1968

Quantitative Analysis of Beach Sand Movement, Virginia Beach, Virginia

John D. Boon

College of William and Mary - Virginia Institute of Marine Science

Follow this and additional works at: <https://scholarworks.wm.edu/etd>

Part of the [Geomorphology Commons](#)

Recommended Citation

Boon, John D., "Quantitative Analysis of Beach Sand Movement, Virginia Beach, Virginia" (1968).
Dissertations, Theses, and Masters Projects. Paper 1539617401.
<https://dx.doi.org/doi:10.25773/v5-kpx0-q629>

This Thesis is brought to you for free and open access by the Theses, Dissertations, & Master Projects at W&M ScholarWorks. It has been accepted for inclusion in Dissertations, Theses, and Masters Projects by an authorized administrator of W&M ScholarWorks. For more information, please contact scholarworks@wm.edu.

**QUANTITATIVE ANALYSIS OF BEACH SAND MOVEMENT,
VIRGINIA BEACH, VIRGINIA**

A Thesis

Presented to

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

In Partial Fulfillment

**Of the Requirements for the Degree of
Master of Arts**

By

John D. Boon, III

1968

ProQuest Number: 10625047

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.

ProQuest 10625047

Published by ProQuest LLC (2017). Copyright of the Dissertation is held by the Author.

All rights reserved.

This work is protected against unauthorized copying under Title 17, United States Code
Microform Edition © ProQuest LLC.

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 - 1346

APPROVAL SHEET

This thesis is submitted in partial fulfillment of
the requirements for the degree of
Master of Arts

Author

Approved, February, 1968

John J. Norcross, M.A.

P. Wyman Harrison, Ph.D.

Evon P. Ruzecki, M.S.

ACKNOWLEDGMENTS

The author is indebted to Professor John J. Norcross and Dr. P. Wyman Harrison for much helpful guidance and constructive criticism during the course of the present study. Professor Norcross, of VIMS, provided numerous suggestions and instructions regarding statistical applications and impressed upon the author the importance of such applications in the natural sciences. Dr. Harrison, as Director of the Land and Sea Interaction Laboratory (LASIL) of the U. S. Environmental Science Services Administration, introduced the author to the technique of sand tracing and the systematic study of beaches, and also provided the necessary materials for the accomplishment of the field study. Dr. Robert Byrne, of LASIL, read portions of the preliminary manuscript and made valuable suggestions which were incorporated in the final text of the thesis.

Field operations were carried out in conjunction with a related LASIL study at Virginia Beach, Virginia. The author was able to secure the services of, and is grateful to, members of the LASIL staff including Messrs. E. Rayfield, D. Tyler, B. Grant, and G. Reynolds. Finally, gratitude is expressed to members of Girl Scout Troop 266 (Trailblazers) of Virginia Beach, who also assisted in field operations.

Thanks and appreciation are given to the Corps of Commissioned Officers, U. S. Environmental Science Services Administration, especially to RADM James C. Tison, Jr. and RADM John C. Bull for permitting the author to pursue the research leading to the present thesis.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	iii
LIST OF TABLES	v
LIST OF FIGURES	vi
ABSTRACT	vii
I. INTRODUCTION	2
II. PREVIOUS INVESTIGATIONS	4
III. PRESENT STUDY	8
Description of Area	8
Design of Experiment	9
Model Selection	9
Stochastic-Process Models	11
Tracer Particle Displacement Model	13
Execution of Experiment	14
Preparation of Tracers	14
Injection of Tracers and Sampling Technique	16
Measurement of Environmental Factors	18
Laboratory Work	21
Method of Counting Fluorescent Grains	21
Method of Rapid Sand Analysis	22
Method of Computing Foreshore Erosion-Deposition	24
Data Analysis	25
Distribution of Tracers	25
Fourier Trend Surface Analysis	25
Bivariate Data Analysis	30
Comparison of Group Means	33
Time-Stratification of Mean Displacement	34
Regression Estimates of X_p and Y_p	35
Estimates of Mean Particle Velocities	37
Discussion of Results	38
Comparison of Particle Movement and Environmental Factors	38
Comparison of Mean Particle Velocity with Expected Particle Velocity	41
Estimation of Mean Rate of Sand Transport	45
Recommendations for Future Studies	47

TABLE OF CONTENTS (CONT.)

	Page
IV. SUMMARY	50
V. APPENDIX	52
VI. LITERATURE CITED	53
VII. VITA	57

LIST OF TABLES

Table

1. List of environmental factors measured near Pendelton Transect, September 16, 2200 hrs. (HW), and September 17, 1100 hrs. (HW), 1966
2. Tracer concentration data
3. Summary of chi-square tests, zones versus X displacements
4. Computer output of program MAT
5. Pendelton tracer data, X displacements; "t" tests of $H_0: \mu_1 = \mu_2$ for four pairs of group mean data per dynamic zone
6. Pendelton tracer data, Y displacements; "t" tests of $H_0: \mu_1 = \mu_2$ for four pairs of group mean data per dynamic zone

LIST OF FIGURES

Figure

1. Location map for area of study (after Harrison, et al., 1965)
2. Characteristics of beaches (after Ingle, 1966).
A: General features and terminology.
B: Designation of dynamic zones and idealized water-circulatory patterns.
3. Map showing bottom topography and position of surf and swash zones, Pendelton Transect, Sept. 17, 1100 hrs. (datum: arbitrary).
4. Row-column grid showing points of tracer particle release and sand sample recovery.
5. Device used to obtain sand cores at Pendelton Transect.
6. Mean settling velocities, $\bar{U}_s$, of sand samples. A: $\bar{U}_s$ plotted against distance along column CD for Sept. 16, 2200 hrs., Sept. 17, 1100 hrs., and for tracer material ($\bar{U}_s = 4.15$ cm./sec.)
B: Map of field distribution of $\bar{U}_s$, Sept. 17, 1100 hrs.
7. Schematic section of beach showing method of determining Q_f for two successive high tides, Sept. 16, 2200 hrs., and Sept. 17, 1100 hrs. (modified from Harrison, et al., 1968). (A) is the position of top of swash on successive high water stands, and (B) is the innermost position of inshore margin of breaker zone on successive high water stands.
8. Fourier trend continuous symbol map of tracer particle concentration 10 min. after release (contours added by the author).
9. Fourier trend continuous symbol map of tracer particle concentration 20 min. after release (contours added by the author).
10. Fourier trend continuous symbol map of tracer particle concentration 30 min. after release (contours added by the author).
11. Fourier trend continuous symbol map of tracer particle concentration 40 min. after release (contours added by the author).
12. Fourier trend continuous symbol map of tracer particle concentration 50 min. after release (contours added by the author).

LIST OF FIGURES (CONT.)

Figure

13. Schematic diagram showing derivation of bivariate displacements data for N recovered tracer particles.
14. Frequency-displacement diagrams for the swash zone including fitted normal curves, Sept. 17, 1100 hrs.
15. Frequency-displacement diagrams for the surf zone including fitted normal curves, Sept. 17, 1100 hrs.
16. Time-displacement diagrams showing group means with approximate confidence intervals, Sept. 17, 1100 hrs.
17. Schematic diagram showing the relationship between the position of tracer particles, X_0 , upon injection and the "impulse" displacement, X_p , away from the injection point immediately following release. The same relationship holds for the Y direction.
18. Schematic representation of tracer particle dilution with time in a sand matrix and subsequent "loss" of tracer at depth.
19. Time-frequency graph for tracer particles recovered by Yasso (1965) at Sandy Hook, New Jersey.

ABSTRACT

The present study describes a new approach to quantitative sediment tracing with dyed (fluorescent) particles, which can be used to obtain estimates of grain velocity, estimates of mobile layer thickness, and estimates of the rate of longshore sand transport.

A simplified stochastic-process model was employed involving the use of statistical procedures to analyze tracer displacement data on a time-stratified basis. The procedures provide meaningful estimates of the direction and magnitude of the movement of beach sand through set intervals of time.

Results of a single tracer experiment are reported from a beach located near Virginia Beach, Virginia. The tracer particle-displacement data obtained were: 1) subjected to preliminary tests to determine the need to separate the data according to two dynamic zones; 2) treated as normally distributed populations in which mean particle displacements were computed for specific times following tracer release and compared with one another using "t" tests to determine significant mean differences; 3) time-stratified where successfully tested so that weighted mean displacements representing the time interval 0 to 50 minutes could be computed; and 4) converted to mean particle velocities by dividing adjusted mean displacements by average travel time. For the morning of September 17, 1966, during moderate wave conditions at high tide, average particle velocity was determined for the swash and surf zones. In the swash zone, $\bar{V}(X) = 0.44$ ft./min. (0.22 cm./sec.) in the longshore direction. In the surf zone, $\bar{V}(Y) = 0.37$ ft./min. (0.19 cm./sec.) in the offshore direction.

Computed mean grain velocities and certain environmental data gathered prior to the time of the tracer experiment were used to make an estimate of the thickness of the mobile layer (the depth interval in which semi-continuous motion of the grains occurs). The thickness, based on grain velocity in the offshore direction and the measured rate of sand accretion seaward, was about 0.5 in. (1.3 cm.); assuming this to be the thickness of the mobile layer in the swash zone as well, an estimate of the longshore rate of sand transport was then computed using known values of swash zone width and longshore grain velocity. A transport value of 440 yd.³/day (336 m.³/day), in a longshore direction was obtained.

**QUANTITATIVE ANALYSIS OF BEACH SAND MOVEMENT,
VIRGINIA BEACH, VIRGINIA**

I. INTRODUCTION

This study examines the movement of sand particles on an ocean beach. It includes a method for estimating average rates of beach sand movement in the littoral zone. The method utilized involves the use of sand tracers consisting of quartz grains coated with fluorescent dye. Tracers released in areas of sand transport can reveal the direction of this transport, and the average velocity of the individual grains estimated through a statistical procedure applied to the tracer recovery data.

A substantial amount of sand is transported daily along most beaches under the influence of wave-induced longshore currents. A large storm can effect highly significant changes in the profiles of beaches and at such times it is evident to the most casual observer that large volumes of sand have been moved into or out of a given area. Indeed, measurement of the areas enclosed by time-sequential profiles has been the standard means by which coastal engineers estimate the net "cut" or "fill" per unit time at selected locations (e.g., Caldwell, 1956; Johnson, 1956). This involves multiplying the area enclosed between two successive profiles by a unit distance along the beach (usually one meter), whereupon the net volume change is found for this section of the beach. However, while the net volume change may occasionally be near zero (an equilibrium beach), the gross transfer of material over a given period of time could be considerable, meaning that a steady transport of sand exists at some

point but no net erosion or deposition occurs there. In such cases, sand traps or the accumulation of material against a natural barrier usually provide an estimate of the gross material change. Although time consuming and expensive to acquire, the quantitative information gained has its value in the design of adequate protective measures in areas undergoing excessive sand accumulation or erosion. For example, severe seasonal erosion in the foreshore zone may be offset by intermittent dredging or pumping of sand from other areas to the area of concern. The cost of such operations requires some previous knowledge of the quantities of sand being exchanged at various times if the method is to be efficient.

II. PREVIOUS INVESTIGATIONS

At present, the volume of sand transported across a section of beach in a given time is being calculated in more direct ways than by simple comparisons of profile data. Recent investigators have been more concerned with the dynamics of the beach-ocean-atmosphere system, and have begun to examine the movement of individual sand particles in devising ways of estimating the average sand transport along a beach.

Russell (1960) first used tracers to obtain a quantitative estimate of littoral drift. He released quantities of dyed pebbles at a single point, at one week intervals, to establish a semi-continuous source of tracer material. He assumed tracers would seek a certain level on the foreshore and move with similarly sized pebbles in response to hydrodynamic forces, and visualized a two-way system of transport with the zone of travel divided into imaginary compartments. Further, the dimensions of the initial compartment were chosen so that if it contained M pounds of material, pM pounds would go to the left and qM pounds would go to the right, where $p + q = 1$ over a time interval of one week. After many injections, mathematically derived tracer distributions for several combinations of p and q values were compared with the actual field distribution, as determined from unit area surface counts of dyed pebbles, so that estimates of p and q were obtained. The net rate of transport was then $(p-q) M/t$, where M/t in pounds per week was also found mathematically from a knowledge of the tracer distribution. Using this technique, Russell calculated the net transport along a shingle beach at Rye, England to be

31,000 tons per year as compared to 53,000 tons per year for this beach according to available profile data. As a caution, he also mentioned the failure of his method to account for any offshore-onshore tracer movement, and did not recommend its use on sandy beaches where such movement often occurs.

Ingle (1966) presented data on the average grain velocity of beach sand in a comprehensive monograph on the use of fluorescent sand tracers. Whereas Russell employed essentially a line of sampling points, Ingle obtained data from a sampling grid by collecting sand with grease-coated cards along several transects perpendicular to the shoreline. His areal data were used to construct equal-value contours, or isopleths, of tracer grain concentration (dyed grains per unit area) in a plane approximating the sediment-water interface. The dimensions of his study areas were about 200 by 500 feet, the long dimension occurring parallel to the beach, and the shorter one extending between the upper swash limit and the breaker zone. Ingle found that patterns of tracer distribution were better developed if the tracer was released at several points along a line rather than at a single point. He determined the total amount of tracer in the study area at given intervals of time by multiplying the value of each tracer isopleth by the area within the isopleth (obtained by planimeter). In this way the depletion rate, or percent amount of tracer leaving the area in a unit of time, was found. The average velocity of the tracers was then obtained by dividing the average distance of travel (central injection point to main exit from study area) by the time required for half of the initial tracer quantity to be depleted. This procedure is herewith termed the area-integration or depletion method of estimating average particle velocities. To obtain net sand transport values,

Ingle points out that one has to derive a value for the thickness of the mobile sand layer, the limits of which are not precisely known at present. Einstein (1948) estimated the thickness to be only a few grain diameters, depending on the location and average sand grain diameter there. Working with available sand volume data from engineering studies, Ingle utilized the following expression:

$$\bar{U}_{ga} \cdot A \cdot B = \bar{Q}_l$$

where $\bar{U}_{ga}$ = average annual tracer velocity; A = average annual unit of sand transport (average annual beach width $\times$ 1.0 ft.); B = thickness of mobile bed; $\bar{Q}_l$ = estimated average annual rate of littoral drift.

