntyre for critically reading the manuscript.

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INTRODUCTION

Beaches undergo continual changes in morphology, volume, and sediment characteristics; this constant flux has long been recognized and is well documented in the scientific literature. The multiplicity of factors controlling beach changes has been studied intensively since the closing years of World War II; although understanding has advanced to the point where it is possible to make rather crude predictions, the ability to forecast the behavior of beaches in response to a variety of causal elements remains largely inadequate. This limited progress is due in large part to the complex interactions of the many variables responsible for changes in beaches; indeed, the very number of elements acting on and within the beach system discourages many researchers from taking an active interest in coastal problems.

Factors affecting characteristics

The primary factors responsible for the size and the configuration of beaches are the type and the quantity of sediment available, and the action of the wind-generated surface waves which impinge on the shoreline. Source materials are the result of long-term geologic factors and tend to change very gradually; the waves striking the beach are responsible for the rapidly changing, short-term, and often rhythmic, variations in beach properties. The turbulence created by breaking waves stirs up and transports sand to a degree dependent on the size and shape of the wave, and on the type of beach material. The interaction between waves and beach, however, is regulated by the position and pressure head of the beach water table, which is in turn primarily a function of wave input, tidal level, and permeability of the sand body. This paper will focus attention upon the water table of a marine beach and attempt to elucidate some interactions of beach process variables and fluctuations of the water table.

PREVIOUS WORK

In spite of the considerable amount of research effort which has gone into studies of beach processes, the relationships between beach characteristics and fluctuations of the water table have received scant attention.

Bagnold (1940) studied the formation of beaches by waves, performing model experiments in a wave tank. He noted that the beach built up as a result of percolation of the swash into unsaturated sand, causing a loss of swash volume and loss of potential energy, and the attendent deposition of some part of the suspended load. He further noted accelerated erosion due to the emplacement of an impervious wall or plate near the beach, and concluded that the acceleration was due to saturation of the beach and the lack of energy loss to percolation.

Grant (1948) presented arguments of a qualitative nature and observations in support of the thesis that a high water table promotes beach erosion, and that conversely, a low water table may result in pronounced accretion on the foreshore. He recognized that there was a gradual diminution of velocity as the swash rushed up the beach face, and that the transporting power of the water was reduced accordingly, until at some point the velocity became zero and the suspended sediment was deposited; accompanying the loss of velocity was a change from the turbulent to the laminar flow regime and a loss of swash volume by percolation into the unsaturated sand. All of these factors reduced the carrying capacity of the returning backwash, and resulted in a net increase of sand on the upper foreshore. In contrast, the lower foreshore, below the outcrop of the water table, was subject to erosion because of the increased volume of the backwash, due to the addition of groundwater from the effluent zone.

Measurements of beach profiles and water-table levels by Emery and Foster (1948) supported the earlier work of Bagnold and Grant and documented the changes of the water table near the foreshore due to the fluctuations of the tidal plane. A time lag of one to three hours was observed in the response of the water table to the tidal oscillations at a distance of 20 to 40 feet from the shoreline; a decrease in amplitude was noted that was a function of distance from the shoreline and of the permeability of the sand body. Emery and Foster determined a seaward flow velocity of groundwater of approximately 4.5 feet per hour (approximately 0.04 cm/sec) and observed that such a velocity might be sufficient to cause dilation of sand grains on the foreshore and their eventual loss.

Water tables of 10 Pacific-coast beaches were investigated with the aim of establishing a datum related to the tidal stage of ocean beaches (Issacs and Bascom, 1949). Water tables of these beaches were divided into two parts: a seaward section which fluctuates with the tide, and a landward section which remains relatively fixed. They found that the water table was affected only in a narrow zone of the beach face. The tidal wave was considered to have proceeded through the sand with reduced amplitude, the magnitude of which was related to the duration of the tide, the permeability of the sand, and the distance traveled. The average rate of groundwater flow for the beaches studied was found to be about one foot per hour (approximately 0.008 cm/sec).

Interaction of the water table and sea level was investigated by Duncan (1964). He showed that zones of erosion and deposition migrated up and down the foreshore in response to the relative positions of the water table and still water level. As the swash surges above and beyond the outcrop of the water table, it loses water through percolation into the unsaturated sand; the sand deposited by the swash is not returned seaward because of the loss of potential energy, and thus carrying power, of the backwash. A lens of sediment is thus deposited above the water-table outcrop. As the tide rises, an accompanying rise of the water table also occurs; the swashes then cut into the seaward margin of the depositional wedge, carrying sand landward. The wedge thus migrates landward with a rising tide. On a falling tide, the major part of the swash-backwash zone lies below the water-table outcrop. The backwash volume, thus the speed, is increased by the addition of the groundwater effluent and the backwash begins to erode the wedge, which gradually thins and broadens; maximum deposition on a falling tide was found to be near the boundary of the surf zone and swash zone.

Similar results were reported by Strahler (1964) on Cape Cod beaches. He observed rhythmic patterns of foreshore erosion and deposition as a result of tidal oscillations. For a given foreshore station, he recognized a short phase of initial deposition near the upper limit of swash action on a rising tide, followed by a scour phase in the swash-backwash zone. The scour was in turn followed by the deposition of the sediment wedge associated with the landward migration of the step. A completely analogous reverse sequence was observed on a falling tide, except for the absence of a terminal phase of deposition near the swash limit.

Giese (1966) also found such a pattern of erosion in the mid-swash zone and deposition near the swash limit and at the inner boundary of the surf zone. Using the shapes of pebbles as indices of swash energy, Giese found that the swash zone energy balance depends upon the amount of foreshore infiltration per wave.

Quantitative investigations of shore processes, including the action of the groundwater table, have been made along the Virginia Coast (Harrison, et al., 1968; Harrison, 1969), utilizing a "process-response" model and linear multiple regression techniques developed in an earlier study by Harrison and Krumbein (1964). By analyzing a 26-day time series of observations, Harrison was able to show that the strongest predictors of foreshore erosion and deposition are (1) the breaker steepness, and (2) the ratio of the hydraulic head of the beach water table to the swash runup distance.

OBJECTIVES OF THE PRESENT STUDY

Given the demonstrated importance of the water table to beach stability, it is germane to inquire into the nature of beach water-table fluctuations. The specific problems treated here relate to the response characteristics of the water table; i.e., the manner in which the water table responds to waves, tides, and atmospheric pressure:

(1) how does the relative importance of the causative variables vary with distance from the shoreline?

(2) what is the time of propagation of the input tidal wave as a function of distance from the shoreline; is the lag time a function of tidal amplitude?

(3) what range of water-table fluctuations can be expected for a given tidal amplitude?

(4) are broad trends present which may be due to atmospheric pressure variations or to rainfall?

DESCRIPTION OF THE STUDY SITE

The site chosen for study is located on the seaward side of Cape Henry, Virginia, (Fig. 1) adjacent to the mouth of the Chesapeake Bay. The site is on the northern end of a straight stretch of coastline bearing N 15° W; it has a gently-shoaling offshore zone with a few bottom irregularities.

A transect was established normal to the shoreline immediately north of the southeastern boundary of the Fort Story Military Reservation (Figs. 2 and 3). Also shown in Figure 3 is a typical beach profile showing the location and spacing of water-table monitoring wells and profile-station markers.

The beach is composed of fine to medium quartzose sand; an average median diameter of 0.41 mm was determined from seven channel samples (extending from the beach surface to the water table) spaced along the study transect. Lenses of coarse sand are present but not abundant. The average width of the beach, from shoreline to dune ridge is approximately 55 meters; the average slope of the foreshore is approximately 6°.

Tides are of the semi-diurnal type, with a slight diurnal inequality; the average range of the tides is 0.85 meters, and the spring range is 1.04 m. The nearshore current system is influenced by the ebb and flood of the tide through the adjacent mouth of Chesapeake Bay, but the currents flow predomintly in a northerly

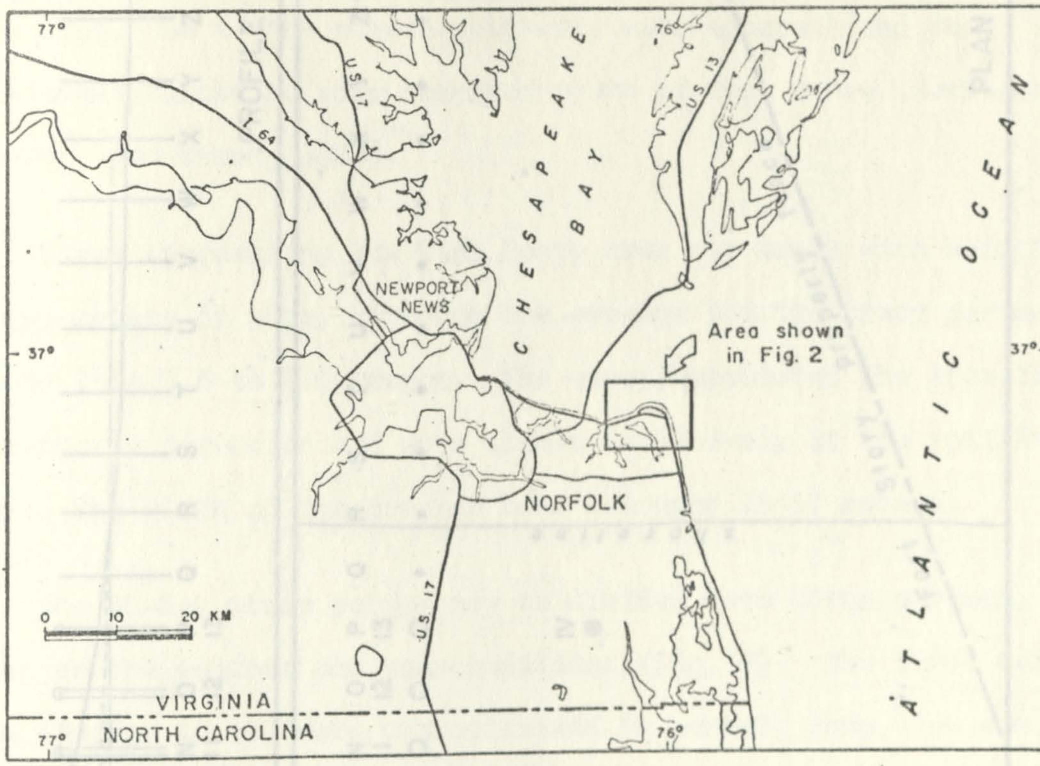

Fig. 1. Regional location map

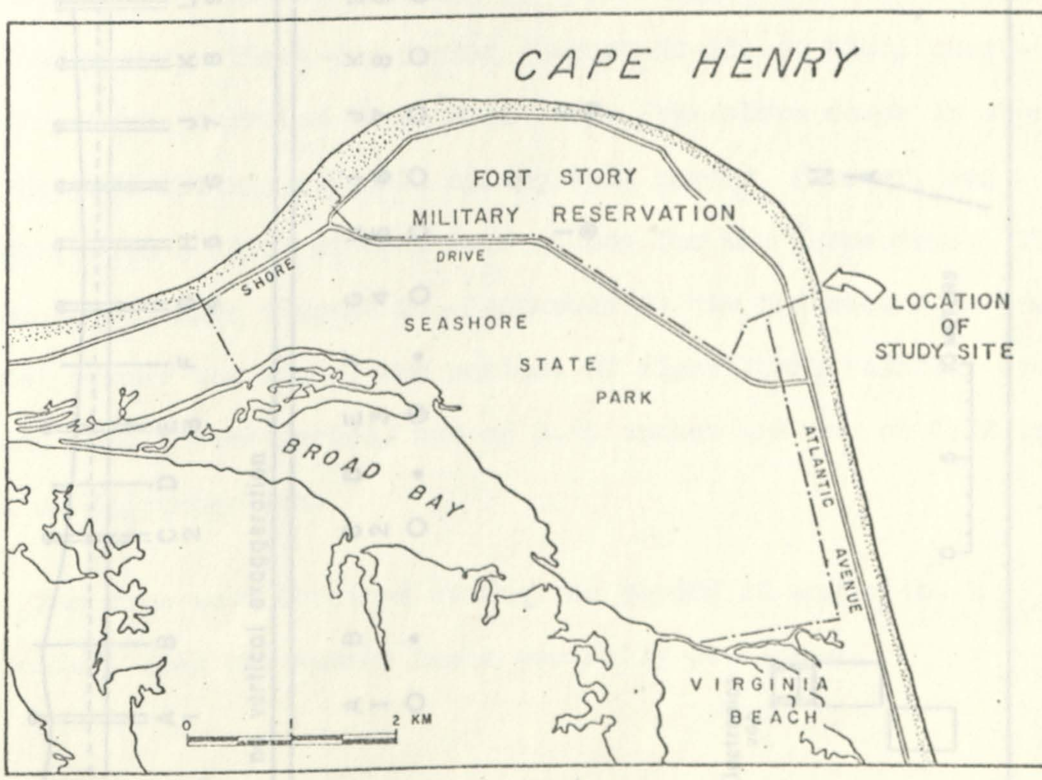

Fig. 2. Location of the Fort Story study site.

