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U.S. Army
Coastal Engineering
Research Center

NEARSHORE TIDAL AND NONTIDAL CURRENTS, VIRGINIA BEACH, VIRGINIA

TECHNICAL MEMORANDUM NO.5
April 1964

DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS

NEARSHORE TIDAL AND NONTIDAL CURRENTS, VIRGINIA BEACH, VIRGINIA

by

W. Harrison, Morris L. Brehmer, and Richard B. Stone

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FOREWORD

The importance of current patterns in coastal waters to submarine sewage outfalls has been repeatedly emphasized in the literature as has been, to a lesser degree, the importance of nearshore circulation to problems of beach erosion and inlet stability. In either case, precise information relative to the horizontal and vertical velocity characteristics of the nearshore system is required at several points in the area. Current measurements and precision estimates of mixing and diffusion are needed not only at or near the surface but also simultaneously at several depths.

This Technical Memorandum presents the results of measurements made by the Virginia Institute of Marine Science and the U. S. Coast and Geodetic Survey in the nearshore area off Virginia Beach, Virginia. The data permit resolution of the general circulatory system, as well as partial separation of tidal and non-tidal currents. Specific information on the characteristics of turbulent diffusion in one of the tidal currents is also presented.

This report was prepared by Dr. Wyman Harrison, Associate Marine Scientist, Virginia Institute of Marine Science, in pursuance of Contract DA-49-055-CIV ENG-63-6 with the Beach Erosion Board and in collaboration with Dr. M. L. Brehmer, Senior Marine Scientist, and Mr. R. B. Stone, graduate student at the Institute. Funds for the drift bottle and dye study portions of this study were provided by the Hampton Roads Sanitation District Commission and the Virginia Institute of Marine Science. Precision monitoring of the currents using Roberts Radio Current Meters was conducted by the U. S. Coast and Geodetic Survey in a cooperative study requested by the Virginia Institute of Marine Science.

This report is published under authority of Public Law 166, 79th Congress, approved July 31, 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

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NEARSHORE TIDAL AND NONTIDAL CURRENTS, VIRGINIA BEACH, VIRGINIA

by

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ABSTRACT

Simultaneous measurements by Eulerian and Lagrangian methods were made continuously between 30 July and 5 August 1962. The survey zone extended southward along the shore 11.5 km (7.2 mi.) from the Cape Henry Light and offshore for a distance of 1.4 km (0.87 mi.). Three Roberts Radio Current Meter Stations were established along the seaward margin of the zone; five stations were established on shore for longshore-current and wave measurements.

Wave heights for the 7-day period ranged between 0.3 and 0.5 m, wave lengths between 14 and 159 m, and wave energies between 6.3 and 553 kg-m/m. Winds were less than 16 mph during the period, total wind movements being greatest from the east and southeast. Shoaling waves made angles with the shore line that should have resulted in a southward longshore current during 48 of 69 observations, on a coast uninfluenced by other currents. Direction of longshore current movement was measured as northerly, however, in 55 instances, owing to tidal and non-tidal currents.

Current meter observations at Cape Henry and just south of Rudee Inlet revealed semi-diurnal tidal currents that were roughly reversing on the flood and rotary on the ebb, at the surface. A meter midway between the Cape Henry and Rudee Inlet meters indicated reversing currents at the surface, as did all intermediate depth and near-bottom meters. When 280 returns of neutrally-buoyed drift bottles, released over a year's period, are integrated with detailed current-survey data, a circulation model can be constructed. This model confirms earlier speculation that the nontidal drift describes a clockwise eddy movement south of Cape Henry. The southern limit appears to be near Rudee Inlet.

Diffusion was investigated in one of the tidal currents during ebb flow by continuous tagging with rhodamine-B dye at the rate of 0.7 g/sec and by monitoring dye concentrations with fluorimeters. A log-log plot of a "concentration ratio," $c \cdot M^{-1} \cdot D$ vs x, for values of x between 800 and 3800 m, fitted an x^{-1} relationship where c equals peak dye concentration, M equals rate of dye discharge (g/sec), D equals layer depth (m) and x equals distance along the axis of the plume. Neighbor diffusivity, F (ℓ) had a minimum value of 316 cm^2/sec and the coefficient ϵ, in $F(\ell) = \epsilon \ell^{4/3}$ had the minimum value of 0.062.

INTRODUCTION

Circulation along the ocean flanks of the mouths of large estuaries has been studied little. Our attempts to understand the circulation in the vicinity of the southern flank of the entrance to Chesapeake Bay (Figure 1) have been prompted by the practical considerations involved with locating submarine sewage outfall pipes and the recommendation of beach protection measures along the shore line of Virginia Beach, Virginia (Figure 1). The sum of previous work in the area known to us consists of current observations from lightships by Haight (1942, Figure 15), of measurements of the U. S. Coast and Geodetic Survey summarized in Special Publication 162, of drift bottle surveys mentioned by Joseph et al. (1960) and Norcross et al. (1962), and of casual observations reported in a beach erosion study by the U. S. Army Corps of Engineers (U. S. Congress, 1953, p. 15). In combination, these sources suggest that the offshore shelf waters exhibit a dominantly southerly drift, but that the inshore waters south of Cape Henry, to an unknown distance seaward of the shore, describe a clockwise eddy movement extending "approximately 3 to 4 miles south of Cape Henry" (U. S. Congress, 1953, p. 15). Our examination of the grosser aspects of the circulation began with the drift bottle releases described below.

RESULTS OF DRIFT BOTTLE RELEASES

A total of 898 drift bottles were released at the five stations shown on Figure 2, during the months of April, May, June, July, August, and October 1962. Results of the releases are summarized in Table 1 and Figure 2.

TABLE 1

RESULTS OF DRIFT BOTTLE RELEASES AT STATIONS OF FIGURE 2

	TIDAL CONDITIONS AT RELEASE		
	Slack Both Before Ebb and Flood	Slack Before Ebb	Slack Before Flood
Number bottles released	898	450	448
Percent recovered	38.9	-	-
Percent recovered in 10 days	24.6	16.4	8.2
Average time out (days)	5.2	4.6	6.4
Average distance traveled (km)	34.5	34.0	36.0
(Naut. mi.)	18.6	18.3	19.4
Release months		May, June, July, August	October, April

The general picture is one of southward-moving water that has moved out of Chesapeake Bay impinging upon the shore line to the south of Cape Henry. That the outflow should take such a course in the northern hemisphere is predicted by theory (cf. Defant,1961, Figure 251a). Because of a prevailing southward movement of shelf water beyond the bay mouth (Norcross et. al., 1962), however, the magnitude of the right hand deflection in the direction of movement is increased. Additional drift bottle returns from a release point off Little Creek Inlet (Figure 3) on Chesapeake Bay may be cited here. Of interest are the seeming "depositories" of drift bottles south of Cape Henry indicating, among other things, the considerable influence of southward moving shelf waters beyond the bay entrance.