Solving for B, several thicknesses were found for different areas and a correlation of mobile bed thickness with average median grain diameter was developed. Typical values of B were found to be 0.05 and 0.10 inches (0.12 and 0.25 cm.).

Another means of quantifying sand movement involves use of the time-integration method, developed in laboratory experiments by Crickmore and Lean (1962a; 1962b). Its principle concepts were adapted for use in the field by Bruun and Purpura (1964), Yasso (1965), and Bruun (1965). The essence of this method is the delineation of a "mode" or maximum tracer concentration which moves progressively downdrift in the littoral zone under the influence of the longshore current. At some point down beach, sampling is done at close intervals so that a curve of the frequency of tracer recovery versus time may be developed. The apex or central point of the curve yields the mean travel time of the tracers; the distance traveled being known, the average velocity of the grains is obtained. Usually this method requires extensive sampling for full development of the time-frequency curve. For this reason, Bruun and

Purpura (1964) installed sediment pumps along an ocean pier in Florida to sample tracer concentration continuously for several hours.

III. PRESENT STUDY

Description of Area

The beach selected for study is located south of the borough of Virginia Beach, Virginia, on the Atlantic Coast (fig. 1). All measurements and samples were taken near a fence perpendicular to the shoreline, which marked the boundary between Virginia Beach and Camp Pendelton, a military training area. The study area will hereafter be referred to as the "Pendelton Transect".

The terminology associated with the study of beaches and used in this paper is the same as that given by Ingle (1966, pp. 12-13). Figure 2 (A) shows the classical beach profile and associated terminology and figure 2 (B) represents the division of an idealized beach into dynamic zones. Beaches with steep foreshore slopes often lack a surf zone at higher tidal levels; however, due to a relatively flat foreshore slope (about 6 deg.), this zone was usually well-developed at the Pendelton Transect during the period of study (late summer of 1966). A small secondary breaker zone sometimes developed between the swash and surf zones. Figure 3 shows in plan view the topography in the vicinity of the Pendelton Transect, as obtained by leveling on September 17, 1966, the date of the main tracer experiment. After visually locating the limits of surf and swash backwash in relation to marker rods shown in figure 3 it was found that the bottom slopes reflected a similar delineation between the inner two zones depicted in figure 2 (B).

Waves approaching the Virginia Beach shore may attain breaking heights of six feet or more, usually from swell generated by distant ocean storms. The normal breaker height, however, is probably between three and four feet during summer and early fall months, the breakers being either the plunging or spilling type. Offshore bar and trough systems superimposed on a gently sloping bottom frequently set up multiple breaker zones. Having passed these zones, the final set of waves impinging on the beach generally have small angles of approach (the orthogonals to the wave crests deviating no more than 10 degrees from the direction perpendicular to the shoreline). Regardless of their low angle of approach, the net effect of large amplitude waves is an elevated water level which, combined with even a slight wave angle, normally produces a fairly strong longshore current. The effects of the waves on the beaches are only slightly modified by the relatively low mean tidal range of 3-4 feet at Virginia Beach.

In addition to the present investigation, other studies (Harrison and Morales-Alamo, 1964; Harrison and Wagner, 1964; Harrison, et al., 1964; Harrison and Krumbein, 1964) have been conducted in the Virginia Beach area dealing with various aspects of the local beach-ocean environment. The information in these reports guided the development of the present study.

Design of Experiment

Model Selection --- A primary step in planning a new experiment such as the present one is that of proper experimental design. The study of beaches has been facilitated by the use of a variety of models, including scale models with dimensions reduced for ease of measurement. Whenever measurement data are being collected, mathematical models are very often

used, these being either the deterministic or the statistical type. Deterministic models utilize variables and constants but lack a statistical component so that, measurement errors excluded, all relationships set forth must be exact (Krumbein and Graybill, 1965, pp. 15-17). An example of a deterministic relationship that is often involved in beach problems is Stoke's law which relates the terminal settling velocity of a small sphere in a fluid to the difference in density between sphere and fluid, the acceleration of gravity, the square of the sphere's radius, and the viscosity of the fluid.

In a statistical model, values of one or more of the functional components is random.¹ A common example is the simple linear model (Krumbein and Graybill, 1965, p. 224) which may be expressed:

$$Y = \alpha + \beta X + e$$

where Y is an observable random quantity, X is an observable quantity that is not random, α and β are unknown parameters, and e is an unobservable random error with mean zero and variance σ^2 . The above expression is termed linear because of the way the parameters α and β are related. Hence a number of observations result in several simultaneous linear equations which can be solved for α and β by the method of least squares, whereby e is minimized. The simple linear model is easily developed into more complicated forms by increasing the number of unknown parameters and their corresponding independent variables which may themselves have added complexity (e.g., X, X^2 , $\cos X$). A solution to any linear model consists of finding a combination of parametric values that will reduce e to the lowest possible level so that Y, the dependent variable, can be computed directly from subsequent sets of independent

¹'In connection with probability and statistics, the term random implies collective or long-run regularity' [Glossary of Meteorology, p. 467, 1959].

variable data. The final equation, then, may be termed a "predictor" equation, where the independent variable(s) are called predictors and the dependent variable is called the predictand.

Although a number of deterministic models have been specifically developed for the beach environment, most of them have had limited success as predictors of actual beach conditions. For example, an empirical equation to predict grain size and sorting patterns in the offshore zone on the basis of wave height, length, celerity, still water depth, and particle fall velocity was developed by Ippen and Eagleson (1955) in laboratory studies; assuming this relationship would hold under certain equilibrium conditions, Miller and Zeigler (1958) found good approximations to the same under ideal field conditions, but later found little correlation where bottom topography was irregular (Miller and Zeigler, 1964).

Because a variety of mechanical processes are functioning at any given time in the beach environment, it is not surprising that good agreement between field observations and the corresponding theoretical values of a single deterministic equation is seldom attained. Possibly, when all or most of the basic processes are understood, the behavior of the beach environment will one day be completely described. However, until these theoretical concepts become fully developed, it may well be that the statistical model has more to offer the marine scientist engaged in field work. A particular type of statistical model that has found increasing use in recent years, the stochastic-process model, will be examined in the present study.

Stochastic-Process Models -- The word stochastic is synonymous with probabilistic, and was originally used to signify a given physical or biological process having random changes associated with it which could

be dealt with through the laws of probability (Bartlett, 1960). More recently, the definition of the term stochastic process has been given as "...a family of random variables with infinitely many members" (Krumbein and Graybill, 1965, p. 375). Doob (1953, p. 46) stated that such a family of random variables must have a common time-parameter which can be either continuous or discrete. An example of a stochastic process present in the ocean environment is the random distribution of wave heights, X , having a continuous time-parameter, t , so that $X(t)$ represents time-dependent populations of wave heights over some time interval. For any fixed time, t , the simultaneous measurement of all waves in an area would reveal the true distribution of X at that instant (this is now being done with synchronous stereo-pairs of aerial photos). However, for a given interval of time, an infinite number of heights of waves, $X(t)$, exists. Other stochastic-process models may have discrete time-parameters wherein certain events (e.g., radioactive emissions) occur randomly at discrete times. It may be noted that random distributions themselves may be continuous, as are the normal, lognormal, and gamma distributions; or discrete, as are the binomial and poisson distributions.

Stochastic-process models are becoming increasingly important in describing natural phenomena. Scheidegger (1958, 1964) assumed randomness in his study of fluid flow through porous media. Krumbein (1967) gives examples and illustrations of Markovian processes used in simulation of stratigraphic sections. A stochastic mechanism, the simple Markov process stipulates that the state of a system at time t_r , point X_r , or event E_r is dependent upon the state at t_{r-1} , X_{r-1} , or E_{r-1} . Another type of stochastic process, the random-walk model, has been used

by Leopold and Langbein (1962) to describe drainage networks of connecting rivers and streams. Scheidegger and Langbein (1966) also discussed random-walk models as applicable to transport processes used in determining the random evolution of landscapes, stating:

The transport process has a stochastic element in it, that is, there is a random element determining which "particle" moves at what time so that the transport process can be regarded as the result of a "random walk" of the individual "particles" making up the landscape....the process is not truly random since the small scale effects involved are all mechanically completely determined. However, the mechanics of these small scale effects is so complicated that the details concerning most individual particles will remain forever unknown. (p. C3)

Accordingly, processes similar to the random-walk transport model are necessarily being recognized in quantitative analyses of sand transport in the dynamic zones of beaches (Ingle, 1966, p. 40). Here sediment motion is caused by a combination of sheer stresses generated by wave and current actions (Bruun, 1965) with individual particles alternately moving in temporary suspension within the fluid medium and along the bottom as bed load. Additional dispersive stress resulting from particle collisions aids in transferral of momentum to both sand grains and fluid medium (Bagnold, 1963). Further complexities are found in a unique relationship between grain size, settling velocity, and fluid "threshold" velocity required to initiate grain motion, as explained by Hjulström (1935) and Inman (1949). All of these effects interact to create random patterns of grain motion in the field, perhaps nowhere better demonstrated than in studies utilizing fluorescent tracers.

Tracer Particle Displacement Model -- Recognizing the inherent variability in the movement of sand particles in an active nearshore environment, a decision must be made as to which variables, spatially and

temporally, will be considered as having random distributions. In this experiment, the displacements X and Y of an individual tracer particle from some arbitrarily placed origin ($X = 0$, $Y = 0$) at time t over the interval $0 \leq t \leq T$, were selected as random variables. This formulation clearly invokes the stochastic mechanism as previously defined, since at any fixed time, t , there will be two groups of displacements [$X(t)$, $Y(t)$] represented by a large number of tracer particles recovered after having been released at a single point [$X(0)$, $Y(0)$] and acted upon by waves and currents during the time interval 0 to T . In other words, the random variables selected have spatial coordinates and are subject to a continuous time-parameter within the framework of a stochastic process.

To implement the above model, a row-column sampling grid was devised (fig. 4) with each sample located by X and Y orthogonal coordinates. X values were made to increase in a northerly direction parallel to the shoreline with Y values increasing in the onshore direction. The origin of the coordinate system was placed in the lower left corner of the grid as indicated in figure 4, so that all X and Y values would be positive. Fluorescent tracers were released at predetermined, centrally located points within the grid, and samples of sand were collected at regular intervals of time at each station shown in figure 4. The data thus obtained were grouped according to the time of collection, assuming simultaneous sampling of the entire grid, so that the distribution of particle displacements as represented by X and Y values could be examined independently with reference to a common time-parameter.

Execution of Experiment

Preparation of Tracers -- Numerous methods of tracing sea-bed materials have been used. The methods fall into two categories; namely,

those which utilize radioactive coatings or artificially-induced radiation and those which use coatings of fluorescing dyes and pigments on selected natural objects (ranging in size from clay to cobble). Due to the hazards of radioactive substances, this type of tracer has been used mostly offshore (Inman and Chamberlain, 1960) and along restricted beaches (Kidson, et al., 1958; Inose and Shiraishi, 1956). Fluorescent dyes are much cheaper than radioactive tracers and offer no potential danger, hence dyes have been far more extensively used. The first use of a fluorescing compound to mark tracer grains is attributed to the Soviets (Medvedev and Aibulatov, 1956). Since their work, scientists in many countries have employed fluorescent tracers, their methods differing mainly in the type of coating procedure and the compounds used. Wright (1962, pp. 2-3) and Ingle (1966, p. 10, Appendix 1) give good summaries of the work and methods used in fluorescent tracer studies to date. For the present study, a method developed by Yasso (1962) was employed. Yasso utilized a commercial grade of fluorescent acrylic lacquer ("safety paint") to which he added a quantity of bonding agent consisting of toluene and bettle resin before applying it in thin coats to dried grains of sand. The application of this lacquer to large quantities of sand is done easily and at a very low cost.

Yasso's recommendations were followed closely in this study except for the method of application; i.e., the mixture was introduced into a large plastic bag containing the required amount of sand and then shaken by hand. Approximately 100 lbs. of sand was dyed using Day-Glo No. 202-18 (signal green) acrylic paint with bonding agent and allowed to dry. When dry, the tracer material was worked with a pressing tool to eliminate clumps which had about the same consistency as those of sugar.

Samples of the dyed grains were examined under a microscope using long-wave ultraviolet light to determine the nature of the coating. Most grains contained patches of dye in small crevices, not affecting the initial size or shape of the grain significantly, yet providing a brilliant source of light for positive identification with the unaided eye. When mixed with undyed sand, a single tracer grain among thousands of ordinary grains could be quickly detected.

The material selected for dyeing was an almost pure quartz sand taken from the dune area of the beach. Before being treated, each quantity collected was passed through a 30-mesh screen and shaken vigorously on a 50-mesh screen so that the final quantity retained fell within the size range 0.29-0.59 mm. This size range closely approximates that of numerous nearshore sand samples taken from several Virginia Beach localities, whose composition was mainly quartz (Harrison and Morales, 1964, pp. 34-35).

Injection of Tracers and Sampling Technique -- A single tracer experiment was conducted at the time of high tide on the morning of September 17. Seeding was done during the time of maximal tidal height so that sea level change would be minimal during the experiment (minimal tidal height would have sufficed as well). Approximately 100 lbs. of tracer sand, divided into four equal portions, was released at the Pendelton Transect at the positions shown in figure 4. The positions were chosen to favor a southerly drift indicated by the presence of a fairly strong longshore current. The tracer was released at four points along a line perpendicular to the shoreline to aid the initial dispersal into the swash and surf zones, as recommended by Ingle (1966, p. 21). It may be noted (figure 4) that the mean position of the tracers at time

$t = 0$ may nevertheless be imagined as a single point ($X = 125$ ft., $Y = 37.5$ ft.) along the boundary of the two dynamic zones. For analyses of displacement distributions, all grains were considered to have entered the system at that point.

