PHYSICAL ASPECTS

OF

BASELINE STUDIES FOR THE ENVIRONMENTAL

ASSESSMENT OF SUSSEX COUNTY

OCEAN OUTFALLS

By

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SUMMARY

This report concerns the physical aspects of a baseline study for the environment assessment of two proposed ocean outfalls for Sussex County, Delaware. The work reported here is part of a total baseline study for environmental assessment which included a study of the water quality and biological aspects of the baseline survey and a study of the possibilities for artificial recharge in the coastal aquifers. Reports on those studies were prepared separately by others. The project was performed for the Sussex County Engineer's Office through a contact administered by the College of Marine Studies of the University of Delaware.

The studies reported herein include a summary of the physical baseline data gathered for the assessment of the mixing characteristics of likely outfall locations and configurations. Analyses for a variety of locations and diffuser configurations for outfalls in the offshore waters in the vicinity of Hen and Chickens Shoal and South Bethany Beach were performed. These analyses provide several options for outfall siting in the two general areas and estimates of the mixing and transport characteristics of each of these options in terms of the near-field and far-field dilution capabilities.

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I. Introduction and Background

The purpose of this study was to investigate the physical aspects of the marine environment at two site areas along the coast of Delaware regarding the possible location of ocean outfalls. The performance of possible outfall systems in these site areas was to be evaluated. Concurrent biological and water quality baseline studies were conducted, and reported elsewhere, for the two areas.

The northern outfall site area would provide for a maximum discharge of about 30 mgd of effluent from secondary (or better) sewage treatment at the John M. Lecato District Plant. The ocean disposal area considered for the outfall system for this plant was the coastal waters of the Atlantic Ocean east of Cape Henlopen (see Figure 1). The site area includes the offshore (0 - 4 miles) waters approximately between 38° 46' and 38° 49' latitude. This area is bounded to the north by the entrance to Harbor of Refuge in Delaware Bay and contains Hen and Chickens Shoal, a shoal running to the SSE approximately 4 miles from the Cape. Its proximity to the entrance to Delaware Bay makes this physical environment of this coastal area closely linked with the estuarine behavior of the Bay. This site is referred to as the "Hen and Chickens Shoal site" or "HCS site."

The second disposal site is approximately 16.5 miles south of Cape Henlopen. The maximum discharge of effluent from secondary (probably plus tertiary) sewage treatment would be approximately 25 mgd. The site area includes the South Bethany Beach offshore (0 - 3 miles) waters approximately between 38° 30' and 38° 31' latitude (see Figure 2). The site is approximately

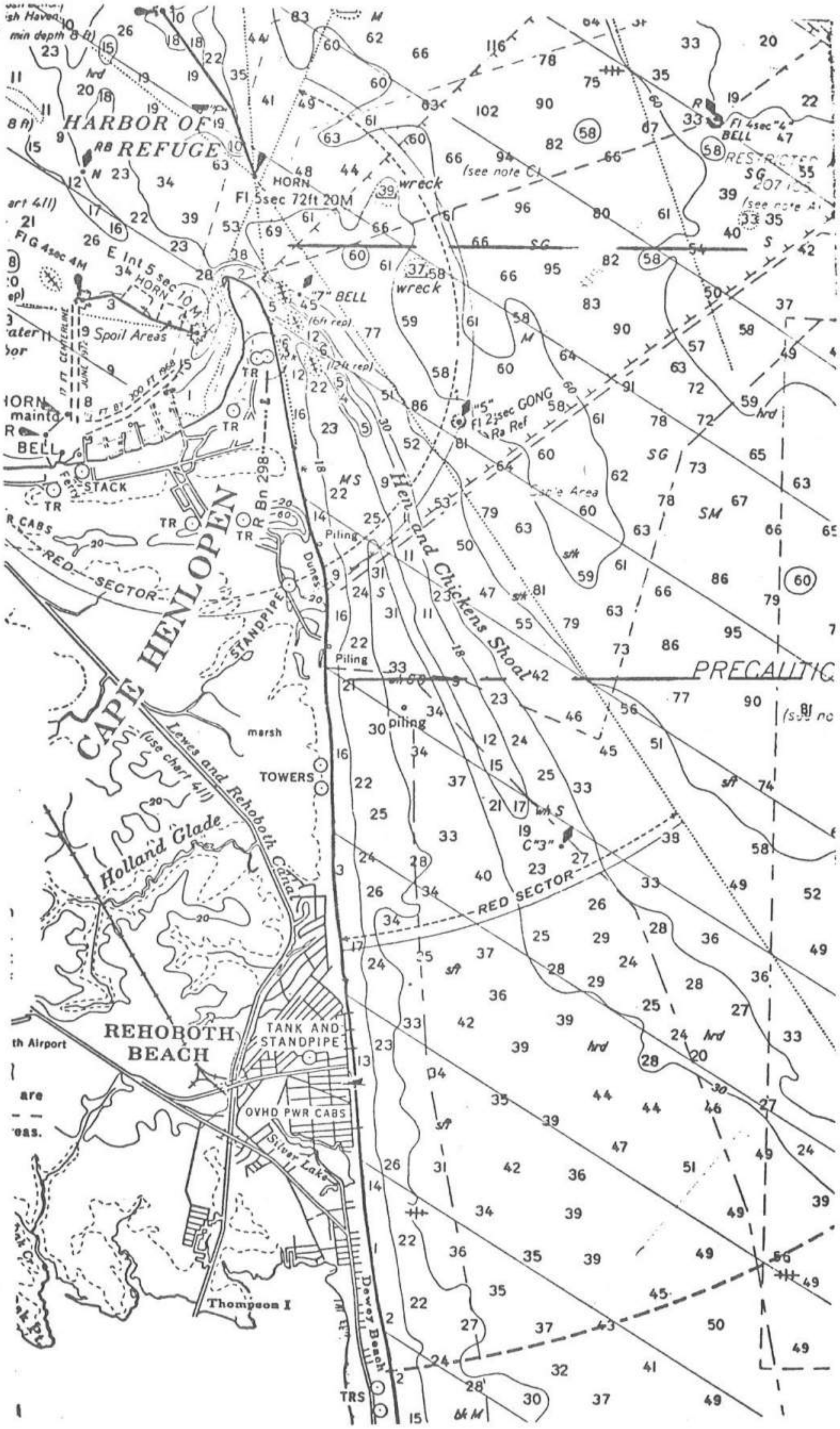

HARBOR OF REFUGE
CAPE HENLOPEN
Hen and Chickens Shoal
REHOBOTH BEACH
Holland Glade
Lewes and Rehoboth Canal
TANK AND STANDPIPE
OVHD PWR CABS
Silver Lake
Dewey Beach
Thompson I
TOWERS
STANDPIPE
STACK
RED SECTOR
PRECAUTIC
Spoil Areas
Fl 5sec 72ft 20M
"7" BELL
"5" Fl 2½sec GONG
C "3"
R Bn 298
marsh
Dunes
Piling
wreck
TRS

Figure 1

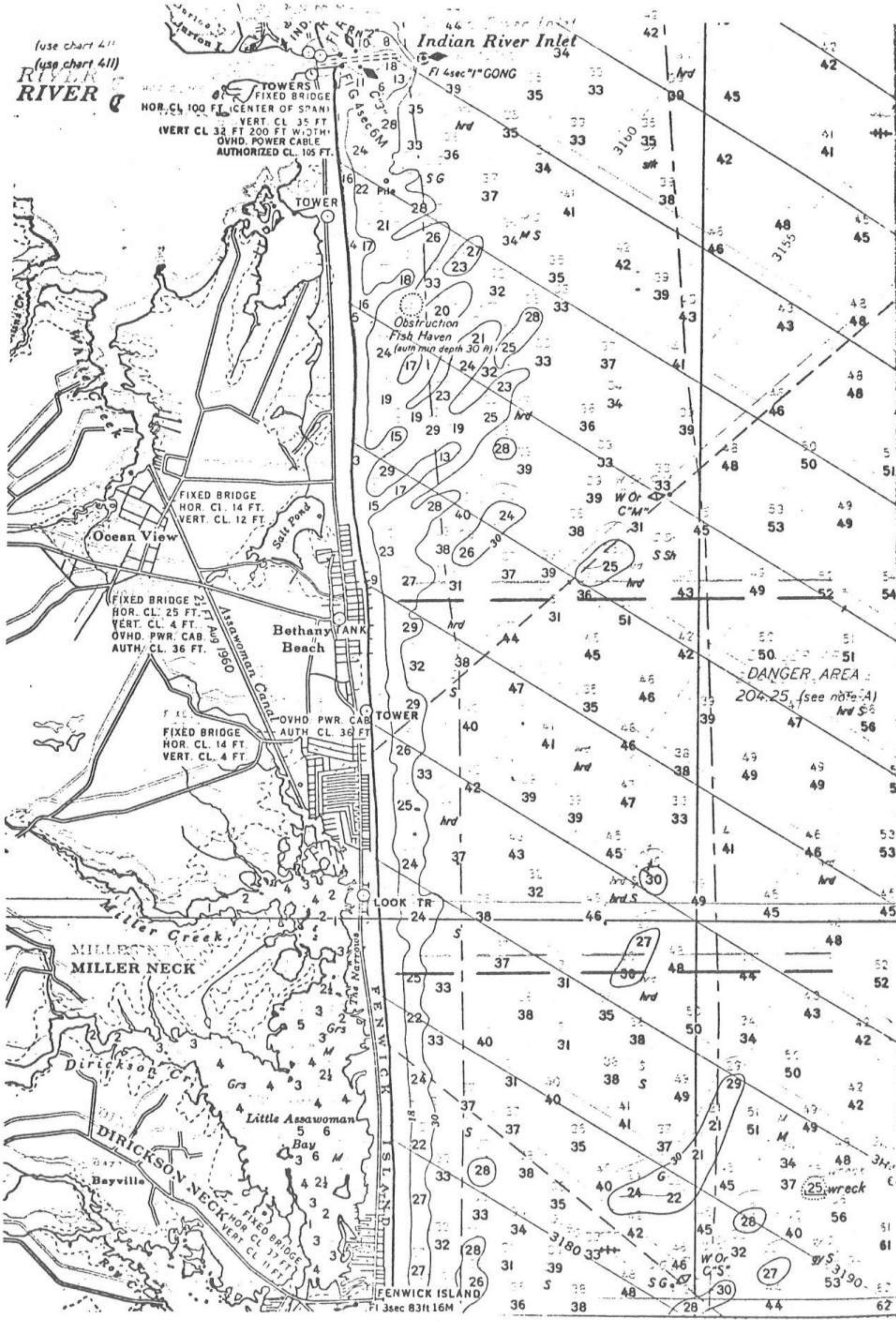


Figure 2

Figure 2

5.5 miles from Indian River Inlet and consists of coastal waters without any notable bottom relief features and beaches running N-S. This site is referred to as the "South Bethany Beach site" or "SBB site."

The study included the field measurement of currents and circulation at the two site areas, and field determination of the density structure throughout the year. These measured environmental data in conjunction with existing data were used in the evaluation of possible ocean outfall locations and configurations at each of the site areas. The physical mixing performance of several outfall options at each site was studied for a variety of receiving water conditions.

The data collected regarding the physical environment at the site areas are presented and discussed in Section II. The mixing analyses are outlined in Section III. Section IV deals with the analyses and results of the near-field mixing performance of several options at each site. Section V includes the analyses and results of the far-field mixing performance. The implications of the data and analyses for ocean outfall location and design are presented in Section VI.

II. Environmental Data

A. Density Data

The behavior of submerged buoyant discharges, such as sewage treatment plant effluent into coastal waters, depends on the initial buoyancy of the discharge relative to the receiving water and on the vertical density structure of the receiving water. Thus, for the design of outfall discharge systems it is necessary to know the range of receiving water densities to be expected and the degree to which vertical density stratification exists.

The density of water in the Hen and Chickens Shoal and South Bethany Beach site areas is principally determined by the water temperature and salinity, as these waters, though not clear, are relatively free of suspended matter in concentrations large enough to influence the density. Temperature, salinity, and depth measurements were made with an Interocean CSTD-513 and recorder system during four cruises in 1973 and with a Yellow Springs S-C-T meter during six cruises in 1974. Using the temperature and salinity data and an equation of state for seawater, water densities were determined.

Typically, vertical measurements were made at two or more locations in a site area. If there seemed to exist weak to significant density stratification, as many as a dozen more vertical profiles were made as a function of time and location. In this way, spatial and short-term temporal variations in density could be observed. If the water column appeared to be of uniform density from initial observations, detailed surveying was not carried out.

A summary of density structure data for the various physical study cruises to both site areas is shown in Table 1. Surface and Bottom temperature data from the water quality studies as reported by Maurer and Tinsman (15) are presented in Table 2. Of the physical study cruises, on two days weak stratification was found to exist at each site. Only one cruise showed significant

Table 1

Vertical Density Structure

Date of Cruise	Site Area	Stratification	Temp. °C	Salinity o/oo	Density g/ml
				Typical Values	
7/18/73	HCS	weak	17.4-20	27.3-29	1.018-1.020
	SBB	weak	17.4-20.8		1.019-1.020
8/2/73	HCS	negligible? (Only 2 pts.)	17.4	29.1	1.021
8/10/73	HCS	significant		See Figure 3	
	SBB	significant		See Figure 4	
8/24/73	HCS	negligible	22	29	1.019
	SBB	negligible	22	30	1.020
6/11/74	HCS	negligible	20-21	29	1.020
6/12/74	SBB	negligible	20-23	30	1.020
6/13/74	HCS	negligible	19-21	28	1.019
6/14/74	SBB	weak	19.5-21	30	1.019
8/29/74	SBB	negligible	22	30	1.020
8/30/74	HCS	weak	21.5-24	28	1.019

Table 2

24-Hour Studies
Hen and Chickens Shoal
Temperature (°C)

8/13 - 8/14/73

Station #		4T	4B	11T	11B
Time	1200	19.2	15.7	21.5	18.5
	1600	23.5	17.5	22.3	21.3
	2000	22.8	16.4	18.4	17.5
	2400	21.0	14.6	20.7	17.6
	0400	21.4	17.5	21.2	19.1
	0800	21.9	18.9	17.4	16.9

10/ 3 - 10/ 4/73

Station #		4T	4B	11T	11B
Time	1200	24.4	20.8	24.4	21.0
	1600	22.0	20.8	24.4	20.9
	2000	21.7	20.8	21.5	20.8
	2400	21.0	20.9	21.0	21.0
	0400	20.8	20.8	21.0	20.8
	0800	20.9	20.8	21.0	20.7

12/ 3 - 12/ 4/73

Station #		4T	4B	11T	11B
Time	1200	10.0	10.1	10.1	10.1
	1600	10.4	10.1	10.3	10.2
	2000	10.3	10.2	10.2	10.2
	2400	9.8	9.8	10.1	9.9
	0400	10.3	10.2	10.4	10.2
	0800	10.2	10.1	10.2	10.1

Table 2 (cont'd)

Quarterly Benthic Sampling
Hen and Chickens Shoal
Temperature (°C)

7/24/73

Station	1	2	3	4	5	6	7	8	9	10	11	12
Top	19.7	21.1	26.0	22.0	22.5	19.8	22.0	23.0	18.0	17.7	20.5	20.5
Bottom	18.2	17.3	21.9	21.0	20.5	17.2	16.8	21.5	17.3	17.5	17.3	19.5

10/18/73

Station	1	2	3	4	5	6	7	8	9	10	11	12
Top	17.6	18.0	18.1	17.9	18.2	18.2	18.2	18.3	17.6	18.1	18.2	18.0
Bottom	17.7	17.6	18.1	17.9	18.2	18.2	18.2	18.3	18.2	18.2	18.2	18.2

Table 2 (cont'd)

24-Hour Studies
Hen and Chickens Shoal
Salinity (o/oo)