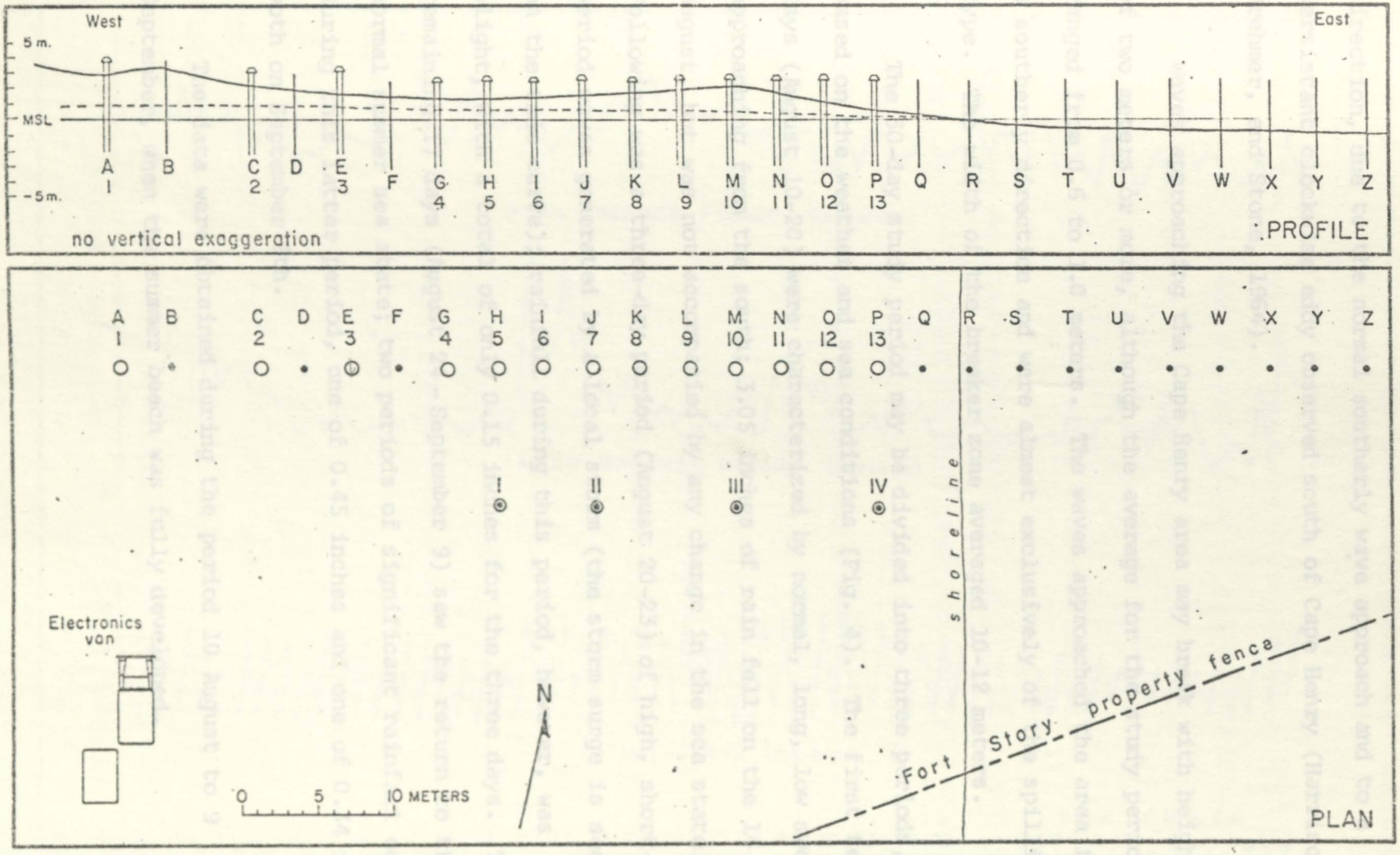

Fig. 3. Plan and profile views of the Fort Story study site, showing typical beach and water table profiles, and the spatial distribution of profile stations (A-Z), water table monitoring wells (1-13), and water table sampling probes (I-IV).

direction, due to the normal southerly wave approach and to a persistant clockwise eddy observed south of Cape Henry (Harrison, Brehmer, and Stone, 1964).

Waves approaching the Cape Henry area may break with heights of two meters or more, although the average for the study period ranged from 0.6 to 1.0 meters. The waves approached the area from a southerly direction and were almost exclusively of the spilling type. The width of the breaker zone averaged 10-12 meters.

The 30-day study period may be divided into three periods, based on the weather and sea conditions (Fig. 4). The first ten days (August 10-20) were characterized by normal, long, low swells approaching from the south; 3.05 inches of rain fell on the 14 of August, but was not accompanied by any change in the sea state. Following was a three-day period (August 20-23) of high, short-period waves generated by a local storm (the storm surge is seen on the tide curve); rainfall during this period, however, was slight, with a total of only 0.15 inches for the three days. The remaining 17 days (August 24 - September 9) saw the return to the normal summer sea state; two periods of significant rainfall occurred during this latter period, one of 0.45 inches and one of 0.34 inches, both on September 9th.

The data were obtained during the period 10 August to 9 September, when the summer beach was fully developed.

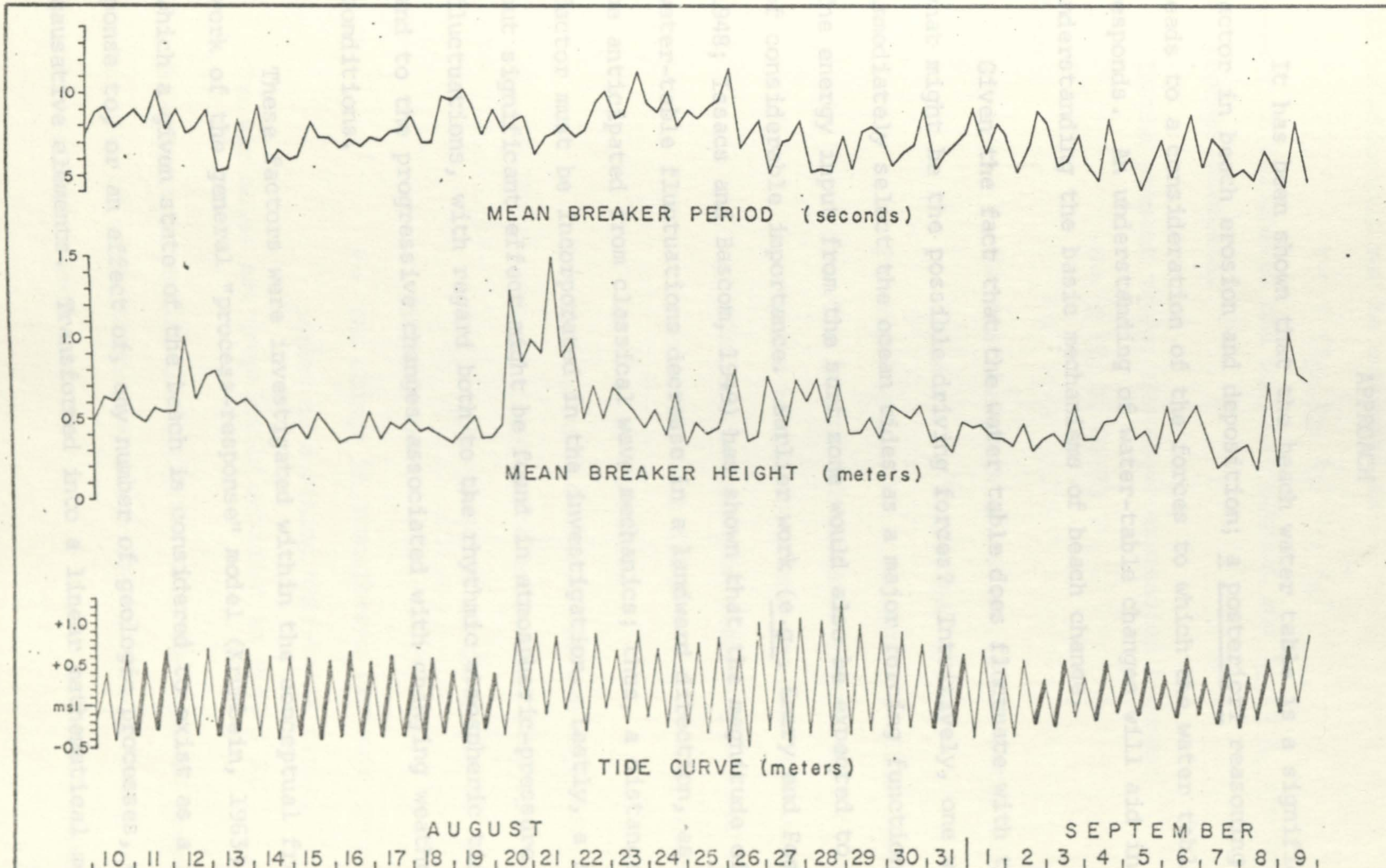

Fig. 4. Wave and tide data for the study period.

APPROACH

It has been shown that the beach water table is a significant factor in beach erosion and deposition; a posteriori reasoning leads to a consideration of the forces to which the water table responds. An understanding of water-table changes will aid in understanding the basic mechanisms of beach change.

Given the fact that the water table does fluctuate with time, what might be the possible driving forces? Intuitively, one would immediately select the ocean tides as a major forcing function. The energy input from the surf zone would also be expected to be of considerable importance. Earlier work (e.g., Emery and Foster, 1948; Issacs and Bascom, 1949) has shown that the magnitude of the water-table fluctuations decrease in a landward direction, as would be anticipated from classical wave mechanics; thus, a distance factor must be incorporated in the investigation. Lastly, a small but significant effect might be found in atmospheric-pressure fluctuations, with regard both to the rhythmic atmospheric tides and to the progressive changes associated with changing weather conditions.

These factors were investigated within the conceptual framework of the general "process-response" model (Krumbein, 1963), in which a given state of the beach is considered to exist as a response to, or an effect of, any number of geologic processes, or causative elements. Transformed into a linear mathematical model, this relationship may be expressed as

$$Y = f(X_1, X_2, X_3, .., X_n)$$

where Y is designated the response element and X_1 to X_n are termed the process elements.

In the present study, the above expression becomes:

$$W = f(T, X, D, P)$$

where

W = The change in elevation of the water table for a rising half-tidal cycle.

T = Tidal range for a rising half-tidal cycle.

X = The horizontal distance from a well to a point on the foreshore one-half the vertical distance between the preceding low and the succeeding high still-water levels, measured at time of mid-tide.

D = The vertical distance between high-tide still water level and a horizontal line representing the average position of the swash at its highest level.

P = The change in atmospheric pressure over the period of a rising half-tidal cycle.

The variables are graphically depicted in Figure 5.

In order to simplify the analysis, only the factors responsible for the rise of water level were investigated; accordingly, all regression variables were cast in terms of the rising half-tidal cycle.

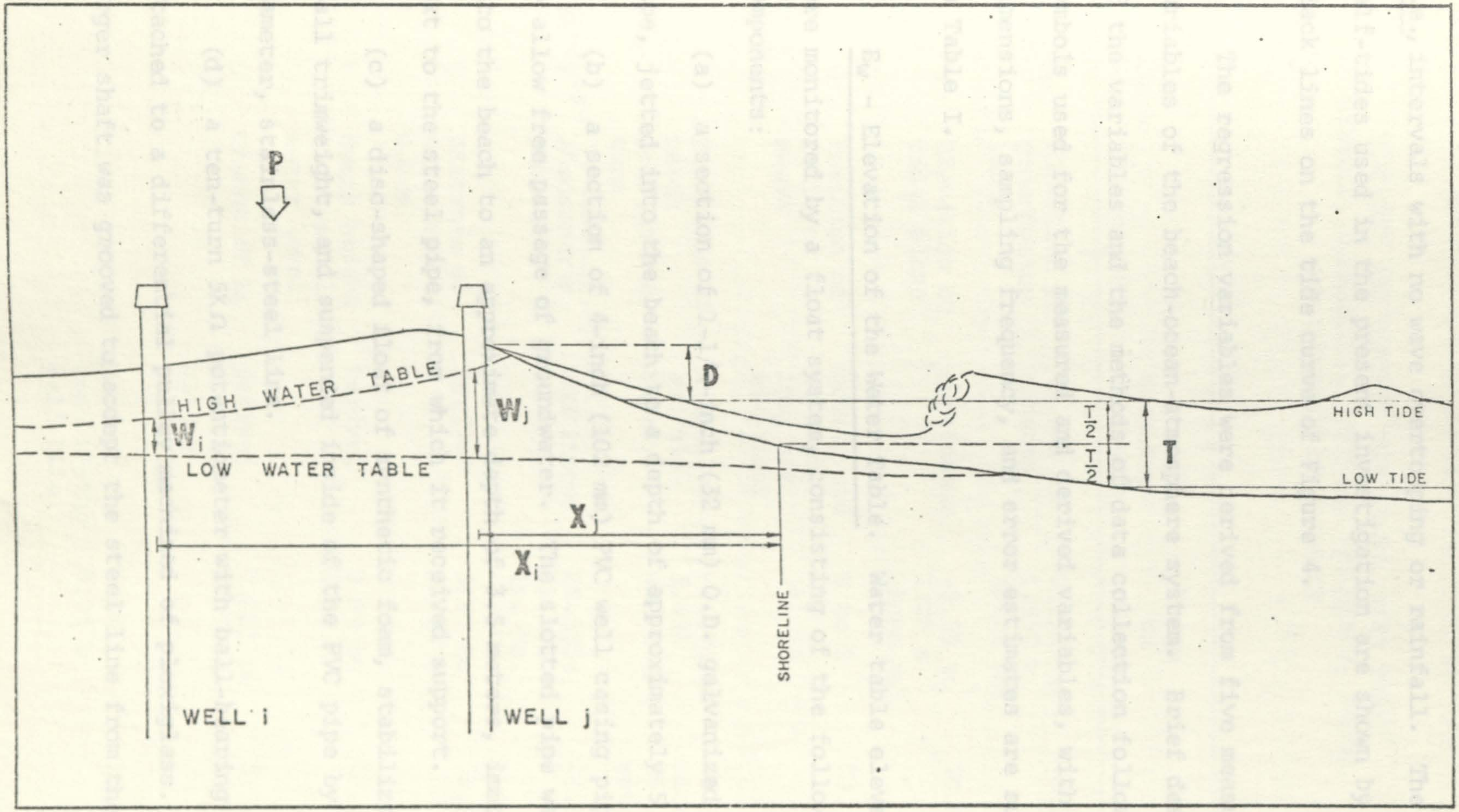

Fig. 5. Diagrammatic representation of the variables W, T, X, D, and P used in the regression analysis.