RESULTS OF DETAILED SURVEY

Tidal and Nontidal Currents. At the request of the Virginia Institute of Marine Science, the U. S. Coast and Geodetic Survey established three Roberts Radio Current Meter Stations at the points shown on Figure 4. Data were gathered continuously from eight meters at the three stations, for between 9 and 13 tidal cycles, during the period July 30 - August 5, 1962. These data were reduced by personnel of both organizations, according to the methods described in U. S. Coast and Geodetic Survey Special Publication 215.

Winds (Figure 5) and waves (Figure 6) during the 6-day period were subdued. Although runoff in the Chesapeake Bay drainage basin was below average for that time of year (F. J. Flynn, 1963, written communication) and the tide ranges were slightly below average, we believe the observed current vectors of Figure 4 to be a reasonable representation of the expectable tidal and nontidal currents in the area. Wind data were obtained from the hourly records of the U. S. Weather Bureau Station (Figures 6 and 7) at Cape Henry. Wave heights, periods, and approach angles were obtained at 4-hour intervals at the end of the 15th Street fishing pier (the station on Figure 6 just north of the inlet). Heights were estimated by an observer, in water depths estimated at 3.0 m (or about 10 feet).

Surface currents appear to be roughly reversing on the flood and rotary on the ebb at the northern and southern Roberts Meter stations, while they are reversing at the middle station (Figure 4). Mid-depth and bottom currents are generally reversing (Figure 4) for both flood and ebb currents.

Current drogues consisting of weighted plywood crosses attached to buoyed and flagged spars were released at slack before ebb and traced on 31 July and 1 August (Figure 6). Accurate positioning was accomplished by means of transit fixes from three shore stations in radio communication with each other. Drogue movements at the three depths indicated on Figure 6 corresponded well with current tendencies indicated by the Cape Henry Roberts Meters when the drogues were in their immediate vicinity. A clockwise, ellipsoidal movement of the drogue at 6.1 m on 31 July (Figure 6) is of interest. The excursion of this drogue over the ebb tidal flow approximates that predicted by theory (Haight, 1942, p. 7).

A number of plastic, umbrella-shaped, very slightly negatively-buoyant bottom drifters (Woodhead-Bumpus Sea Bed Drifters) were released at slack water before ebb on 31 July at the point shown on Figure 7 (Release Point). Recovery of 80 percent of the drifters was made a few hours later at 21st Street (Figure 7) some 5 km south of the release point. Four bottom drifters also were released on 1 August at 0800 (Figure 7) at a time indicated in tide tables as that of slack water before flood. A flood current never developed and one of the drifters was recovered the next day (Figure 7) some 3.7 km (2 mi.) south of its release point.

Longshore Currents. Detailed studies of the velocities and directions of these currents were made at five stations (Figure 6) on four successive days, in conjunction with the Roberts meter observations. The timed movement of fluorescein dye patches within the breaker zone was used to measure longshore current drift. Measurements were hampered at times by the narrowness of the breaker zone, low breaker heights (H_b, Fig. 6), and the consequently weak current flow. Dye patches at times spread unavoidably into the water just seaward of the breaker zone. Water movement thus traced was possibly the movement induced by winds or by the prevailing tidal or nontidal currents. At any rate, it was observed that although shoaling waves made angles with the shore line that should have resulted in a southward longshore current during 48 of 69 total observations, the direction of longshore flow was measured as northerly in 55 instances. The effect just mentioned seemed to be most readily exhibited when waves of low energy, with fronts nearly parallel to the shore (Figure 6, 3 August) were common. Longshore current velocities ranged from nearly zero to 0.3 m/sec (0.6 kn). Rip currents (Figure 6, 2 August, 1200 hours) were rarely observed.

Diffusion Measurements. Studies of turbulent diffusion in estuarine and inshore waters have given recent impetus to the development of a superior technique for tagging water masses and detecting the decrease in concentration of the tag through time. Independent research by scientists of the Japanese Governmental Agencies (1958) and the Chesapeake Bay Institute (Pritchard and Carpenter, 1960) led to the selection of rhodamine-B dye, an organic pigment, as a tagging agent, and to the development of fluorescence analysis as a detecting technique. The fluorescence spectrum of rhodamine-B has a maximum at 575 millimicrons and use of a Turner Model III fluorometer permits detection to 0.02 - 0.004 ppb. A review of the technique and its limitations has been presented by Pritchard and Carpenter (1960). Studies by the Virginia Institute of Marine Science have utilized their experimental techniques.

Okubo (1962) has made a comprehensive analysis of the recent theoretical treatments of diffusion in the sea and of the results of experimental studies. He proposes a solution to the diffusion equations (1962, p. 56) that involves an "energy dissipation" parameter having the dimensions $cm^{2/3}/sec$.

On August 1, 1962, between 0800 and 1400 hours, personnel of the Virginia Institute of Marine Science and the U. S. Coast and Geodetic Survey initiated, maintained, and monitored a continuous release of dye from a point approximately 800 meters off Cape Henry (Figure 7). The rate of release of rhodamine-B was 0.7 g/sec and the vehicle solution was adjusted to the density and temperature of the surrounding water (1.01 g/cc and 25°C, respectively). Release was from a point source at approximately 4 meters depth. In addition, a small number of surface and bottom drifters were introduced at the point of dye release (Figure 7) to gain a crude measure of neighbor diffusion, in the event that the dye study should fail in some respect.

Tide tables had indicated that slack water before flood would occur at 0800 hours on 1 August 1962. Thus, it was expected that the dye would be carried into the bay on the flood current. The flood current did not develop, however, and an ebb outflow began about 0900 hours. This led to an unusually long southward flow. (This flow was induced by an unusually heavy rainfall in the vicinity of Chesapeake Bay entrance on the previous day.)

Wind, current, and wave data for portions of the release period are shown in Figure 7, The average current velocity, $\overline{U}$, integrated along the axis of the dye plume, was 0.30 m/sec (0.54 kn) during the period of monitoring (1130 - 1230 hours) upon which the results below are based.

Neighbor diffusivity, F (ℓ) was calculated from returns of drift bottles. F (ℓ) had a minimum value of 316 cm^2/sec and the coefficient ϵ, in $F(\ell) = \epsilon\ell^{4/3}$ had the minimum value 0.062. This last value was calculated using Stommel's (1949) expression.

$$F\left[\frac{\overline{(\ell_1 + \ell_0)}}{2}\right] = \left[\frac{\overline{(\ell_1 - \ell_0)^2}}{2T}\right]$$

for the reduction of the experimental observations, where ℓ is initial neighbor separation (cm), ℓ_1 is separation after time T (sec), and the bars denote averages. The minimum value of ϵ falls within the range of values (0.006 - 0.08) that have been determined (cf. Pearson, 1956, Table 10; Harrison, 1963, Table 1) for other oceanic areas subject to tidal currents of variable strength. A calculation that allows for the turning of the drifters as they enter the longshore current system shows that a maximum value for ϵ would not exceed 0.075.