The release of the tracers was accomplished by transporting the four quantities of sand in plastic bags to the release points, whereupon they were placed on the bottom and torn open by hand (using four assistants to achieve a simultaneous release). Prior to release, a wetting agent (commercial detergent) was mixed with the contents of each bag.

Sampling of the tracer distribution was conducted at 10-minute intervals up to 50 minutes after release. Two special coring devices (fig. 5), designed by the author, were used along columns AA, BB, CC, and DD (fig. 4), and hand sampling of the upper 0.5 in. (1.3 cm) of the sand surface was done along columns AB, BC, and CD. The latter group of samples supplemented the core samples. The cores were taken in short (8.0 in., 20 cm.) cellulose acetate butyrate tubes of 2.0 in. (5.1 cm.) diameter by driving them into the bottom with the coring device (valve open), then extracting the core (valve closed) and quickly sealing the bottom end with a plastic cap. Cores were marked and immediately carried to shore by two teams of field assistants. The average time required to sample the entire grid was about four minutes.

Owing to a tendency for beach sands to travel in a mobile layer of limited thickness, as mentioned in previous investigations, it was deemed necessary to obtain core samples such that the grains immediately beneath the surface would have an equal chance of appearing in the sample. In addition, the presence of a rippled bottom was noted. Ripple crests

are known to migrate at low fluid velocities (Shepard, 1963, pp. 116-117), and their movement was expected to advance and bury some grains, while exposing others in the following troughs. These in turn were carried forward over the crests. Therefore, because marked particles could be rather quickly incorporated into the bottom, the top 0.5 in. (1.3 cm.) of each core was saved for counting purposes. Because a larger number of sand samples were desired than there were plastic tubes available, 18 of every 42 samples obtained were collected by hand (getting approximately the top 0.5 in. of sand) and stored in small bags. These samples were later divided in the laboratory to obtain a quantity of sand equal in volume to that taken from the sand cores.

Measurement of Environmental Factors -- A number of dynamic factors were measured near the time of high tide the morning of September 17 and also during the preceding high tide. These factors include the following:

Mean height of breaking waves - $\bar{H}_b$

This value was obtained by measuring the trough to crest distance of fifty consecutive waves using a portable tide staff graduated in feet and tenths. The measurement error was estimated to be ± 0.3 ft. (0.1 m.).

Mean height of significant breakers - $\bar{H}_{bs}$

In the set of fifty consecutive waves, the highest one-third were averaged to get an estimate of the significant wave height. This procedure tends to isolate the higher amplitude waves present in the wave spectrum as the main contributors to the total wave energy.

Mean period of breaking waves - $\bar{T}_b$

The beginning and ending times of a set of wave measurements,

divided by the number of measurements, gives the mean breaker period. Measurement error was estimated as ± 0.2 second.

Significant wave heights - H_s
(Average height of the 1/3 highest waves)

Values were obtained from a significant wave strip-chart analysis of wave records from the Coastal Engineering Research Center's step-resistance wave gage located at the end of a 950-ft.-long fishing pier (approximately 1000 yds. north of the Pendalton Transect). Water depth at the end of the pier was about 20 ft. (6 m.) and a given value of wave height is precise to about ± 0.1 m.

Significant wave period - T_s
(Average period of the 1/3 highest waves)

These values were obtained in the analyses for H_s . T_s is determined to the nearest 0.5 sec. in the range 3 to 6 sec., and to the nearest whole second for values above 6 sec.

Mean acute angle between the shoreline
and the crests of breaking waves - α

This angle was measured using a tripod-mounted bearing circle equipped with sights and placed as close to the inshore margin of the breakers as possible. After sighting along a line parallel to the shoreline, then turning to a line passing through the breaker crests, the breaker angle was recorded as the angular difference between bearings read; a mean value was obtained from three such readings (precision was probably ± 2 degrees).

Mean trough to bottom distance_
in front of a breaking wave - z

This distance was measured directly and averaged for five individual observations, giving a measurement error of about ± 0.5 in. (1.3 cm.).

Mean longshore current velocity - $\bar{V}$

Estimates of the wave-induced longshore current were obtained in the surf zone by releasing fluorescein dye in the water and timing the movement of the center of the dye patch over a known distance. Three dye releases were made and the results averaged to obtain the mean travel time. This value was then converted to mean current velocity after noting the distance and direction of travel.

Mean wind direction and speed - $\bar{W}_d, \bar{W}_s$

A Weather Bureau Model F420 wind vane and anemometer with direct readout module was installed at the end of a fishing pier (fig. 1C) at Virginia Beach. Mean wind direction was recorded to the nearest 5 degrees and mean wind speed error was probably within 2 miles per hour.

Sea water density - ρ_t

A Taylor mercurial thermometer mounted in a standard USCG&GS water sampler was used to record water temperature to the nearest 0.2°C. Water samples were collected and stored in citrate of magnesia bottles for later determinations of salinity in the laboratory using a Hytech induction salinometer. Sea water density (g/cm^3) was determined from the temperature and salinity using a U.S. Naval Oceanographic Office nomograms.

Mean slope of the foreshore - $\bar{m}$

Foreshore slopes were determined from cross-sectional data used in computing Q_f , which is described in the following paragraph. The precision of a given slope measurement is about ± 0.2 degrees.

Mean settling velocity and
foreshore changes - $\bar{U}_s$ and Q_f

Data were obtained regarding the vertical fluctuations and size composition of the beach surface. Rods placed at approximately 20-ft. intervals along the main transect were marked near their upper ends and referenced to mean sea level through a leveling network. During the tidal extremes in question, measurements were made of the distance between the sand surface and the reference mark at each rod; also, a small quantity of sand was collected near each rod by scraping off the uppermost layer of grains. These measurements and samples were saved for laboratory procedures, to be described shortly in which Q_f , the quantity of sand eroded from (-) or deposited upon (+) the beach foreshore in one tidal cycle was calculated, along with the mean settling velocities, $\bar{U}_s$, of the individual sand samples.

All data pertaining to the environmental factors measured in the field are presented in table 1, in both English and metric units. It is intended that these measurements should serve to convey the general environmental conditions prevailing just prior to the beginning of the tracer experiment.

Laboratory Work

Method of Counting Fluorescent Grains -- Core samples collected during the experiment were later extruded from their plastic liners and the top 0.5 in. (1.3 cm.) removed with a small spatula. Each quantity of sand thus obtained (1.6 in.³, 26 cm.³) was washed and dried prior to examination under long-wave ultraviolet light for an initial estimation of the tracer grain content. Samples estimated to contain approximately 100 tracer grains or less were left intact while those estimated to contain significantly more tracers were split one or more times using

a CARPCO micro-splitter. Each sample or subsample was then spread evenly, a portion at a time, over a rectangular grid in a counting dish and moved about with a small probe to insure exposure of all tracer grains. The total number of tracers in the dish at one time was obtained by summing the number of fluorescing particles in each grid square, as viewed in turn under a low-power stereo microscope. For samples that required splitting, the total number of tracer grains per unit volume was estimated by multiplying the subsample count by $(2)^N$, where N equals the number of times the original sample was split. The supplementary hand samples were split to obtain the approximate unit volume of the core samples, then the samples were subjected to the usual counting procedure.

A number of duplicate counts using the same field sample were compared for an analysis of the counting error; except for samples with very small tracer concentrations, this error usually varied between 2 and 3 percent. Tracer concentrations for the 42 samples of the sampling grid (fig. 4) are listed in table 2.

Method of Rapid Sand Analysis -- Sand samples collected during the experiment, including the samples subjected to tracer counting procedures, were analysed using a Woods Hole Rapid Sand Analyzer (Zeigler, et al., 1960). The instrument was modified, having a fall tube with a 4.0 in. (10 cm.) I.D. instead of the standard 2.0 in. (5 cm.) I.D., and having an improved release mechanism consisting of a 250-mesh screen applicator instead of a gate-type device. The basic procedure followed for the present analyses has been outlined by Harrison and Morales-Alamo (1964). Briefly stated, the procedure consisted of placing a 7-8 gm. sample (previously washed, dried, and split) on the screen applicator and wetting it. This is followed by inversion of the sample

and application to the water surface at the top of the fall tube (rupture of surface tension effects the actual sample release). As the first few grains reach the lower limit of the pressure field (length - 1.0 m.), a mark is made on the accompanying pressure-time curve to establish a plateau value representing 100 percent sample pressure (weight). Beyond the plateau mark, falling pressure values and corresponding times are noted at five percentile points (P_5 , P_{16} , P_{50} , P_{84} , and P_{95}) and used to compute the mean settling velocity, $\bar{U}_s$, as

$$\bar{U}_s = \frac{100}{\bar{T}_s} \quad (\text{cm./sec.})$$

where
$$\bar{T}_s = \frac{P_5 + 2P_{16} + 4P_{50} + 2P_{84} + P_{95}}{10} \quad (\text{sec./m.})$$

Precision estimates of particle settling velocity made by successive runs of a sample of green tracer were approximately ± 0.10 cm./sec. All samples were analyzed in fresh water and were corrected using the tables of Zeigler and Gill (1959) to standard settling velocities at 24.0°C.

Figure 6A is a graphic representation of $\bar{U}_s$ varying with distance along the Pendelton Transect during the times of two adjacent high tides. Figure 6B is a contour map of the distribution of $\bar{U}_s$ within the area of the tracer study on September 17 at 11:00 AM. These distributions are important to the study in that they show the extent to which the green tracer sand matches the in-situ sand as regards settling velocity; i.e., figure 6A indicates little net changes in values of $\bar{U}_s$ over one tidal cycle, and figure 6B shows that $\bar{U}_s$ for the tracer (4.16 cm./sec.) falls at the lower end of the in-situ range of $\bar{U}_s$ (4.0-6.0 cm./sec.). Inasmuch as the latter amounts to a range in grain diameter of 0.29-0.40 mm., for a Corey shape factor of 0.7 (Zeigler and Gill, 1959), the matching of

average in-situ tracer particle size was achieved, therefore, to within 0.1 mm.

Regardless of the degree to which tracer particles match in-situ particles in size, it is evident from the distribution of $\bar{U}_g$ shown in figure 6B that a certain amount of size sorting occurred within the area of study. Thus, the inshore limit of the swash zone (fig. 3) and scattered areas within the surf zone (hatched contours of fig. 6B) have low $\bar{U}_g$ values, and are visualized as "sinks" toward which the relatively fine tracer grains will migrate. This type of grain motion is viewed as an inevitable occurrence in a changing natural environment such as that of an ocean beach, and must be considered an integral part of the overall movement of beach sand due to the major transport mechanisms. Wherever the effects of sorting show a tendency towards local accumulation of tracer particles, one must depend upon appropriate statistical methods to separate local variations from regional trends in particle distribution. These methods will be discussed later.

Method of Computing Foreshore Erosion-Deposition -- Changes in elevation of the beach surface were used to compute Q_f , the volume of sand eroded from (-) or deposited upon (+) the foreshore over one tidal cycle, or between successive high tides in this instance. Elevational data obtained from rod measurements before and after one tidal cycle were profiled at a 1:1 reduced scale on 8 ft. lengths of K.&E. Albanene paper. Figure 7 shows schematically how the areas between two profiles (measured by planimeter), when multiplied by a unit beach length, gave the net change in volume, Q_f . Due to small changes in elevation, profiles were carefully drawn on a large scale in order to avoid excessive measurement errors. These errors were probably less than ± 2.0 ft.³ for final estimates of Q_f .

Data Analysis

Distribution of Tracers -- A preliminary analysis of tracer distribution in space and time was undertaken to determine the nature of resulting dispersal patterns. The tracer concentration data (table 2) were grouped into five row-column matrices, each representing a single sampling time. Because of the physical evidence for two distinct dynamic zones (p. 8), it was deemed necessary to test to see if the forces present in the two dynamic zones produced significant differences in the distribution of the tracer particles.

For each of the five sampling times, the tracer concentration data were stratified into two groups; namely, counts made in the swash zone consisting of the shorewardmost four rows and seven columns of the original data grid, and the counts made in the surf zone consisting of the seawardmost four rows and seven columns. Thus, an overlap of one row was planned between zones. After summing the column values for each zone, a chi-square test for homogeneity (particle displacement in the swash zone versus particle displacement in the surf zone) was made for each of the five sampling times. The results (table 3) indicate that the data are not homogenous and the displacement values of the two zones should not be analyzed as one.

Fourier Trend Surface Analysis -- Trend analysis offers an objective method of examining mappable data. This technique involves the computation of mathematical surfaces of "best fit". The mathematical derivation of trend surfaces reduces the subjectivity involved in free-hand drawing of isopleths and often reveals in a relatively objective manner the inherent "trends" present in the data and also the extent to which these trends account for variations from the data mean. In this

study trend analyses were used to outline the basic patterns of tracer particle dispersion.

Basically, trend surfacing is an extension of the simple linear model (p. 10). For a given set of mappable data, the variation may be separated into two components; 1) a mathematically defined trend component, and 2) a residual component, the deviation. The form of the trend component for polynomial functions is

$$X_n = a_0 + a_1U + a_2V + a_3U^2 + a_4UV + a_5V^2 + a_6U^3 + a_7U^2V + \dots \quad (1)$$

where U and V are coordinate values locating the n th observation point on a rectangular grid, X_n is the value of a given property at that point measured along an ordinate perpendicular to the grid, and $a_0, a_1, a_2, \dots$ are coefficients. For a given number of coefficients, n equations (n observations) may be solved simultaneously, with the coefficients as unknowns using least squares fitting. Substituting the coefficient values into equation (1), trend surfaces may be computed for map presentation. This type of trend surface, known as the polynomial trend, was first used by Miller (1956) and has since been employed by many investigators, among them Whitten (1963) who presented an excellent summary of methods together with a computer program for performing the necessary calculations.