8/13 - 8/14/73

Station #		4T	4B	11T	11B
Time	1200	29.5	30.8	30.3	30.6
	1600	26.7	30.2	28.1	28.5
	2000	30.5	27.3	30.2	30.2
	2400	28.9	31.4	28.7	30.1
	0400	27.4	30.0	28.1	29.3
	0800	27.2	29.7	30.1	30.5

10/ 3 - 10/ 4/73

Station #		4T	4B	11T	11B
Time	1200	29.6	29.9	30.1	30.1
	1600	29.5	29.9	29.7	30.0
	2000	29.6	30.2	29.9	29.9
	2400	28.7	29.9	29.2	29.6
	0400	29.6	30.0	29.9	30.0
	0800	29.6	30.3	30.0	30.0

12/ 3 - 12/ 4/73

Station #		4T	4B	11T	11B
Time	1200	28.9	29.9	29.9	29.4
	1600	29.8	28.5	30.2	30.2
	2000	27.6	29.9	30.0	30.1
	2400	29.5	29.8	29.5	--
	0400	29.8	30.2	30.3	30.1
	0800	30.0	31.0	29.7	29.5

Table 2 (cont'd)

Quarterly Benthic Sampling
Hen and Chickens Shoal
Salinity (o/oo)

7/24/73

Station	1	2	3	4	5	6	7	8	9	10	11	12
Top	27.8	26.1	25.2	24.9	25.6	26.5	29.5	25.6	--	29.7	29.7	29.7
Bottom	28.7	28.9	26.9	28.4	27.3	29.0	25.7	29.8	29.7	29.6	29.6	29.2

10/18/73

Station	1	2	3	4	5	6	7	8	9	10	11	12
Top	29.7	29.1	29.8	29.5	29.8	30.0	29.7	29.8	29.9	29.8	29.6	29.9
Bottom	29.2	29.5	29.6	29.6	29.9	30.0	29.7	29.8	29.7	29.3	29.8	29.9

Table 2 (cont'd)

24-Hour Studies
South Bethany Beach
Temperature (°C)

7/31 - 8/ 1/73

Station #		4T	4B	6T	6B
Time	1200	21.8	19.6	21.8	20.1
	1600	23.1	16.9	24.3	20.1
	2000	24.0	16.6	23.5	17.9
	2400	23.1	16.6	23.3	19.6
	0400	22.7	16.7	21.9	19.9
	0800	22.4	16.7	21.2	18.4

9/20 - 9/21/73

Station #		4T	4B	6T	6B
Time	1200	20.2	20.3	20.3	20.4
	1600	20.4	20.4	20.7	20.4
	2000	21.0	20.3	20.5	20.4
	2400	20.3	20.3	19.0	20.2
	0400	20.3	20.2	20.3	20.1
	0800	20.2	20.2	20.3	20.2

11/13 - 11/14/73

Station #		4T	4B	6T	6B
Time	1200	11.4	11.4	11.8	11.4
	1600	11.9	11.8	12.0	11.4
	2000	11.8	11.7	11.3	11.4
	2400	11.6	11.9	11.4	11.4
	0400	11.5	11.5	11.5	11.4
	0800	11.3	11.3	11.3	11.4

Table 2 (cont'd)

Quarterly Benthic Sampling
South Bethany Beach
Temperature (°C)

7/23/73

Station	1	2	3	4	5	6	7	8	9	10	11	12
Top	19.5	20.1	20.9	19.5	19.9	19.1	19.0	18.5	18.1	--	--	--
Bottom	18.7	18.7	16.9	18.1	18.6	17.9	17.7	15.1	13.2	--	--	--

10/17/73

Station	1	2	3	4	5	6	7	8	9	10	11	12
Top	19.0	18.9	18.9	18.9	19.0	18.9	19.0	19.0	18.9	18.9	19.0	18.9
Botoom	19.0	18.9	18.9	18.9	19.0	18.9	19.0	18.9	18.9	18.9	19.0	18.9

Table 2 (cont'd)

24-Hour Studies
South Bethany Beach
Salinity (o/oo)

7/31 - 8/ 1/73

Station #		4T	4B	6T	6B
Time	1200	29.0	29.5	29.7	28.9
	1600	29.0	28.5	29.0	29.4
	2000	29.2	30.0	28.8	28.2
	2400	28.7	29.7	29.2	29.7
	0400	29.2	30.2	29.3	29.7
	0800	29.0	28.8	29.2	29.0

9/20 - 9/21/73

Station #		4T	4B	6T	6B
Time	1200	30.1	30.2	30.1	30.1
	1600	30.2	30.4		
	2000	30.1	30.4	30.1	30.2
	2400	29.9	29.9	30.2	30.1
	0400	30.2	30.3	30.0	30.2
	0800	29.8	29.7	29.7	29.7

11/13 - 11/14/73

Station #		4T	4B	6T	6B
Time	1200	30.0	30.7	30.8	30.3
	1600	30.7	30.9	30.9	31.0
	2000	30.9		30.9	30.8
	2400	30.7	30.3	30.9	30.9
	0400	30.5	30.8	30.7	30.3
	0800	30.5	30.9	31.0	30.9

Table 2 (cont'd)

Quarterly Benthic Sampling
Bethany Beach
Salinity (o/oo)

7/23/73

Station	1	2	3	4	5	6	7	8	9	10	11	12
Top	28.6	28.6	29.0	28.3	28.1	--	28.0	28.4	28.2	--	--	--
Bottom	28.7	28.7	29.3	29.4	28.2	27.6	28.8	28.5	28.7	--	--	--

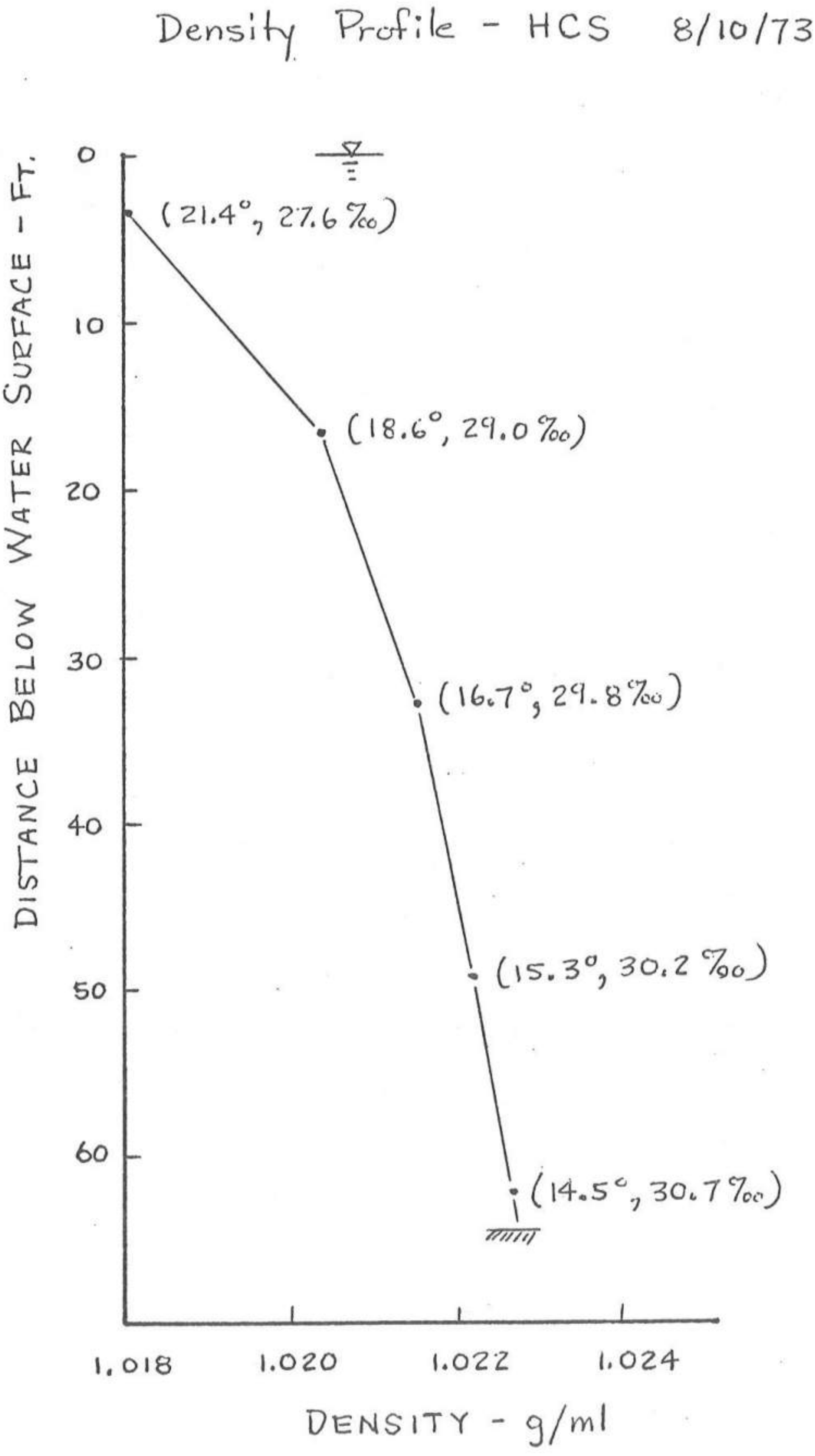
10/17/73

Station	1	2	3	4	5	6	7	8	9	10	11	12
Top	30.1	30.1	30.1	30.4	30.2	30.4	30.3	30.2	30.1	30.3	30.2	--
Bottom	30.4	30.6	30.5	30.4	30.2	30.1	30.2	30.0	30.6	30.5	30.3	--

density stratification at both sites. All other physical cruises showed negligible vertical density structure. It appears that the seasonal thermocline structure which develops in the deeper offshore waters in the early summer and remains somewhat stable, in a gross sense, throughout the summer does not occur in the nearshore waters of the two site areas. The shallowness of these two areas seems to promote the breakdown of the thermal structure during windy periods. For instance, while there exists evidence for strong stratification at the Hen and Chickens Shoal site from the physical cruise of 8/10/73 and the water quality cruise of 8/13-14/73, the physical cruise of 8/24/73 shows negligible stratification. Yet the water quality cruise of 10/3-4/73 indicates a renewed top to bottom temperature difference of 4°C. For the South Bethany Beach site, however, the water quality survey data of 9/20-21/73 and 10/17/73 indicate negligible density stratification renewal after significant stratification on 8/10/73.

Hen and Chickens Shoal Site

The density stratification found at the Hen and Chickens Shoal site area on 8/10/73 varied somewhat with location and time in the site area. The surface to bottom density difference was greatest in the deep (90') zone and least in near the Shoal itself. The stratification did not appear to vary significantly during the change in tide (the 24-hr. water quality surveys also indicated little change during the periods of study). A typical density profile in the 60' zone for this date is shown in Figure 3. It appears from the collected data that, because of the deeper water near shore, the Hen and Chickens Shoal site may be slightly less vulnerable to wind mixing than the South Bethany Beach site and thus can maintain a vertical density structure under conditions which cause the shallower South Bethany Beach site to become uniform.



Density Profile - HCS 8/10/73
DISTANCE BELOW WATER SURFACE - FT.
0
10
20
30
40
50
60
(21.4°, 27.6 ‰)
(18.6°, 29.0 ‰)
(16.7°, 29.8 ‰)
(15.3°, 30.2 ‰)
(14.5°, 30.7 ‰)
1.018
1.020
1.022
1.024
DENSITY - g/ml

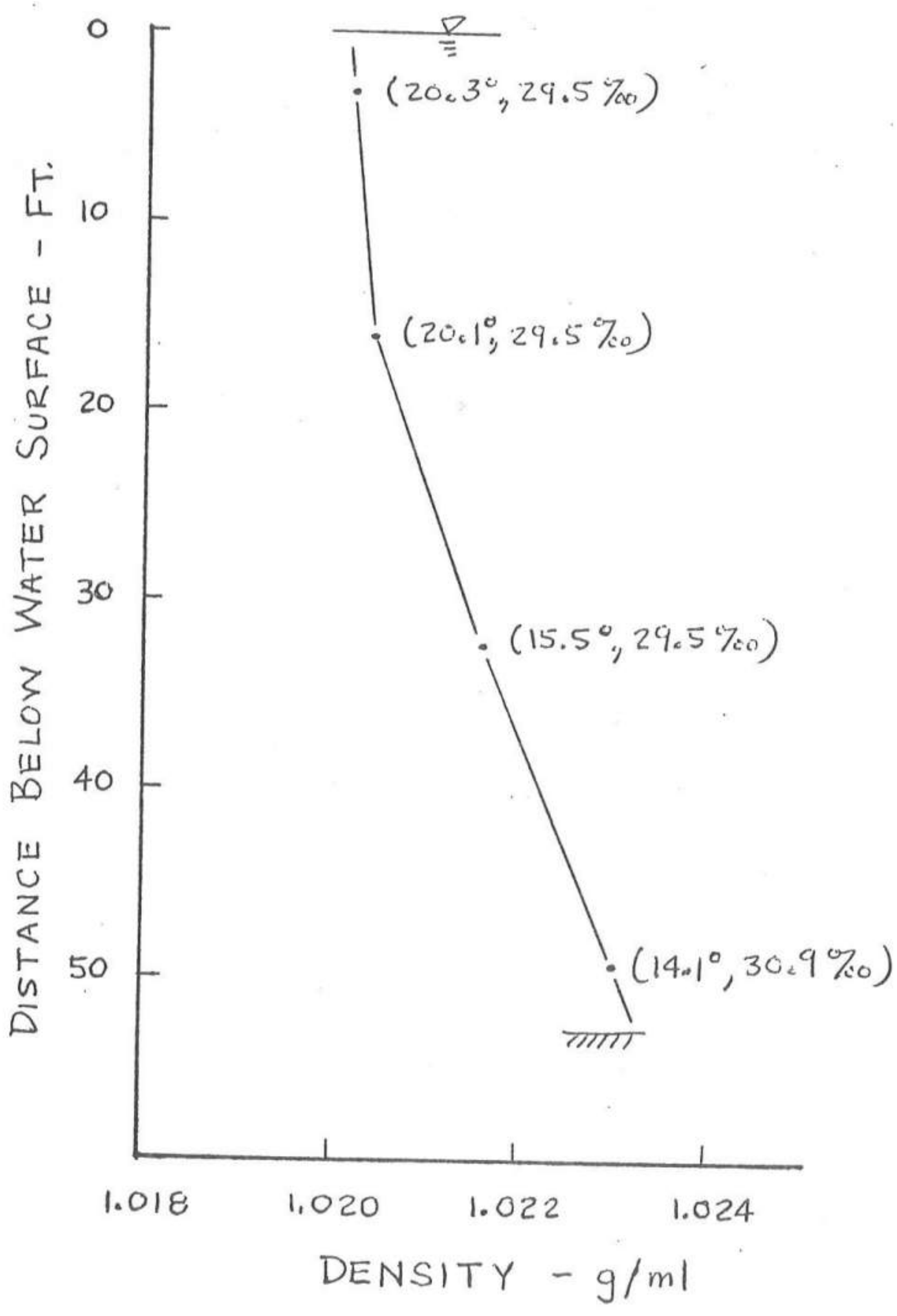
Figure 3

South Bethany Beach Site

The most significant density stratification found at the South Bethany Beach site area was on 8/10/73. The stratification was "strongest" offshore (2.5 miles) and diminished inshore (23' of water). A typical density profile for the offshore waters on that date is given in Figure 4. The surface to bottom density difference is not as great as was found at the Hen and Chickens Shoals site on that day. The collected data indicate that density stratification at the South Bethany Beach site area is less likely to occur there than at Hen and Chickens Shoal. The shallowness of the site area for more than two miles from shore seems to allow greater opportunity for development of uniform density structure.