Additional diffusion values were calculated from measurement of dye concentration along the axis of the steady state plume (Figure 7). A log-log plot (Figure 8) of a "concentration ratio", $c \cdot M^{-1} . D$ versus x, for values of x between 800 and 3800 meters, fits an x^{-1} relationship where c equals peak dye concentration, M equals rate of dye discharge (g/sec), D equals layer depth (meters) and x equals distance in meters along the axis of the plume. Thus, there was a decrease in dye concentration downstream from the discharge point proportional to the minus one power of the distance.

Calculation of the so-called "diffusion velocity" yielded a value of 2×10^{-3} m/sec. This value was computed from a relationship proposed by Schonfeld (1959) and expressed by Okubo (1962) as:

$$\overline{S}\ (x,y) = \frac{m/\overline{U}}{\pi} \quad \frac{\omega\, x/\overline{U}}{\omega^2\ (x/\overline{U})^2 + y^2}$$

where $\overline{S}$ (x,y) equals the mean concentration at some point (x,y) in the plume, x being in the direction along the axis of the plume and y the direction perpendicular to the axis of the plume, m equals the number of particles released per unit time, $\overline{U}$ equals the mean flow, and ω equals the "diffusion velocity". When solving for ω, $\overline{S}$ (x) is expressed as the concentration ratio (mentioned above), in order to correct for depth-dependent variations in dye concentration along the axis of the plume. The approximate value for diffusion velocity (2×10^{-3}m/sec) found in this study has been found also by Pritchard and Carpenter (1960) in some of their experiments with continuous dye releases in waters influenced by currents. Figure 9 is a plot of dye concentration versus distance from the plume axis, showing lateral distribution of dye concentration.

Clockwise Eddy Movement. The following quote is taken from the Virginia Beach, Virginia, Erosion Control Study (U. S. Congress, 1953, p. 15):

> "A review of Special Publication No. 162, titled 'Tides and Currents in Chesapeake Bay and Tributaries', prepared by the United States Coast and Geodetic Survey, indicates that the tidal flow through the Virginia Capes probably affects the erosion forces at work on the shore at Cape Henry and vicinity. The observations by that agency indicate that the tidal current strikes northwest and southeast on flood and ebb tides, respectively, when passing a line joining the two capes at the bay entrance; that about 10 to 12 miles east of this point the general trend of the current is due east; and that 18 to 20 miles east of the bay entrance the trend of the current is toward the northeast. Coast and Geodetic Chart No. 1222 indicates that the deeper water in the bay entrance lies close in to the Cape Henry shore and follows a southeast course for 4 or 5 miles past the cape. It is, therefore, apparent that the greater portion of the ebb flow through the Virginia capes, particularly that confined to the deeper water, initially strikes to the southeast, then recurves and eventually moves off to the northeast, due probably to the influence of the northward movement of the Gulf Stream and prevailing ocean currents. It is believed that a minor part of the ebb flow, particularly that moving over the shallow areas near the bay entrance, is diverted to the south by the prevailing northward oceanic currents, with a subsequent recurving clockwise movement. This clockwise eddy movement apparently extends approximately 3 to 4 miles south of Cape Henry and tends to partially explain the forces at work to preserve the northern section of the beach, where some accretion has been observed, as against the south end of the beach, where advanced erosion has occurred."

Confirmation of this inferred clockwise eddy movement is apparent from (1) the nontidal current values (Figure 4) that indicate northerly water movements at the central Roberts Meter Station and (2) those drift bottle strandings from the Little Creek and Cape Henry release points (Figures 2 and 3), that are for bottles that had been out long enough to have come under the influence of the nontidal drift. The inferred northeastwardly recurving movement of the Chesapeake Bay outflow, however, has not been confirmed by other drift bottle studies in that area (Norcross et.al., 1962, Figure 1), a prevailing southerly drift having been observed whose velocity approximates 10 to 14 miles per day (Joseph et. al., 1960).

An apparent dividing zone for nearshore nontidal drift currents moving to the north - induced by the outflow from Chesapeake Bay striking roughly southeast (Figure 4) - and nontidal drift to the south induced by the prevailing oceanic currents from the north, is found in the vicinity of Rudee Inlet (Figure 4). This inference seems to explain the scarcity of drift bottles recovered in the vicinity of Rudee Inlet (for bottles out long enough to be influenced by the nontidal drift) and the longer residence time in the sea of most of the bottles released near Rudee Inlet (that were recovered from 2 to 10 days after their release).

Figure 10 shows the inferred average nontidal circulation as based on these measurements. Although the center of the clockwise eddy is by no means known, it is believed to be placed here (Figure 10) in its most logical position. Additional measurements, perpendicular to shore, would be of great value in this area. The presence of Rudee Inlet in the area of diverging currents may be additional confirmation of the validity of this circulation model (Figure 10), for currents transport sand across mouths of inlets and close them. The sand deposits at Cape Henry that are indicated by the bottom contour shown on the nontidal drift diagram (Figure 4) similarly reflect the area of converging currents shown in our model (Figure 10).

The dimensions, position of the center, and rates of water movement in the eddy system will all vary as the pressure gradient undergoes modifications by runoff variations and/or the frictional drag of winds (especially from the north) and longshore and nearshore currents.

Tidal currents in the area are generally moderate to strong, maximum velocities of 1.6 m/sec (3.0 kn) having been noted on the ebb and 0.87 m/sec (1.7 kn) on the flood, at the Cape Henry station. The characteristic of the ebb tidal current to sweep surface water southward and toward the shore between 3 and 9 hours after flood at nearly all three stations has been observed (Figure 4). Bottom water, however, tends to move directly onshore or northward and obliquely toward the shore between 8 hours after flood and flood, and between flood and one hour after flood, in the central portion of the area (Figure 4).

The detailed current data and inferred circulation model presented here are being used for prediction studies of the inshore transportation of sediment and the design and positioning of sewage outfall structures. It is hoped that the techniques and findings presented will provide some guidance to other workers planning similar investigations of nearshore currents and circulation at the mouths of estuaries.

ACKNOWLEDGMENTS

Cooperation of the U. S. Coast and Geodetic Survey, especially Commander Jones and the crew of the C. & G. S. S. MARMER, and members of the Tides and Currents Branch, is gratefully acknowledged. Funding of part of the study was provided by the Hampton Roads Sanitation District Commission of Virginia. Preparation of illustrations was supported by the Beach Erosion Board, U. S. Army Corps of Engineers.