Furthermore, only periods of normal conditions were investigated; i.e., intervals with no wave overtopping or rainfall. The rising half-tides used in the present investigation are shown by heavy black lines on the tide curve of Figure 4.

The regression variables were derived from five measured variables of the beach-ocean-atmosphere system. Brief descriptions of the variables and the methods of data collection follow; the symbols used for the measured and derived variables, with their dimensions, sampling frequency, and error estimates are summarized in Table I.

E_w - Elevation of the Water Table. Water table elevations were monitored by a float system, consisting of the following components:

(a) a section of 1-1/4-inch (32 mm) O.D. galvanized steel pipe, jetted into the beach to a depth of approximately 5 meters.

(b) a section of 4-inch (102 mm) PVC well casing pipe, slotted to allow free passage of groundwater. The slotted pipe was jetted into the beach to an approximate depth of 3.5 meters, immediately next to the steel pipe, from which it received support.

(c) a disc-shaped float of synthetic foam, stabilized by a small trimweight, and suspended inside of the PVC pipe by a small-diameter, stainless-steel line.

(d) a ten-turn 5KΩ potentiometer with ball-bearing shaft, attached to a differential pulley machined of plexiglass. The larger shaft was grooved to accept the steel line from the float at

TABLE I

MEASURED AND DERIVED VARIABLES, WITH THEIR SYMBOLS, DIMENSIONS, SAMPLING FREQUENCY, RANGE, AND ESTIMATE OF ACCURACY

Symbol	Dimensions	Description	Sampling frequency	Range in values	Estimate of Accuracy
E_w	L	Elevation of groundwater table	10 and 15 minutes	0.291 to 1.999 m above msl	±0.01 m
E_t	L	Elevation of tidal plane	continuous	-0.55 to 1.27 m above msl	±0.05 m
S	0	Position of limit of swash	hourly and at high, low, and mid-tides	G to Z	±0.25 m
E_b	L	Elevation of beach profile station	high, low, and mid-tides	-0.940 to 3.693 above msl	±0.05 m above water ±0.10 m below water
P	$ML^{-1}T^{-2}$	Atmospheric pressure	continuous	29.550-30.285 in. Hg.	±0.005 in. Hg.
X	L	Distance of well from datum	Derived	6.83 to 72.62 m	±0.20 m
D	L	Swash height above still water level	Derived	0.04 to 0.56 m	±0.25 m
W	L	Change of E_w	Derived for each rising half-tide	0.003 to 0.870 m	±0.005 m
T	L	Tidal range	Derived for each rising half-tide	0.46 to 0.04 m	±0.05 m

a ratio of 30.48 centimeters per revolution. The smaller shaft was smooth and accepted a monofilament line which supported a counter weight suspended inside of the 32 mm steel pipe. The float system was designed by John D. Boon, III, after a pattern developed by the U.S. Geological Survey.

As the water level in a well changed, the motion was transmitted via the float and pulley system, to the potentiometer, whose resistance was changed in direct proportion to the vertical fluctuation of the water table. The signals from the potentiometers were hard-lined to a low-level data acquisition system, where they were digitized and recorded on computer-compatible magnetic tape.

Thirteen well systems were emplaced in the beach along a transect normal to the shoreline, at intervals of approximately three, six, and ten meters (see Fig. 3).

E_b - Elevation of the beach surface. Beach elevations were measured at 26 stations along the transect, 13 of which coincided with the water-level monitoring wells. The stations were marked by lengths of galvanized steel pipe and were spaced at approximately three meter intervals. Reference marks of colored tape were placed on the pipes at distances of 1.04, 1.95, and 3.78 meters above mean sea level. Elevations were determined with an engineers level and were referenced to a bench mark at the south gate of Fort Story. The elevation of the sand surface was found at each station pole by measuring down from the top of the tape to the beach surface, using a standard meter-stick. Measurements on the foreshore were taken at times of high, low, and mid-tides; backshore measurements were taken once daily or more often during times of overwash.

E_t - Still water level. Still water level was continuously monitored using a recording bubbler gauge of the type used by the U.S. Coast & Geodetic Survey (Manual of Tide Observations, Publ. 30-1, U.S. C & G. S.). The record was referenced to the msl datum as used for the leveling of the profile markers. The gauge was emplaced in approximately 10 feet of water directly offshore of the study site.

S - Runup distance. The positions of maximum runup of 10 consecutive swashes were recorded with references to the station marker poles; values were recorded hourly throughout the study period.

P - Atmospheric pressure. Hourly values for atmospheric pressure were obtained from the U.S. Weather Bureau station at the Norfolk Regional Airport, 13 kilometers distant from the study site.

In an attempt to reduce the number of variables to be examined, the following assumptions were made:

(a) The beach is internally homogenous, in texture and sediment characteristics, with no variation in porosity or permeability.

(b) Changes in temperature, and thus in the density and viscosity of the sea water and ground water, were not significant during the study period.

(c) The angle of wave approach did not significantly alter the swash runup distance.

Analytical Methods

A sequential linear multiregression analysis was chosen to determine the relative importance of the four process elements determining the magnitude of the water table fluctuations. This method was developed by Krumbein (Krumbein, Benson, and Hempkins, 1964) and is reviewed and utilized by Harrison and Krumbein (1964).

The method consists essentially of first performing a simple regression analysis of the dependent variable against the independent variables, taken one at a time. Regressions are then run using all possible pairs, triplets, etc., until all possible combinations of the variables have been exhausted. The advantages of this method are that interrelationships among the independent variables themselves become apparent, and that data redundancy; *i.e.*, the degree to which the same information is found in two or more variables, can be determined. Such an approach also may be used to rank the "independent" variables taken singly and in combination, in the order of their relative importance.

Simple linear regression analyses are performed to derive a mathematical expression for the decrease in amplitude of water table fluctuations as a function of distance from the shoreline, and for the lag time of the input tide wave as a function of distance from the shoreline.

RESULTS

General water table dynamics

Time-dependent fluctuations of the water table for each of the 13 wells are represented by the curves in Figures 6 and 7. These are selected, but typical, parts of the 30-day record. Figure 6 depicts changes in water level for normal, low-breaker conditions and will be used to illustrate several features of water table dynamics. Of particular interest are the following points:

(1) The rise of the water table is generally more rapid than the fall. This phenomonon is due to the normal seaward-directed pressure head of the groundwater table, which, on a rising tide, adds water to a given area at the same time that water is being added from the sea; on a falling tide water is being lost seaward, but water is being added from a landward direction by the water table. Thus, at a point near the foreshore there is a rapid rise due to the addition of water from both directions, while the rate of fall is lessened due to the continuing addition of fresh ground water.

(2) At times of higher high tides, the water table elevations on the foreshore exceed those on the backshore, resulting in a landward sloping water table. A landward flow of sea water might therefore be expected. Note also that such a slope reversal is uncommon on the lower high tide maxima.

(3) The time required for the passage of the damped tidal wave through the sand prism is clearly seen. The time of maximum

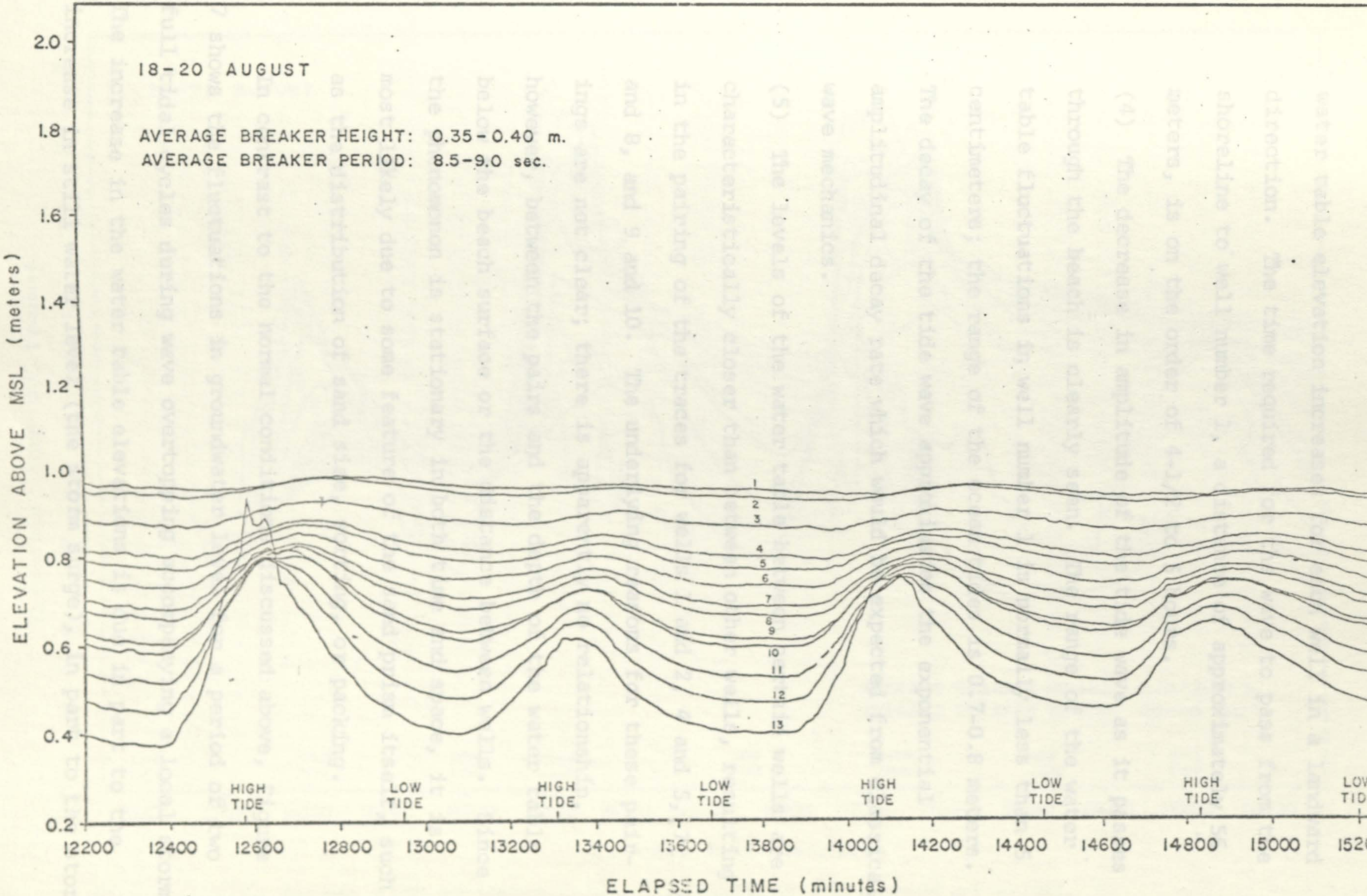

Fig. 6. Time series plot of water table fluctuations for period of normal waves and tides.

water table elevation increases for each well in a landward direction. The time required for the wave to pass from the shoreline to well number 1, a distance of approximately 56 meters, is on the order of 4-1/2 to 5 hours.

(4) The decrease in amplitude of the tide wave as it passes through the beach is clearly seen. The range of the water table fluctuations in well number 1 is normally less than 5 centimeters; the range of the ocean tides is 0.7-0.8 meters. The decay of the tide wave approximates the exponential amplitudinal decay rate which would be expected from classical wave mechanics.

(5) The levels of the water table between certain wells are characteristically closer than between other wells, resulting in the pairing of the traces for wells 1 and 2, 4 and 5, 7 and 8, and 9 and 10. The underlying reasons for these pairings are not clear; there is apparently no relationship, however, between the pairs and the depth of the water table below the beach surface or the distance between wells. Since the phenomonon is stationary in both time and space, it is most likely due to some feature of the sand prism itself, such as the distribution of sand size, sorting, or packing.