A more recently developed type of trend surface known as the Fourier trend, has been described by James (1966a). The reader is referred to this work for the details of the methods involved. The basic equation used is a double Fourier series:

$$\begin{aligned}
X(U,V) = & \sum_{i=0}^{KC} \sum_{j=0}^{LC} cc_{ij} \cos(2\pi iU/M) \cos(2\pi jV/N) \\
& + \sum_{i=0}^{KC} \sum_{j=1}^{LS} cs_{ij} \cos(2\pi iU/M) \sin(2\pi jV/N) \\
& + \sum_{i=1}^{KS} \sum_{j=0}^{LC} sc_{ij} \sin(2\pi iU/M) \cos(2\pi jV/N) \\
& + \sum_{i=1}^{KS} \sum_{j=1}^{LS} ss_{ij} \sin(2\pi iU/M) \sin(2\pi jV/N)
\end{aligned}$$

where U = the North-South coordinate axis increasing to the South and with origin at Northern map edge

V = the East-West axis increasing to the East and with origin at the Western map edge

$X(U,V)$ = mapped variable

M = maximum U value plus one

N = maximum V value plus one

KC = maximum cosine harmonic in U direction

LC = maximum cosine harmonic in V direction

KS = maximum sine harmonic in U direction

LS = maximum sine harmonic in V direction

If M is even, $KC = M/2$; $KS = (M-2)/2$

If N is even, $LC = N/2$; $LS = (N-2)/2$

If M is odd, $KC = KS = (M-1)/2$

If N is odd, $LC = LS = (N-1)/2$

cc_{ij} , cs_{ij} , sc_{ij} , ss_{ij} are the coefficients of the series, linearly combined.

A comparison of polynomial and Fourier trend surfacing techniques, has been presented by Krumbein (1966).

The Pendelton tracer concentration data, arranged in map fashion on the sampling grid (fig. 4) were analyzed by Fourier trend analysis using a computer program called FOURFIT (James, 1966b). The program input requires values determining the degree of the surface desired which is a function of the number of coefficients employed. It was found that the 25 coefficients of the first and second harmonic terms produced surfaces of sufficiently high degree of fit to account for approximately 80 percent of the total variability. Variability was computed from the following formula:

$$SS (\%) = \frac{\sum X_{comp}^2 - (\sum X_{comp})^2/n}{\sum X_{obs}^2 - (\sum X_{obs})^2/n} \times 100 \quad (2)$$

where X_{obs} = the observed value of tracer concentration at one point and X_{comp} = the computed value at that same point. Equation (2) gave information as to how well the trend surfaces fitted the actual distribution of data in each case. In general, whenever 80 percent of the variation can be accounted for by the trend surface, the "fit" of the computed surface is considered excellent. Another output value of program FOURFIT was the computation of "F", which determined that each fitted surface was significant regarding separation of the mathematical trend from the deviation.

Figures 8-12 are continuous-symbol maps, produced by the computer, showing in plan view the distribution of tracer concentrations at five 10-minute time intervals (five data series). In place of areal dimension values U and V of program FOURFIT, X and Y values were substituted in accordance with the previously defined grid system of this study (fig. 4). The map contours at 10-minutes indicate a single well-defined mode of tracer concentration with values steadily diminishing therefrom. Some skewness is evident toward the upper-left hand corner of the map.

The 20 and 30-minute series show the same skewness with some southerly displacement of the central mode. In addition, an overall decrease in the magnitude of the concentration contours may be noted. The 40 and 50-minute series indicate the development of a bimodal distribution of tracer concentration with one mode occurring in the southerly (downdrift) direction in the swash zone and the other remaining near the release points in the surf zone.

The aforementioned maps reveal information that would be difficult to obtain from a hand-drawn contour map. Mathematically derived surfaces may show the effects of the physical mechanisms acting on the tracer grains amid the inherent variation present in any complex environment. One such mechanism, particularly evident in nearshore regions, is that of turbulent diffusion, and concentric patterns of tracer dispersion about a point source have been predicted from the theory of this process acting in fluids (Roberts, 1923; Haltiner and Martin, 1957, ch. 16; Murray, 1967). Although better models for depicting the effects of fluid turbulence on conservative properties undoubtedly exist, the Fourier trends of figures 8-12 appear to take into account these effects as well as those due to the application of fluid stress on randomly moving grains (i.e., tractive forces) to give an approximation of the ideal distribution of tracers with time. Two features found in figures 8-12 are worthy of note, namely; 1) a gradual separation of the original tracer mass into two distinct concentrations, and 2) a central or unimodal tendency within each of these concentrations. The first of these features further reveals a southerly displacement of the shorewardmost tracer concentration relative to the seawardmost concentration. With regard to the second feature, a cross-section through one of the trend surface maxima in either the X or Y direction would strongly suggest

unimodal distributions similar to those expounded by Bruun (1965) and Yasso (1965) in the time integration method (p. 6).

Bivariate Data Analysis -- Having obtained evidence from the Fourier trend maps of figures 8-12 that the tracer particle concentrations shown therein had discernable patterns in time, a method of quantifying the movement of the tracer particles (and thus the movement of the in-situ population of ordinary sand particles) was devised. It was intended that this method should follow the basic concepts of the stochastic-process model (p. 12) in that a family of random variables should be employed, all having a common time-parameter. By defining the family of variables in terms of spatial coordinates, appropriate statistical procedures were adopted to analyze quantitatively the movement of particles whose positions are denoted by these same coordinates.

Considering tracer recovery data, imagine that the ith particle recovered has coordinates X_i and Y_i with reference to the sampling grid (fig. 13). At any time, t , the values of the coordinates may be considered as two separate components of the ith particle displacement as measured from the grid origin although at time $t=0$ the ith particle may, in fact, have lain a long way from this origin depending on where this particle was injected into the system. The ith grain, then, upon its recovery becomes a single item in a sample consisting of many such grains where two variables are being examined, the X and the Y displacements. Such bivariate data allows the motions of the grains to be treated as random.

Employing the concept of random particle displacement, bar graphs of tracer grain frequency versus X and Y distances in feet are presented in figures 14 and 15, respectively. These graphs were constructed by summing column values to obtain the frequencies of the X displacements, and by summing row values to obtain the frequencies of the Y displacements

within two slightly overlapping areas representing the swash and surf zones (i.e., two 4x7 data grids, p. 25). Although set coordinate values in 15 and 25 ft. increments were selected for sampling, the entire population of displaced particles (represented by the total number of grains in 100 lbs. of tracer) could have assumed any of an infinite number of positions, hence, the horizontal scale in the graphs of figures 14 and 15 is continuous. One can speculate as to whether or not the particle displacements approximate a certain continuous statistical curve, such as that given by the normal distribution.

Without testing for normality, most of the bar graph distributions in figures 14 and 15 were assumed to be representative of normal distributions on the basis of a visual comparison with equivalent normal curves (solid lines in each graph). These curves were constructed according to an abbreviated method from Krumbein and Graybill (1965, pp. 181-183). Neglecting skewness in some instances (e.g., surf zone at 10 minutes, fig. 15), the assumption of normality was considered reasonable for the majority of cases.

The major statistical measures commonly applied to a normal distribution were calculated for the displacement data of figures 14 and 15 using a revised version of computer program MAT (Seymour, 1956), a computer program for obtaining bivariate means and medians. These measures were required in order to 1) examine the distributions of tracer displacement values, 2) determine where significant mean differences occur, and 3) utilize these differences to quantify particle motion. The following computations were made and included in the output program MAT:

$$SA = \sum_{i=1}^N A_i, \text{ sum of recovered grains, or sample size}$$

$$SX = \sum_{i=1}^N X_i A_i, \text{ sum of the X displacements}$$

$$\bar{X} = SX/SA, \text{ mean X displacements}$$

$$SSX = \sum_{i=1}^N X_i^2 A_i, \text{ sums of squares of X displacements}$$

$$CSSX = SSX - (SX)^2/SA, \text{ corrected sums of squares}$$

$$MSX = CSSX/(SA-1.0), \text{ mean square, or variance}$$

$$RMSX = \sqrt{MSX}, \text{ root mean square, or standard deviation about the mean}$$

The remainder of the program was devoted to computation of the bivariate median through an iterative least squares process. This measure locates the "center of gravity" of the distribution of X and Y values. Graphic plots of the median for different times revealed highly erratic, and obviously erroneous, patterns of tracer particle movement not amenable to further use.

Table 4 contains the printed output of the MAT program pertaining to the displacement means. The means were plotted against the five sampling times of the experiment (fig. 16) with confidence intervals at the 95 percent level placed about each mean. Examination of figure 16 reveals several point of information concerning the tracer particle movement in two directions within the two zones: 1) in the X (alongshore) direction the mean particle displacement values decrease almost linearly with time in the swash zone, which is in keeping with the directional sense of the predefined coordinate system and is in agreement with the motion imparted by an existing southerly longshore current (table 1, $\bar{V}$); 2) X displacement in the surf zone appears to be nonlinear over the 50 minutes total travel time with overlap of confidence intervals between some of the adjacent means; 3) Y displacement in the swash zone remains almost constant, indicating little or not net motion of the tracer grains

here in the onshore-offshore direction; 4) a net linear displacement exists in the offshore (Y decreasing) direction within the surf zone.

It may be remembered that the data points in figure 16 represent the mean of a group of displacements occurring at each point of elapsed time following the release of the tracers. This is a consequence of the stochastic process and an indication that simple linear regression of time on displacement, which some of the diagrams in figure 16 appear otherwise suited for, is not appropriate here.

Comparison of Group Means -- The information derived from figure 16 permits a qualitative analysis of the general motion of the tracer particles. It is desirable that a quantitative analysis be made as well. Before an attempt is made to do this, two basic facts must be recognized at this point. First of all, only the tracer distributions themselves are followed through time; no information exists about the paths followed by specific particles. Hence, one cannot "pair" successive particle displacements of specific grains and use these as raw data to obtain a mean displacement covering the entire period of experimentation. Instead, at regular intervals of time (10, 20, 30 minutes) there are group means which can be compared successively. Secondly, an allowance must be made for an anomalous displacement at the time of tracer release which will affect particle displacements during the interval 0 to 10 minutes (fig. 16). The latter result is due to an unavoidable circumstance, the introduction of tracer into the upper portions of the water column during release. Normally, sand grains move by rolling or saltating at or near the sediment-water interface, traveling much slower here than they would in the presence of higher fluid turbulence and advection at some distance above the interface. Therefore, some time must be allowed for tracers to become fully entrained in the

existing sedimentary transport system.

Each pair of adjacent (time-successive) group means of the particle displacement data were compared for significant differences by use of the "t" test at the 95 percent level of confidence (Snedecor, 1956, p. 207). These tests were the basis for inferring a mean difference between the true populations of tracer displacements which could, in fact, be zero indicating no net particle motion over the time interval specified. The results of the tests, summarized in tables 5 and 6, indicate lack of separation of some of the group means for the X displacements in the surf zone, and the Y displacements in the swash zone. Where this occurs, a net particle motion of zero cannot be disproven. Accordingly, no further attempts to quantify the motion of tracers in these zones were made, assuming that a lack of significant mean difference anywhere in the corresponding time-displacement curve of figure 16 meant either a lack of significant net motion over the entire period or that an acceleration (nonlinearity) within the motion was present.

Time-Stratification of Mean Displacement -- Because of the significant differences between each pair of group mean displacements tested (tables 5 and 6), the X displacement values for the swash zone and the Y displacement values for the surf zone were found to represent components of net particle motion of non-zero magnitude in each case. Also figure 16 shows a pronounced linearity in the trend of group mean displacements over the time interval 10-50 min. for these particular components. These factors allow one to consider the net motion of tracer particles for the above zones and directions as being both finite and uniform. Imagining, therefore, a population of particle displacements which vary only with time (except for a certain amount of random variation),

a time-stratification scheme can be utilized which will permit derivation of a single mean displacement representative of the entire sampling period. An estimate of the mean of the total population is made using

$$\bar{S}_w = \frac{\sum N_t \bar{S}_t}{\sum N_t} \quad (3)$$

where N_t is the number of items (particles) in the t th stratum and $\bar{S}_t$ is the sample mean in the t th stratum. Equation (3) is the weighted mean, in either the X or the Y directions, of all tracer displacements. However, whereas values of X and Y displacements have heretofore been relative displacements (relative to the zero point of an arbitrary grid system), values of $\bar{S}_t$ will be made absolute by the following formulation:

$$\bar{S}_t(X) = \bar{X}_t - (X_o + X_p); \quad \bar{S}_t(Y) = \bar{Y}_t - (Y_o + Y_p) \quad (4)$$

in which X_o and Y_o are the mean release points of the tracer at time $t = 0$, $\bar{X}_t$ and $\bar{Y}_t$ are the mean displacements in the t th time stratum, and X_p and Y_p are termed "impulse" displacements occurring during the first few seconds after tracer release. Values for the last two parameters must be estimated separately using a regression technique. The formula, (4), yielding $\bar{S}_t(X)$ will give positive values whenever the displacement is positive in the sense of the coordinate system.

Regression Estimates of X_p and Y_p -- The initial rates of motion of the tracer particles, even when released close to the bottom, were probably of a relatively high magnitude. Average settling velocity of the tracers (4.16 cm./sec.) would account for a second or two of suspension, such suspension being augmented by the effects of fluid turbulence. In addition, many tracer grains were deposited in quantities sufficient to produce a slight local elevation of the bottom upon which fluid forces would act to remove almost immediately working the grains into positions more in equilibrium with the prevailing flow regime.