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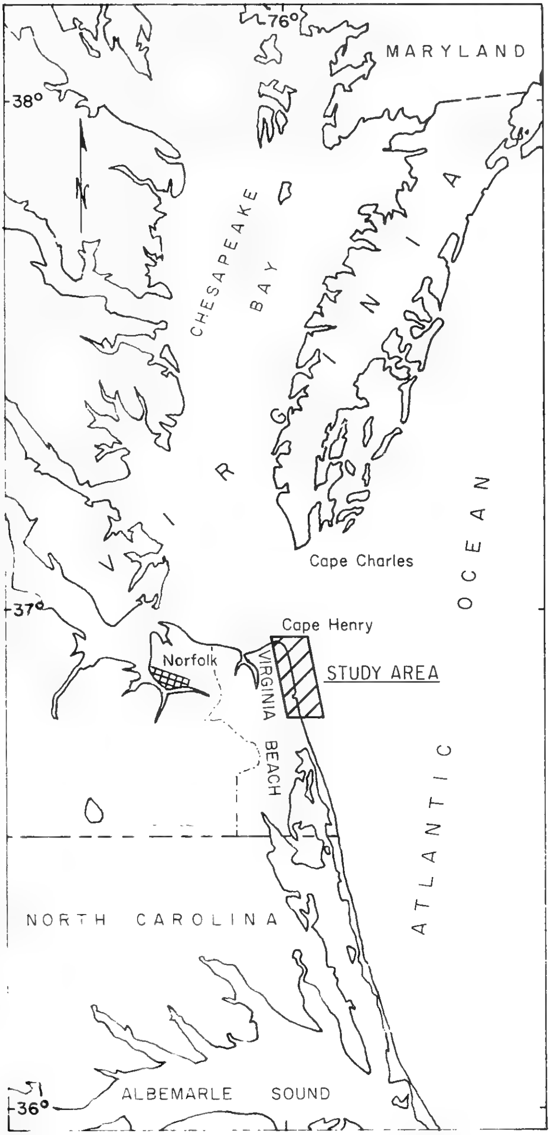