Composite Density Stratification

For the purpose of studying the behavior of effluent plumes discharged into "strongly" density-stratified receiving waters at the proposed outfall site areas a measure of a typical summer density profile was required. Using data from the 8/10/73 cruise from both the Hen and Chickens Shoal site and the South Bethany Beach site areas, a vertical density profile for 90' of water was developed. That profile is shown in Figure 5. This profile has the property that it provides a good representation of the deep water density structure found at the Hen and Chickens Shoal site and its upper 40' provide a good representation of the density differences found at the offshore stations at the South Bethany Beach site. The density gradient may be a little large for the inshore density structure measured at South Bethany Beach, and as such, should be considered as a possible upper bound on density stratification there.



Density Profile - SBB 8/10/73

Figure 4

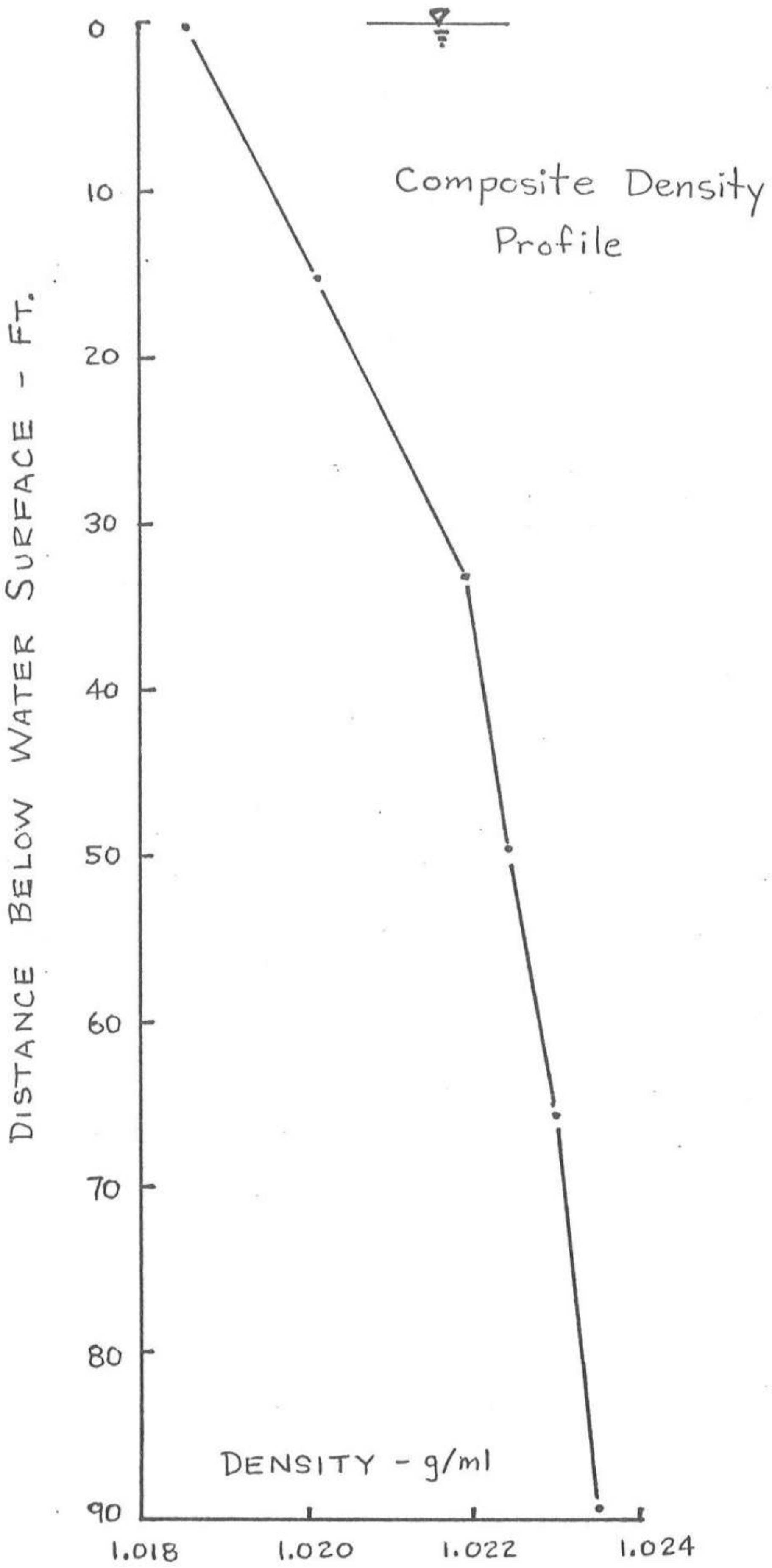

Composite Density
Profile
DISTANCE BELOW WATER SURFACE - FT.
0
10
20
30
40
50
60
70
80
90
DENSITY - g/ml
1.018
1.020
1.022
1.024

Figure 5

B. Current Data

General

The currents in the site areas are of concern because of their effects on the behavior of buoyant jets in the near-field, the transport of water for dilution to the diffuser site, and the transport of the surface or sub-surface effluent from the site. The currents in the near-coast waters of both site areas are primarily tidal currents with wind effects modifying them in both magnitude and direction. Currents at the Hen and Chickens Shoal site are clearly influenced by the proximity to the Bay and are expected to follow closely the estuarine tidal cycle in the Bay. Current vectors in the general vicinity of Cape Henlopen are given in the current charts (14) for Delaware Bay. On the other hand, the currents at the South Bethany Beach site, far removed from the Bay entrance and the influence of Indian River Inlet, are expected to exhibit less estuarine character. In this study, current measurements were undertaken to confirm the extent to which these general characteristics were true and to provide estimates of the currents and circulation at both sites for physical mixing predictions.

Current Measurements

Current measurements at both sites were made by employing drogues. The drogue consisted of a crossed-vaned submerged section attached to a surface float by a line of adjustable length. The surface float held a flagpole and flag approximately five feet above the water. The vanes were each approximately 4' x 2' x 1/2" plywood sections joined together with angle-irons for rigidity and to overcome buoyancy. The surface floats were approximately 1-1/4' x 1-1/4' x 3" pieces of styrofoam with the sides streamlined to reduce drag on the floats. Connections for varied line length between float and crossed-vanes were provided. Drogues were numbered and/or color-coded to allow positive identification at the water surface. The drogues were designed to minimize the drag on the line, surface float, and thin fiberglas flagpole relative to the drag on the crossed-vanes, thus assuring a good approximation of the water mass motion at the depth of the crossed-vanes by the float motion.

Current measurement by drogues is a Lagrangian measure, that is, a measure of the displacement of a particular water mass (that surrounding the crossed-vanes) as contrasted with an Eulerian measurement, that is, measurement of the velocities of many water masses passing a fixed point in the water column. Drogue measurements were particularly well-suited for this study as they provided not only estimates of the "instantaneous" velocities of water masses in the site areas, but also provided the trajectories of water masses over time periods as long as a flood or ebb tide.

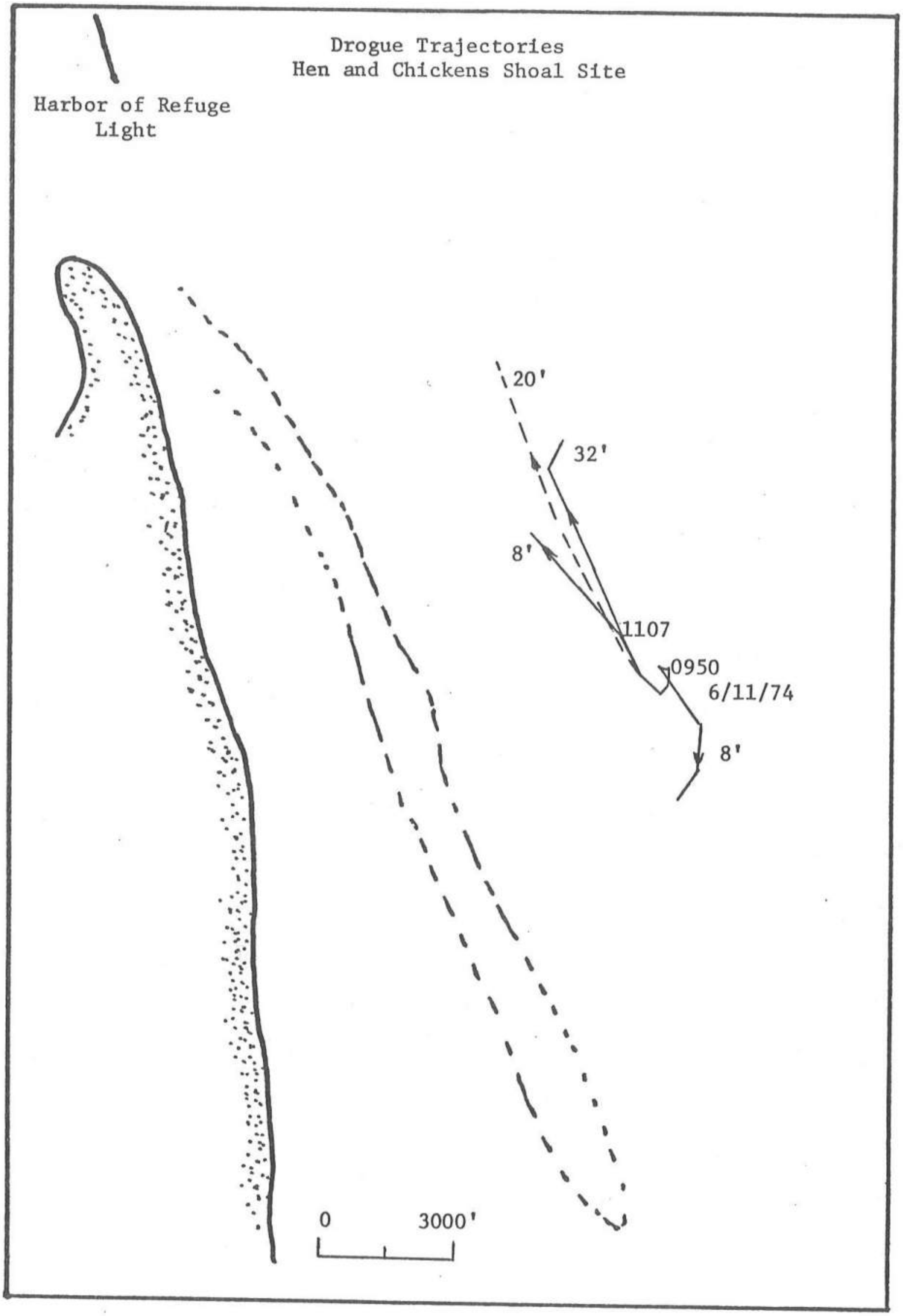
The current measurements using the drogues were carried out as follows. A group of drogues (or single drogue) were deployed from a vessel with crossed-vanes adjusted to a variety of depths from near-surface downward. The initial time and location of the drogues were noted. The location was determined by using two sexton angles to onshore charted objects such as towers, water tanks, etc. when the vessel was in close proximity to the surface float. Typically, the new locations of the drogues were found after displacements of several hundred feet by moving the vessel within a few feet of the surface float. The time-history of drogue locations were plotted to determine drogue trajectories and the average velocity of drogue between consecutive locations calculated.

In addition, a study of the mixing of fluorescein dye into the surface waters and the subsequent drift of such dye patches (described below) indicated the drogues with crossed-vanes fixed at near-surface depths located initially in the dye patches drifted with the dye. This result confirmed previous calculations regarding the negligible effects of wind drag on the surface floats and reinforced the concept of near-surface drogues giving a satisfactory indication of the surface water mass motion.

Currents at Hen and Chickens Shoal Site

Figures 6 and 7 and Table 3 give data for drogue studies during a period of flood tide through slack and the beginning ebb tide for June 11, 1974 at the Hen and Chickens Shoal site. Measurements indicated no significant vertical variation in temperature or density for that day. Figures 6 and 7 indicate the trajectories of drogues located 8', 20', and 32' below the water surface and initially deployed at points slightly less than two miles offshore. The wind was from the WNW to NW at an average of about 12 knots throughout the study period for the day. The effect of the wind on the surface current was demonstrated by the fact that the first surface drogue was deployed some 95 minutes after predicted low water slack and moved in a southeasterly and then southerly direction. Subsequent deployment of a deeper drogue also resulted in an initial displacement in a direction opposite the tidal motion before displacement by the tide took place (Figure 6). Figure 7 shows the trajectories of drogues released in the site area near maximum flood tide. Their movements are approximately parallel to Hen and Chickens Shoal until slack water and ebb tide when the 32' drogue reversed direction and the 8' and 20' drogues moved eastward (probably in response to the wind). The maximum drogue velocity during the flood excursion was about 2.0 fps, and the average was about 1.3 fps. Separation of drogue trajectories indicated the presence of some vertical velocity shear, however, the general direction and speed indicated uniform water mass movement.

Figures 8, 9, 10, and 11 and Table 4 give data for drogue studies for a period of ebb tide through slack to the maximum flood tide for June 13, 1974



Drogue Trajectories
Hen and Chickens Shoal Site
Harbor of Refuge
Light
20'
32'
8'
1107
0950
6/11/74
8'
0
3000'

Figure 6

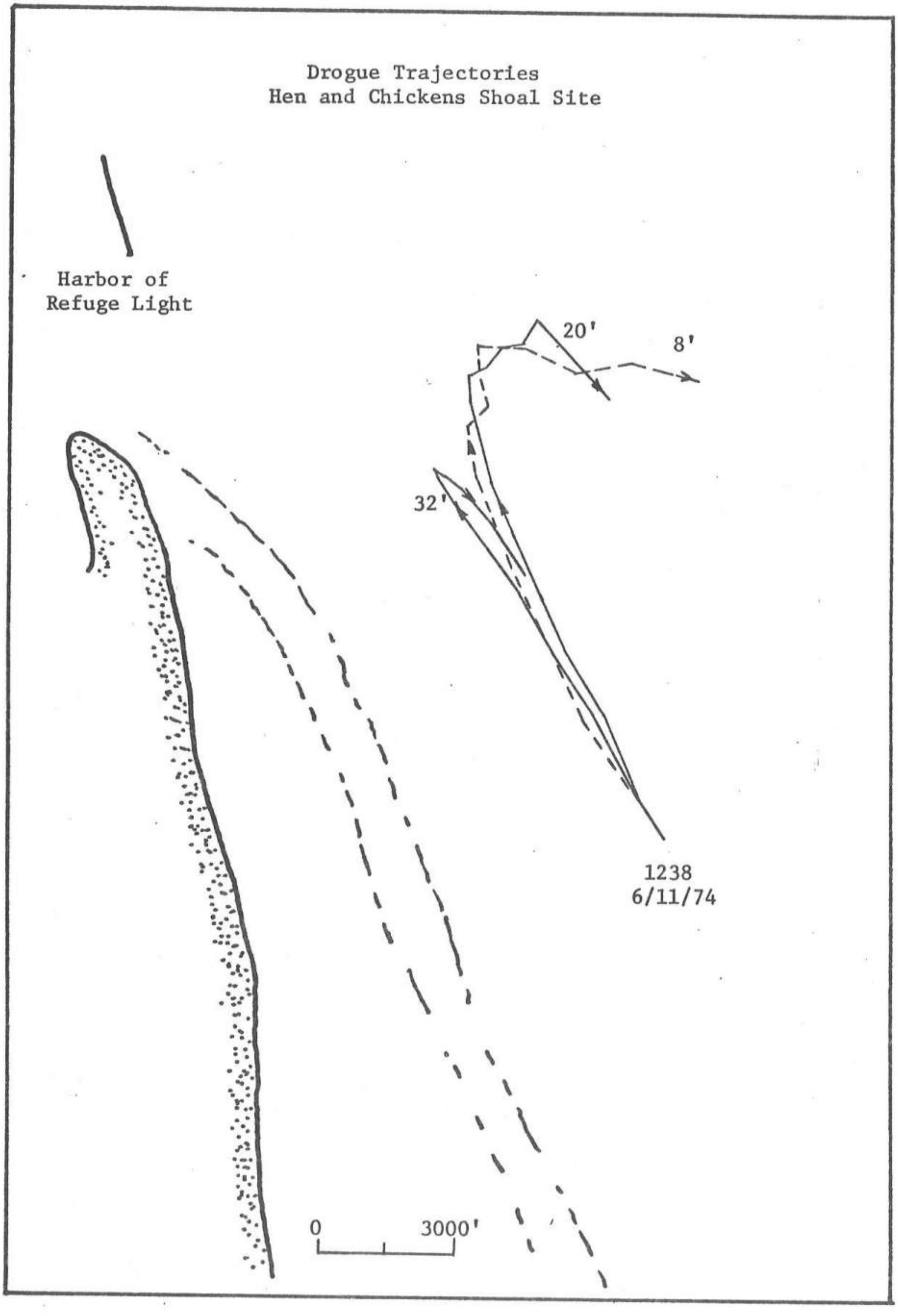

Drogue Trajectories
Hen and Chickens Shoal Site
Harbor of
Refuge Light
20'
8'
32'
1238
6/11/74
0
3000'

Figure 7

Table 3

Current Data - Hen and Chickens Shoal Site

6/11/74

<u>Tides</u> (Delaware Bay Entrance, Breakwater Harbor)

High	0120
Low	0738
High	1358
Low	1947

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (feet)	Remarks
6	8'	1005	Start		
		1022	1500	1.47	1.84 mi. offshore
		1037	1050	1.17	60' of water
		1055	750	0.70	

Max. Distance from Start 3090'
Aver. Velocity = 1.03 fps.