In contrast to the normal conditions discussed above, Figure 7 shows the fluctuations in groundwater level for a period of two full tidal cycles during wave overtopping accompanying a local storm. The increase in the water table elevations is due in part to the increase in still water level (the storm surge), in part to the storm

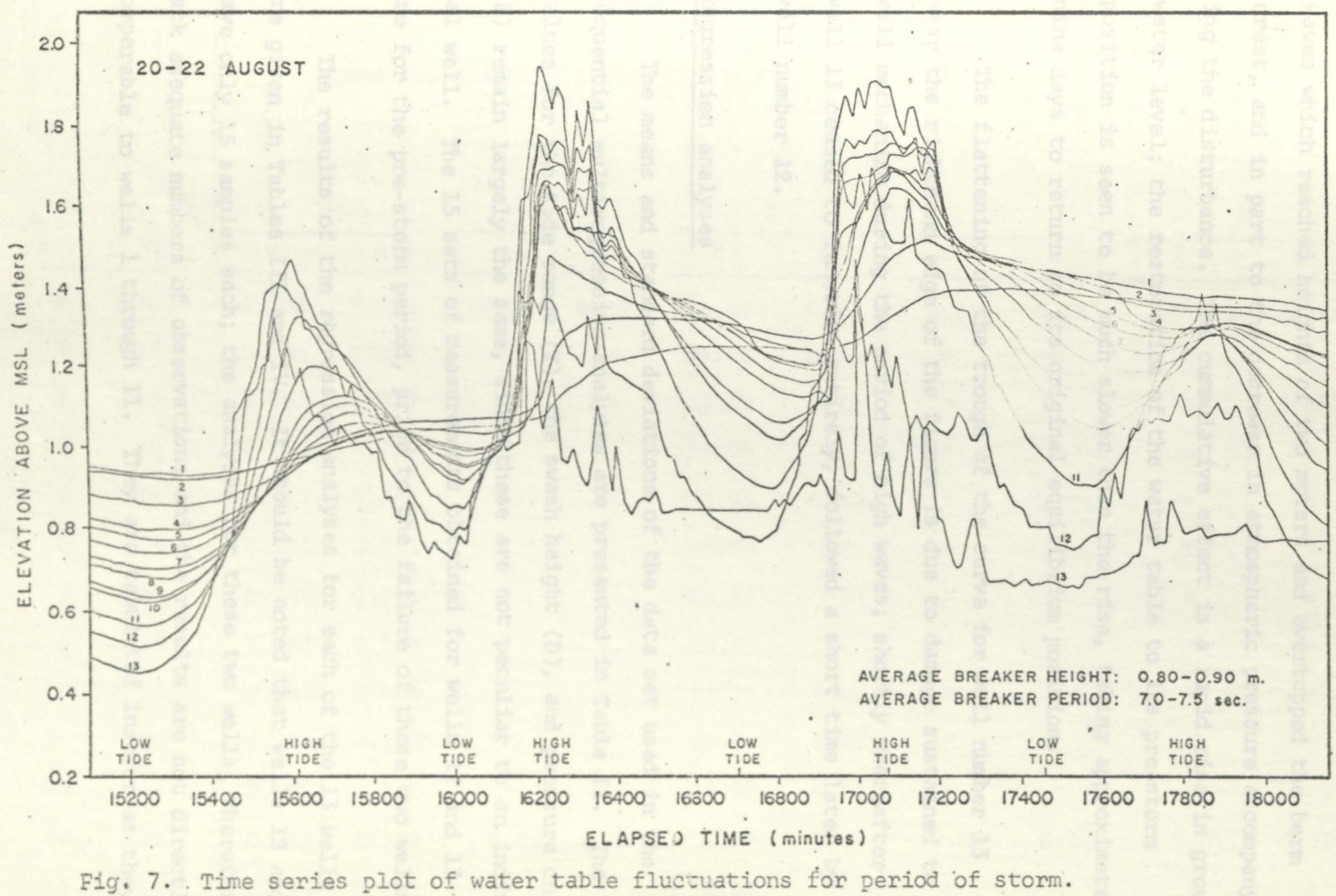

Fig. 7. Time series plot of water table fluctuations for period of storm.

waves which reached heights of two meters and overtopped the berm crest, and in part to the decrease in atmospheric pressure accompanying the disturbance. The cummulative effect is a rapid rise in groundwater level; the restoration of the water table to its pre-storm position is seen to be much slower than the rise, taking approximately nine days to return to its original equilibrium position.

The flattening of the trough of the curve for well number 13 near the righthand edge of the figure is due to damage sustained to the well mechanism during the period of high waves; shortly thereafter well 13 ceased to function entirely, followed a short time later by well number 12.

Regression analyses

The means and standard deviations of the data set used in the sequential multiregression analyses are presented in Table II. The values for the tide range (T), the swash height (D), and pressure change (P) remain largely the same, since these are not peculiar to an individual well. The 15 sets of measurements obtained for wells 12 and 13 are for the pre-storm period, prior to the failure of these two wells.

The results of the regression analyses for each of the 13 wells are given in Tables III and IV. It should be noted that wells 12 and 13 have only 15 samples each; the analyses for these two wells, therefore, lack adequate numbers of observations, and the results are not directly comparable to wells 1 through 11. They are tabulated insofar as they

TABLE II

MEANS AND STANDARD DEVIATIONS FOR W, T, X, D, AND P FOR EACH OF THE 13 WELLS

Well No.	n	W $\bar{x}$	W s	T $\bar{x}$	T s	X $\bar{x}$	X s	D $\bar{x}$	D s	P $\bar{x}$	P s
1	28	0.033	0.020	0.81	0.17	59.37	6.38	0.28	0.14	-0.003	0.040
2	28	0.045	0.023	"	"	50.17	6.39	"	"	"	"
3	28	0.063	0.029	"	"	43.67	6.38	"	"	"	"
4	28	0.089	0.036	"	"	37.28	"	"	"	"	"
5	29	0.107	0.042	"	"	33.95	6.27	"	0.13	"	"
6	29	0.135	0.051	"	"	30.75	"	"	"	"	"
7	29	0.164	0.061	"	"	27.52	"	"	"	"	"
8	29	0.183	0.069	"	"	24.30	"	"	"	"	"
9	29	0.236	0.089	"	"	21.11	6.29	"	"	"	"
10	29	0.284	0.110	"	"	17.97	6.26	"	"	"	"
11	29	0.360	0.148	"	"	14.90	6.27	"	"	"	"
12	15	0.391	0.135	0.89	0.11	16.08	5.84	0.26	0.14	0.011	0.026
13	15	0.517	0.191	"	"	12.82	"	"	"	"	"

may serve as indicators of trends on the foreshore.

Table III lists the predictor equations derived for each well and serves to show the signs of correlation for the process variables. Tidal range (T) and swash height above still water level (D) are positively correlated; i.e., an increase in the magnitude of each independent variable causes an increase in the elevation of the water table in each of the 13 wells. The distance of a well from the foreshore (X), and change in atmospheric pressure (P), on the other hand, are negatively correlated; an increase in either of these variables results in a decrease in the level of the water table in a given well. The correlations are consistent throughout the data set, except for (P) in well number 13, which, as stated above, lacked a sufficient number of data points.

The total percent reductions of the sums of squares of W accounted for by T, X, D, and P taken together are given in Table IV. Also given are the individual contributions of T, X, D, and P, presented as percentages of the total sums of squares reduction for all four process variables; these values are plotted in Figure 8. The results show that the four process variables chosen account for a greater per cent of the variability in the water table fluctuations near the shoreline than they do on the backshore. They show also that the effects of atmospheric pressure on water-table fluctuations are relatively more significant near the dune line, but become less so in a seaward direction; the distance of an individual well from the shoreline and the swash height above still

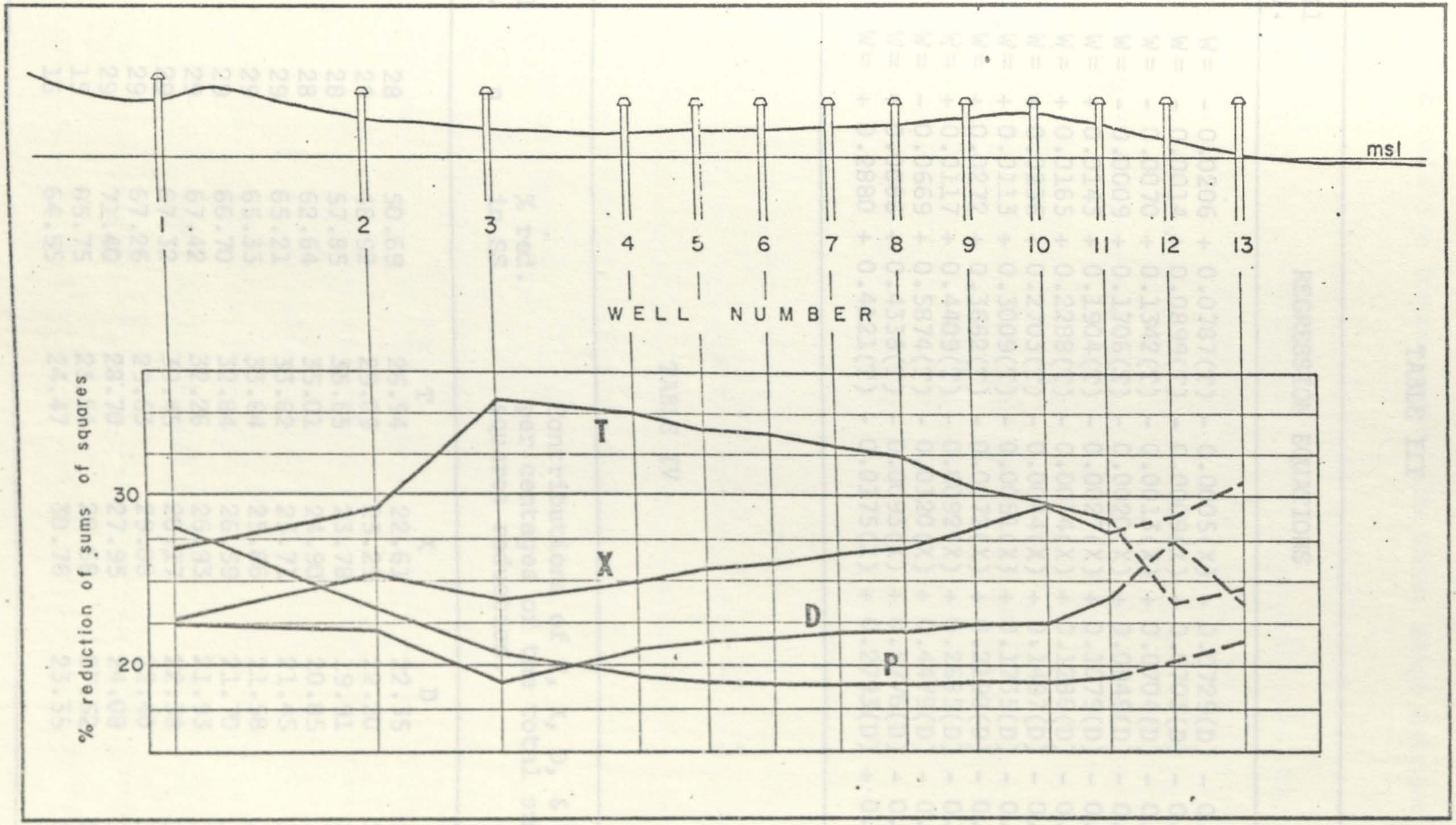

Fig. 8. Relative importance of T, X, D, and P in reduction of sums of squares of W.

TABLE III

Well no.	REGRESSION EQUATIONS
1	W= - 0.0206 + 0.0787(T) - 0.0005(X) + 0.0729(D) - 0.3301(P)
2	W= - 0.0014 + 0.0899(T) - 0.0009(X) + 0.0703(D) - 0.2707(P)
3	W= - 0.0070 + 0.1342(T) - 0.0013(X) + 0.0704(D) - 0.2825(P)
4	W= - 0.0009 + 0.1706(T) - 0.0020(X) + 0.0949(D) - 0.2603(P)
5	W= + 0.0143 + 0.1904(T) - 0.0027(X) + 0.1079(D) - 0.2278(P)
6	W= + 0.0165 + 0.2288(T) - 0.0034(X) + 0.1286(D) - 0.2273(P)
7	W= + 0.0236 + 0.2703(T) - 0.0044(X) + 0.1497(D) - 0.2097(P)
8	W= + 0.0113 + 0.3009(T) - 0.0051(X) + 0.1735(D) - 0.2323(P)
9	W= + 0.0272 + 0.3662(T) - 0.0072(X) + 0.2190(D) - 0.1968(P)
10	W= + 0.0117 + 0.4409(T) - 0.0092(X) + 0.2685(D) - 0.1509(P)
11	W= - 0.0669 + 0.5874(T) - 0.0120(X) + 0.4479(D) - 0.1757(P)
12	W= + 0.0086 + 0.4336(T) - 0.0093(X) + 0.5776(D) - 0.6278(P)
13	W= + 0.2880 + 0.4121(T) - 0.0175(X) + 0.2793(D) + 0.1360(P)

TABLE IV

Well no.	n	% red. in SS	Contributions of T, X, D, & P as per centages of the total sums of squares reduction.			
			T	X	D	P
1	28	50.69	26.94	22.61	22.35	28.08
2	28	48.92	29.09	25.29	22.20	23.39
3	28	57.85	35.65	23.78	19.91	20.63
4	28	62.64	35.01	24.90	20.85	19.22
5	29	65.21	33.82	25.71	21.45	19.00
6	29	65.33	33.64	25.86	21.58	18.90
7	29	66.70	32.84	26.59	21.70	18.84
8	29	67.42	32.26	26.93	21.93	18.96
9	29	67.32	30.45	28.17	22.38	18.98
10	29	67.26	29.63	29.08	22.40	18.88
11	29	71.40	28.70	27.95	24.08	19.24
12	15	85.75	23.54	28.68	27.52	20.23
13	15	64.55	24.47	30.76	23.35	21.40

water level become relatively more important toward the shoreline, while the relative importance of the tidal range becomes less.

DISCUSSION

The equations listed in Table III are the results of linear multiple regression analyses. It is known, however, that non-linear relationships exist between the water table fluctuations and certain of the independent variables; e.g., water table changes and distance from the shoreline (Fig. 9). A deterministic equation for fluctuations of the water table must account for these non-linear dependencies; predictive equations based on multiregression analysis for each well, on the other hand, need not account for the non-linearity if the data are such that they may be satisfied by a linear expression. Scatter diagrams for individual wells indicated that the latter method could be used here. The data plotted in Figure 9 represent the combined data from the 13 wells; these data were in fact analyzed in 13 individual regression analyses, and resulted in predictor equations for water-table fluctuations at 13 points on the beach.