FIGURE I. LOCATION MAP

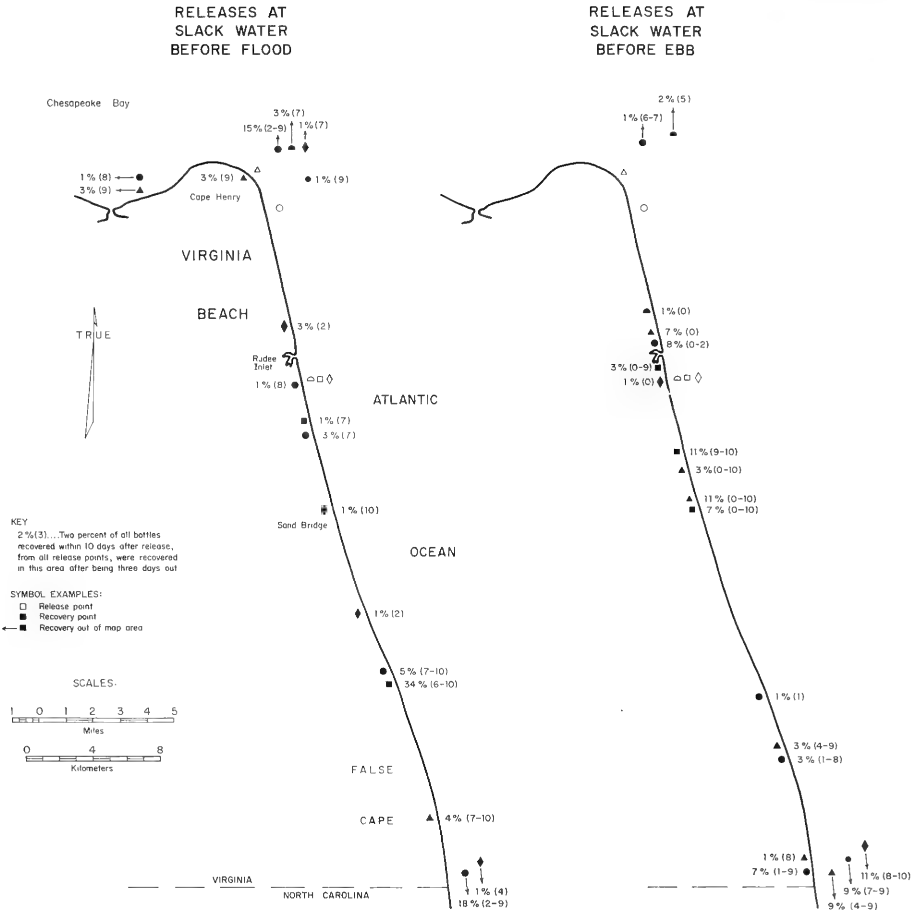

FIGURE 2. RESULTS OF DRIFT BOTTLE RELEASES SOUTH OF CAPE HENRY

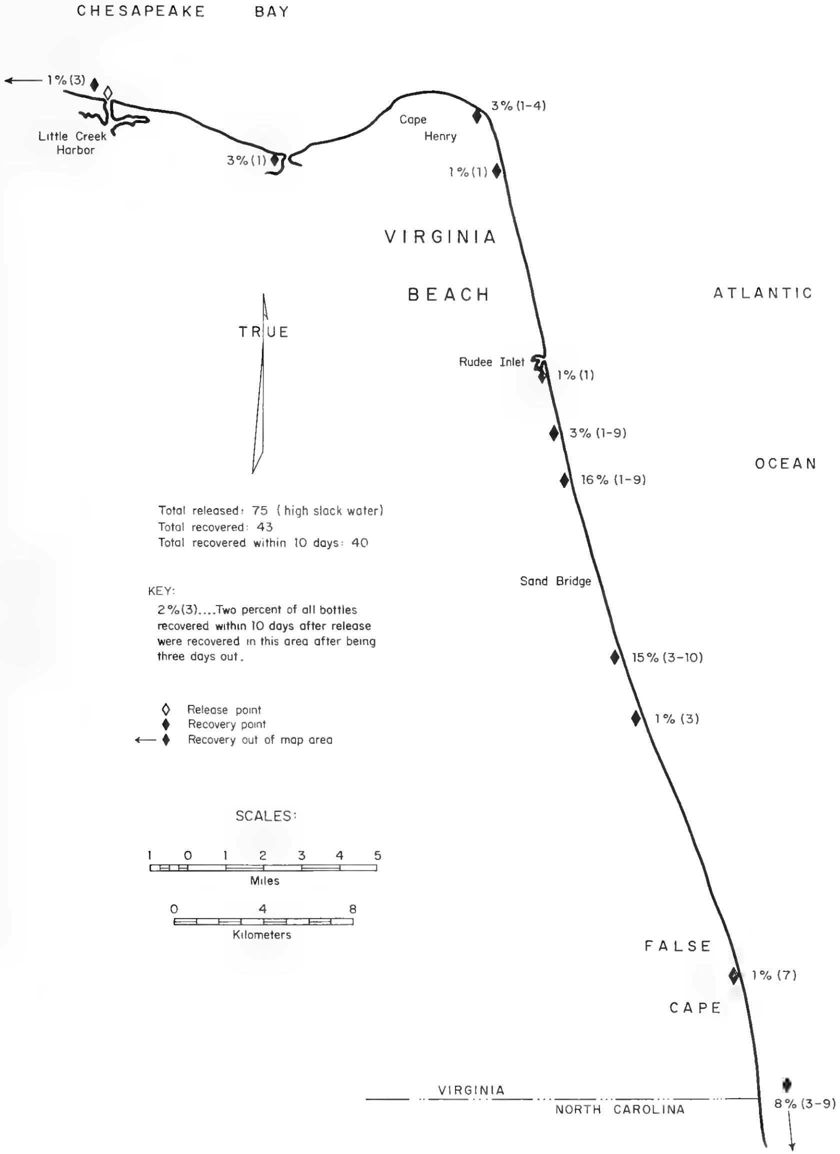

FIGURE 3. RESULTS OF DRIFT BOTTLE RELEASES OFF LITTLE CREEK HARBOR

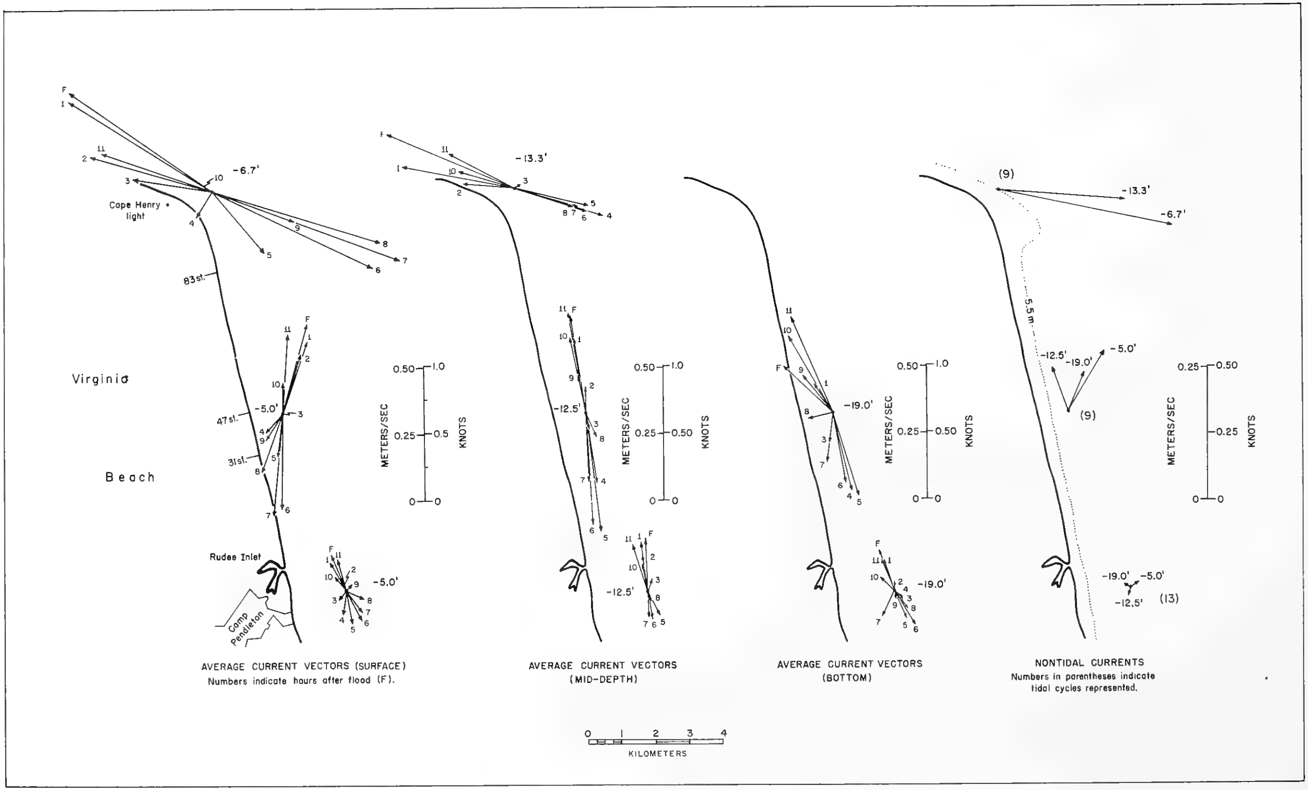

FIGURE 4. TIDAL AND NONTIDAL CURRENT VECTORS AT THREE STATIONS SOUTH OF CAPE HENRY
JULY 30 – AUGUST 5, 1962

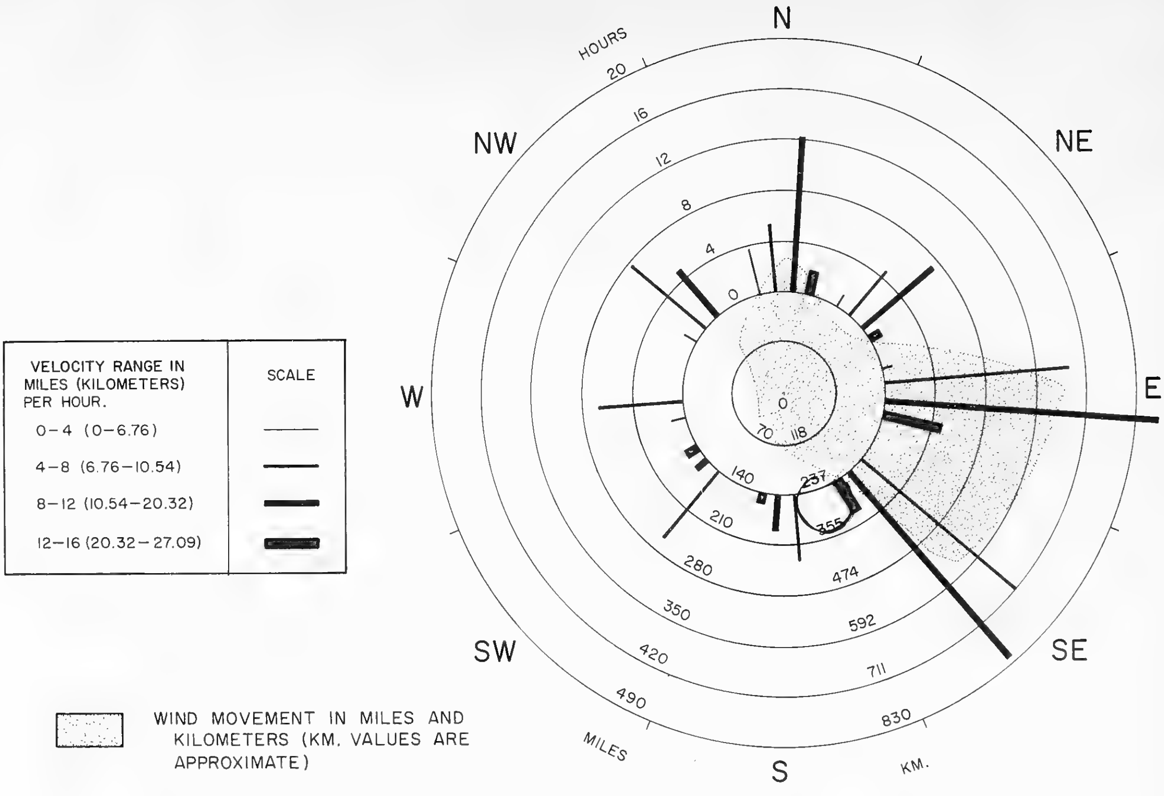

FIGURE 5. WIND DATA – JULY 30– AUGUST 5, 1962

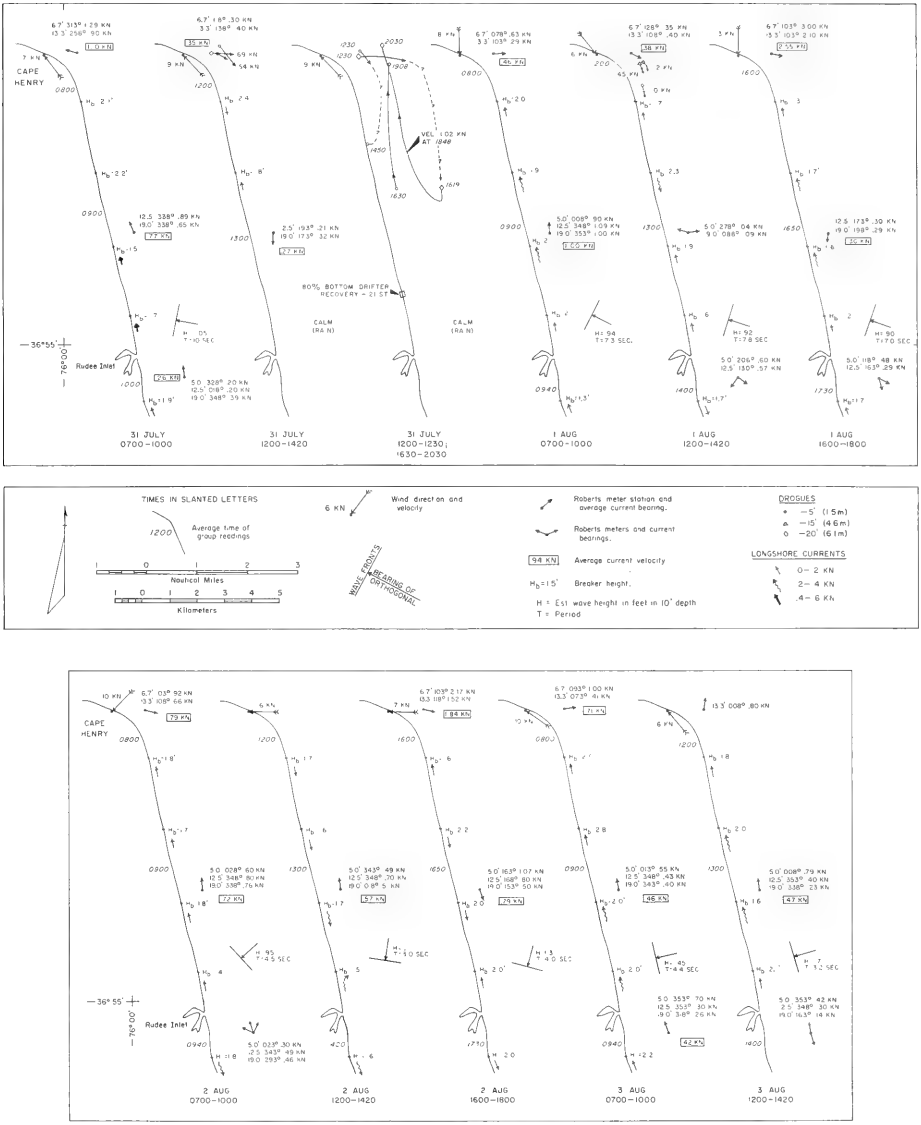

FIGURE 6. WIND, WAVE AND CURRENT DATA OFF VIRGINIA BEACH
JULY 31 – AUGUST 3, 1962

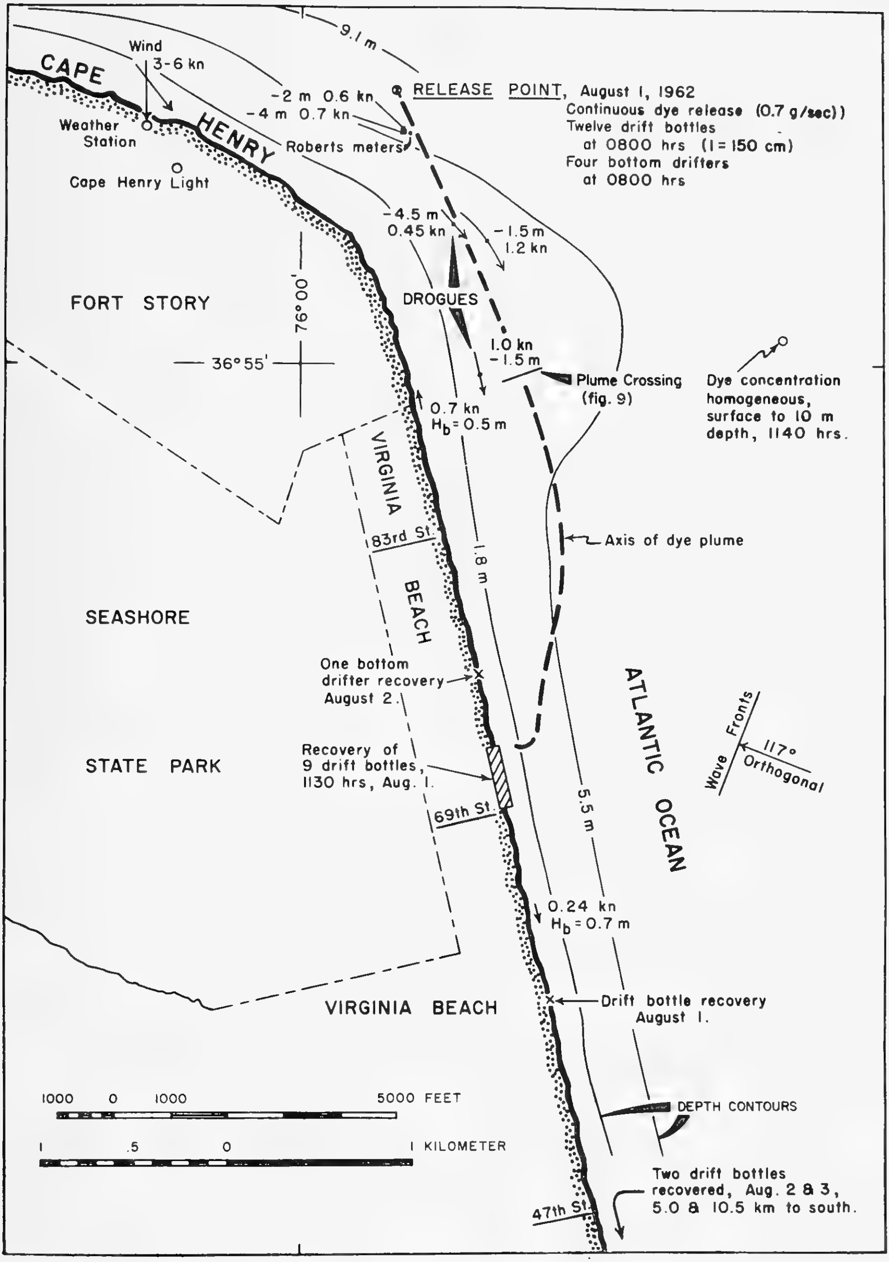

FIGURE 7. DYE AND DRIFTER OBSERVATIONS-AUGUST 1-3, 1962

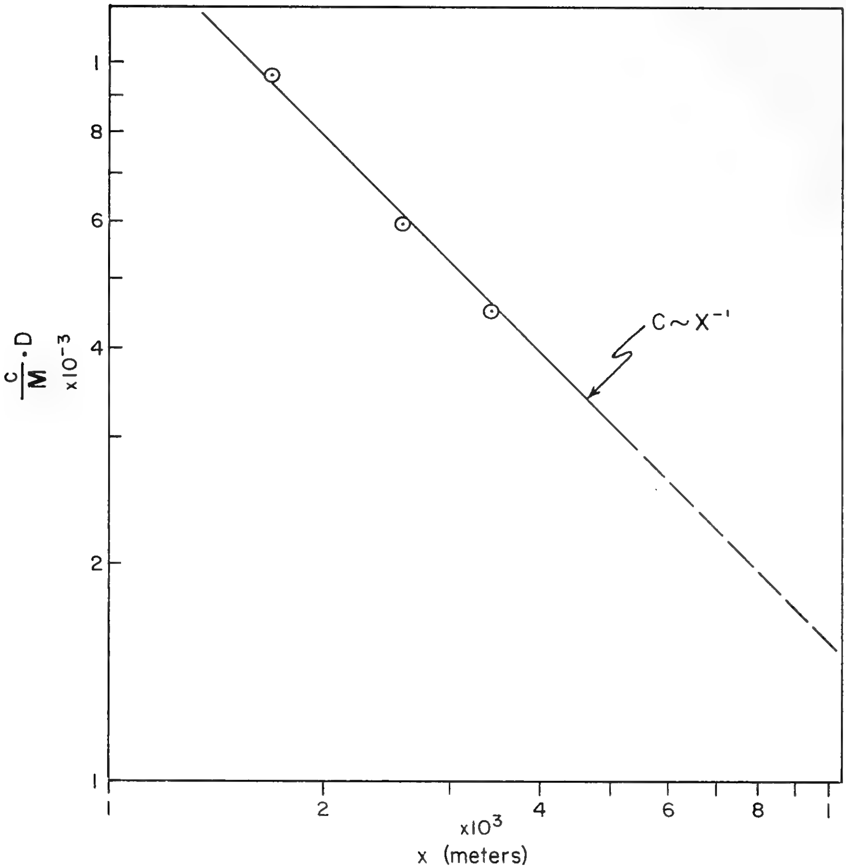

FIGURE 8. DYE CONCENTRATION RATIO VERSUS DISTANCE ALONG PLUME AXIS