Total Distance Traveled 3600'
Aver. Velocity = 1.2 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (feet)	Remarks
6	8'	1107	Restart		1.76 mi. offshore
		1127	1350	1.13	60' of water
		1146	1725	1.51	

Max. Distance from Start 3150'
Aver. Velocity = 1.35 fps.

Total Distance Traveled 3150'
Aver. Velocity = 1.35 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (feet)	Remarks
6	20'	0950	Start		
		1006	225	0.23	1.84 mi. offshore
		1018	300	0.42	60' of water
		1034	300	0.31	
		1049	300	0.33	
		1106	525	0.51	
		1125	675	0.59	
		1144	1500	1.32	
		1206	1800	1.36	
		1221	3750	3.29	

Max. Distance from Start 7800'
Aver. Velocity = 0.86 fps.

Total Distance Traveled 9300'
Aver. Velocity = 1.03 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (feet)	Remarks
6	32'	1049	Start		
		1107	1200	1.11	
		1123	1575	1.64	
		1142	1350	1.18	
		1159	1050	1.03	
		1211	825	1.15	

Max. Distance from Start 5700'
Aver. Velocity = 1.16 fps.

Total Distance Traveled 6000'
Aver. Velocity = 1.22 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (feet)	Remarks
7	8'	1238	Start		1.84 mi. offshore
		1257	1800	1.58	60' of water
		1313	1575	1.64	
		1327	1725	2.05	
		1345	1725	1.60	
		1403	1500	1.39	
		1417	1200	1.43	
		1431	1675	1.96	
		1445	675	0.80	
		1500	900	1.00	
		1516	450	0.47	turning
		1534	400	0.83	
		1549	1350	1.50	
		1605	1290	1.34	
		1626	1575	1.25	

Max. Distance from Start 12,075'
Aver. Velocity = 1.28 fps.

Total Distance Traveled 16,500'
Aver. Velocity = 1.21 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (feet)	Remarks
7	20'	1238	Start		1.84 mi. offshore 60' of water
		1254	1350	1.41	
		1311	1800	1.76	
		1325	1500	1.79	
		1343	1500	1.39	
		1400	1650	1.62	
		1416	1125	1.17	
		1430	1920	1.14	
		1500	630	0.66	
		1515	450	0.47	turning
		1535	450	0.38	
		1550	630	0.70	
		1607	630	0.62	
		1630	2490	1.81	

Max. Distance from Start 12,150'
Aver. Velocity = 0.87 fps.

Total Distance Traveled 15,900'
Aver. Velocity = 1.14 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (feet)	Remarks
7	32'	1238	Start		1.84 mi. offshore 60' of water
		1256	1800	1.67	
		1312	1800	1.88	
		1327	1650	1.83	
		1344	1500	1.47	
		1401	1500	1.47	
		1419	1050	0.97	
		1434	600	0.67	
		1448	225	0.27	
		1505	150	0.15	turning
		1521	225	0.23	
		1539	525	0.49	
		1557	975	0.90	
		1615	1425	1.32	

Max. Distance from Start 9900'
Aver. Velocity = 1.01 fps.

Total Distance Traveled 13,050'
Aver. Velocity = 1.00 fps.

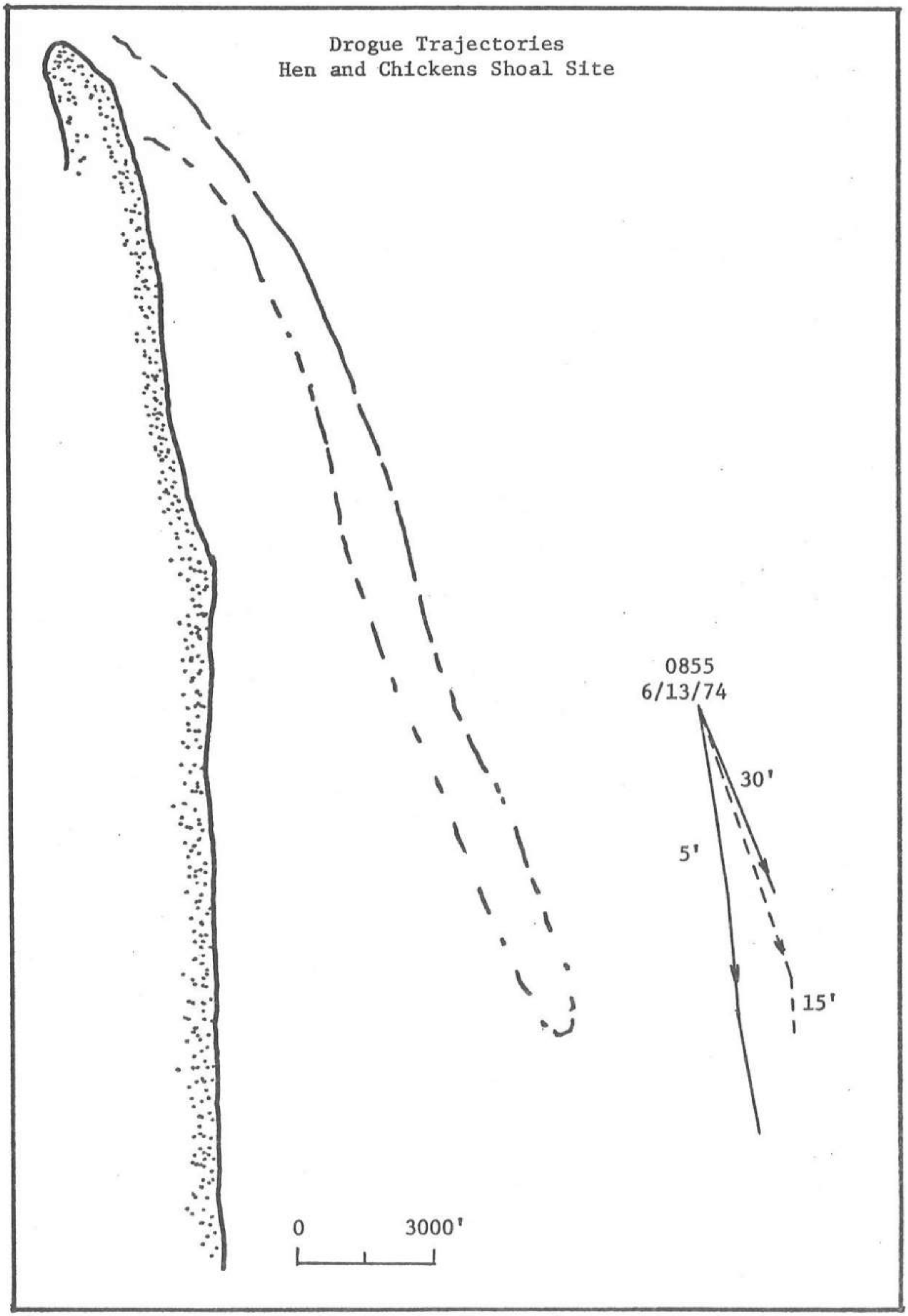

Drogue Trajectories
Hen and Chickens Shoal Site
0855
6/13/74
30'
5'
15'
0
3000'

Figure 8

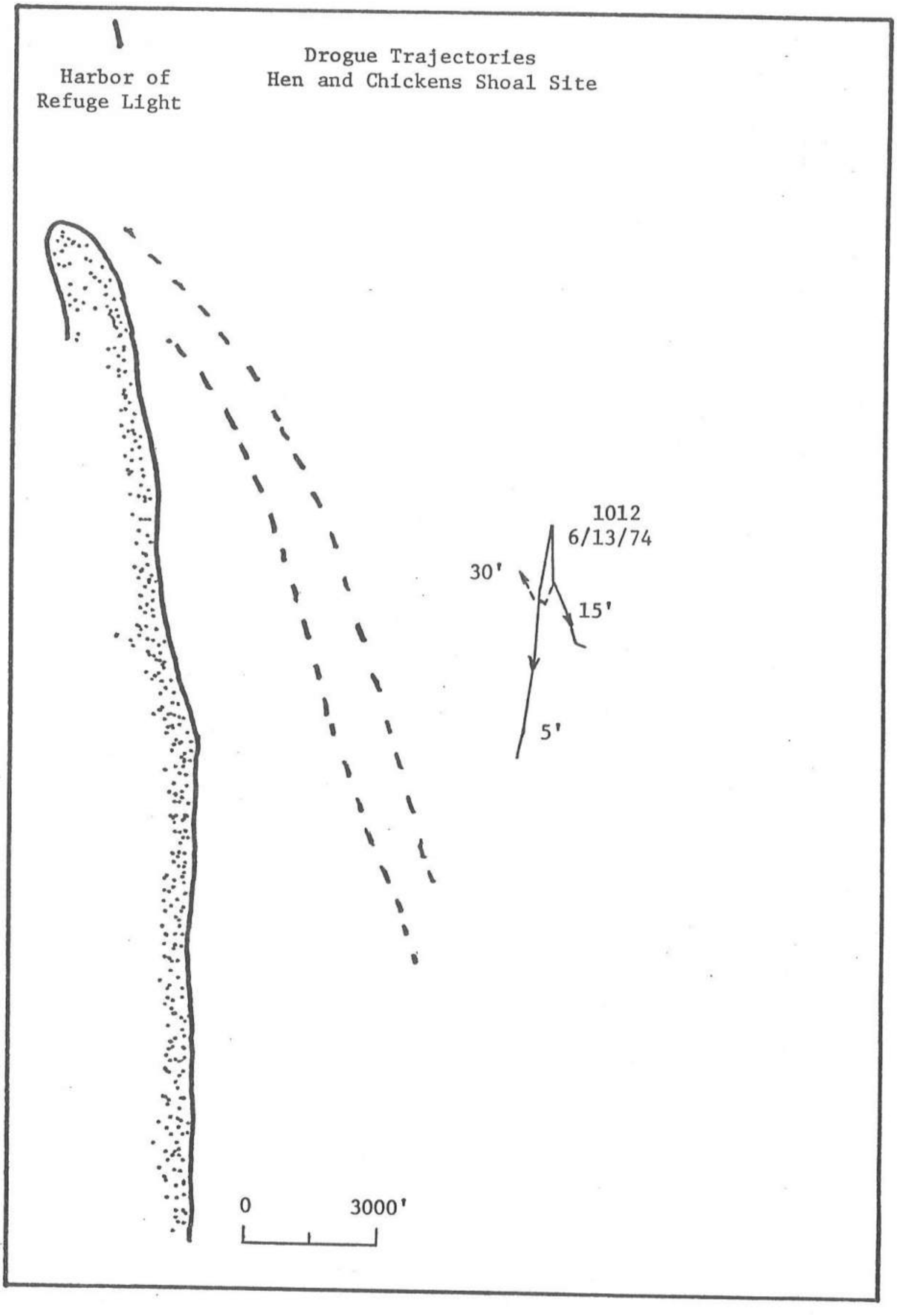

Drogue Trajectories
Hen and Chickens Shoal Site
Harbor of
Refuge Light
1012
6/13/74
30'
15'
5'
0
3000'