The reliability of the predictor equations listed in Table III, as indicated by the per cent sums of squares accounted for, ranges from fair in the backshore area to good on the foreshore; the sums of squares accounted for generally increases in a seaward direction. It may be concluded from these observations that water-table fluctuations in the backshore and duné areas are significantly influenced by variables not taken into account in the present study. The major factor believed to be of significance in the backshore is

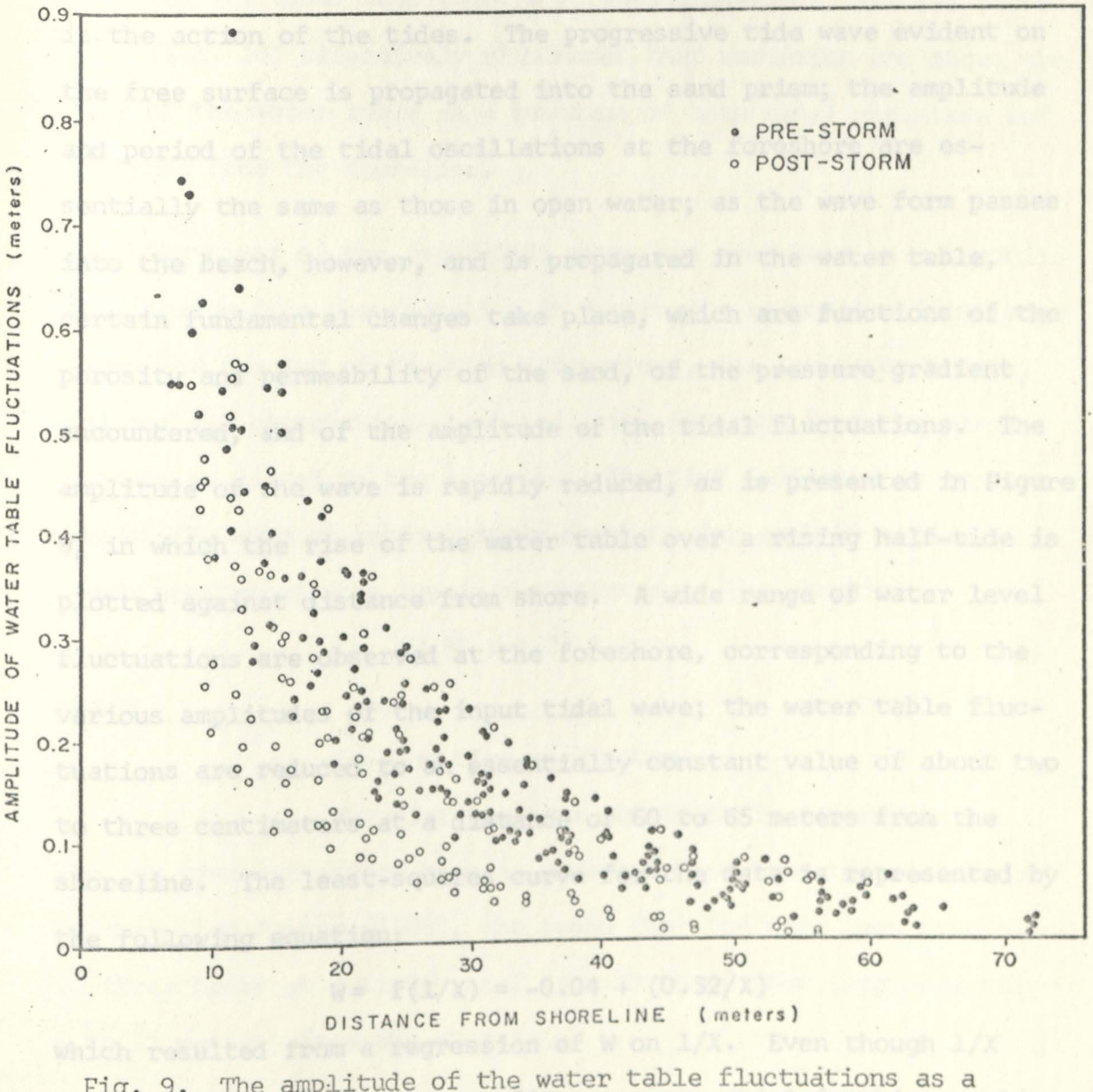

Fig. 9. The amplitude of the water table fluctuations as a function of distance from the shoreline.

the groundwater pressure head, as influenced by local weather conditions in the supply or charging area.

The major forcing function, as shown by the regression analyses, is the action of the tides. The progressive tide wave evident on the free surface is propagated into the sand prism; the amplitude and period of the tidal oscillations at the foreshore are essentially the same as those in open water; as the wave form passes into the beach, however, and is propagated in the water table, certain fundamental changes take place, which are functions of the porosity and permeability of the sand, of the pressure gradient encountered, and of the amplitude of the tidal fluctuations. The amplitude of the wave is rapidly reduced, as is presented in Figure 9, in which the rise of the water table over a rising half-tide is plotted against distance from shore. A wide range of water level fluctuations are observed at the foreshore, corresponding to the various amplitudes of the input tidal wave; the water table fluctuations are reduced to an essentially constant value of about two to three centimeters at a distance of 60 to 65 meters from the shoreline. The least-squares curve for the data is represented by the following equation:

$$W = f(1/X) = -0.04 + (0.52/X)$$

which resulted from a regression of W on 1/X. Even though 1/X resulted in a somewhat better fit, an exponential function would physically be more appealing.

The greater variation of the post-storm data exhibited in Figure 9 reflects the greater variability of the tidal amplitudes following the strom (see Fig. 4). A plot of the ratio of the water table rise and the tidal amplitude, W/T, versus distance from the shoreline (Fig. 10) effectively eliminates that variation and shows the rise of the water table as a function of both tidal amplitude and distance from the shoreline.

Lag times of the input tide waves are presented as a function of distance from the shoreline in Figure 11; regression lines are shown for the lag of the high water crest, the low water trough, and for all observations combined. The data are from the sample periods as listed in the appendix. The plot indicates an average lag of the wave of approximately one hour for each 18 meters of beach penetrated; the lag is represented by the equation

$$L = 50.38 + 3.27\,X$$

where

L = lag time in minutes

X = distance from shoreline in meters

The lag time determined here is somewhat less than those observed by Emery and Foster (1948), who found that the wave lags from one to three hours at a distance of from 20 to 40 feet (approximately 6 to 13 meters) from the shoreline.

The slope of the low water regression line is less steep than the high water line, indicating that the high water crest is propagated

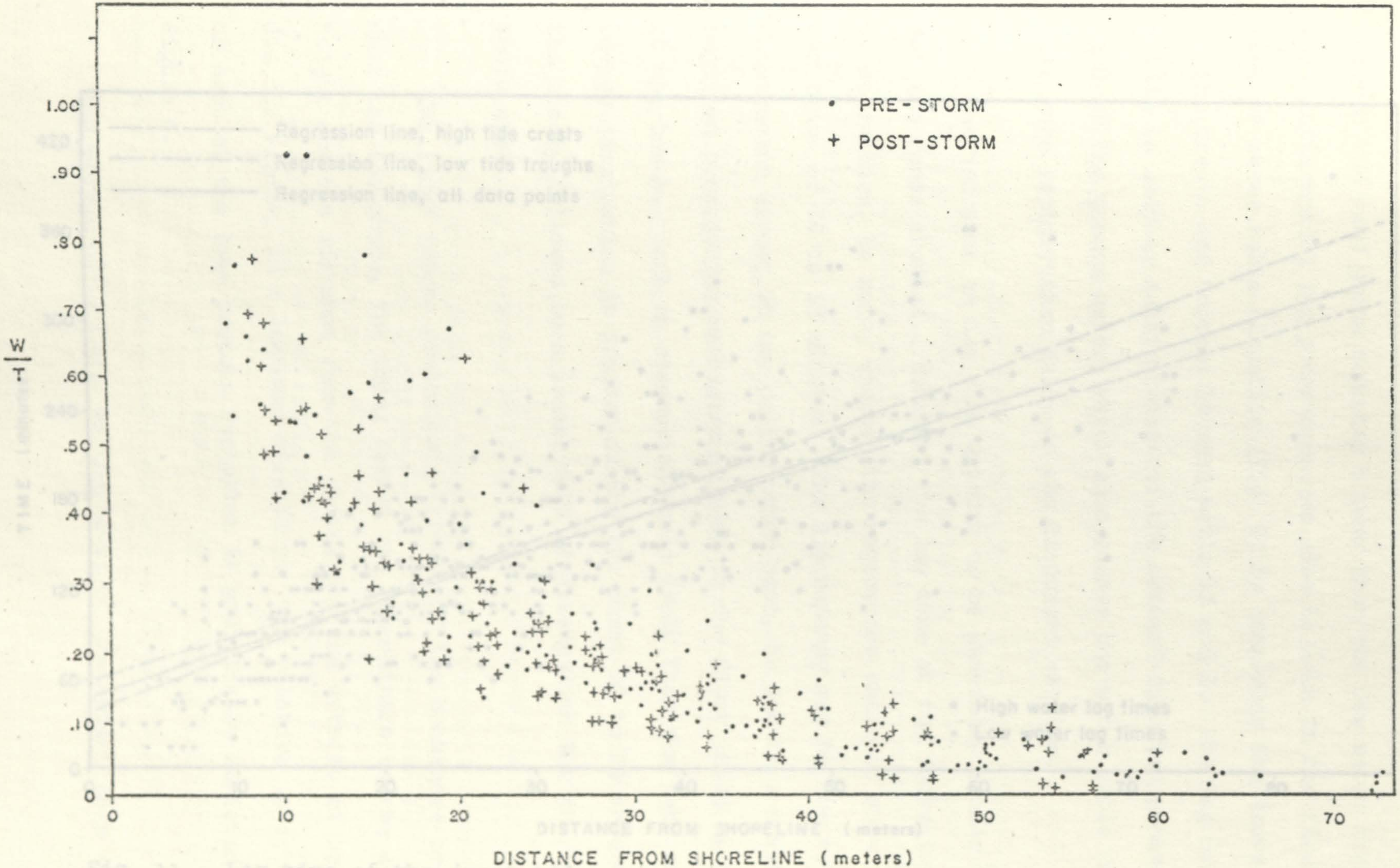

Fig. The ratio of the rise of the water table and the rise in still water level as a function of distance from the shoreline.

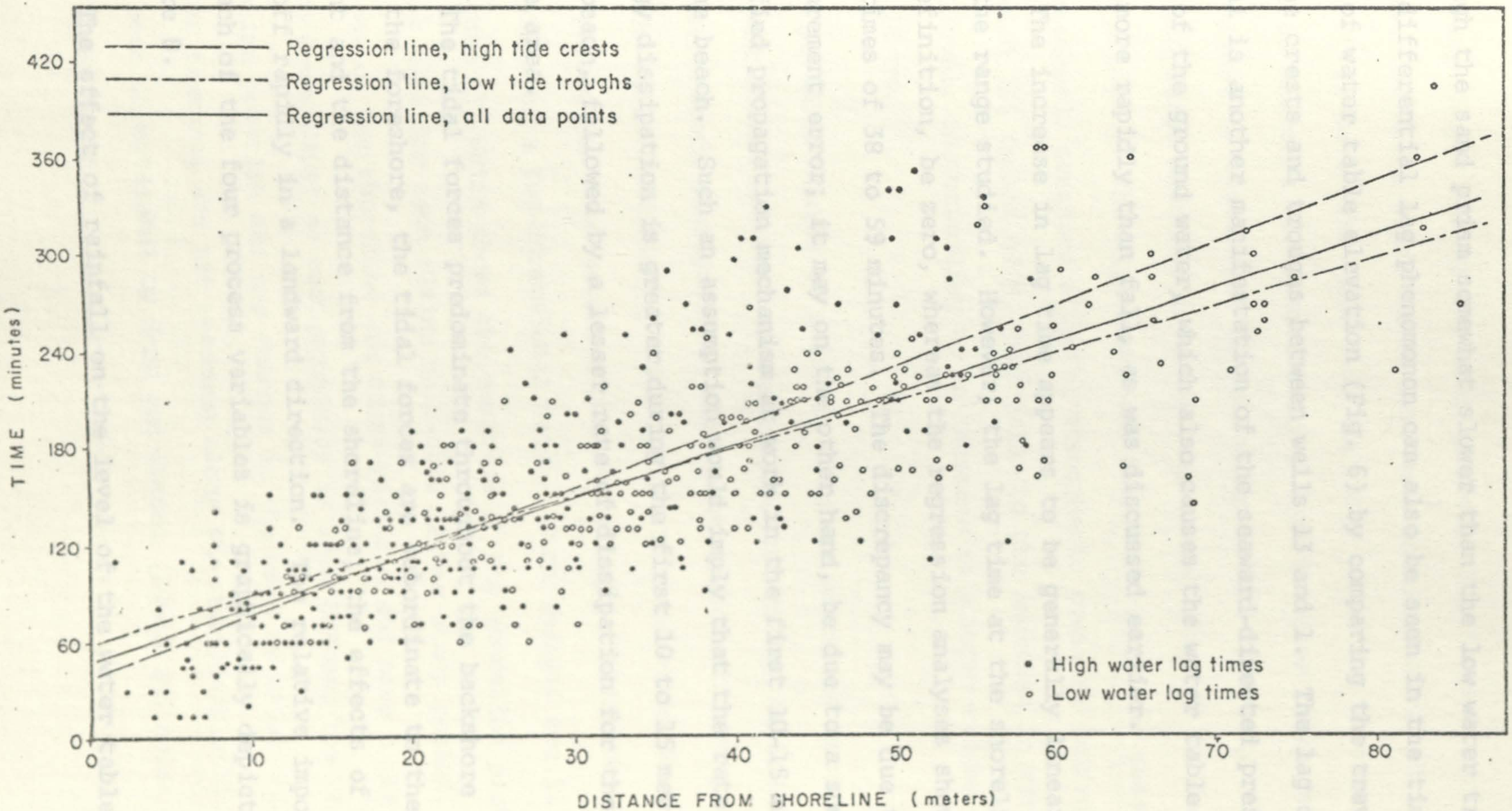

Fig. 11. Lag time of the input tide waves, as a function of distance from the shoreline.

through the sand prism somewhat slower than the low water trough; this differential lag phenomonon can also be seen in the time series plot of water table elevation (Fig. 6) by comparing the travel times of the crests and troughs between wells 13 and 1. The lag differential is another manifestation of the seaward-directed pressure head of the ground water, which also causes the water table to rise more rapidly than fall, as was discussed earlier.