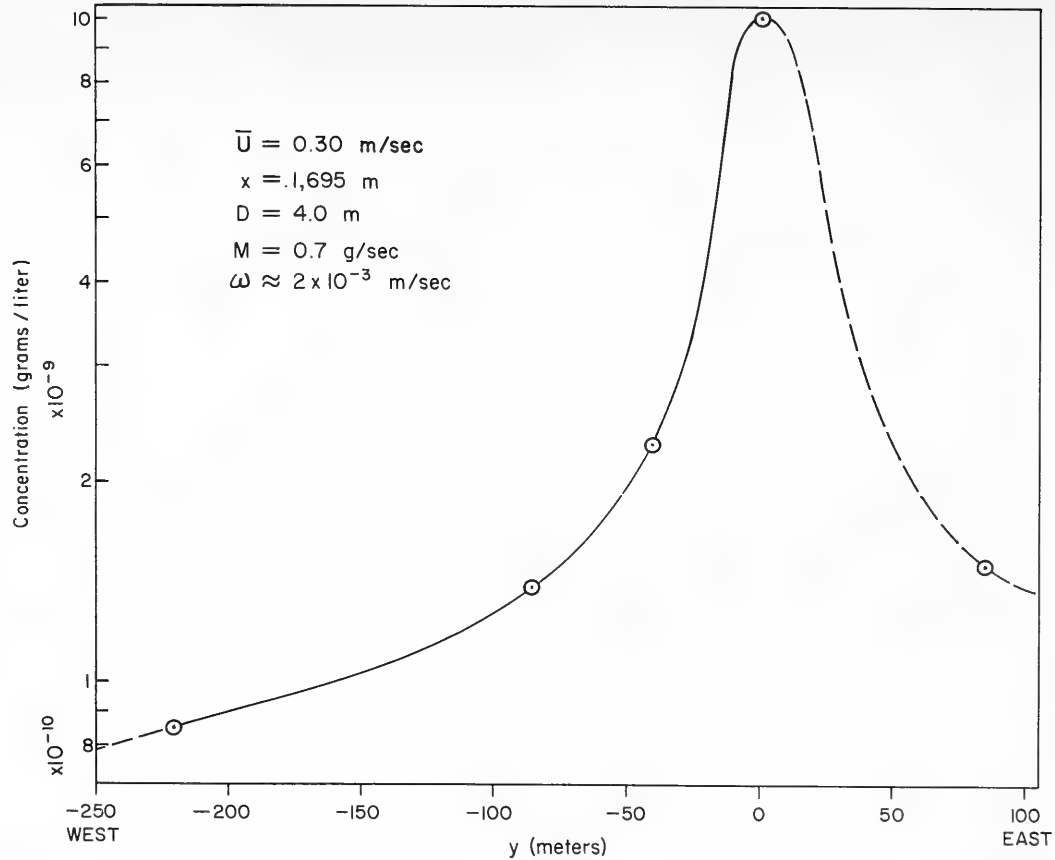

FIGURE 9. DYE CONCENTRATION VERSUS DISTANCE PERPENDICULAR TO PLUME AXIS

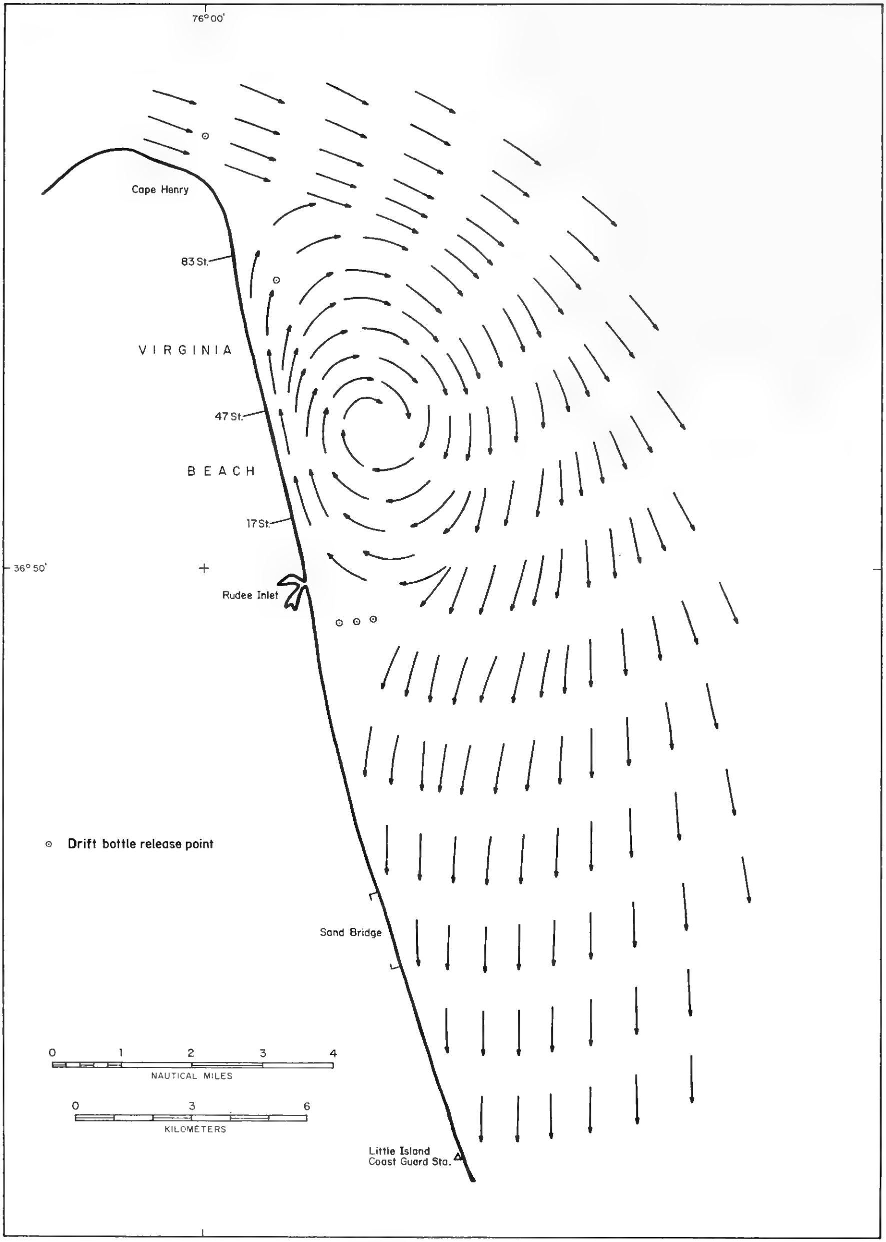

FIGURE 10. INFERRED MEAN POSITION AND EXTENT OF NONTIDAL DRIFT SYSTEM

U.S. ARMY COASTAL ENGRG. RES. CENTER, CE., WASH., D.C.

NEARSHORE TIDAL AND NONTIDAL CURRENTS, VIRGINIA BEACH, VIRGINIA by W. Harrison, M. L. Brehmer, and R. B. Stone, April 1964, 20 pp. including 1 table and 10 illus.

TECHNICAL MEMORANDUM No. 5 UNCLASSIFIED

1. Currents - Va. Beach
2. Tidal Currents
3. Diffusion
4. Wave Observ., Va. Beach

I Harrison, W.
II Brehmer, M. L.
III Stone, R. B.
IV Title

Simultaneous measurements by Eulerian and Lagrangian methods were made continuously during a 1-week period in the nearshore area south of Cape Henry. Three Roberts Radio Current Meter stations were also