Figure 9

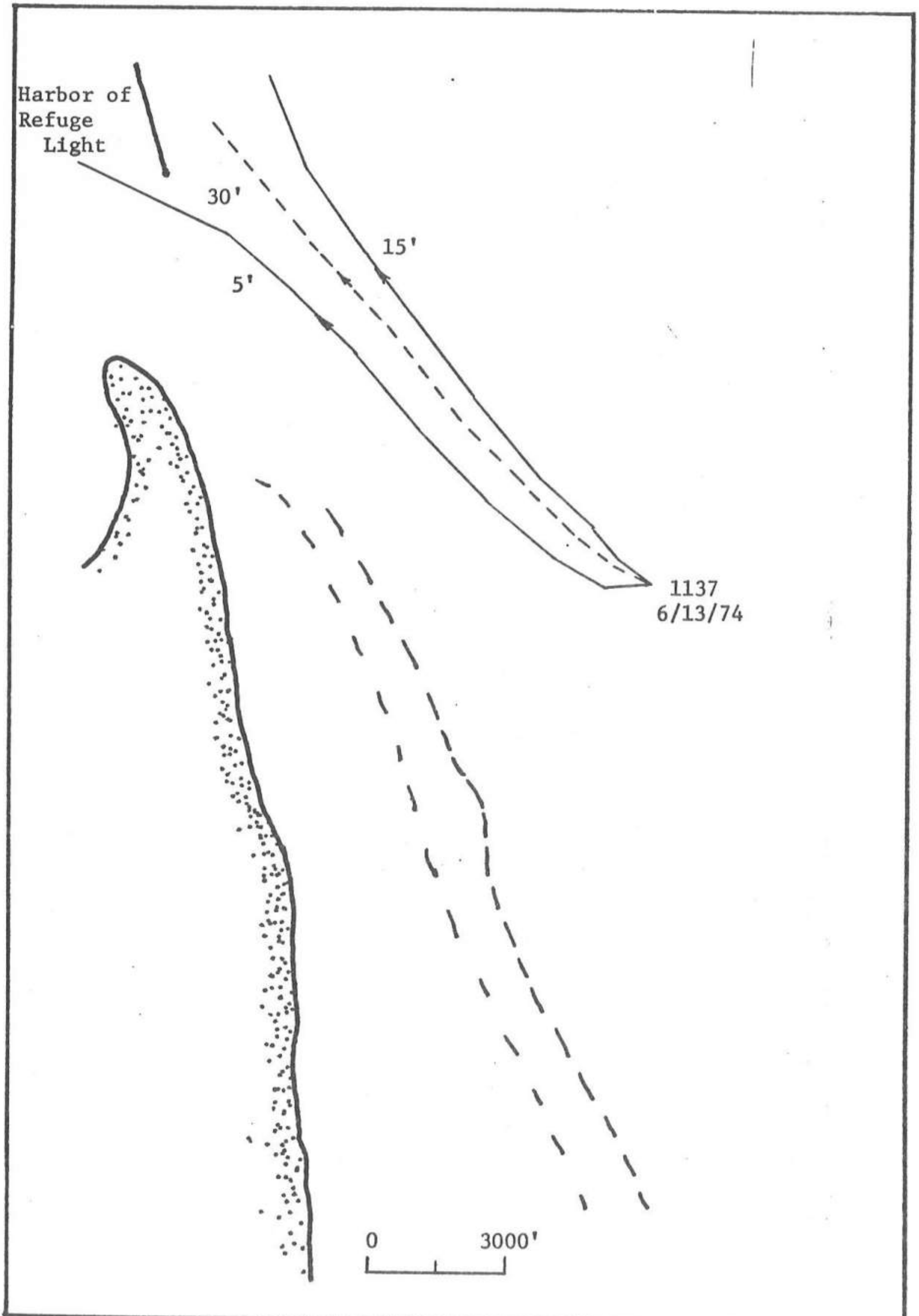


Figure 10

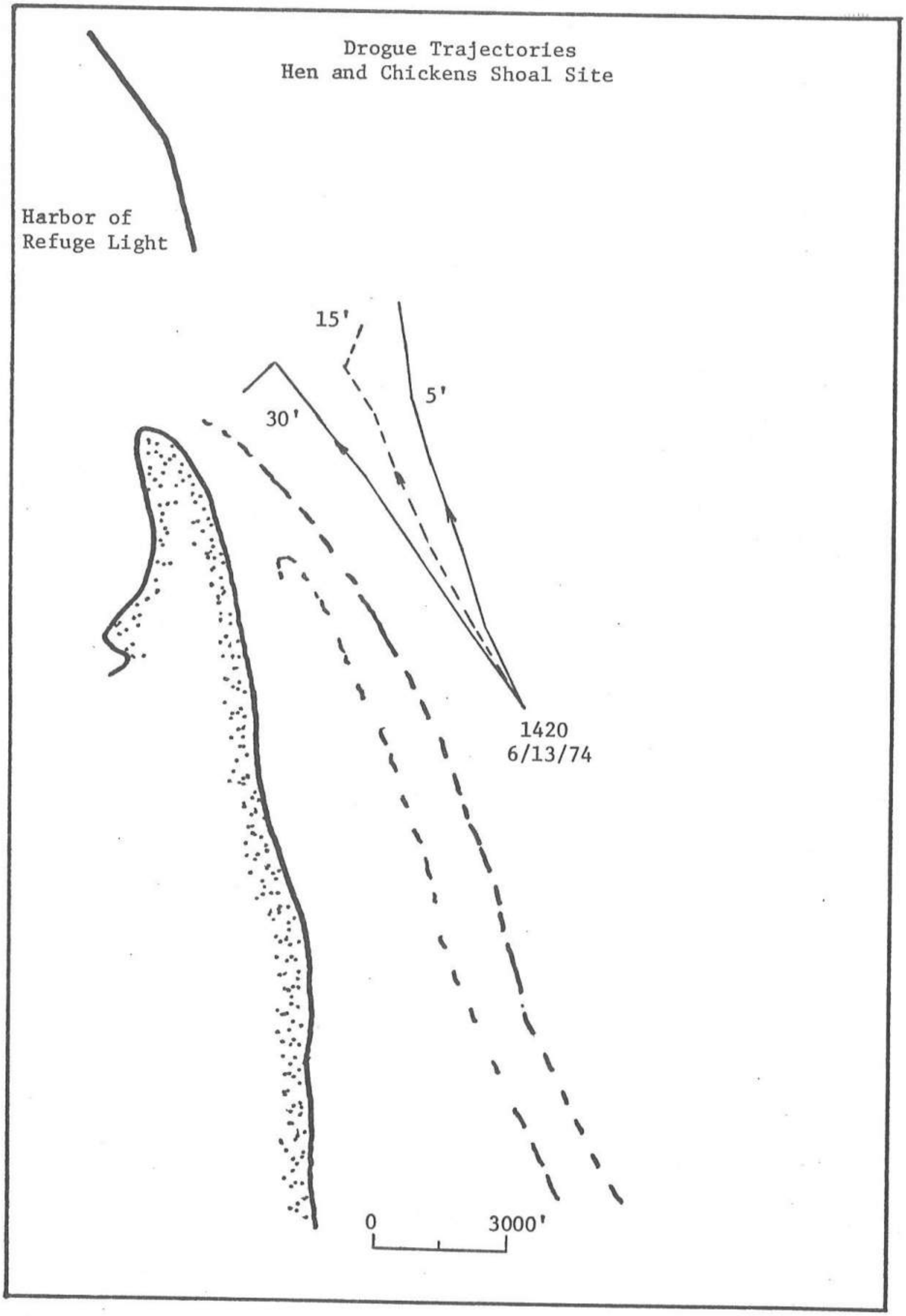

Drogue Trajectories
Hen and Chickens Shoal Site
Harbor of
Refuge Light
15'
5'
30'
1420
6/13/74
0
3000'

Figure 11

Table 4

Current Data - Hen and Chickens Shoal Site

6/13/74

Tides (Delaware Bay Entrance, Breakwater Harbor)

High	0256
Low	0906
High	1538
Low	2142

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
8	5'	0855	Start		2.1 mi. offshore 60' of water
		0916	4500	3.60	
		0930	2550	3.04	
		0947	2700	2.65	

Max. Distance from Start 9750'
Aver. Velocity = 3.13 fps.

Total Distance Traveled 7500'
Aver. Velocity = 2.6 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
8	15'	0855	Start		2.1 mi. offshore 60' of water
		0912	3525	3.46	
		0933	3000	2.38	
		0943	1080	1.80	

Max. Distance from Start 7500'
Aver. Velocity = 2.60 fps.

Total Distance Traveled 7605'
Aver. Velocity = 2.64 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
8	30'	0855	Start		2.1 mi. offshore 60' of water
		0920	2850	1.90	
		0937	1650	1.62	

Max. Distance from Start 4500'
Aver. Velocity = 1.79 fps.

Total Distance Traveled 4500'
Aver. Velocity = 1.79 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
9	5'	1012	Start		1.73 mi. offshore 60' of water
		1026	1500	1.79	
		1042	1725	1.80	
		1057	1500	1.67	
		1115	600	0.56	

Max. Distance from Start 5400'
Aver. Velocity = 1.43 fps.

Total Distance Traveled 5400'
Aver. Velocity = 1.43 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
9	15'	1012	Start		1.73 mi. offshore 60' of water
		1028	1380	1.44	
		1049	840	0.67	
		1109	600	0.56	
		1128	300	0.26	

Max. Distance from Start 2880'
Aver. Velocity = 0.68 fps.

Total Distance Traveled 2880'
Aver. Velocity = 0.68 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
9	30'	1028	Start		1.67 mi. offshore 61' of water
		1051	480	0.35	
		1109	330	0.31	
		1128	660	0.65	

Max. Distance from Start 690'
Aver. Velocity = 0.17 fps.

Total Distance Traveled 1470'
Aver. Velocity = 0.41 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
10	5'	1137	Start		1.78 mi. offshore 60' of water
		1159	1080	0.82	
		1218	1260	1.11	
		1238	1980	1.65	
		1257	2250	1.97	
		1312	2250	2.50	
		1326	1920	2.29	
		1338	1950	2.71	
		1359	3660	2.90	

Max. Distance from Start 15,900'
Aver. Velocity = 1.94 fps.

Total Distance Traveled 16,500
Aver. Velocity = 1.94 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
10	15'	1137	Start		1.78 mi. offshore 60' of water
		1158	915	0.73	
		1214	920	0.96	
		1231	1560	1.53	
		1249	2280	2.11	
		1307	2280	2.11	
		1322	2250	2.50	
		1334	1800	2.50	
		1349	2250	2.50	

Max. Distance from Start 14,250'
Aver. Velocity = 1.80 fps.

Total Distance Traveled 14,255'
Aver. Velocity = 1.80 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
10	30'	1137	Start		1.78 mi. offshore 60' of water
		1157	1080	0.90	
		1216	1080	0.95	
		1229	1475	1.83	
		1247	2160	2.00	
		1303	2700	2.81	
		1320	2550	2.50	
		1331	1950	2.95	
		1345	1575	1.88	

Max. Distance from Start 14,250'
Aver. Velocity = 1.86 fps.

Total Distance Traveled 14,250'
Aver. Velocity = 1.89 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
11	5'	1420	Start		
		1437	2100	2.06	
		1455	1875	1.74	
		1513	2100	1.94	
		1529	1590	1.66	
		1546	1110	1.09	
		1604	990	0.92	

Max. Distance from Start 9750'
Aver. Velocity = 1.56 fps.

Total Distance Traveled 9750'
Aver. Velocity = 1.56 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
11	15'	1420	Start		
		1436	1875	1.95	
		1454	2190	2.03	
		1510	1920	2.00	
		1526	1275	1.33	
		1544	1380	1.28	
		1600	960	1.00	

Max. Distance from Start 9450'
Aver. Velocity = 1.58 fps.

Total Distance Traveled 9795'
Aver. Velocity = 1.63 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Remarks
11	30'	1420	Start		
		1434	2100	2.50	
		1451	2280	2.24	
		1508	2100	2.06	
		1524	1650	1.72	
		1535	1500	2.27	
		1552	960	0.94	

Max. Distance from Start 9630'
Aver. Velocity = 2.14 fps.

Total Distance Traveled 10,530'
Aver. Velocity = 1.91 fps.

at the Hen and Chickens Shoal site. Measurements indicated no significant vertical density structure on that day. The wind was from the ENE at the beginning of the study period and shifted to the E at flood tide as indicated in Table 8. Figures 8 and 9 show the ebb tide displacements of drogues at 5', 15', and 30' below the water surface initially deployed about two miles offshore in the site area. In both cases, the drift was approximately parallel to the coast, and, as indicated in Figure 9 the deepest drogue responsed first to the change in tide as the wind moved surface water in the ebb direction. Figures 10 and 11 show the flood tide displacements of drogues at 5', 15', and 30' below the water surface initially deployed about two miles offshore. This particular set of circumstances, a flood tide and an 11 knot wind from the E to NE, provided an opportunity to observe the drift toward the Harbor of Refuge at high drift speeds (clearly, larger wind speeds from this direction generate even larger currents, but the conditions on this day produced what must be higher than average flood currents). Figure 10 indicates the drogue trajectories near maximum flood tide and Figure 11 up to high water slack. The drogues at all depths moved as group with some lateral separation from the deployment area to the mouth of the Harbor of Refuge. The maximum velocity observed was about 3 fps and the average near-surface drift velocity during the flood excursion toward the Harbor of Refuge was about 1.9 fps. The drogue trajectories were nearly parallel to Hen and Chickens Shoal.

A comparison of measured currents and those predicted for tidal currents and those predicted for tidal current and wind data is shown in Table 7. The tidal current data for 6/13/74 were developed using the Tidal Current Charts (14) and Tidal Current Tables (13) for the period of drogue measurement. The Tidal Current Charts indicate the velocity vectors for the upper 20' of water based on historical data. The Hen and Chickens Shoal site area is just at the geographic limit of the charts as shown in Figure 12 and cannot be expected

Table 7

Comparison Between Predicted and Measured Currents

Hen and Chickens Shoal Site 6/13/74

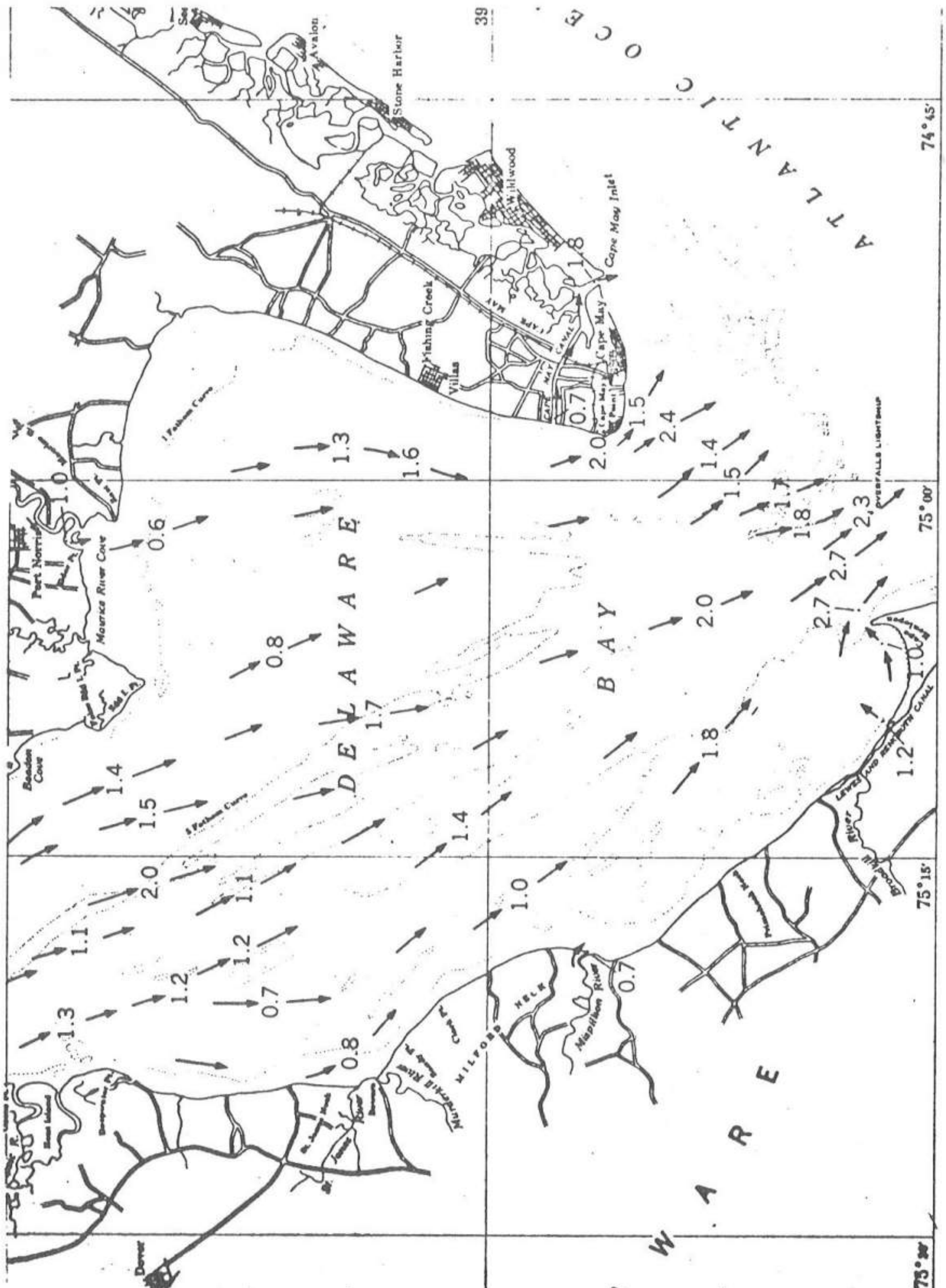
Time	Predicted Tidal Vel. (kts)	Tidal Direction °from N	Wind mph	Wind Current (kts)	Direction & Deflection ° from N	Resultant Vel. kts	Resultant °from N	Measured Vel. kts.	Measured °from N
0925	0.84	150	11 ENE	0.3	243.5	0.87	170	1.85	170
1025	0.70	180	13 ENE	0.4	243.5	0.95	202	1.1	200
1154	1.05	300	14 NE	0.4	218.	1.17	280	0.5	270
1254	1.54	315	13 NE	0.4	218.	1.54	300	1.2	315
1354	1.68	315	13 NE	0.4	238.	1.68	301	1.8	300
1454	1.25	315	10 E	0.3	256.	1.43	305	1.1	325
1554	0.49	315	11 E	0.3	256.	0.69	293	0.7	250

Table 8

Wind Data - South Bethany Beach Site

(taken at Roosevelt Inlet and in agreement with on-board observations at the site)

Date	Time	Wind (mph)		(aver. over hour)
6/12/74	0800	8	SSW	
	0900	7	SSW	
	1000	8	SW	
	1100	14	NW	
	1200	12	NW	
	1300	9	NW-NE	
	1400	8	NE	
	1500	7	NE	
	1600	7	NE	
6/14/74	0800	7	ENE	
	0900	10	ENE	
	1000	11	NE	
	1100	12	NE	
	1200	11	NE	
	1300	11	NE	
	1400	11	E	
	1500	12	ESE	



MAXIMUM EBB AT DELAWARE BAY ENTRANCE

Figure 12

to be valid far from the Bay entrance. Wind data were collected at Roosevelt Inlet during the study period as presented in Table 8 and agreed with on-board estimates during the study. Wind-induced currents were calculated by assuming that the current magnitude was 3% of the wind speed and that the direction was that of the wind plus or minus the deviations provided from historical records for Hen and Chickens Shoal in the Tidal Current Tables (13). The predicted tidal current and wind-induced current vectors were added to produce the predicted current magnitude and direction as shown in Table 7. Comparison with drogue velocity vectors at the times of calculated is good with regard to direction and fair with regard to magnitude. Best agreement was found during flood tide when the direction of the tidal current can be well predicted along the shoal. In general, current predictions by this crude technique is in reasonable agreement with measurements considering the lack of chart data along the shoal and the limitations of chart predictions including the absence of long-term wind effects on the tidal predictions.