No direct method of estimating X_p and Y_p is known to the author; therefore, reliance was placed on a regression estimate using the standard equation

$$\hat{d} = \underline{a} + \underline{b}t$$

where $\hat{d}$ the dependent variable was chosen alternately as the X and Y displacement, with time (t) as the independent variable and $\underline{a}$, $\underline{b}$ as regression parameters. In this instance, it is the X-axis intercept, $\underline{a}$, that is required. Two estimates of $\underline{a}$ corresponding to the X and Y directions were obtained by plotting the appropriate displacement values individually against time using data given in table 2. These plots were not intended for predictive use, rather they were a means of estimating certain unique values, otherwise unknown. The $\underline{a}$ values computed were a reflection of the expected displacements at time $t = 0$ based on a form of extrapolation from the displacements at $t = 10, 20, \dots, 50$ minutes. Figure 17 shows this procedure graphically. Estimates of X_p and Y_p were taken as the differences (+ or -) between estimates of $\underline{a}$ and the corresponding release displacements (X_0 and Y_0), under the assumption that the time required to produce X_p and Y_p was very small compared to the lowest measured travel time of 10 minutes. This procedure adjusts the coordinates of tracer particle injection into the system at $t = 0$, thus minimizing the effects of impulsive (forced) tracer movement due to the method of release. The sign values of X_p and Y_p are in accordance with the directional sense of the grid; e.g., an initial impulse, X_p , in a southerly direction (decreasing X, fig. 17) would have a negative sign value.

Regression analyses of the data of table 2 yielded $\underline{a}$ values of 110.64 ft. (33.70 m.) and 41.99 ft. (12.80 m.) for the X direction in the swash zone and the Y direction in the surf zone, respectively.

Since $X_0 = 125.0$ ft. (38.2 m.) and $Y_0 = 45.0$ ft. (13.7 m.), estimates of X_p and Y_p were -14.4 ft. (4.4 m.) and -3.0 ft. (0.9 m.), respectively. The latter two values were entered in equation (4) to yield adjusted values of mean displacements.

Estimates of Mean Particle Velocities -- In applying normal statistics to the present set of tracer data, primary attention was given to an analysis of particle displacement because this variable alone possesses a component of randomness requiring statistical analysis. However, as previously mentioned (p. 14), the present model incorporates a continuous time-parameter which is not random. This parameter was used to compute the estimated mean particle velocity of the total tracer population once an estimate of the mean displacement of particles in the population had been determined. Thus, mean velocity, $\bar{v}$, was obtained by dividing the final mean displacement as computed using equation (3) by the average travel time (30 minutes). The results were:

Swash Zone -

$$\bar{S}_w(X) = 13.22 \text{ ft. (4.04 m.)} \quad (\text{south})$$

$$\bar{v}(X) = 0.44 \text{ ft./min. (0.22 cm./sec.)} \quad (\text{south})$$

Surf Zone -

$$\bar{S}_w(Y) = 11.13 \text{ ft. (3.40 m.)} \quad (\text{offshore})$$

$$\bar{v}(Y) = 0.37 \text{ ft./min. (0.19 cm./sec.)} \quad (\text{offshore})$$

An evaluation of the error associated with the above mean velocities revealed three possible sources: 1) the method of computing the final means of particle displacement, $\bar{S}_w(X)$ and $\bar{S}_w(Y)$; 2) the regression estimates of X_p and Y_p using a; 3) various field measurements in time and space. The first of these sources contains the error of the second two, and all three enter into the final estimate of the mean particle velocity.

For the swash zone and the surf zone, the standard errors of the mean displacements $\bar{S}_w(X)$ and $\bar{S}_w(Y)$ were found to be 0.31 ft. (9.5 cm.) and 0.20 ft. (6.1 cm.), respectively, or about 2.3 percent for the former and 1.8 percent for the latter. At the 95 percent level of confidence, $\bar{S}_w(X)$ and $\bar{S}_w(Y)$ are expected to have fallen within ± 0.61 ft. (± 19 cm.) and ± 0.39 ft. (± 12 cm.), respectively, of the true population means. These interval estimates, divided by the mean travel time, will suffice for the mean particle velocities as well, provided that the average travel time (30 minutes) was determined exactly. This was probably not the case, as all field samples could not be collected simultaneously at their designated recovery times; nevertheless, all sampling was done in order, so that a given station was visited once every 10 minutes, allowing several seconds of error. Assuming that time errors are not cumulative from one sampling period to the next, average travel time was probably accurate to within ± 1 minute. Accordingly, the variation due to time of sampling may have caused an error of approximately ± 0.02 ft./min. (± 0.01 cm./sec.) which is additive to both velocity estimates. The final estimates are then

$$\bar{v}(X) = 0.44 \pm 0.04 \text{ ft./min. } (0.22 \pm 0.01 \text{ cm./sec.})$$

$$\bar{v}(Y) = 0.37 \pm 0.03 \text{ ft./min. } (0.19 \pm 0.02 \text{ cm./sec.})$$

Discussion of Results

Comparison of Particle Movement and Environmental Factors -- A

comparison was made regarding what is known or theorized about the movement of beach sand in the nearshore region, and the results of the present experiment. This was not an attempt to extrapolate the data obtained in any way, as it is not intended that these results should take the form of a prediction of average conditions in the vicinity of Virginia Beach.

King (1959, pp. 125-127) gives an account of tank experiments in which deep water wave steepness (height-to-length ratio) was related to sediment movement inside the breaker zone. Her experiments revealed a critical deep water wave steepness (H'_0/L_0) of 0.012 which, when exceeded, resulted in seaward movement of bottom material, the amount increasing with wave steepness and decreasing with decreasing water depth in a shoreward direction. It was further shown that an onshore wind markedly increased the rate of seaward transport. Saville (1950) conducted tank experiments which showed that longshore transport of sand was linked to wave steepness. For breaking wave angles of 10 degrees, Saville found a critical steepness value of 0.03, differentiating steep-wave transport in the breaker zone as opposed to flat-wave transport.

In the Pendelton field experiments, deep water wave steepness was computed using H_g and T_g (table 1, Sept. 17) as entering arguments in appropriate graphs and tables found in Wiegand (1964) for progressive, linear waves in both deep and shallow water. A value of 0.0092 was obtained for the deep water wave steepness at the time and place of the experiment. This steepness value, based on present knowledge, is considered indicative of a flat wave regime. This regime was accompanied by a light onshore wind (NE at 6 kts.).

By way of comparison with Saville's results, it may be noted that longshore transport of sand was evidenced in the swash zone during the present experiment, as would be expected for a flat wave regime. Regarding King's experimental evidence, the offshore transport of sand in the surf zone of the Pendelton Transect was not in the direction expected, based on flat wave conditions. However, discrepancies have been noted between critical steepness values for field and laboratory waves, with some evidence showing that field values may be lower by comparison (King, p. 250). Moreover, King's tank experiments did not

specifically recognize a surf zone - swash zone delineation shoreward of the breaker zone as is often observed in the field.

Hamada's (1951, pp. 93-94) work on model beaches specifically recognized a surf zone shoreward of the breaker zone, and for spilling type breakers, he observed a well-developed return flow (seaward) along the bottom in the surf zone. In addition, field measurements in the surf zone by Shepard and Inman (1950) and Schiffman (1965) have revealed the existence of a layered flow with a persistent seaward component along the bottom. In theory, net shoreward transport of surface water is balanced by seaward bottom flow in a system of circulation about the horizontal axis, whereas intermittent "rip" currents generated by long-shore water transport are part of a separate circulation about a vertical axis (Hamada, p. 94). The bottom flow, measured at consistently better than 1.2 ft./sec. by Schiffman, probably best explains the seaward particle displacement, $\bar{S}_w(Y)$, of this study.

A value of Q_f was computed (p. 24) from the environmental data which corresponded to the net volume change that occurred in a unit length of the foreshore, from one high tide to the next, prior to the tracer experiment on September 17. This result is given in table 1. Using the basic graphic data (beach elevations plotted along the foreshore width normal to the shoreline), the net value of Q_f was separated into its positive (depositional) and negative (erosional) components and the general location of these components noted in relation to the grid system of the tracer experiment. It was found that almost all of the erosional component of Q_f (4.02 yd.³, 1.11 m.³) was distributed along a 40 ft. section at the seaward edge of the surf zone and beyond. Thus, active erosion in the general area of tracer release was concomitant with sand

accumulation in the outer surf zone, toward which tracer particles steadily moved. Also, there was little net change over most of the swash zone which agrees well with the lack of an offshore-onshore component of tracer displacement there (fig. 16). These comparisons are important, inasmuch as they demonstrate a unique type of information obtainable through the use of tracers; i.e., tracers can give the observer an almost instantaneous picture of the trends in sediment movement as opposed to a much slower, time-averaged result obtained through profile measurements. This fact allows one to utilize tracers in preliminary investigations of a site chosen for more extensive study, as well as to correlate sand movement with environmental factors, measured simultaneously, in a given tracer experiment.

Comparison of Mean Particle Velocity with Expected Particle

Velocity -- There are several examples in the literature in which estimates of longshore particle velocity have been made using sand tracers. These estimates are compared with $\bar{v}(X)$ values obtained in this study. However, no estimates have been made, insofar as the author is aware, of the particle velocities between dynamic zones in the onshore-offshore direction. Ingle (1966) observed that some of his tracers moved from the inshore to the offshore regions under the influence of rip currents (a fact made obvious by the turbid appearance of the seaward-moving "heads" of these currents in otherwise clear water), but did not attempt to quantify this movement. Others (Zeigler, et al., 1959; Bowen and Inman, 1966) have discussed in a general way the budgetary aspects of onshore-offshore sand deposits. Probably longshore sediment transport has received more attention because, compared to onshore-offshore transport, it is easier to measure, it is continuous over longer distances, and is important to the design of breakwaters

and groins. This is perhaps unfortunate, because many investigators tend to assume that longshore sediment transport occurs in a closed, two-way system with no loss of tracer material either seaward or at depth. That such an assumption is unlikely is best released in certain cases of severe shoreline erosion (recession) where longshore currents are practically zero. At any rate, there are no means of comparing $\bar{v}(Y)$ at present.

The numbers of estimates of longshore particle velocity are few to date, some of these being in the form of pilot experiments mentioned in preliminary progress reports (e.g., Inman, 1967). Even final reports, however, point out that a wide range of estimates of velocity values are possible. Siebold (1963) reported average particle velocities ranging from 0.5 ft./min. to 5.5 ft./min. for low-energy waves on the Baltic coast. Ingle (1966) reported the results for a series of experiments on the California coast under somewhat greater wave-energy conditions, obtaining particle velocities of from 3.6 to 22.7 ft./min. (with an average of 10.0 ft./min.).

It appears from these examples that the value for $\bar{v}(X)$ of 0.44 ft./min. in the present experiment represents a rather minimal particle velocity. However in view of the environmental data (table 1), this result does not appear unreasonable. For example, the angle of wave approach was only 4 degrees, and mean breaker height was less than 2 ft.. Such a combination of factors would tend to produce a low component of energy parallel to the shoreline in the direction of particle movement. In addition, a low value of the mean foreshore slope (about 2 deg., $\bar{m}$, table 1) and a fairly long wave period (about 6 sec., T_s , table 1) were expected to have minimized this

component. The alongshore component of wave-energy proved to be the only dynamic variable that Ingle could correlate with his range of tracer grain velocities, and, if one can judge by his results (pp. 151-152), very little correlation exists between grain velocities and other seemingly important variables such as longshore current velocity. Ingle used a value which he termed the relative alongshore energy, computed as

$$\overline{H_b^2} (\cos \bar{\alpha} \sin \bar{\alpha})$$

to obtain his best linear correlation ($r = 0.85$) with average tracer grain velocity, deriving the regression equation

$$Y = 5.012 + 3.832X$$

where X and Y are respectively the energy and velocity variables. One notes that the intercept of this line indicates a grain velocity of slightly more than 5 ft./min. for zero alongshore wave energy. This rate of movement is then an approximation of the error involved in Ingle's area-integration or depletion method of obtaining mean tracer velocities (pp. 5-6), inasmuch as a reversal in direction of alongshore wave energy would demand that the corresponding reversal in particle velocity pass through zero. Part of this error may be due to the lack of any means of adjusting velocity estimates for nonrepresentative initial grain motion (X_p and Y_p in this study).

Another reason for the above error in the depletion method of tracer analysis may lie in the fact that no account was taken of possible tracer dilution with some loss of material at depth. Such dilution was found to be a limiting factor as regards running time of flume experiments with radioactive sand tracers (Crickmore and Lean, 1962a). Figure 18 is a diagram showing how this may occur. Boon (1967) conducted a field study of tracer distribution patterns

on a carbonate beach at several depth intervals within 39 sand cores and observed that significant amounts of tracer occurred locally in some samples as much as 10.0 cm. (4.0 in.) below the surface. Using the area-integration method, such quantities of tracer would be erroneously credited with having left the study area through surface travel, thereby causing a biased estimate of particle velocity. Figures 14 and 15 show graphically that, although an overall diminution of particle frequency did occur with time in the present experiment, the distribution of particle displacements remained well defined for those tracers remaining at or near the surface within the active zone of transport (mobile layer). Conversely, any tracer particles falling below the zone of active transport were without means of appearing in the core samples, and therefore could not affect horizontal particle velocity estimates $\bar{v}(X)$ and $\bar{v}(Y)$.

Using the time-integration method, Yasso (1965) obtained grain velocity estimates in the foreshore (swash) zone of a beach at Sandy Hook, New Jersey. For a 5.3 second breaker period having a maximum height of 0.73 m. (2.4 ft.) and an angle of approach of approximately 5 degrees, he found maximum longshore particle velocities of between 2.0 cm./sec. (3.9 ft./min.) and 2.8 cm./sec. (5.5 ft./min.) as indicated by arrival times of the first few grains at a known distance from the point of release. However, the average particle velocity as denoted by the arrival time of the main body of tracer was only 1.2 cm./sec. (2.4 ft./min.). The latter value is still higher than the mean particle velocity (0.22 cm./sec., 0.44 ft./min.) obtained at the Pendelton Transect, even though wave conditions were very nearly the same and bottom slopes in the swash zone were almost identical (about 6.5 deg.) for both areas. Figure

19 is a graph taken from Yasso's report which gives the frequency-time data of his tracers for a travel distance of 30.5 m. (100 ft.). An immediate similarity may be seen between this graph and figures 14 and 15, the main difference being in the choice of the variable, i.e., time as opposed to distance. In regard to sampling procedures, however, Yasso sampled only a 3.0 m. (9.8 ft.) section perpendicular to the shoreline beginning at the backwash limit and moving shoreward. One can question, therefore, whether the movement in the remaining portion of the swash zone, whose total width was not given, was of similar magnitude. It may also be noted that the arrival time of the maximum tracer concentration in figure 19 (Yasso stated that it was 42.3 min.) is a unique value which must be accepted as is; i.e., no comparisons are possible with time and thus no initial impulse displacements (X_p and Y_p in this study) are taken into account.