established offshore, and 5 onshore stations were established for longshore current and wave measurement. Data therefrom are presented and a circulation model constructed which confirms earlier speculation that nontidal drift describes a clockwise eddy movement south of Cape Henry, the southern limit of which is apparently near Rudee Inlet. Diffusion was investigated in one of the tidal currents during ebb flow by tagging with rhodamine-B dye, and specific information thereon is also presented.

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Simultaneous measurements by Eulerian and Lagrangian methods were made continuously during a 1-week period in the nearshore area south of Cape Henry. Three Roberts Radio Current Meter stations were also established offshore, and 5 onshore stations were established for longshore current and wave measurement. Data therefrom are presented and a circulation model constructed which confirms earlier speculation that nontidal drift describes a clockwise eddy movement south of Cape Henry, the southern limit of which is apparently near Rudee Inlet. Diffusion was investigated in one of the tidal currents during ebb flow by tagging with rhodamine-B dye, and specific information thereon is also presented.

U.S. ARMY COASTAL ENGRG. RES. CENTER, CE., WASH., D.C.

NEARSHORE TIDAL AND NONTIDAL CURRENTS, VIRGINIA BEACH, VIRGINIA by W. Harrison, M. L. Brehmer, and R. B. Stone, April 1964, 20 pp. including 1 table and 10 illus.

TECHNICAL MEMORANDUM No. 5 UNCLASSIFIED

1. Currents - Va. Beach
2. Tidal Currents
3. Diffusion
4. Wave Observ., Va. Beach

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