In summary, currents at the Hen and Chickens Shoal site area are predominately controlled by the tidal currents generated by the estuary-ocean exchanges. Wind can modify these tidal currents somewhat, but does not sufficiently overcome tidal effects to generate totally unexpected current directions. East and southeast winds can, however, add measureably to the flood currents outside the Shoal near the Cape. And as the data demonstrate, flood currents can cause transport from the "Gong 5" area to the Harbor of Refuge in less than three hours.

Currents at the South Bethany Beach Site

Figure 13 and Table 5 present the results of drogue measurements of currents at the South Bethany Beach site area on June 12, 1974. Two pairs of drogues

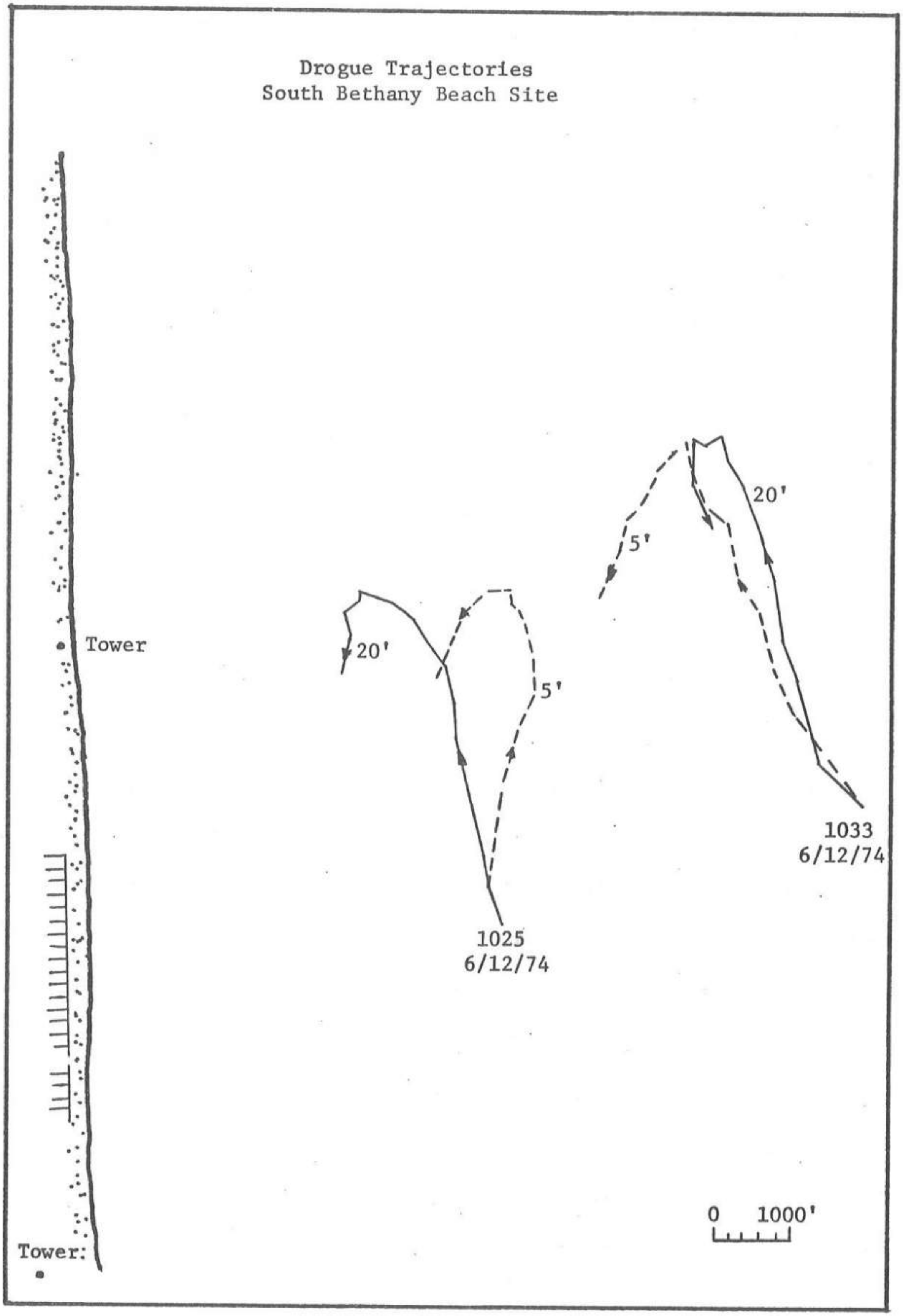

Drogue Trajectories
South Bethany Beach Site
Tower
20'
5'
1025
6/12/74
20'
5'
1033
6/12/74
0 1000'
Tower

Figure 13

Table 5

Current Data - South Bethany Beach Site

6/12/74

Tides	Rehobeth	Fenwick Light House
High	0106	0100
Low	0715	0656
High	1343	1337
Low	1951	1932

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Direction °from N	Remarks
13	5'	1033	Start			2 mi. offshore
		1058	750	0.50	321	50' of water
		1130	900	0.47	321	
		1150	650	0.54	334	
		1218	775	0.46	344	
		1239	575	0.46	324	
		1300	700	0.56	348	
		1322	400	0.30	308	
		1343	325	0.25	330	
		1403	550	0.46	352	
		1424	325	0.26	223	
		1446	250	0.19	223	
		1506	500	0.42	208	
		1526	300	0.25	217	
		1546	400	0.33	193	
		1611	650	0.43	202	

Max. Distance from Start 5500'
Aver. Velocity = 0.24 fps.

Total Distance Traveled 8050'
Aver. Velocity = 0.23 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Direction °from N	Remarks
13	20'	1033		Start		2 mi. offshore 50' of water
		1056	850	0.62	313	
		1129	1175	0.59	344	
		1148	600	0.53	335	
		1217	850	0.49	351	
		1237	525	0.44	340	
		1257	375	0.31	340	
		1320	400	0.29	340	
		1340	400	0.33	325	
		1400	375	0.31	349	
		1422	250	0.19	234	
		1444	200	0.15	305	
		1503	150	0.13	305	
		1523	325	0.27	270	
		1544	450	0.36	270	
		1607	800	0.58	159	

Max. Distance from Start 3400'
Aver. Velocity = 0.43 fps.

Total Distance Traveled 7000'
Aver. Velocity = 0.35 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Direction °from N	Remarks
13	5'	1025		Start		1.1 mi. offshore 46' of water
		1047	475	0.36	334	
		1110	600	0.43	5	
		1141	800	0.43	8	
		1207	800	0.51	14	
		1225	550	0.51	23	
		1245	525	0.44	355	
		1307	350	0.27	342	
		1328	325	0.26	334	
		1348	150	0.13	326	
		1409	200	0.16	348	
		1429	325	0.27	268	
		1451	150	0.11	221	
		1511	375	0.31	221	
		1531	300	0.25	202	
		1552	625	0.50	202	

Max. Distance from Start 4500'
Aver. Velocity = 0.33 fps.

Total Distance Traveled 6550'
Aver. Velocity = 0.33 fps.

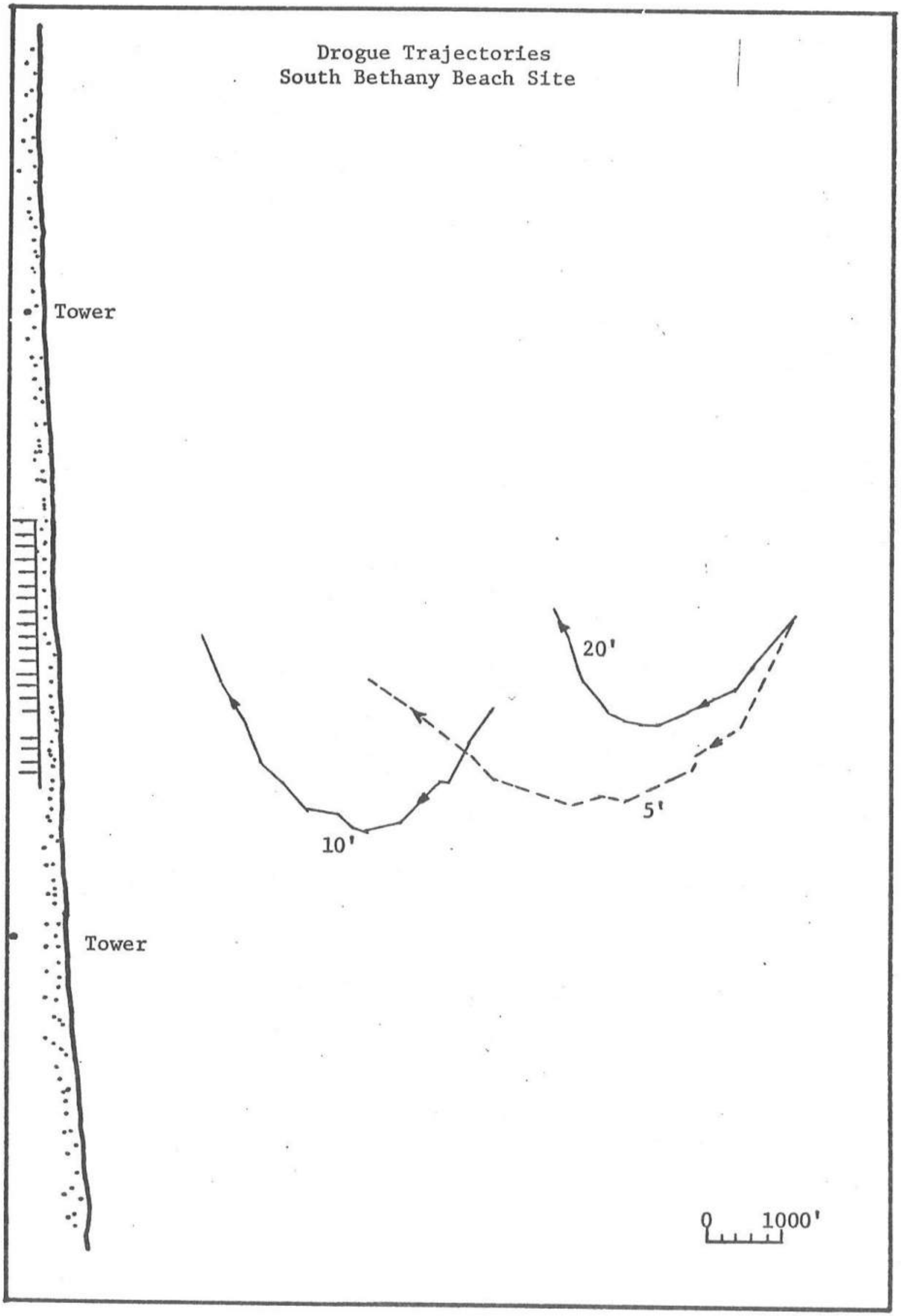
Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Direction °from N	Remarks
13	20'	1025	Start			1.1 mi. offshore 46' of water
		1047	475	0.36	336	
		1111	525	0.36	348	
		1140	775	0.45	345	
		1208	775	0.72	347	
		1228	475	0.40	354	
		1248	450	0.38	347	
		1310	450	0.34	325	
		1331	400	0.32	325	
		1351	400	0.33	302	
		1412	200	0.16	288	
		1433	200	0.16	288	
		1454	100	0.08	180	
		1514	150	0.13	230	
		1533	150	0.13	164	
		1557	600	0.42	195	

Max. Distance from Start 4900'
Aver. Velocity = 0.33 fps.

Total Distance Traveled 6000'
Aver. Velocity = 0.30 fps.

at 5' and 20' below the water surface were deployed at locations approximately one mile and two miles offshore during the flooding (northward) portion of the tide and recovered during the ebb (southward) portion. No significant vertical density structure evident from temperature and salinity measurements. Both pairs of drogues moved northward inclined slightly toward the shore until the ebb began and motion was southward inclined toward the shore. Some vertical current shear appeared in terms of trajectory separation as seen in Figure 13. This was likely due to wind effects on the surface currents. The wind during the flood tide was from the NW and shifted quickly to the NE during the ebb. The inshore drogues appear to respond to the wind as the 5' drogue moves offshore relative to the 20' drogue. However, the 5' drogue of the offshore pair moved inshore slightly relative to the 20' drogue during flood, but did respond during ebb by moving onshore. The average velocity of the offshore pair of drogues during flood was about 0.44 fps and that of the nearshore pair of drogues was about 0.34 fps.

Figure 14 and Table 6 present the results of drogue measurements at the same site area on June 14, 1974. For that day at pair of drogues at 5' and 20' below the water surface were deployed about 2 miles offshore and a single drogue at 10' was placed about 1 mile offshore during flood tide. No significant vertical density structure evident from temperature and salinity measurements. The wind was from the NE (see Table 10) and apparently delayed the flood tide drift as all drogues moved SW initially. The drogues finally turned northward at about 4 hours after the predicted (Tide Tables) low tide time. The effect of the onshore directed wind was clearly evident from the separation between the 5' and 20' drogues and the general onshore drift of all drogues. The combined effects of wind and tidal current resulted in an onshore drift of the 5' drogue of about 0.4 fps. In four hours the net northward drift was less



Drogue Trajectories
South Bethany Beach Site
Tower
20'
5'
10'
Tower
0 1000'

Figure 14

Table 6

Current Data - South Bethany Beach Site

6/14/74

Tides	Rehobeth	Fenwick Light House
High	0247	0241
Low	0902	0905
High	1527	1521
Low	2252	2255

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Direction °from N	Remarks
14	5'	1017	Start			1.9 mi. offshore 40' of water
		1036	1000	0.88	206	
		1053	625	0.61	206	
		1114	750	0.60	235	
		1125	200	0.30	189	
		1142	600	0.59	243	
		1157	450	0.50	243	
		1214	350	0.34	281	
		1230	350	0.36	256	
		1245	500	0.56	288	
		1304	625	0.55	288	
		1321	375	0.37	316	
		1340	575	0.50	307	
		1400	550	0.46	307	
		1422	700	0.53	304	

Max. Distance from Start 5850'
Aver. Velocity = 0.39 fps.

Total Distance Traveled 7400'
Aver. Velocity = 0.50 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Direction °from N	Remarks
14	20'	1017	Start			1.9 mi. offshore 40' of water
		1035	800	0.74	221	
		1052	450	0.44	216	
		1113	325	0.26	245	
		1127	375	0.45	245	
		1140	425	0.54	245	
		1155	275	0.31	267	
		1211	225	0.23	284	
		1228	275	0.27	295	
		1243	100	0.11	322	
		1302	225	0.20	322	
		1318	275	0.29	322	
		1336	200	0.19	339	
		1351	400	0.44	339	
		1417	475	0.30	330	

Max. Distance from Start 3300'
Aver. Velocity = 0.23 fps.

Total Distance Traveled 4825'
Aver. Velocity = 0.33 fps.