Difficult as it may be to draw conclusions from single experiments, the results of the present study suggest that previous estimates of the longshore particle velocity on ocean beaches may have been too high or else not quite representative of the overall particle movement. This is not to say that under conditions of higher along-shore energy a repeat of the procedures used here would not yield much higher particle velocities. As a matter of intuitive judgement, there should be minimal particle velocities associated with minimal energy conditions.

Estimation of Mean Rate of Sand Transport -- In order to obtain an estimate of the rate of sand transport in a given area, both average particle velocity expressed as a vector, and the cross-section-1 area of active transport normal to this vector must be known. Inasmuch as the direction and magnitude of longshore particle veloci-

ty is known, along with the width of the cross-sectional area (width of the swash zone), there remains only the vertical thickness of the mobile layer to be determined. Unfortunately, this is one of the most elusive unknowns in the field of beach research, and at the same time one of the most important; by having only slight differences in the thickness of the mobile layer, one can derive vastly different values of longshore transport.

Ingle's (1966) estimates of mobile bed thicknesses varied between 0.05 and 0.10 in. on the average (p. 6); being derived as a function of his average tracer velocities, they are therefore subject to the same errors as may be associated with those velocities. At any rate, certain facts suggest that the estimates of thicknesses must be more than a few grain diameters. Wherever tracer grains are entrained in ripples on the bottom, as they often are on beaches, it seems logical to suppose that their vertical excursions during forward movement would be at least as much as the amplitude of the ripple wave form (which usually exceeds 0.10 in.). In addition, field experiments with dyed sand in England (King, 1959) have shown that the depth of wave-induced bottom disturbance in cm. is about equal to the breaker height in feet. In the case of the Pendelton Transect, a disturbed layer 1.8 cm. (0.71 in.) deep could then be expected.

If the mobile layer can be assumed constant at most points inside the breaker zone, then thickness may be directly computed using the data of the present experiment. This was done by further assuming that the accretional (+) portion of Q_f at the outer limit of the surf zone (fig. 3) was the result of offshore transport. The latter is a reasonable assumption since little longshore transport was evidenced in this zone and the adjacent breaker zone forms a

substantial barrier against onshore transport (Hamada, 1951, p. 96).

Using the equation

$$Q_f(Y) = \bar{v}(Y) \cdot A \cdot B$$

where $Q_f(Y)$ = rate of sand accretion (1.45 yd.³ in 13 hours or 0.054 ft.³/min.), $\bar{v}(Y)$ = mean particle velocity offshore (0.37 ft./min.), and A = unit width used to obtain Q_f (1.0 m. or 3.28 ft.), B the mobile layer thickness was found to be 0.50 in.. This value, by fortuitous coincidence, was exactly the thickness removed from the top of each core for tracer counting. In like manner, the rate of longshore sand transport, $Q_f(X)$, was computed using equation (3) with $B = 0.50$ in., $A = 45.0$ ft. (width of the swash zone), and $\bar{v}(X) = 0.44$ ft./min. giving an estimate of 0.82 ft.³/min. (440 yd.³/day). This value is within the broad range of sand transport rates obtained by coastal engineers (Fairchild, 1966, p. 33) using profile data. A more exact comparison cannot be made owing to the lack of sufficient precision in large-scale beach surveying methods.

Recommendations for Future Studies -- The conclusions of the present study are the product of a single field experiment. It is apparent, therefore, that more work is required to confirm and enlarge upon the results. Certain basic assumptions about the movement of sand on an ocean beach were examined in the light of previous studies and, if nothing more, the data and methods given in this paper point to the need for a better understanding and resolution of the problems involved.

Although there are many ways to collect samples of a population of tracers released on a beach, all fall within two basic categories; one can either collect surface grains or take samples including subsurface grains. There is a definite advantage to sampling in depth

as the results of several studies, including this one, have shown. However, it must be recognized that the number of cores or hand-grabs that can be obtained is limited by the short collection periods required if the total sample is to be nearly synchronous. Consequently, if only a few of the cores or hand-grabs taken should fall outside the field distribution of tracers, a serious shortage of data could result. On the other hand, the greased-card technique used by many investigators collects only surface grains, but these can be obtained at a faster rate over a wider area. In view of the relative advantages and disadvantages of both surface and subsurface samples, one may wish to make a final choice based on the specific requirements of the study. For example, where tracer grain motion in only one direction is anticipated, such as in an inlet or an estuary, one may wish to use long strips of greased-film. These can be unrolled along the bottom to pick up surface material, thereby resulting in a fully continuous record of particle displacements in the chosen direction at any given time. In sum, more field experiments are recommended to evaluate all of the methods of collection which are now possible.

Along with improvements in the design of sampling techniques, there is a need for still greater emphasis on finding the best statistical techniques for adequately describing various types of grain motion. The present study utilized a simple stochastic-process model incorporating normal statistics. Beach sand movement in this model was visualized as a series of partial displacements having a component of randomness. More advanced stochastic-process models such as those involving Markov chains (p. 12) may become feasible with further study. To employ a Markov model, one must find a way of locating the same tracer particle again and again over a sufficient interval of time without

removing it from the transport system. Having accomplished this, the probability of a given magnitude of particle displacement occurring during one interval of time is then based on the displacement magnitude observed during one or more preceding intervals of time. Using Markov chains of sufficient length, one might ultimately be able to describe not only linear but periodic particle movement. The reader interested in computer programs written for related experiments incorporating the Markov model is referred to Krumbein (1967).

IV. SUMMARY

The present study at the Pendelton Transect in Virginia employed a tracer technique that is new in several respects. Because beach phenomena exhibit considerable variation attributable to a complex variety of interacting physical mechanisms, a type of stochastic-process model was envisioned as having acted through the variable of particle displacement. The study was then designed to sample an infinite number of random particle displacements, $X(t)$, where t is time. Each sample, then, consisted of a large number of displacements denoted by tracer grains recovered over a fixed horizontal grid system after a specific time. The number of items in the sample, or sample size, was therefore equal to the total number of grains recovered at any given time. Actual recovery of grains at any point was accomplished in subsamples of the beach material obtained in plastic coring tubes and by hand, care being taken to retrieve the top 0.5 in. of sand in a constant volume for counting purposes.

The resultant tracer data of the Pendelton experiment were arranged in a row-column matrix for certain preliminary tests. These tests consisted of a chi-square homogeneity test and a Fourier trend surface analysis which revealed a separation of the data based on two dynamic beach zones, the swash zone and the surf zone. Using these two sets of data, bivariate normal statistics were applied to displacements in the alongshore (X) and onshore-offshore (Y) directions. The resultant mean displacements ($\bar{X}$, $\bar{Y}$) were converted to mean velocities [$\bar{v}(X)$, $\bar{v}(Y)$] after a weighting procedure was carried out and an average travel time was computed. It was found that a

well developed southerly longshore grain velocity was confined to the swash zone on the day in question, while offshore motion prevailed in the surf zone.

In addition to the grain velocity estimates finally computed (0.44 ft./min. south in the swash zone and 0.37 ft./min. offshore in the surf zone), a value representing the thickness of the mobile layer of sand was determined using $\bar{v}(Y)$ offshore and beach profile data obtained during the study. The resultant thickness was about 0.50 in. (1.3 cm.).

The thickness of the mobile layer, along with the width of the swash zone and the longshore estimate of grain velocity, was used to compute an independent estimate of the rate of longshore sand transport. Thus, using a value of 0.50 in. for the mobile layer thickness, a value of 45 ft. for the width of swash zone (fig. 3), and the average longshore particle velocity computed as 0.44 ft./min., a transport value of 440 yd.³/day (336 m.³/day) was obtained.

APPENDIX

**Figure 1. Location map for area of study (after Harrison,
et al., 1965).**

**Figure 2. Characteristics of beaches (after Ingle, 1966).
A: General features and terminology. B: Designation
of dynamic zones and idealized water circulatory
patterns.**

A

B

Figure 3. Map showing bottom topography and position of surf and swash zones, Pendelton Transect, Sept. 17, 1100 hrs. (datum: arbitrary).

Figure 4. Row-column grid showing points of tracer particle release and sand sample recovery.

**Figure 5. Device used to obtain sand cores at Pendelton
Transect.**

Figure 6. Mean settling velocities, $\bar{U}_s$, of sand samples.
A: $\bar{U}_s$ plotted against distance along column CD for
Sept. 16, 2200 hrs., Sept. 17, 1100 hrs., and for
tracer material ($\bar{U}_s = 4.15$ cm./sec.). B: Map of
field distribution of $\bar{U}_s$, Sept. 17, 1100 hrs..

Figure 7. Schematic section of beach showing method of determining Q_s for two successive high tides, 16 Sept., 2200 hrs. and 17 Sept., 1100 hrs. (modified from Harrison, et al., 1968). (A) is the position of top of swash on successive high water stands and (B) is the innermost position of inshore margin of breaker zone on successive high water stands.

**Figure 8. Fourier trend continuous symbol map of tracer
particle concentration 10 min. after release
(contours added by the author).**

☐ — tracer release point

X (FEET) →

**Figure 9. Fourier trend continuous symbol map of tracer
particle concentration 20 min. after release
(contours added by the author).**

☐ — tracer release point

**Figure 10. Fourier trend continuous symbol map of tracer
particle concentration 30 min. after release
(contours added by the author).**

□ — tracer release point

**Figure 11. Fourier trend continuous symbol map of tracer
particle concentration 40 min. after release
(contours added by the author).**

☐ — tracer release point

Figure 12. Fourier trend continuous symbol map of tracer particle concentration 50 min. after release (contours added by the author).

☐ — tracer release point

Figure 13. Schematic diagram showing derivation of bivariate displacement data for N recovered tracer particles.

$0 < i \leq N$; $N = \text{sample size}$

Figure 14. Frequency-displacement diagrams for the swash zone including fitted normal curves, Sept. 17, 1100 hrs..

FREQUENCY (NO. OF GRAINS) $\longrightarrow$

$\times 10^3$

10 min.

20 min.

30 min.

40 min.

50 min.

X (FEET) $\longrightarrow$

SWASH

Y (FEET) $\longrightarrow$

ZONE

**Figure 15. Frequency-displacement diagrams for the surf
zone including fitted normal curves, Sept. 17,
1100 hrs..**

FREQUENCY (NO. OF GRAINS) $\times 10^3$

X (FEET) $\longrightarrow$

Y (FEET) $\longrightarrow$

SURF

ZONE

**Figure 16. Time-displacement diagrams showing group means
with approximate confidence intervals, Sept. 17,
1100 hrs..**

TIME (MIN) →

SWASH ZONE

SURF ZONE

Figure 17. Schematic diagram showing the relationship between the position of tracer particles, X_0 , upon injection, and the "impulse" displacement, X_p , away from the injection point immediately following release. The same relationship holds for the Y direction.

**Figure 18. Schematic representation of tracer particle
dilution with time in a sand matrix and subsequent
"loss" of tracer at depth.**

BEFORE
DILUTION

AFTER
DILUTION

Figure 19. Time-frequency graph for tracer particles recovered by Yasso (1965) at Sandy Hook, New Jersey.

TABLE 1

List of environmental factors measured near
Pendelton Transect, September 16, 2200 hrs.(HW),
and September 17, 1100 hrs.(HW), 1966.*

Variable	Units	16/2200	17/1100
$\bar{H}_b$	ft.	1.9	1.7
	m.	0.57	0.52
$\bar{H}_{bs}$	ft.	1.9	1.8
	m.	0.58	0.54
$\bar{T}_b$	-	-	-
	sec.	6.5	6.4
	ft.	1.9	1.4
H_s	m.	0.58	0.44
	-	-	-
T_s	sec.	4.0	5.8
	-	-	-
$\bar{\alpha}$	deg.	5	4
	ft.	2.0	3.2
$\bar{z}$	m.	0.62	0.98
	ft./sec.	2.4	0.8
$\bar{V}$	m./sec.	0.72	0.23
	-	-	-
$\bar{W}_d$	deg.	084	044
	kts.	12	6
$\bar{W}_s$	m./sec.	6	3
	lb./ft. ³	63.5	63.5
ρ_t	g./cm. ³	1.0183	1.0187
	-	-	-
$\bar{m}$	deg.	1.5	2.2
	ft. ³	(+)54.5	(+)67.8
Q_f	m. ³	(+)1.54	(+)1.92

*

For an explanation of symbols, refer to text.