The increase in lag time appears to be generally linear throughout the range studied. However, the lag time at the shoreline should, by definition, be zero, whereas the regression analyses show initial lag times of 38 to 59 minutes. The discrepancy may be due to measurement error; it may on the other hand, be due to a somewhat modified propagation mechanism at work in the first 10-15 meters of the beach. Such an assumption would imply that the rate of energy dissipation is greater during the first 10 to 15 meters of the beach, followed by a lesser rate of dissipation for the backshore area.

The tidal forces predominate throughout the backshore area; near the foreshore, the tidal forces are subordinate to the swash height and the distance from the shoreline; the effects of both die off rapidly in a landward direction. The relative importance of each of the four process variables is graphically depicted in Figure 8.

The effect of rainfall on the level of the water table appeared to be very slight during the study period, The largest period of rainfall for which water table data were obtained amounted to 0.83 inches (2.11 cm). The effect on the water table can be seen (Fig. 12) as an increase of approximately 1.5 cm in water table level; the increase is consistant for all wells in the transect. The rapid and large increase in water table level (Fig. 7) is due mainly to the action of the high waves and the storm surge and possibly to atmospheric pressure effects; atmospheric pressure suddenly dropped 0.735 inches of H_g just prior to the increase in water table level, corresponding to an increase in a water column of about 18 cm.

A possible source of noise in the data which may account for some part of the low sums of squares reductions may be found in changes in beach configuration which were not due to changing wave or water table conditions. Such changes were observed in the long-shore passage of sand waves, a phenomonon which belies the original assumption of a two-dimensional beach. Such changes are illustrated in Figure 13, which shows the position of the shoreline plotted against time for each rising half-tide of the study period. The fluctuations of the shoreline are quasi-periodic and have a period of six to seven days; no correspondence is seen between the changes in shoreline position and any changes in the wave or tidal characteristics. Similar features are not uncommon along the middle-Atlantic coast and have been investigated by Sonu and Russel (1966) and Dolan (1970) at Nags Head, North Carolina, where they are quite pronounced. Future

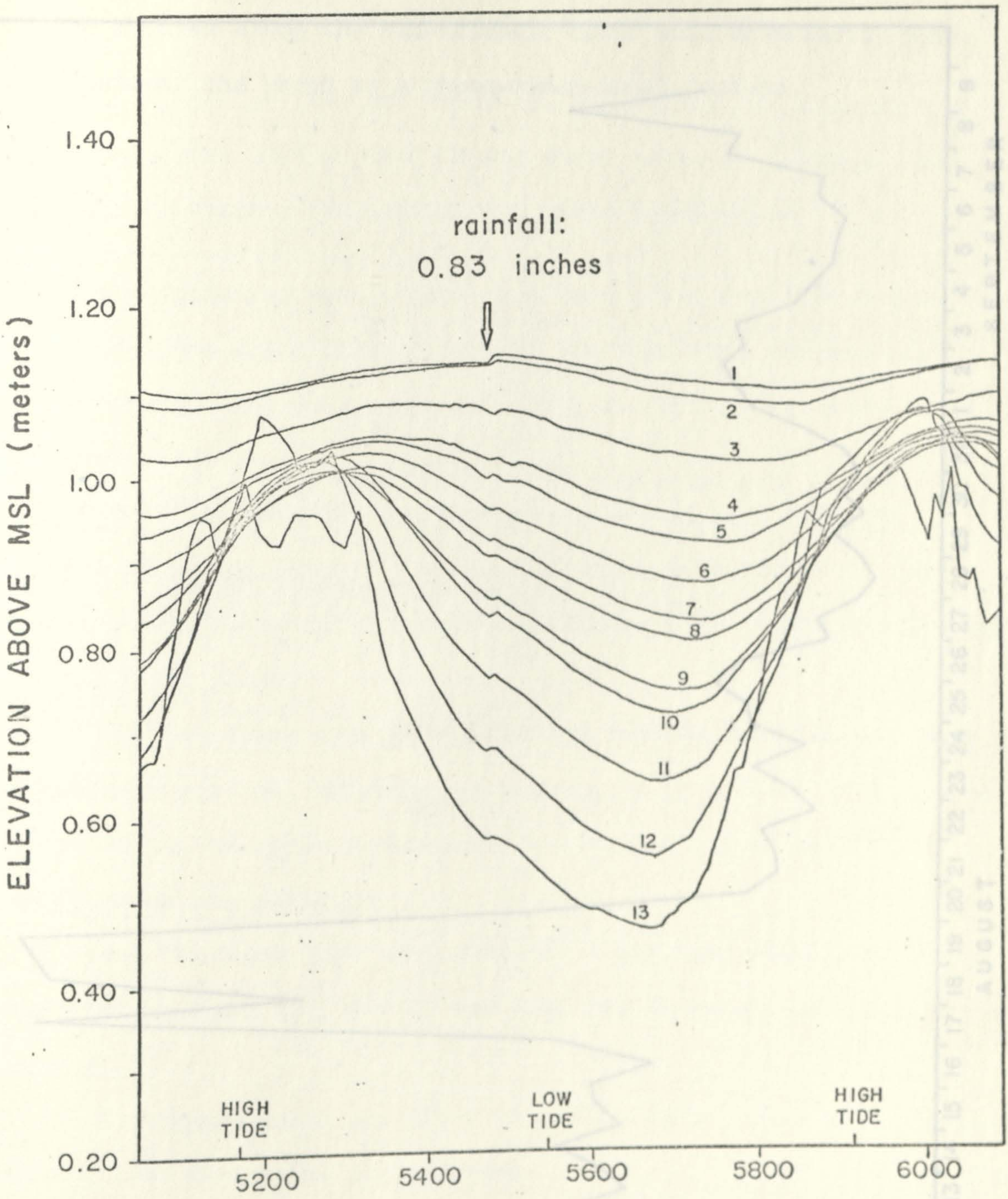

Fig. 12. Effect of rainfall on the level of the water table.

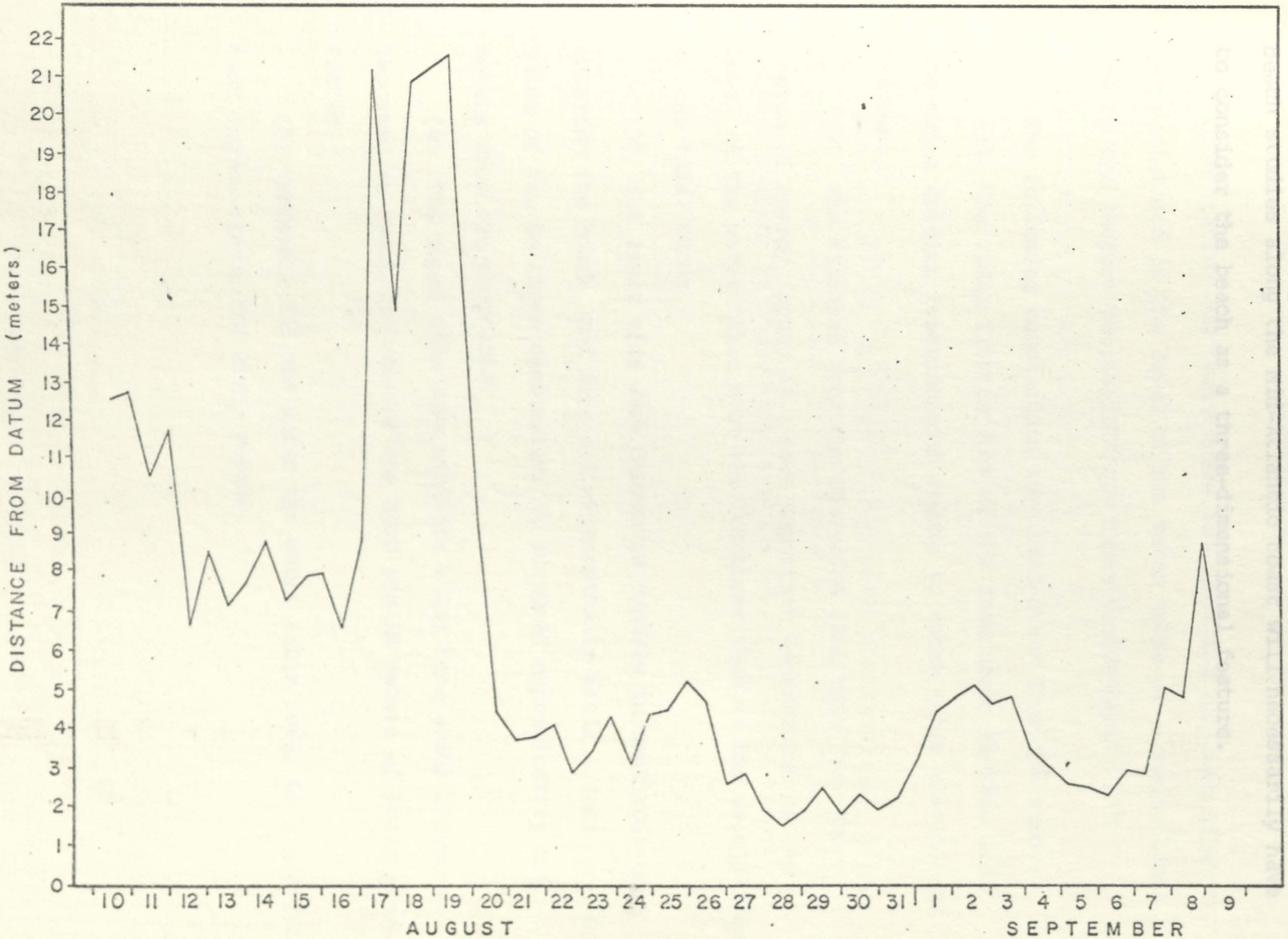

Fig. 13. Position of the shoreline as a function of time for the 30-day study period.

beach studies along the Mid-Atlantic coast will necessarily have to consider the beach as a three-dimensional feature.

CONCLUSIONS

Quantitative and qualitative consideration has been given to the variations in the level of the water table of a marine beach and to the factors responsible for these variations.

The following conclusions have been drawn from the study:

(1) The tidal fluctuations of the free ocean surface are the major forcing function with regard to water table elevational changes.

(2) The distance from the shoreline (and thus from the source of energy input) is a more important determinant of the level of the water table near the foreshore than is the oscillation of the tidal plane.

(3) The input tide wave decreases rapidly in amplitude upon entering the beach, and dies off exponentially until a semi-constant value of two to three centimeters is attained approximately 60 meters from the shoreline.

(4) The input tide wave exhibits a lag time which increases landward at about the rate of one hour per 18 meters of beach penetrated.

(5) Rainfall did not alter the water table level to a significant degree during the study period.

APPENDIX

The thirteen data sets used in the sequential multiple regression analysis are given.

Elapsed time, given in minutes, is referenced to 1805 hours, 9 August, 1969.

The rise of the water table (W), tidal amplitude (T), distance from the shoreline (X), and swash height (D) are given in meters. Change in barometric pressure (P) is given in inches of mercury.

WELL NO.	SAMPLE NO.	ELAPSED TIME OF LW	ELAPSED TIME OF HW	W	T	X	D	P
1	1	1900	2220	0.012	0.89	63.70	0.09	0.020
1	2	2590	2990	0.060	0.94	61.50	0.23	0.015
1	3	3365	3661	0.038	0.69	62.65	0.56	0.020
1	4	4813	5173	0.047	0.92	59.54	0.49	0.010
1	5	7783	8173	0.029	0.91	58.33	0.34	0.053
1	6	8527	8899	0.025	0.94	58.83	0.20	0.010
1	7	9265	9625	0.034	1.04	58.98	0.24	-0.015
1	8	9997	10363	0.023	0.88	57.63	0.14	-0.015
1	9	10717	11101	0.040	0.98	59.88	0.33	0.040
1	10	11467	11827	0.015	0.82	72.22	0.31	0.050
1	11	12193	12583	0.028	0.96	65.85	0.23	0.035
1	12	12955	13315	0.005	0.76	72.02	0.17	0.000
1	13	13681	14071	0.026	1.01	72.27	0.04	-0.015
1	14	14461	14835	0.020	0.67	72.62	0.17	-0.030
1	15	30900	31235	0.039	1.02	53.00	0.41	0.050
1	16	31675	31970	0.010	0.88	53.35	0.29	0.030
1	17	32767	32767	0.007	0.56	56.23	0.40	0.040
1	18	32767	32767	0.047	0.84	55.78	0.40	-0.005
1	19	32767	32767	0.055	0.79	52.61	0.38	-0.010
1	20	32767	32767	0.065	0.52	54.18	0.46	0.000
1	21	32767	32767	0.041	0.70	53.70	0.41	-0.050
1	22	32767	32767	0.017	0.46	53.60	0.33	-0.025
1	23	32767	32767	0.056	0.73	53.40	0.37	-0.025
1	24	32767	32767	0.005	0.50	54.08	0.15	-0.040
1	25	32767	32767	0.077	0.78	53.98	0.28	-0.100
1	26	32767	32767	0.003	0.58	56.23	0.34	-0.035
1	27	32767	32767	0.061	0.88	55.98	0.06	-0.100
1	28	32767	32767	0.055	0.91	60.09	0.09	0.015
2	1	1900	2220	0.023	0.89	54.51	0.09	0.020
2	2	2590	2990	0.075	0.94	52.31	0.23	0.015
2	3	3365	3661	0.056	0.69	53.46	0.56	0.020
2	4	4813	5173	0.052	0.92	50.35	0.49	0.010
2	5	7783	8173	0.040	0.91	49.14	0.34	0.053
2	6	8527	8899	0.036	0.94	49.64	0.20	0.010
2	7	9265	9625	0.049	1.04	49.79	0.24	-0.015
2	8	9997	10363	0.036	0.88	48.44	0.14	-0.015
2	9	10717	11101	0.049	0.98	50.69	0.33	0.040
2	10	11467	11827	0.022	0.82	63.03	0.31	0.050
2	11	12193	12583	0.042	0.96	56.66	0.23	0.035
2	12	12955	13315	0.011	0.76	62.83	0.17	0.000
2	13	13681	14071	0.036	1.01	63.08	0.04	-0.015
2	14	14461	14835	0.025	0.67	63.43	0.17	-0.030
2	15	30900	31235	0.066	1.02	43.81	0.41	0.050
2	16	31675	31970	0.023	0.88	44.16	0.29	0.030
2	17	32767	32767	0.015	0.56	47.04	0.40	0.040
2	18	32767	32767	0.069	0.84	46.59	0.40	-0.005
2	19	32767	32767	0.076	0.79	43.32	0.38	-0.010
2	20	32767	32767	0.068	0.52	44.99	0.46	0.000
2	21	32767	32767	0.059	0.70	44.51	0.41	-0.050
2	22	32767	32767	0.024	0.46	44.41	0.33	-0.025
2	23	32767	32767	0.070	0.73	44.21	0.37	-0.025
2	24	32767	32767	0.012	0.50	44.89	0.15	-0.040
2	25	32767	32767	0.073	0.78	44.79	0.28	-0.100
2	26	32767	32767	0.012	0.58	47.04	0.34	-0.035
2	27	32767	32767	0.078	0.88	46.79	0.06	-0.100
2	28	32767	32767	0.080	0.91	50.90	0.09	0.015