Figure No	Drogue Depth	Time	Δ Distance (feet)	Velocity (fps)	Direction °from N	Remarks
14	10'	1009	Start			1.1 mi. offshore 40' of water
		1026	650	0.72		
		1043	600	0.59		
		1100	100	0.10		
		1116	750	0.78		
		1132	550	0.57		
		1147	225	0.25		
		1203	275	0.29		
		1219	425	0.44		
		1235	425	0.44		
		1252	400	0.39		
		1310	600	0.56		
		1326	600	0.63		
		1345	650	0.57		

Max. Distance from Start 4100'
Aver. Velocity = 0.32 fps.

Total Distance Traveled 6250'
Aver. Velocity = 0.48 fps.

than 1000' while the drift onshore was over 1 mile for the surface drogues.

The tidal currents at the South Bethany Beach site are relatively weak and wind induced currents may have significant effects on the magnitude and direction of the velocity. Drogue trajectories indicated that the tidal current portion of the motion may be more of the rotary type than the estuarine type found at the Hen and Chickens Shoal site. There exist no tidal current predictions along the coast as close to shore as the South Bethany Beach site, but rotary tidal currents are predicted at for the Fenwick Shoal Lighted Whistle Buoy 2 area, some fourteen miles offshore of the site (13). These predictions of tidal current magnitude and direction for two different days are compared with the deep (20') drogue motions in Table 9. The direction of motion was predicted reasonably as well as the magnitude, although wind effects on the water mass motion were neglected. A third comparison is shown in Table 9 which includes a prediction of the wind effects. Wind data for the study period (see Table 10) were used to estimate wind-induced current magnitude and direction. Again wind-induced current magnitude was estimated to be 3% of the wind speed. That current was combined in a vector sense with the rotary tidal current to provide predictions of water motion in the site area. Comparison with measured data indicated reasonable agreement with current direction and magnitude. Considering the distance offshore of the rotary tidal current predictions and the neglect of shoreline geometry, these predictions seem remarkably good.

In summary, the currents in the South Bethany Beach site area seem to be composed of rather weak tidal currents, which appear rotary in nature, and are substantially modified direction and magnitude by the wind. Measurements indicate that a tidal excursion, under conditions where wind in unimportant, accounts for drift parallel to the coastline of only about two miles. Wind conditions can modify this excursion length by causing onshore or offshore drift which

Table 9

Comparison Between Predicted and Measured Currents

South Bethany Beach Site

a) For 20′ nearshore drogue 6/12/74

(Predicted rotary tidal currents for Fenwick Shoal Lighted whistle Buoy 2)

Time	Predicted Velocity	Predicted Direction	Measured Velocity	Measured Direction
	fps	° from N	fps	° from N
1027	0.17	282	—	336
1127	0.34	318	0.40	346
1203	0.34	342	0.72	354
1303	0.34	349	0.34	325
1403	0.17	357	0.16	288
1503	0.17	43	0.13	164

b) For 20′ offshore drogue 6/14/74

(Predicted rotary tidal currents for Fenwick Shoal Lighted Whistle Buoy 2)

Time	Predicted Velocity	Predicted Direction	Measured Velocity	Measured Direction
	fps	° from N	fps	° from N
1017	0.34	185		221
1117	0.17	226	0.26	245
1217	0.17	282	0.23	295
1317	0.34	318	0.29	339

c) For 5′ offshore drogue 6/14/74

(Predicted rotary tidal currents for Fenwick Shoal Lighted Whistle Buoy 2 plus wind-induced surface current)

Time	Predicted Velocity	Predicted Direction	Measured Velocity	Measured Direction
	fps	° from N	fps	° from N
1017	0.60	204	0.88	206
1117	0.47	225	0.60	240
1217	0.40	245	0.34	256
1317	0.58	296	0.37	307

Table 10

Wind Data - Hen and Chickens Shoal Site

(taken at Roosevelt Inlet)

Date	Time	Wind(mph) (aver. over hour)
6/11/74	0800	17 WNW
	0900	16 WNW
	1000	14 WNW
	1100	14 WNW
	1200	13 WNW
	1300	13 WNW
	1400	11 NW
	1500	11 NW
	1600	12 NW
6/13/74	0800	8 ENE
	0900	11 ENE
	1000	13 NE
	1100	14 NE
	1200	13 NE
	1300	13 NE
	1400	13 NE
	1500	10 E
	1600	11 E

shorten its length parallel to the shore. Dye studies (discussed below) show that winds from the South can provide significant offshore movement.

C. Dye Studies

A dye study was carried out at each of the site areas. The purposes for these studies were to observe the correlation between the drift of a dye patch and current drogues in the same water mass and to obtain some feel for the degree of mixing due to turbulent diffusion.

The dye studies were carried out as follows. A rhodamine dye solution was mixed with the surface waters of the site by discharging it in the wake of a small boat. Dye patches were formed by having the boat spiral outward from a surface drogue, thus forming a circular dye patch. The location of the patch was found by using sexton angles as was done for the drogues or by using the vessel's Loran navigational system. Drogues were deployed in and around the initial dye patch to determine whether the surface drogues traveled with the dyed water mass. Aerial photographs of the dye patch and vessel were made at regular intervals during the drift and spreading of the patch. These photographs provide a visual measurement of the spreading. Surface water was pumped on board the research vessel and passed through a Turner III Fluorometer and recorder system to aid in the measurement of the patch spreading.

Hen and Chickens Shoal Site

On August 30, 1974 a dye study was conducted at the Hen and Chickens Shoal site during ebb tide. At about 0920 EDT approximately 3 gallons of dye solution were deployed to form a patch about 4 miles offshore. High water slack was at 0900, with maximum ebb tide at 1159 and Low water slack at 1553. The wind was from the W to NW at about 10 knots. The location,

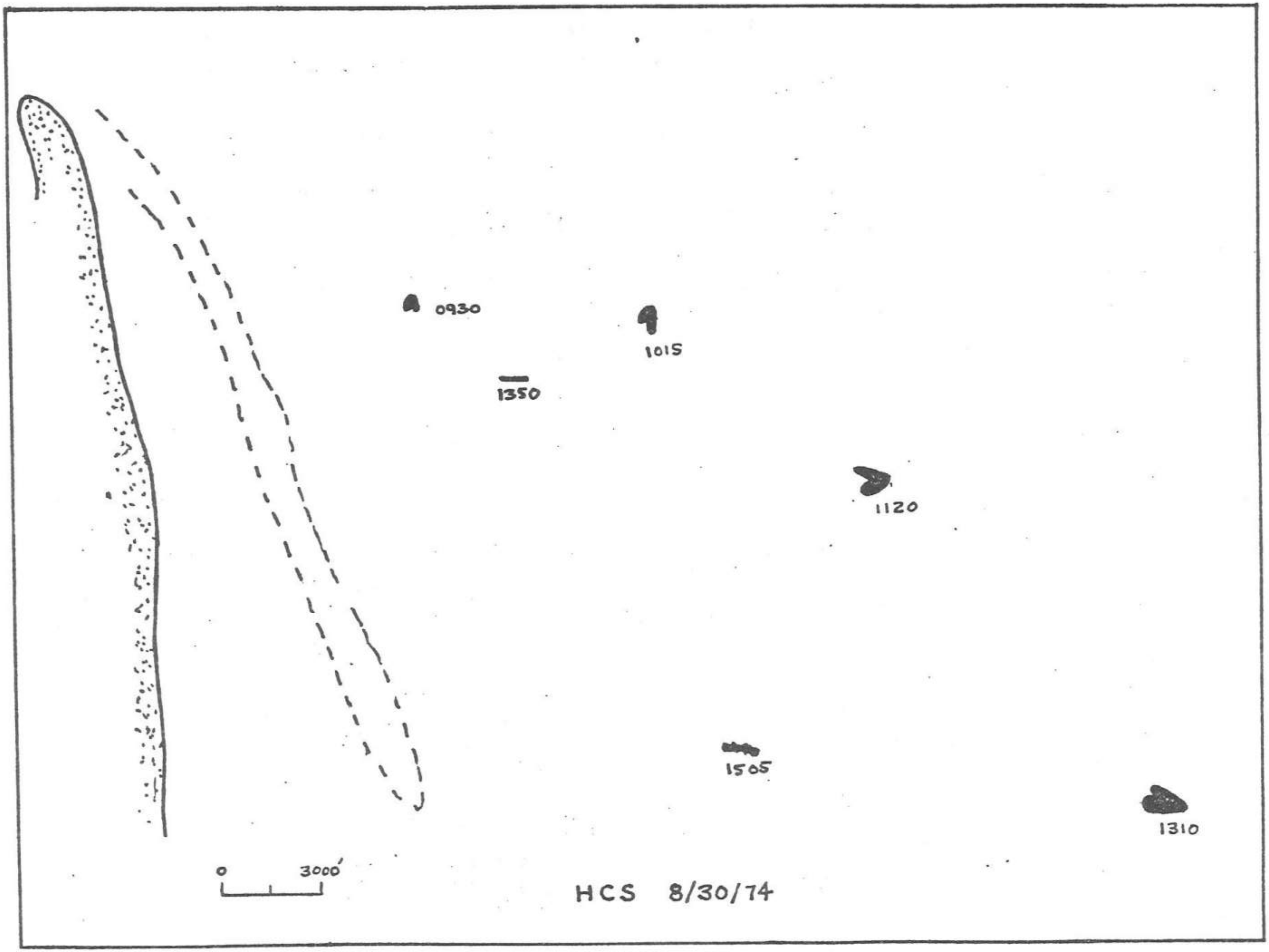


Figure 15

shape, and size of the patch are shown in Figure 15. A line of dye was deployed at about 1340 and 4.5 miles offshore. Its position was recorded until 1526 (Figure 15). The initial patch drifted to a location almost 12 miles offshore in about 3 hours and the line patch drifted SE to a location about 7 miles offshore. For both patches, the surface drogues (5') deployed in and around the dye traveled with the dye at speed exceeding 3 fps due to the combined wind and tide currents. Deeper drogues lagged the surface drift. It appears as though the previous current measurements made using surface drogues (5') are representative of surface water movement at this site.

South Bethany Beach Site

On August 29, 1974 a dye study was conducted at the South Bethany Beach site during the southward ebb of the tide. At about 1100 EDT approximately 5 gallons of dye solution were deployed to form a patch about 2.3 miles offshore. The wind was from the S and SE at about 7 knots and the sea was rough (4' - 5' waves). The location, shape, and size of the patch are shown in Figure 16. The patch moved as would be predicted by rotary tidal calculations (discussed in II B) and the surface drogues stayed with the dye patch. Drift velocities were on the order of 0.3 fps, and the dye stretched out in the SW direction.

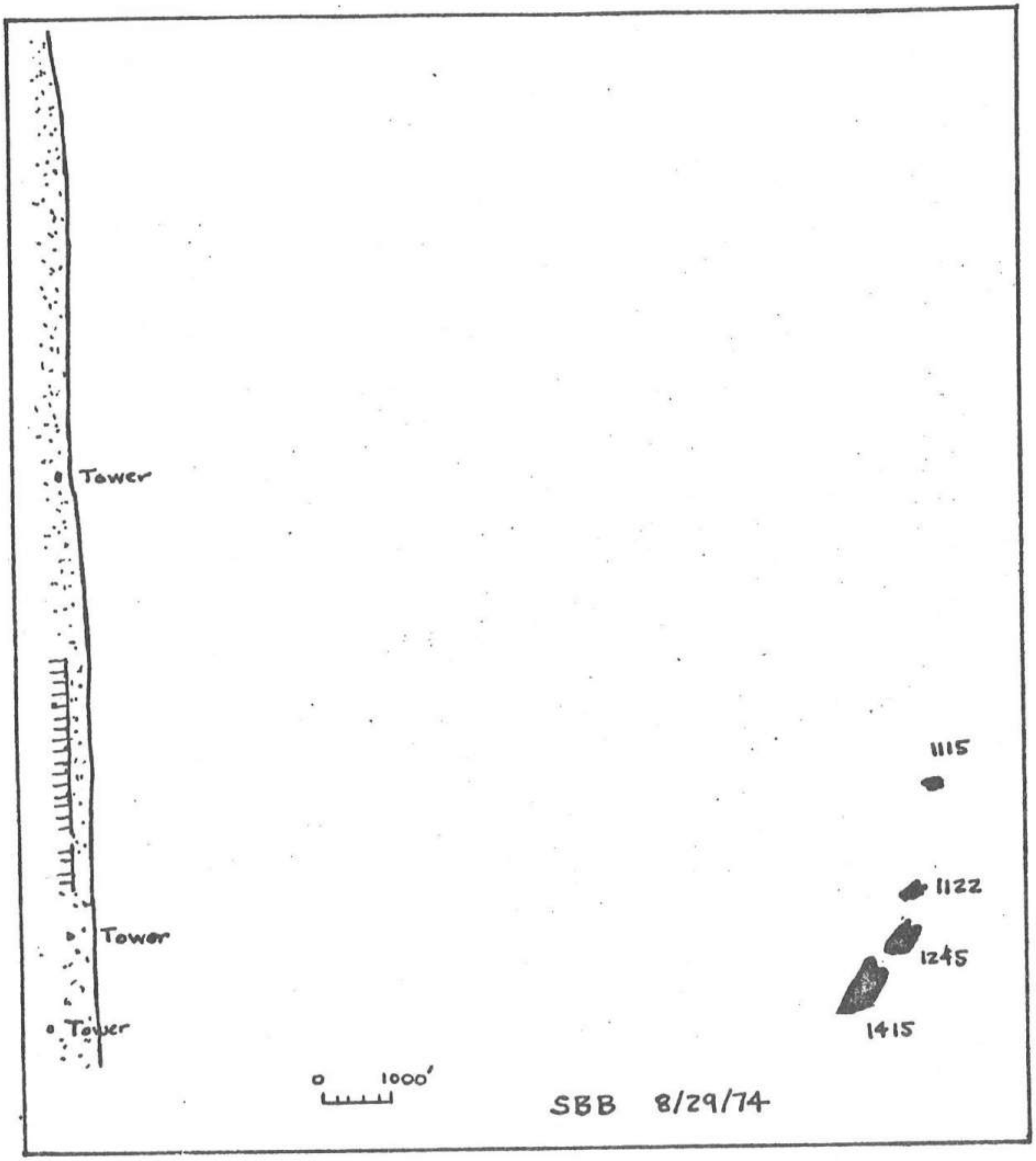


Figure 16

D. Wind Data

The effect of wind-induced currents on the water mass movement at both site areas has been discussed in terms of the current data gathered. Of primary interest with regard to the outfall site evaluation are the predominance and magnitude of winds which will result in transport of the effluent to the shoreline or Bay or other areas of particular concern.

Maurer and Wang (9) have surveyed the literature with regard to wind data in the Delaware Bay and coastal region. Figure 17a, 17b, and 17c show the prevailing wind directions on a monthly basis for seven points of measurement in the area. These results were obtained, without regard to wind speed, by finding the three adjacent wind directions with the highest total frequency of winds for different velocity categories. The data points of particular interest for this study are Indian River Inlet, Cape May, and Five Fathom Lightship. Detail wind rose data, showing frequency of wind direction and speed are given in Figures 18a through 18f for Cape May, Figures 19a through 191 for Five Fathom Lightship, and Figures 20a through 20f for Indian River Inlet.

Hen and Chickens Shoal Site

Because of the orientation of the coastline and the deviation of wind-induced current directions from the wind direction, winds from the NE to E drive wind-induced currents toward the beach and winds from the E to S drive wind-induced currents toward the Harbor of Refuge at the Hen and Chickens Shoal site. Inspection of the wind data indicates that in the winter months (November to March) the prevailing winds are from the WNW and NW. During the spring, the prevailing winds shift to W at the onshore stations and to SES and S at the offshore stations. Summer months show winds prevailing from the

SW and S. October and November records indicate the prevailing winds come from the E and NE.