TABLE 2

Tracer concentration data

CONTROL*	X (ft.)	Y (ft.)	10 min.	20 min.	30 min.
AA1	0.000	75.000	1.000	2.000	4.000
AA2	0.000	60.000	3.000	1.000	3.000
AA3	0.000	45.000	4.000	3.000	4.000
AA4	0.000	30.000	6.000	3.000	7.000
AA5	0.000	15.000	15.000	2.000	3.000
AA6	0.000	0.000	4.000	2.000	5.000
AB1	25.000	75.000	4.000	19.000	24.000
AB2	25.000	60.000	11.000	2.000	31.000
AB3	25.000	45.000	4.000	14.000	11.000
AB4	25.000	30.000	7.000	3.000	1.000
AB5	25.000	15.000	2.000	30.000	9.000
AB6	25.000	0.000	12.000	19.000	6.000
BB1	50.000	75.000	3.000	9.000	31.000
BB2	50.000	60.000	78.000	37.000	215.000
BB3	50.000	45.000	12.000	19.000	72.000
BB4	50.000	30.000	12.000	13.000	36.000
BB5	50.000	15.000	1.000	9.000	31.000
BB6	50.000	0.000	1.000	4.000	25.000
BC1	75.000	75.000	185.000	158.000	261.000
BC2	75.000	60.000	853.000	669.000	342.000
BC3	75.000	45.000	83.000	869.000	681.000
BC4	75.000	30.000	89.000	84.000	181.000
BC5	75.000	15.000	23.000	15.000	46.000
BC6	75.000	0.000	99.000	105.000	96.000
CC1	100.000	75.000	65.000	302.000	165.000
CC2	100.000	60.000	1099.000	736.000	333.000
CC3	100.000	45.000	2609.000	2005.000	1485.000
CC4	100.000	30.000	216.000	911.000	625.000
CC5	100.000	15.000	99.000	305.000	229.000
CC6	100.000	0.000	180.000	11.000	215.000
CD1	125.000	75.000	27.000	19.000	10.000
CD2	125.000	60.000	417.000	370.000	142.000
CD3	125.000	45.000	2405.000	187.000	322.000
CD4	125.000	30.000	1119.000	1216.000	873.000
CD5	125.000	15.000	654.000	653.000	207.000
CD6	125.000	0.000	91.000	15.000	281.000
DD1	150.000	75.000	1.000	1.000	2.000
DD2	150.000	60.000	3.000	3.000	1.000
DD3	150.000	45.000	1.000	1.000	1.000
DD4	150.000	30.000	1.000	2.000	4.000
DD5	150.000	15.000	9.000	2.000	1.000
DD6	150.000	0.000	1.000	1.000	1.000

* First two letters of control indicate column, last digit indicates row beginning with the shoreward-most row as 1.

TABLE 2 (CONT.)

CONTROL	X(ft.)	Y(ft.)	40 min.	50 min.
AA1	0.000	75.000	5.000	21.000
AA2	0.000	60.000	10.000	49.000
AA3	0.000	45.000	21.000	63.000
AA4	0.000	30.000	25.000	6.000
AA5	0.000	15.000	5.000	9.000
AA6	0.000	0.000	4.000	5.000
AB1	25.000	75.000	144.000	66.000
AB2	25.000	60.000	137.000	164.000
AB3	25.000	45.000	27.000	23.000
AB4	25.000	30.000	2.000	12.000
AB5	25.000	15.000	18.000	10.000
AB6	25.000	0.000	2.000	17.000
BB1	50.000	75.000	77.000	168.000
BB2	50.000	60.000	182.000	131.000
BB3	50.000	45.000	74.000	47.000
BB4	50.000	30.000	36.000	53.000
BB5	50.000	15.000	7.000	3.000
BB6	50.000	0.000	46.000	65.000
BC1	75.000	75.000	399.000	301.000
BC2	75.000	60.000	715.000	435.000
BC3	75.000	45.000	248.000	84.000
BC4	75.000	30.000	108.000	50.000
BC5	75.000	15.000	112.000	202.000
BC6	75.000	0.000	107.000	121.000
CC1	100.000	75.000	185.000	161.000
CC2	100.000	60.000	339.000	316.000
CC3	100.000	45.000	501.000	409.000
CC4	100.000	30.000	651.000	717.000
CC5	100.000	15.000	311.000	148.000
CC6	100.000	0.000	503.000	423.000
CD1	125.000	75.000	15.000	13.000
CD2	125.000	60.000	11.000	10.000
CD3	125.000	45.000	147.000	120.000
CD4	125.000	30.000	703.000	690.000
CD5	125.000	15.000	158.000	104.000
CD6	125.000	0.000	461.000	805.000
DD1	150.000	75.000	1.000	5.000
DD2	150.000	60.000	1.000	5.000
DD3	150.000	45.000	3.000	1.000
DD4	150.000	30.000	1.000	1.000
DD5	150.000	15.000	5.000	41.000
DD6	150.000	0.000	2.000	1.000

TABLE 3

Summary of chi-square tests, zones versus X displacements.

Time (min.)	d.f.	χ^2	Probability
10	6	596.7	$P < 0.001$
20	6	190.6	$P < 0.001$
30	6	196.2	$P < 0.001$
40	6	732.2	$P < 0.001$
50	6	672.4	$P < 0.001$

TABLE 4

Computer output of program MAT

 MAT OUTPUT SURF ZONE SEPT 17,66 10MIN

COORDINATES AND AGGREGATE TRAVEL FOR BIVARIATE MEAN
 OX = 112.102 Y = 36.842 TOTAL TRAVEL TO MEAN = 144141.438

OSX = 869800.000 SSX = 99747440.000 SY = 285855.000 SSY = 11849625.
 SA = 7759.000
 CSSX = 2241072.000 MSX = 288.872 RMSX = 16.996
 CSSY = 1318238.000 MSY = 169.920 RMSY = 13.035
 SDMX = 0.193 SDMY = 0.148

 MAT OUTPUT 20MIN
 ***** SURF ZONE

COORDINATES AND AGGREGATE TRAVEL FOR BIVARIATE MEAN
 OX = 102.622 Y = 34.078 TOTAL TRAVEL TO MEAN = 127731.563

OSX = 667350.000 SSX = 71003696.000 SY = 221610.000 SSY = 8510850.
 SA = 6503.000
 CSSX = 2519008.000 MSX = 387.420 RMSX = 19.683
 CSSY = 958799.000 MSY = 147.462 RMSY = 12.143
 SDMX = 0.244 SDMY = 0.151

 MAT OUTPUT 30MIN
 ***** SURF ZONE

COORDINATES AND AGGREGATE TRAVEL FOR BIVARIATE MEAN
 OX = 100.953 Y = 32.177 TOTAL TRAVEL TO MEAN = 121747.438

OSX = 551000.000 SSX = 58068720.000 SY = 175620.000 SSY = 6889050.
 SA = 5458.000
 CSSX = 2443776.000 MSX = 447.824 RMSX = 21.162
 CSSY = 1238192.000 MSY = 226.900 RMSY = 15.063
 SDMX = 0.286 SDMY = 0.204

TABLE 4 (CONT.)

 MAT OUTPUT 40MIN ***** SURF ZONE *****

COORDINATES AND AGGREGATE TRAVEL FOR BIVARIATE MEAN
 OX = 101.846 Y = 23.511 TOTAL TRAVEL TO MEAN = 105668.563

OSX = 434375.000 SSX = 46533056.000 SY = 100275.000 SSY = 3558825.
 SA = 4265.000
 CSSX = 2293536.000 MSX = 537.884 RMSX = 23.192
 CSSY = 1201247.000 MSY = 281.718 RMSY = 16.784
 SDMX = 0.355 SDMY = 0.257

 MAT OUTPUT 50MIN ***** SURF ZONE *****

COORDINATES AND AGGREGATE TRAVEL FOR BIVARIATE MEAN
 OX = 102.937 Y = 20.626 TOTAL TRAVEL TO MEAN = 113819.313

OSX = 435525.000 SSX = 47864304.000 SY = 87270.000 SSY = 3006000.
 SA = 4231.000
 CSSX = 3032832.000 MSX = 716.981 RMSX = 26.777
 CSSY = 1205942.000 MSY = 285.093 RMSY = 16.885
 SDMX = 0.412 SDMY = 0.260

 MAT OUTPUT SWASH ZONE SEPT 17.66 10MIN *****

COORDINATES AND AGGREGATE TRAVEL FOR BIVARIATE MEAN
 OX = 106.509 Y = 47.553 TOTAL TRAVEL TO MEAN = 175663.313

OSX = 992450.000 SSX = 110221856.000 SY = 443100.000 SSY = 22148064.
 SA = 9318.000
 CSSX = 3405184.000 MSX = 365.481 RMSX = 19.118
 CSSY = 1077280.000 MSY = 115.625 RMSY = 10.753
 SDMX = 0.198 SDMY = 0.111

TABLE 4 (CONT.)

```

*****
MAT OUTPUT          20MIN          *****
*****                SWASH ZONE
*****

OOCOORDINATES AND AGGREGATE TRAVEL FOR BIVARIATE MEAN
OX =      98.992      Y =      46.241      TOTAL TRAVEL TO MEAN =      147409.375

OSX =      761050.000      SSX = 78097456.000      SY =      355500.000      SSY = 17803760.
SA =      7688.000
CSSX = 2759648.000      MSX =      359.002      RMSX =      18.947
CSSY = 1365127.000      MSY =      177.589      RMSY =      13.326
SDMX =      0.216      SDMY =      0.152

*****
MAT OUTPUT          30MIN          *****
*****                SWASH ZONE
*****

OOCOORDINATES AND AGGREGATE TRAVEL FOR BIVARIATE MEAN
OX =      95.385      Y =      45.854      TOTAL TRAVEL TO MEAN =      131392.938

OSX =      559625.000      SSX = 56474320.000      SY =      269025.000      SSY = 13407525.
SA =      5867.000
CSSX = 3094384.000      MSX =      527.512      RMSX =      22.968
CSSY = 1071678.000      MSY =      182.693      RMSY =      13.516
SDMX =      0.300      SDMY =      0.176

*****
MAT OUTPUT          40MIN          *****
*****                SWASH ZONE
*****

OOCOORDINATES AND AGGREGATE TRAVEL FOR BIVARIATE MEAN
OX =      88.687      Y =      49.340      TOTAL TRAVEL TO MEAN =      129442.313

OSX =      411950.000      SSX = 39904944.000      SY =      229185.000      SSY = 12525975.
SA =      4645.000
CSSX = 3370448.000      MSX =      725.764      RMSX =      26.940
CSSY = 1217954.000      MSY =      262.264      RMSY =      16.195
SDMX =      0.395      SDMY =      0.238

```

 MAT OUTPUT 50MIN *****
 ***** SWASH ZONE *****

COORDINATES AND AGGREGATE TRAVEL FOR BIVARIATE MEAN
 OX = 86.744 Y = 48.812 TOTAL TRAVEL TO MEAN = 132315.875

OSX = 358425.000 SSX = 35394320.000 SY = 201690.000 SSY = 11040300.
 SA = 4132.000
 CSSX = 4303216.000 MSX = 1041.688 RMSX = 32.275
 CSSY = 1195466.000 MSY = 289.389 RMSY = 17.011
 SDMX = 0.502 SDMY = 0.265

TABLE 5

Pendelton tracer data, X displacements; "t" tests of $H_0: \mu_1 = \mu_2$ for four pairs of group mean data per dynamic zone.

SURF ZONE, 10-20 MIN. SERIES

Sample	Size	$\bar{X}$	MSX	SDMX
10 min.	7759	112.102	288.872	0.193
20 min.	6503	102.622	387.420	0.244
$\bar{X}_{20} - \bar{X}_{10} = -9.480$ $F = 1.341$				
$t = -30.48, P < 0.05, H_0$ rejected				

SURF ZONE, 20-30 MIN. SERIES

Sample	Size	$\bar{X}$	MSX	SDMX
20 min.	6503	102.622	387.420	0.244
30 min.	5458	100.953	447.824	0.286
$\bar{X}_{30} - \bar{X}_{20} = -1.669$ $F = 1.156$				
$t = -4.44, P < 0.05, H_0$ rejected				

SURF ZONE, 30-40 MIN. SERIES

Sample	Size	$\bar{X}$	MSX	SDMX
30 min.	5458	100.953	447.824	0.286
40 min.	4265	101.846	537.884	0.355
$\bar{X}_{40} - \bar{X}_{30} = 0.893$ $F = 1.201$				
$t = 1.96, P > 0.05, H_0$ not rejected				

TABLE 5 (CONTIN.)

SURF ZONE, 40-50 MIN. SERIES

Sample	Size	$\bar{X}$	MSX	SDMX
40 min.	4265	101.846	537.884	0.355
50 min.	4231	102.937	716.981	0.412
$\bar{X}_{50} - \bar{X}_{40} = 1.091$			$F = 1.333$	
$t = 2.01, P < 0.05, H_0$ rejected				

SWASH ZONE, 10-20 MIN. SERIES

Sample	Size	$\bar{X}$	MSX	SDMX
10 min.	9318	106.509	365.481	0.198
20 min.	7688	98.992	359.002	0.216
$\bar{X}_{20}-\bar{X}_{10} = -7.517$			$F = 1.018$	
$t = -25.66, P < 0.05, H_0$ rejected				

SWASH ZONE, 20-30 MIN. SERIES

Sample	Size	$\bar{X}$	MSX	SDMX
20 min.	7688	98.992	359.002	0.216
30 min.	5867	95.385	527.512	0.300
$\bar{X}_{30} - \bar{X}_{20} = -3.607$			$F = 1.469$	
$t = -9.75, P < 0.05, H_0$ rejected				

TABLE 5 (CONTIN.)

SWASH ZONE, 30-40 MIN. SERIES

Sample	Size	$\bar{X}$	MSX	SDMX
30 min.	5867	95.385	527.512	0.300
40 min.	4645	88.687	725.764	0.395
$\bar{X}_{40} - \bar{X}_{30} = -6.698$ $F = 1.376$				
$t = -13.50, P < 0.05, H_0$ rejected				

SWASH ZONE, 40-50 MIN. SERIES

Sample	Size	$\bar{X}$	MSX	SDMX
40 min.	4645	88.687	725.764	0.395
50 min.	4132	86.744	1041.688	0.502
$\bar{X}_{50} - \bar{X}_{40} = -1.943$ $F = 1.435$				
$t = -3.04, P < 0.05, H_0$ rejected				

TABLE 6

Pendelton tracer data, Y displacements; "t" tests of $H_0: \mu_1 = \mu_2$ for four pairs of group mean data per dynamic zone.

SURF ZONE, 10-20 MIN. SERIES

Sample	Size	$\bar{Y}$	MSY	SDMY
10 min.	7759	36.842	169.920	0.148
20 min.	6503	34.078	147.462	0.151
$\bar{Y}_{20} - \bar{Y}_{10} = -2.764$ $F = 1.152$				
$t = -13.1, P < 0.005, H_0$ rejected				

SURF ZONE, 20-30 MIN. SERIES

Sample	Size	$\bar{Y}$	MSY	SDMY
20 min.	6503	34.078	147.462	0.151
30 min.	5458	32.177	226.900	0.204
$\bar{Y}_{30} - \bar{Y}_{20} = -1.901$ $F = 1.539$				
$t = -7.48, P < 0.05, H_0$ rejected				

SURF ZONE, 30-40 MIN. SERIES

Sample	Size	$\bar{Y}$	MSY	SDMY
30 min.	5458	32.177	226.900	0.204
40 min.	4265	23.511	281.718	0.257
$\bar{Y}_{40} - \bar{Y}_{30} = -8.666$ $F = 1.242$				
$t = 26.42, P < 0.05, H_0$ rejected				

TABLE 6 (CONTIN.)