WELL NO.	SAMPLE NO.	ELAPSED TIME OF LW	ELAPSED TIME OF HW	W	T	X	D	P
3	1	1900	2220	0.030	0.89	48.00	0.09	0.020
3	2	2590	2990	0.100	0.94	45.80	0.23	0.015
3	3	3365	3661	0.077	0.69	46.95	0.56	0.020
3	4	4813	5173	0.066	0.92	43.84	0.49	0.010
3	5	7783	8173	0.063	0.91	42.63	0.34	0.053
3	6	8527	8899	0.055	0.94	43.13	0.20	0.010
3	7	9265	9625	0.074	1.04	43.28	0.24	-0.015
3	8	9997	10363	0.060	0.88	41.93	0.14	-0.015
3	9	10717	11101	0.072	0.98	44.19	0.33	0.040
3	10	11467	11827	0.037	0.82	56.52	0.31	0.050
3	11	12193	12583	0.061	0.96	50.16	0.23	0.035
3	12	12955	13315	0.025	0.76	56.32	0.17	0.000
3	13	13681	14071	0.053	1.01	56.57	0.04	-0.015
3	14	14461	14835	0.038	0.67	56.92	0.17	-0.030
3	15	30900	31235	0.101	1.02	37.30	0.41	0.050
3	16	31675	31970	0.048	0.88	37.65	0.29	0.030
3	17	32767	32767	0.028	0.56	40.53	0.40	0.040
3	18	32767	32767	0.100	0.84	40.08	0.40	-0.005
3	19	32767	32767	0.107	0.79	36.91	0.38	-0.010
3	20	32767	32767	0.024	0.52	38.49	0.46	0.000
3	21	32767	32767	0.090	0.70	38.00	0.41	-0.050
3	22	32767	32767	0.039	0.46	37.90	0.33	-0.025
3	23	32767	32767	0.093	0.73	37.70	0.37	-0.025
3	24	32767	32767	0.027	0.50	38.38	0.15	-0.040
3	25	32767	32767	0.082	0.78	38.28	0.28	-0.100
3	26	32767	32767	0.025	0.58	40.53	0.34	-0.035
3	27	32767	32767	0.099	0.88	40.28	0.06	-0.100
3	28	32767	32767	0.106	0.91	44.39	0.09	0.015
4	1	1900	2220	0.049	0.89	41.61	0.09	0.020
4	2	2590	2990	0.136	0.94	39.41	0.23	0.015
4	3	3365	3661	0.112	0.69	40.56	0.56	0.020
4	4	4813	5173	0.093	0.92	37.45	0.49	0.010
4	5	7783	8173	0.089	0.91	36.24	0.34	0.053
4	6	8527	8899	0.079	0.94	36.74	0.20	0.010
4	7	9265	9625	0.105	1.04	36.89	0.24	-0.015
4	8	9997	10363	0.083	0.88	35.54	0.14	-0.015
4	9	10717	11101	0.102	0.98	37.79	0.33	0.040
4	10	11467	11827	0.054	0.82	50.13	0.31	0.050
4	11	12193	12583	0.086	0.96	43.77	0.23	0.035
4	12	12955	13315	0.030	0.76	49.93	0.17	0.000
4	13	13681	14071	0.074	1.01	50.18	0.04	-0.015
4	14	14461	14835	0.050	0.67	50.53	0.17	-0.030
4	15	30900	31235	0.153	1.02	30.91	0.41	0.050
4	16	31675	31970	0.077	0.88	31.26	0.29	0.030
4	17	32767	32767	0.048	0.56	34.14	0.40	0.040
4	18	32767	32767	0.131	0.84	33.69	0.40	-0.005
4	19	32767	32767	0.139	0.79	30.52	0.38	-0.010
4	20	32767	32767	0.057	0.52	32.09	0.46	0.000
4	21	32767	32767	0.117	0.70	31.61	0.41	-0.050
4	22	32767	32767	0.054	0.46	31.51	0.33	-0.025
4	23	32767	32767	0.119	0.73	31.31	0.37	-0.025
4	24	32767	32767	0.040	0.50	31.99	0.15	-0.040
4	25	32767	32767	0.102	0.78	31.89	0.28	-0.100
4	26	32767	32767	0.040	0.58	34.14	0.34	-0.035
4	27	32767	32767	0.129	0.88	33.89	0.06	-0.100
4	28	32767	32767	0.137	0.91	38.00	0.09	0.015

WELL NO.	SAMPLE NO.	ELAPSED TIME OF LW	ELAPSED TIME OF HW	W	T	X	D	P
5	1	1900	2220	0.059	0.89	38.33	0.09	0.020
5	2	2590	2990	0.157	0.94	36.13	0.23	0.015
5	3	3365	3661	0.138	0.69	37.28	0.56	0.020
5	4	4813	5173	0.117	0.92	34.17	0.49	0.010
5	5	5545	5917	0.145	1.01	32.75	0.35	-0.020
5	6	7783	8173	0.106	0.91	32.96	0.34	0.053
5	7	8527	8899	0.096	0.95	33.46	0.20	0.010
5	8	9265	9625	0.127	1.04	33.61	0.24	-0.015
5	9	9997	10363	0.100	0.88	32.26	0.14	-0.015
5	10	10717	11101	0.120	0.98	34.51	0.33	0.040
5	11	11467	11827	0.061	0.82	46.85	0.31	0.050
5	12	12193	12583	0.100	0.96	40.49	0.23	0.035
5	13	12955	13315	0.034	0.76	46.65	0.17	0.000
5	14	13681	14071	0.085	1.01	46.90	0.04	-0.015
5	15	14461	14835	0.052	0.67	47.25	0.17	-0.030
5	16	30900	31235	0.189	1.02	27.63	0.41	0.050
5	17	31675	31970	0.097	0.88	27.98	0.29	0.030
5	18	32767	32767	0.062	0.56	30.86	0.40	0.040
5	19	32767	32767	0.153	0.84	30.41	0.40	-0.005
5	20	32767	32767	0.166	0.79	27.24	0.38	-0.010
5	21	32767	32767	0.073	0.52	28.81	0.46	0.000
5	22	32767	32767	0.139	0.70	28.33	0.41	-0.050
5	23	32767	32767	0.066	0.46	28.23	0.33	-0.025
5	24	32767	32767	0.138	0.73	28.03	0.37	-0.025
5	25	32767	32767	0.050	0.50	28.71	0.15	-0.040
5	26	32767	32767	0.119	0.78	28.61	0.28	-0.100
5	27	32767	32767	0.054	0.58	30.86	0.34	-0.035
5	28	32767	32767	0.144	0.88	30.61	0.06	-0.100
5	29	32767	32767	0.169	0.91	34.72	0.09	0.015
6	1	1900	2220	0.081	0.89	35.13	0.09	0.020
6	2	2590	2990	0.193	0.94	32.93	0.23	0.015
6	3	3365	3661	0.171	0.69	34.08	0.56	0.020
6	4	4813	5173	0.145	0.92	30.97	0.49	0.010
6	5	5545	5917	0.180	1.01	29.55	0.35	-0.020
6	6	7783	8173	0.136	0.91	29.76	0.34	0.053
6	7	8527	8899	0.122	0.95	30.26	0.20	0.010
6	8	9265	9625	0.156	1.04	30.41	0.24	-0.015
6	9	9997	10363	0.123	0.89	29.06	0.14	-0.015
6	10	10717	11101	0.146	0.98	31.31	0.33	0.040
6	11	11467	11827	0.082	0.82	43.65	0.31	0.050
6	12	12193	12583	0.123	0.96	37.29	0.23	0.035
6	13	12955	13315	0.050	0.76	43.45	0.17	0.000
6	14	13681	14071	0.105	1.01	43.70	0.04	-0.015
6	15	14461	14835	0.069	0.67	44.05	0.17	-0.030
6	16	30900	31235	0.242	1.02	24.43	0.41	0.050
6	17	31675	31970	0.132	0.88	24.78	0.29	0.030
6	18	32767	32767	0.082	0.56	27.66	0.40	0.040
6	19	32767	32767	0.192	0.84	27.21	0.40	-0.005
6	20	32767	32767	0.207	0.79	24.04	0.38	-0.010
6	21	32767	32767	0.092	0.52	25.61	0.46	0.000
6	22	32767	32767	0.173	0.70	25.13	0.41	-0.050
6	23	32767	32767	0.084	0.46	25.03	0.33	-0.025
6	24	32767	32767	0.171	0.73	24.83	0.37	-0.025
6	25	32767	32767	0.066	0.50	25.51	0.15	-0.040
6	26	32767	32767	0.149	0.78	25.41	0.28	-0.100
6	27	32767	32767	0.063	0.58	27.66	0.34	-0.035
6	28	32767	32767	0.174	0.88	27.41	0.06	-0.100
6	29	32767	32767	0.208	0.91	31.52	0.09	0.015

WELL NO.	SAMPLE NO.	ELAPSED TIME OF LW	ELAPSED TIME OF HW	W	T	X	D	P
7	1	1900	2220	0.094	0.89	31.90	0.09	0.020
7	2	2590	2990	0.227	0.94	29.70	0.23	0.015
7	3	3365	3661	0.205	0.69	30.85	0.56	0.020
7	4	4813	5173	0.176	0.92	27.74	0.49	0.010
7	5	5545	5917	0.214	1.01	26.32	0.35	-0.020
7	6	7783	8173	0.170	0.91	26.53	0.34	0.053
7	7	8527	8899	0.151	0.94	27.03	0.20	0.010
7	8	9265	9625	0.189	1.04	27.18	0.24	-0.015
7	9	9997	10363	0.148	0.88	25.83	0.14	-0.015
7	10	10717	11101	0.174	0.98	28.08	0.33	0.040
7	11	11467	11827	0.100	0.82	40.42	0.31	0.050
7	12	12193	12583	0.151	0.96	34.06	0.23	0.035
7	13	12955	13315	0.063	0.76	40.22	0.17	0.000
7	14	13681	14071	0.125	1.01	40.47	0.04	-0.015
7	15	14461	14835	0.091	0.67	40.82	0.17	-0.030
7	16	30900	31235	0.303	1.02	21.20	0.41	0.050
7	17	31675	31970	0.168	0.88	21.55	0.29	0.030
7	18	32767	32767	0.106	0.56	24.43	0.40	0.040
7	19	32767	32767	0.237	0.84	23.98	0.40	-0.005
7	20	32767	32767	0.250	0.79	20.81	0.38	-0.010
7	21	32767	32767	0.113	0.52	22.38	0.46	0.000
7	22	32767	32767	0.207	0.70	21.90	0.41	-0.050
7	23	32767	32767	0.105	0.46	21.80	0.33	-0.025
7	24	32767	32767	0.205	0.73	21.60	0.37	-0.025
7	25	32767	32767	0.085	0.50	22.28	0.15	-0.040
7	26	32767	32767	0.180	0.78	22.18	0.28	-0.100
7	27	32767	32767	0.081	0.58	24.43	0.34	-0.035
7	28	32767	32767	0.205	0.88	24.18	0.06	-0.100
7	29	32767	32767	0.252	0.91	28.29	0.09	0.015
8	1	1900	2220	0.102	0.89	28.68	0.09	0.020
8	2	2590	2990	0.249	0.94	26.48	0.23	0.015
8	3	3365	3661	0.226	0.69	27.63	0.56	0.020
8	4	4813	5173	0.197	0.92	24.52	0.49	0.010
8	5	5545	5917	0.239	1.01	23.10	0.35	-0.020
8	6	7783	8173	0.189	0.91	23.31	0.34	0.053
8	7	8527	8899	0.166	0.94	23.81	0.20	0.010
8	8	9265	9625	0.209	1.04	23.96	0.24	-0.015
8	9	9997	10363	0.161	0.88	22.61	0.14	-0.015
8	10	10717	11101	0.190	0.97	24.86	0.33	0.040
8	11	11467	11827	0.107	0.82	37.20	0.31	0.050
8	12	12193	12583	0.165	0.96	30.84	0.23	0.035
8	13	12955	13315	0.070	0.76	37.00	0.17	0.000
8	14	13681	14071	0.140	1.01	37.25	0.04	-0.015
8	15	14461	14835	0.087	0.67	37.60	0.17	-0.030
8	16	30900	31235	0.344	1.02	17.98	0.41	0.050
8	17	31675	31970	0.191	0.88	18.33	0.29	0.030
8	18	32767	32767	0.118	0.56	21.21	0.40	0.040
8	19	32767	32767	0.268	0.84	20.76	0.40	-0.005
8	20	32767	32767	0.280	0.79	17.59	0.38	-0.010
8	21	32767	32767	0.131	0.52	19.16	0.46	0.000
8	22	32767	32767	0.232	0.70	18.68	0.41	-0.050
8	23	32767	32767	0.116	0.46	18.58	0.33	-0.025
8	24	32767	32767	0.230	0.73	18.38	0.37	-0.025
8	25	32767	32767	0.096	0.50	19.06	0.15	-0.040
8	26	32767	32767	0.203	0.78	18.96	0.28	-0.100
8	27	32767	32767	0.088	0.58	21.21	0.34	-0.035
8	28	32767	32767	0.224	0.88	20.96	0.06	-0.100
8	29	32767	32767	0.279	0.91	25.07	0.09	0.015