SURF ZONE, 40-50 MIN. SERIES

Sample	Size	$\bar{Y}$	MSY	SDMY
40 min.	4265	23.511	281.718	0.257
50 min.	4231	20.626	285.093	0.260
$\bar{Y}_{50} - \bar{Y}_{40} = -2.885$ $F = 1.012$				
$t = -7.90, P < 0.05, H_0$ rejected				

SWASH ZONE, 10-20 MIN. SERIES

Sample	Size	$\bar{Y}$	MSY	SDMY
10 min.	9318	47.553	115.625	0.111
20 min.	7688	46.241	177.589	0.152
$\bar{Y}_{20} - \bar{Y}_{10} = -1.312$ $F = 1.536$				
$t = 6.98, P < 0.05, H_0$ rejected				

SWASH ZONE, 20-30 MIN. SERIES

Sample	Size	$\bar{Y}$	MSY	SDMY
20 min.	7688	46.241	177.589	0.152
30 min.	5867	45.854	182.693	0.176
$\bar{Y}_{30} - \bar{Y}_{20} = -0.387$ $F = 1.029$				
$t = -1.67, P > 0.05, H_0$ not rejected				

TABLE 6 (CONTIN.)

SWASH ZONE, 30-40 MIN. SERIES

Sample	Size	$\bar{Y}$	MSY	SDMY
30 min.	5867	45.854	182.693	0.176
40 min,	4645	49.340	262.264	0.238
$\bar{Y}_{40}-\bar{Y}_{30} = 3.486$			$F = 1.436$	
$t = 11.78, P < 0.05, H_0$ rejected				

SWASH ZONE, 40-50 MIN. SERIES

Sample	Size	$\bar{Y}$	MSY	SDMY
40 min.	4645	49.340	262.264	0.238
50 min.	4132	48.812	289.389	0.265
$\bar{Y}_{50} - \bar{Y}_{40} = -0.528$			$F = 1.103$	
$t = -1.49, P > 0.05, H_0$ not rejected				

LITERATURE CITED

- BAGNOLD, R.A., 1963, Mechanics of marine sedimentation. In: M.N. Hill, E.D. Goldberg, C.O.D. Iselin, and W.H. Munk (Editors), The sea, ideas and observations on progress in the study of the seas: John Wiley & Sons, Inc., v. 3, pp. 507-528.
- BARTLETT, M.S., 1960, Stochastic population models: John Wiley & Sons, Inc., 84 p.
- BOON, J.D., III, 1967, Trend surface analysis of sand tracer distributions on a carbonate beach, Bimini, B.W.I.: Jour. Geol., v. 76, pp. 1-9.
- BOWEN, A.J., and INMAN, D.L., 1966, Budget of littoral sands in the vicinity of Point Arguello, California: U.S. Army Corps of Engineers Tech. Mem. 19, 41 p.
- BRUUN, P., and PURPURA, J., 1964, Quantitative research on littoral drift in field and laboratory: Proceedings of the Ninth Cong. Coastal Eng., Lisbon, Portugal, 18, pp. 267-288.
- BRUUN, P., 1965, Quantitative tracings of littoral drift: U.S. Dept. of Agriculture Misc. Pub. 970, pp. 756-768.
- CALDWELL, J.M., 1956, Wave action and sand movement near Anaheim Bay, California: U.S. Army Beach Erosion Board Tech. Mem. 68, 21 p.
- CRICKMORE, M.J., and LEAN, G.H., 1962a, The measurement of sand transport by means of radioactive tracers: Proc. Roy. Soc. (London) A, v. 266, pp. 402-421.
- CRICKMORE, M.J., and LEAN, G.H., 1962b, The measurement of sand transport by the time-integration method with radioactive tracers: Proc. Roy. Soc. (London) B, v. 270, pp. 27-47.
- DOOB, J.L., 1953, Stochastic processes: John Wiley & Sons, Inc., 387 p.
- EINSTEIN, H.A., 1948, Movement of beach sand by water waves: Trans. Am. Geophys. Union, v. 29, pp. 653-655.
- FAIRCHILD, J.C., 1966, Correlation of littoral transport with wave energy along shores of New York and New Jersey: U.S. Army Corps of Engineers Tech. Mem. 7, 102 p.
- GLOSSARY OF METEOROLOGY, 1959, American Meteorological Society, pp. 467.

- HALTNER, G.J., and MARTIN, F.L., 1957, Dynamical and physical meteorology: McGraw-Hill Book Co., 470 p.
- HAMADA, T., 1951, Breakers and beach erosions: Transportation Tech. Res. Inst. (Tokyo), Rpt. No. 1, pp. 1-151.
- HARRISON, W., and KRUMBEIN, W.C., 1964, Interaction of the beach-ocean-atmosphere system at Virginia Beach, Virginia: U.S. Army Corps of Engineers Tech. Mem. 7, 102 p.
- HARRISON, W., and MORALES-ALAMO, R., 1964, Dynamic properties of immersed sand at Virginia Beach, Virginia: U.S. Army Corps of Engineers, Tech. Mem. 9, 52 p.
- HARRISON, W., and WAGNER, K.A., 1964, Beach changes at Virginia Beach, Virginia: U.S. Army Corps of Engineers Misc. Paper 6, 25 p.
- HARRISON, W., KRUMBEIN, W.C., and WILSON, W.S., 1964, Sedimentation at an inlet entrance, Rudee Inlet, Virginia Beach, Virginia: U.S. Army Corps of Engineers Tech. Mem. 8, 42 p.
- HARRISON, W., PORE, N.A., and TUCK, D.R., JR., 1964, Predictor equations for beach processes and responses: Jour. Geophys. Res., v. 70, pp. 6103-6109.
- HARRISON, W., and OTHERS, 1968, A time series from the beach environment: ESSA Res. Lab. Tech. Mem. (In press).
- HJULSTRÖM, F., 1935, Studies of the morphological activity of rivers as illustrated by River Fyris: Bull. Geol. Inst. Univ. Uppsala, v. 25, pp. 221-527.
- INGLE, J.C., JR., 1966, The movement of beach sand: ElsevierPub. Co., 221 p.
- INMAN, D.L., 1949, Sediment sorting in the light of fluid mechanics: Jour. Sediment. Petrol., v. 19, pp. 51-70.
- INMAN, D.L., and CHAMBERLAIN, T.K., 1960, Littoral sand budget along the southern California coast: Intern. Geol. Congr., 21st Copenhagen, Abstr., pp. 245-246.
- INMAN, D.L., 1966, Mechanics of sedimentation. In: Scripps Institution of Oceanography Progress Report, SIO Ref. 66-5, pp. 62-66.
- INOSE, S., and SHIRAIISHI, N., 1956, The measurement of littoral drift by radioisotopes: Dock Harbour Authority, v. 36, pp. 284-288.
- IPPEN, A.T., and EAGLESON, P.S., 1955, A study of sediment sorting by waves shoaling on a plane beach: U.S. Army Corps of Engineers Tech. Mem. 63, 83 p.
- JAMES, W.R., 1966a, The Fourier series model in map analysis: Office Nav. Res. Geog. Br. Tech. Rpt. 1, 37 p.

- JAMES, W.R., 1966b, Fortran IV program using double Fourier series for surface fitting of irregularly spaced data: State Geol. Surv., Univ. of Kansas, Computer Contrib. 5, 19 p.
- JOHNSON, J.W., 1956, Dynamics of nearshore sediment movement: Bull. Am. Assoc. Petrol. Geologists, v. 40, pp. 2211-2232.
- KIDSON, C., CARR, A.P., and SMITH, D.B., 1958, Further experiments using radioactive materials to detect the movement of shingle over the seabed and alongshore: Geograph. Jour., v. 124, pp. 210-218.
- KING, C.A.M., 1959, Beaches and coasts: Edward Arnold, Ltd., 403 p.
- KRUMBEIN, W.C., and GRAYBILL, F.A., 1965, An introduction to statistical models in geology: McGraw-Hill Book, Co., 475 p.
- KRUMBEIN, W.C., 1966, A comparison of polynomial and Fourier models in map analysis: Office Nav. Res. Geog. Sr. Tech. Rpt. 2, 45 p.
- KRUMBEIN, W.C., 1967, Fortran IV computer programs for Markov chain experiments in geology: State Geol. Surv., Univ. of Kansas, Computer Contrib. 13, 38 p.
- LEOPOLD, L.B., and LANGBEIN, W.B., 1962, The concept of entropy in landscape evolution: U.S. Geol. Surv. Prof. Paper 500-A, 20 p.
- MEDVEDEV, V.C., and AIBULATOV, N.A., 1956, The use of marked sand for the study of the transport of marine detritus: Izv. Akad. Navk. S.S.S.R., Ser. Geography., v. 4, pp. 99-102.
- MILLER, R.L., 1956, 1. The relation of sediment size parameters to current-wave systems and physiography: Jour. Geol., v. 64, pp. 425-446.
- MILLER, R.L., and ZEIGLER, J.M., 1958, A model relating dynamics and sediment pattern in equilibrium in the region of shoaling waves, breaker zone, and foreshore: Jour. Geol., v. 66, pp. 417-441.
- MILLER, R.L., and ZEIGLER, J.M., 1964, A study of sediment distribution in the zone of shoaling waves over complicated bottom topography. In: R.L. Miller (Editor), Papers in marine geology; Shepard commemorative volume. MacMillan Book Co., pp. 135-153.
- MURRAY, S.P., 1967, Control of grain dispersion by particle size and wave state: Jour. Geol., v. 75, pp. 612-634.
- ROBERTS, O.F.T., 1923, The theoretical scattering of smoke in a turbulent atmosphere: Proc. Roy. Soc. (London) A, v. 104, pp. 640-654.
- RUSSELL, R.C.H., 1960, The use of fluorescent tracers for the measurement of littoral drift: Proceedings of the Seventh Conf. Coastal Eng., The Hague, Netherlands, 1, pp. 418-444.
- SAVILLE, T., JR., 1950, Model studies of sand transport along an infinitely straight beach: Trans. Am. Geophys. Union, v. 31, pp. 555-565.

- SCHEIDEGGER, A.E., 1958, The random-walk model with autocorrelation of flow through porous media: Canadian Jour. Physics, v. 36, pp. 649-658.
- SCHEIDEGGER, A.E., 1964, Statistical hydrodynamics in porous media: Advances in Hyrosience, v. 1, pp. 161-181.
- SCHEIDEGGER, A.E., and LANGBEIN, W.B., 1966, Probability concept in geomorphology: Geol. Surv. Prof. Paper 500c, 14 p.
- SCHIFFMAN, A., 1965, Energy measurements in the swash-surf zone: Limnol. Oceanog., v. 10, pp. 255-260.
- SEYMOUR, D.R., 1965, IBM 7090 program for locating bivariate means and medians: Office Nav. Res. Geog. Br. Tech. Rpt. 16, 12.p.
- SHEPARD, F.P., and INMAN, D.L., 1950, Nearshore circulation: Proceedings of First Conf. Coastal Eng., Long Beach, Calif., 5, pp. 50-59.
- SHEPARD, F.P., 1963, Submarine geology, 2 ed.: Harper and Row; Publishers, 557 p.
- SIEBOLD, E., 1963, Geological investigation of nearshore sand transport. In: M. Sears (Editor), Progress in Oceanography, Pergamon Press, 1, pp. 3-70.
- SNEDECOR, G.W., 1956, Statistical methods: Iowa State Univ. Press, pp. 1-523.
- WHITTEN, E.H.T., 1963, A surface fitting program suitable for testing geological models which involve areally-distributed data: Office Nav. Res. Geog. Br. Tech. Rpt. 2, 56 p.
- WIEGEL, R.L., 1964, Oceanographical engineering: Prentice-Hall, Inc., 532 p.
- WRIGHT, F.P., 1962, The development and application of a fluorescent marking technique for tracing sand movements on beaches: Office Nav. Res. Geog. Br. Tech. Rpt. 2, 19 p.
- YASSO, W.E., 1962, Fluorescent coatings on coarse sediments, an integrated system: Office Nav. Res. Geog. Br. Tech. Rpt. 1, 48 p.
- YASSO, W.E., 1965, Fluorescent tracer particle determination of the size-velocity relation for foreshore sediment transport, Sandy Hook, New Jersey: Jour. Sed. Pet., v. 35, pp. 989-993.
- ZEIGLER, J.M., and GILL, B., 1959, Tables and graphs for the settling velocity of quartz in water, above the range of Stokes' Law: Woods Hole Oceanog. Inatit. Ref. 59-36, 13 p.
- ZEIGLER, J.M., HAYES, C.R., and TUTTLE, S.D., 1959, Beach changes during storms on outer Cape Cod, Massachusetts: Jour. Geol., v. 67, pp. 318-336.

VITA

John Daniel Boon, III

Born in Austin, Texas, January 29, 1940. Graduated from Arlington High School, Arlington, Texas, June 1958, Rice University, Houston, Texas, June 1962 (B.A., Geology). Attended University of Washington, 1962-1963, as a graduate student in oceanography, enrolled February 1966, as a graduate student and candidate for the M.A. degree in marine science at the Virginia Institute of Marine Science through the College of William and Mary.

In December 1963, the author was commissioned as an officer in the United States Coast and Geodetic Survey. After serving at sea for two years, he was assigned in 1965 to the Land and Sea Interaction Laboratory (LASIL) of the Environmental Science Services Administration in Norfolk, Virginia. While a member of the LASIL staff, Mr. Boon published a paper entitled: Trend Surface Analysis of Sand Tracer Distributions on a Carbonate Beach, Bimini, B.W.I.