WELL NO.	SAMPLE NO.	ELAPSED TIME OF LW.	ELAPSED TIME OF HW	W	T	X	D	P
9	1	1900	2220	0.127	0.89	25.51	0.09	0.020
9	2	2590	2990	0.309	0.94	23.31	0.23	0.015
9	3	3365	3661	0.285	0.69	24.46	0.56	0.020
9	4	4813	5173	0.250	0.92	21.35	0.49	0.010
9	5	5545	5917	0.302	1.01	19.93	0.35	-0.020
9	6	7783	8173	0.244	0.91	20.14	0.34	0.053
9	7	8527	8899	0.212	0.94	20.64	0.20	0.010
9	8	9265	9625	0.270	1.04	20.79	0.24	-0.015
9	9	9997	10363	0.201	0.88	19.44	0.14	-0.015
9	10	10717	11101	0.239	0.98	21.69	0.33	0.040
9	11	11467	11827	0.137	0.82	34.03	0.31	0.050
9	12	12193	12583	0.201	0.96	27.67	0.23	0.035
9	13	12955	13315	0.103	0.76	33.73	0.17	0.000
9	14	13681	14071	0.170	1.01	34.08	0.04	-0.015
9	15	14461	14835	0.107	0.67	34.43	0.17	-0.030
9	16	30900	31235	0.453	1.02	14.18	0.41	0.050
9	17	31675	31970	0.263	0.88	15.16	0.29	0.030
9	18	32767	32767	0.161	0.56	18.04	0.40	0.040
9	19	32767	32767	0.354	0.84	17.59	0.40	-0.005
9	20	32767	32767	0.361	0.79	14.42	0.38	-0.010
9	21	32767	32767	0.172	0.52	15.99	0.46	0.000
9	22	32767	32767	0.304	0.70	15.51	0.41	-0.050
9	23	32767	32767	0.160	0.46	15.41	0.33	-0.025
9	24	32767	32757	0.297	0.73	15.21	0.37	-0.025
9	25	32767	32767	0.131	0.50	15.89	0.15	-0.040
9	26	32767	32767	0.260	0.78	15.79	0.28	-0.100
9	27	32767	32767	0.121	0.58	18.04	0.34	-0.035
9	28	32767	32767	0.268	0.88	17.79	0.06	-0.100
9	29	32767	32767	0.361	0.91	21.90	0.09	0.015
10	1	1900	2220	0.149	0.89	22.35	0.09	0.020
10	2	2590	2990	0.363	0.94	20.15	0.23	0.015
10	3	3365	3661	0.339	0.69	21.30	0.56	0.020
10	4	4813	5173	0.296	0.92	18.19	0.49	0.010
10	5	5545	5917	0.361	1.01	16.77	0.35	-0.020
10	6	7783	8173	0.301	0.91	16.98	0.34	0.053
10	7	8527	8899	0.256	0.94	17.48	0.20	0.010
10	8	9265	9625	0.326	1.04	17.63	0.24	-0.015
10	9	9997	10363	0.242	0.88	16.28	0.14	-0.015
10	10	10717	11101	0.286	0.98	18.53	0.33	0.040
10	11	11467	11827	0.163	0.82	30.87	0.31	0.050
10	12	12193	12583	0.234	0.96	24.51	0.23	0.035
10	13	12955	13315	0.121	0.76	30.57	0.17	0.000
10	14	13681	14071	0.200	1.01	30.92	0.04	-0.015
10	15	14461	14835	0.124	0.67	31.27	0.17	-0.030
10	16	30900	31235	0.566	1.02	11.56	0.41	0.050
10	17	31675	31970	0.328	0.88	12.00	0.29	0.030
10	18	32767	32767	0.196	0.56	14.88	0.40	0.040
10	19	32767	32767	0.441	0.84	14.43	0.40	-0.005
10	20	32767	32767	0.435	0.79	11.26	0.38	-0.010
10	21	32767	32767	0.224	0.52	12.83	0.46	0.000
10	22	32767	32767	0.365	0.70	12.35	0.41	-0.050
10	23	32767	32767	0.194	0.46	12.25	0.33	-0.025
10	24	32767	32767	0.359	0.73	12.05	0.37	-0.025
10	25	32767	32767	0.161	0.50	12.73	0.15	-0.040
10	26	32767	32767	0.309	0.78	12.63	0.28	-0.100
10	27	32767	32767	0.114	0.58	14.88	0.34	-0.035
10	28	32767	32767	0.312	0.88	14.63	0.06	-0.100
10	29	32767	32767	0.426	0.91	18.74	0.09	0.015

WELL NO.	SAMPLE NO.	ELAPSED TIME OF LW	ELAPSED TIME OF HW	W.	T	X	D.	P
11	1	1900	2220	0.182	0.89	19.33	0.09	0.020
11	2	2590	2990	0.432	0.94	17.13	0.23	0.015
11	3	3665	3661	0.419	0.69	18.28	0.56	0.020
11	4	4813	5173	0.504	0.92	15.17	0.49	0.010
11	5	5545	5917	0.447	1.01	13.75	0.35	-0.020
11	6	7783	8173	0.373	0.91	13.90	0.34	0.053
11	7	8527	8899	0.315	0.94	14.40	0.20	0.010
11	8	9265	9625	0.402	1.04	14.55	0.24	-0.015
11	9	9997	10363	0.294	0.88	13.20	0.14	-0.015
11	10	10717	11101	0.358	0.98	15.45	0.33	0.040
11	11	11467	11827	0.202	0.82	27.79	0.31	0.050
11	12	12193	12583	0.289	0.96	21.43	0.23	0.035
11	13	12955	13315	0.150	0.76	27.49	0.17	0.000
11	14	13681	14071	0.239	1.01	27.84	0.04	-0.015
11	15	14461	14835	0.145	0.67	28.19	0.17	-0.030
11	16	30900	31235	0.796	1.02	8.57	0.41	0.050
11	17	31675	31970	0.428	0.98	8.92	0.29	0.030
11	18	32767	32767	0.246	0.56	11.80	0.40	0.040
11	19	32767	32767	0.555	0.84	11.35	0.40	-0.005
11	20	32767	32767	0.549	0.79	8.18	0.38	-0.010
11	21	32767	32767	0.279	0.52	9.75	0.46	0.000
11	22	32767	32767	0.475	0.70	9.27	0.41	-0.050
11	23	32767	32767	0.255	0.46	9.17	0.33	-0.025
11	24	32767	32767	0.452	0.73	8.97	0.37	-0.025
11	25	32767	32767	0.212	0.50	9.65	0.15	-0.040
11	26	32767	32767	0.382	0.78	9.55	0.28	-0.100
11	27	32767	32767	0.176	0.58	11.80	0.34	-0.035
11	28	32767	32767	0.374	0.88	11.55	0.06	-0.100
11	29	32767	32767	0.519	0.91	15.66	0.09	0.015
12	1	1900	2220	0.226	0.89	16.22	0.09	0.020
12	2	2590	2990	0.545	0.94	14.02	0.23	0.015
12	3	3365	3661	0.540	0.69	15.17	0.56	0.020
12	4	4813	5173	0.503	0.92	12.06	0.49	0.010
12	5	5545	5917	0.543	1.01	10.64	0.35	-0.020
12	6	7783	8173	0.487	0.91	10.79	0.34	0.053
12	7	8527	8899	0.408	0.95	11.29	0.20	0.010
12	8	9265	9625	0.506	1.04	11.44	0.24	-0.015
12	9	9997	10363	0.380	0.88	10.09	0.14	-0.015
12	10	10717	11101	0.446	0.98	12.34	0.33	0.040
12	11	11467	11827	0.255	0.82	24.68	0.31	0.050
12	12	12193	12583	0.376	0.96	18.32	0.23	0.035
12	13	12955	13315	0.188	0.76	24.38	0.17	0.000
12	14	13681	14071	0.290	1.01	24.73	0.04	-0.015
12	15	14461	14835	0.170	0.67	25.08	0.17	-0.030
13	1	1900	2220	0.283	0.89	12.96	0.09	0.020
13	2	2590	2990	0.870	0.94	10.76	0.23	0.015
13	3	3365	3661	0.640	0.69	11.91	0.56	0.020
13	4	4813	5173	0.519	0.92	8.80	0.49	0.010
13	5	5545	5917	0.550	1.01	7.38	0.35	-0.020
13	6	7783	8173	0.700	0.91	7.53	0.34	0.053
13	7	8527	8899	0.598	0.95	8.03	0.20	0.010
13	8	9265	9625	0.687	1.04	8.18	0.24	-0.015
13	9	9997	10363	0.552	0.88	6.83	0.14	-0.015
13	10	10717	11101	0.629	0.98	9.08	0.33	0.040
13	11	11467	11827	0.354	0.82	21.42	0.31	0.050
13	12	12193	12583	0.568	0.96	15.06	0.23	0.035
13	13	12955	13315	0.232	0.76	21.12	0.17	0.000
13	14	13681	14071	0.362	1.01	21.47	0.04	-0.015
13	15	14461	14835	0.203	0.67	21.82	0.17	-0.030

LITERATURE CITED

BAGNOLD, R. A. (1940) Beach formation by waves; some model-experiments in a wave tank. J. Inst. Civil Engrs., 15: 27-52.

DOLAN, R. (1970) Sand waves - Cape Hatteras, North Carolina. Shore and Beach, 38(2): 22-25.

DUNCAN, J. R. (1964) The effects of water table and tide cycle on swash-backwash sediment distribution and beach profile development. Marine Geology, 2(1): 186-197.

EMERY, K. O., and FOSTER, J. F. (1948) Water tables in marine beaches. Journal of Marine Research, 7(3): 644-654.

GIESE, G. S. (1966) Beach pebble movements and shape sorting indices of swash zone mechanics. Ph.D. thesis, Dept. of Geophys. Sci., Univ. Chicago, Chicago, Ill., 65 pp.

GRANT, U. S. (1948) Influence of the water table on beach aggradation and degradation. Journal of Marine Research, 7(3): 655-660.

HARRISON, W., and KRUMBEIN, W. C. (1964) Interactions of the beach-ocean-atmosphere system at Virginia Beach, Virginia. U.S. Army Corps Engrs., Coastal Engineering Research Center, Tech. Memo. 7, 101 pp.

HARRISON, W., BREHMER, M. L., and STONE, R. E. (1964) Nearshore tidal and non-tidal currents at Virginia Beach, Virginia. U.S. Army Corps Engrs., Coastal Engineering Research Center, Tech. Memo 5, 20 pp.

HARRISON, W., RAYFIELD, E. W., BOON, J. D., III, REYNOLDS, G., GRANT, R. B., and TYLER, D. (1968) A time series from the beach environment. E.S.S.A. Res. Lab. Tech. Memo. AOL-1, 85 pp.

HARRISON, W. (1969) Empirical equations for foreshore changes over a tidal cycle. Marine Geology, 7(6): 529-551.

ISSACS, J. D., and BASCOM, W. N. (1949) Water table elevations in some Pacific Coast beaches. Transactions, Amer. Geophys. Union, 30(2): 293-94.

KRUMBEIN, W. C. (1963) A geological process-response model for analysis of beach phenomonon. Bull., Beach Erosion Board, 17: 1-15.

KRUMBEIN, W. C., BENSON, B. T., and HEMPKINS, W. B. (1964) WHIRLPOOL, a computer program for "sorting out" independent variables by sequential linear regression. Northwestern University, Tech. Memo. 14.

SONU, C. J., and RUSSELL, R. J. (1966) Topographic changes in the surf-zone profile. Proceedings, 10th Conference on Coastal Engineering.

STRAHLER, A. N. (1964) Tidal cycle of changes in an equilibrium beach, Sandy Hook, N. J. Columbia University, Dept. of Geology, ONR Task Rept. 4, 51 pp. (also: 1966, Journal of Geology, 74(3): 247-268).

VITA

Leland Edward Fausak

Born in Benton Harbor, Michigan, 5 May 1944. Graduated from Pioneer High School, Whittier, California, June 1962; B.A. degree in geology from the University of California, Santa Barbara, June 1968. Candidate for Master of Science degree in Marine Science at the Virginia Institute of Marine Science and the University of Virginia, 1968 - 1970.