South Bethany Beach Site

Because the coastline extends almost N-S at the South Bethany Beach Site area, wind-induced currents generated by winds from the NE to SE affect transport toward the beach. As discussed above, the prevailing winds are oriented in that way principally during October and November. However, inspection of the wind rose records at Indian River Inlet indicates above average probabilities for NE winds in May and SE winds in June and July.

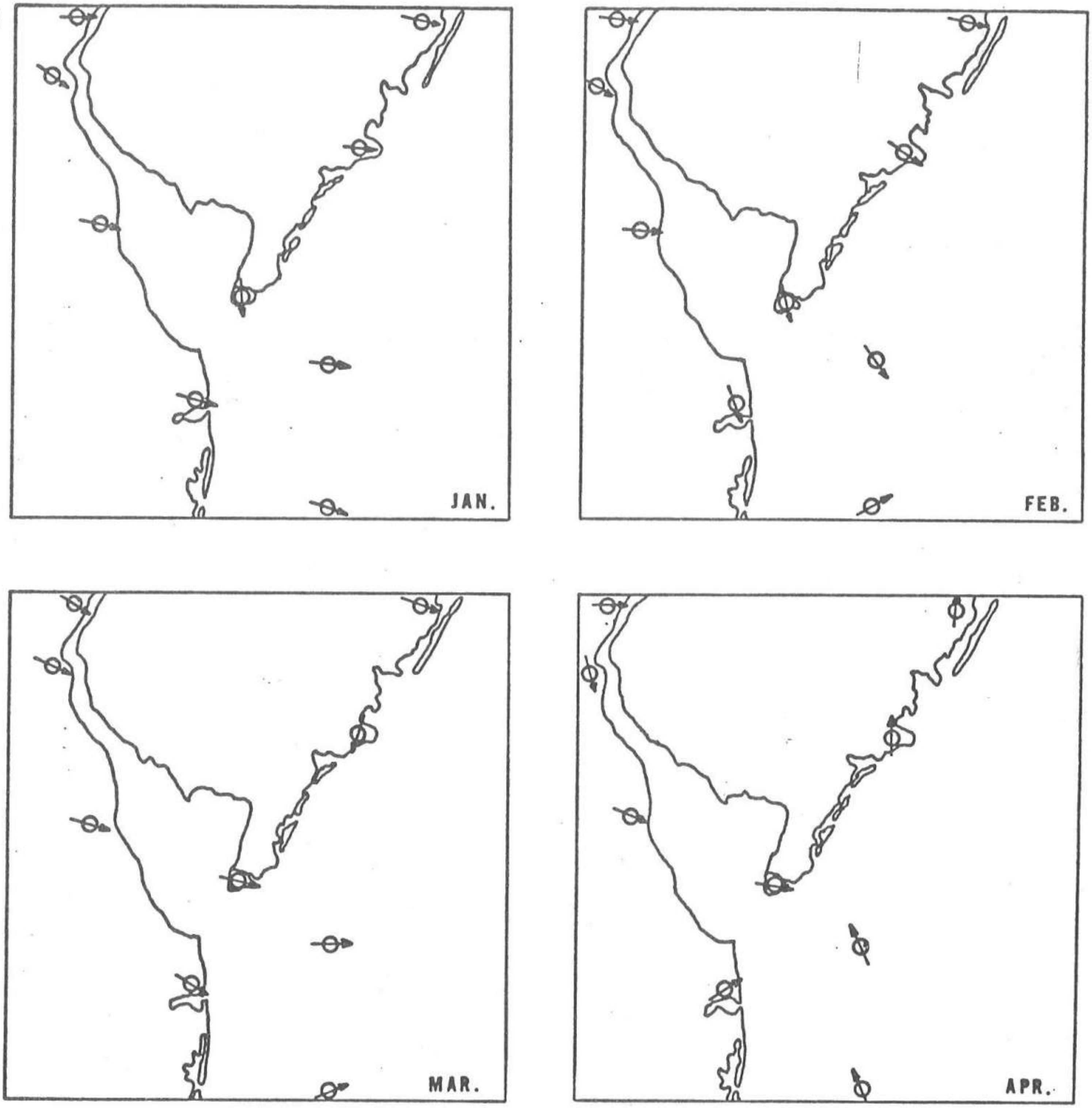


FIGURE 17a. MONTHLY VARIATION IN PREVAILING WIND DIRECTION

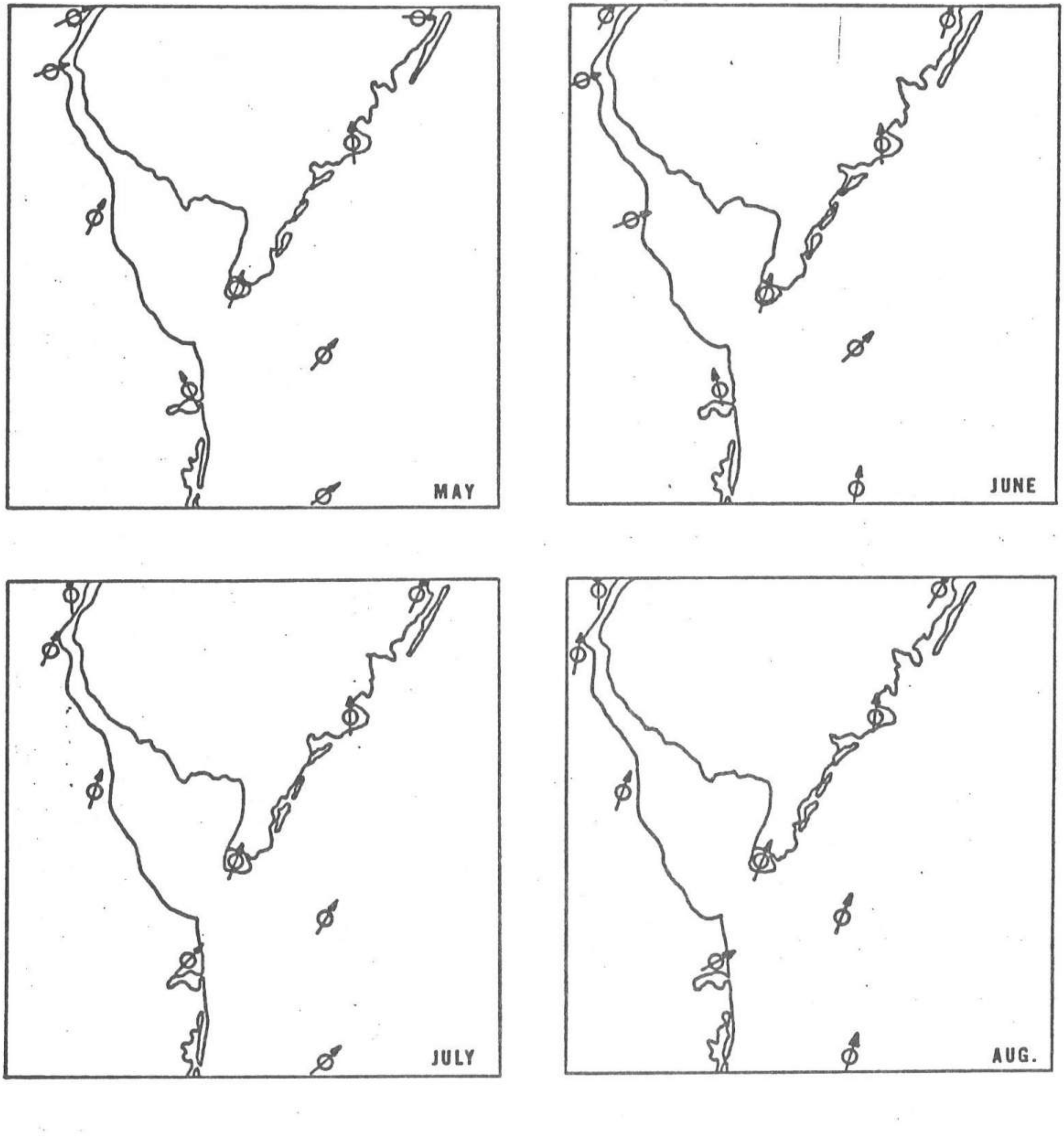


FIGURE 17b. MONTHLY VARIATION IN PREVAILING WIND DIRECTION

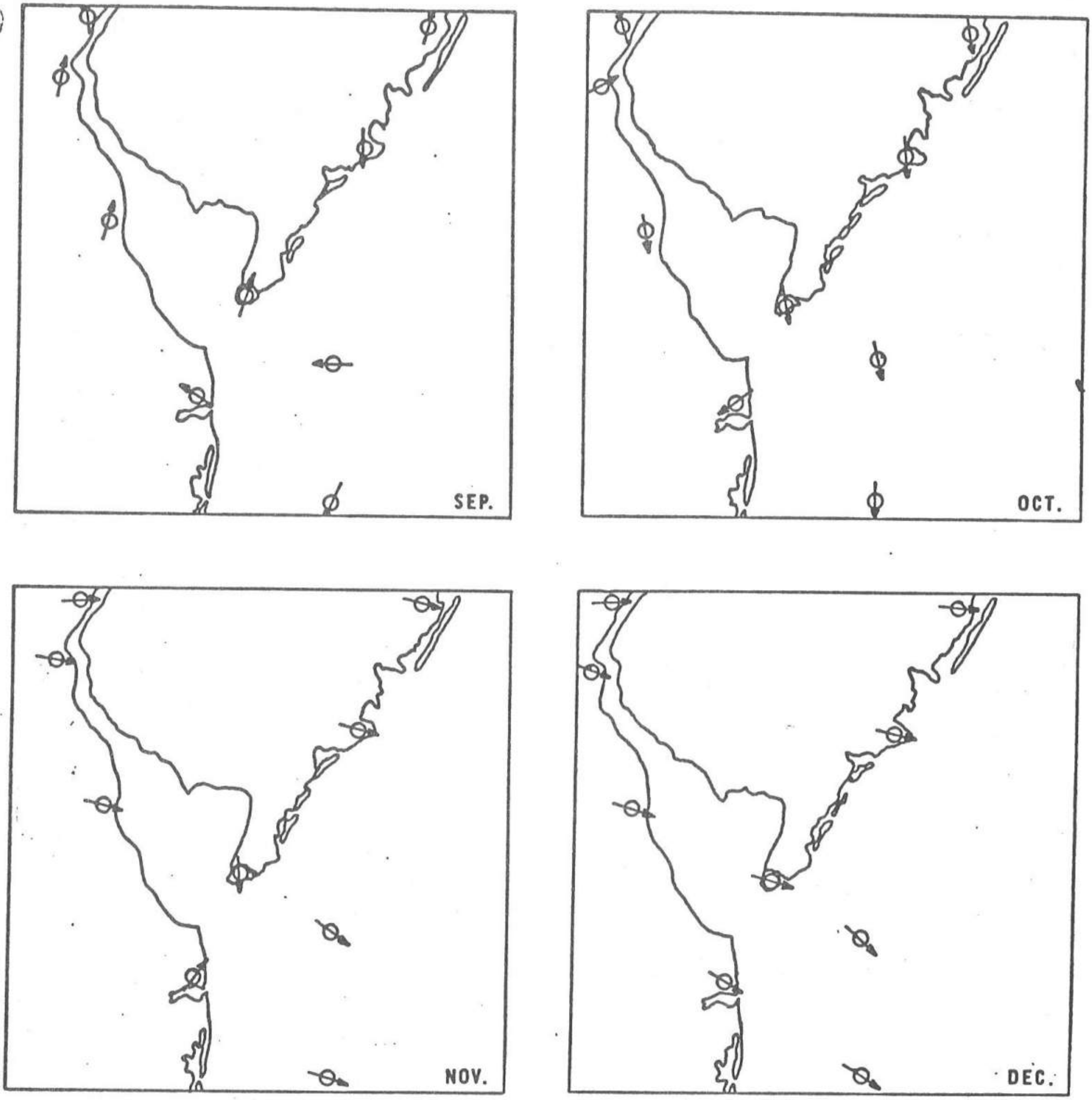


FIGURE 17c. MONTHLY VARIATION IN PREVAILING WIND DIRECTION

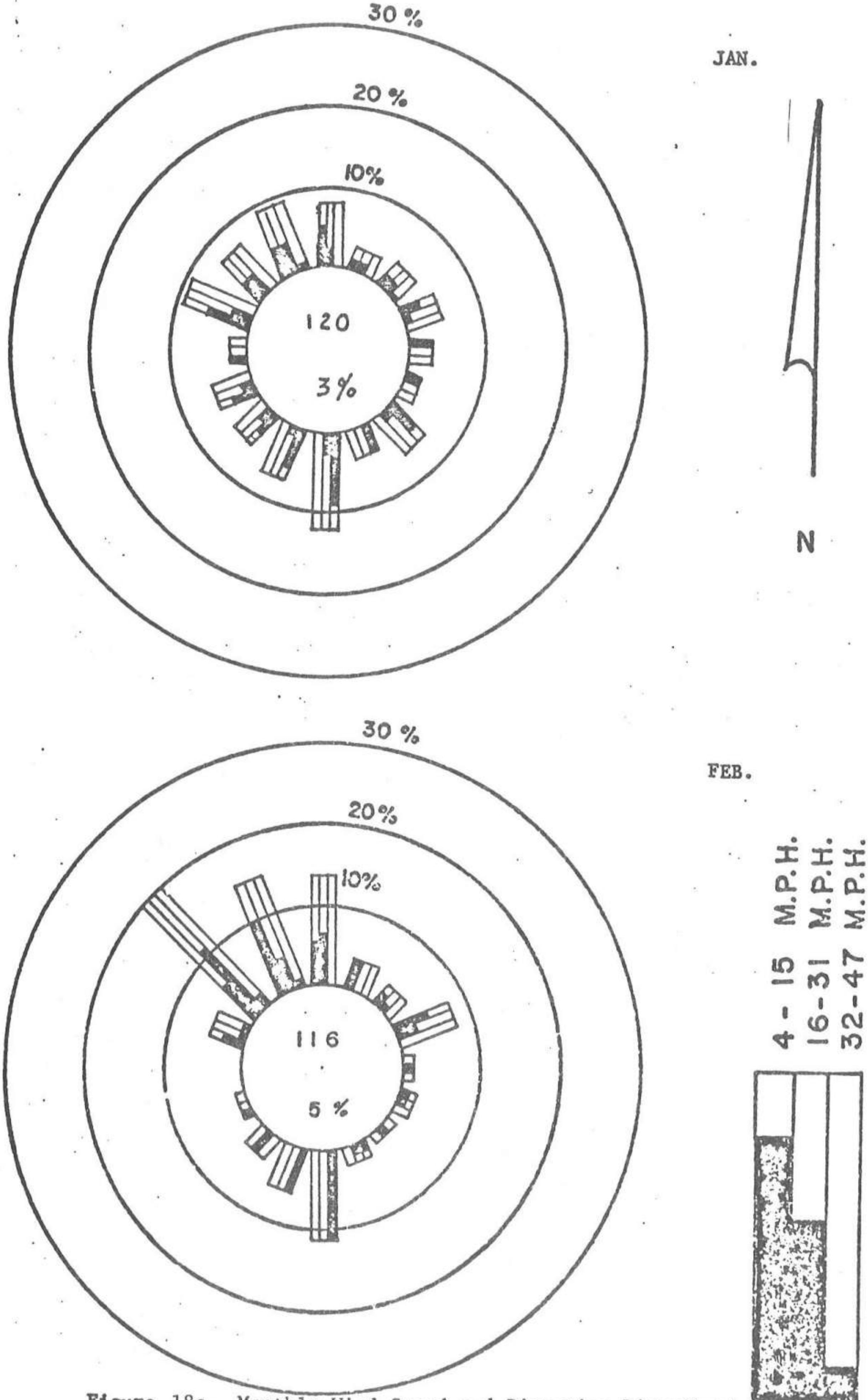


Figure 18a. Monthly Wind Speed and Direction Distributions at Cape May, New Jersey

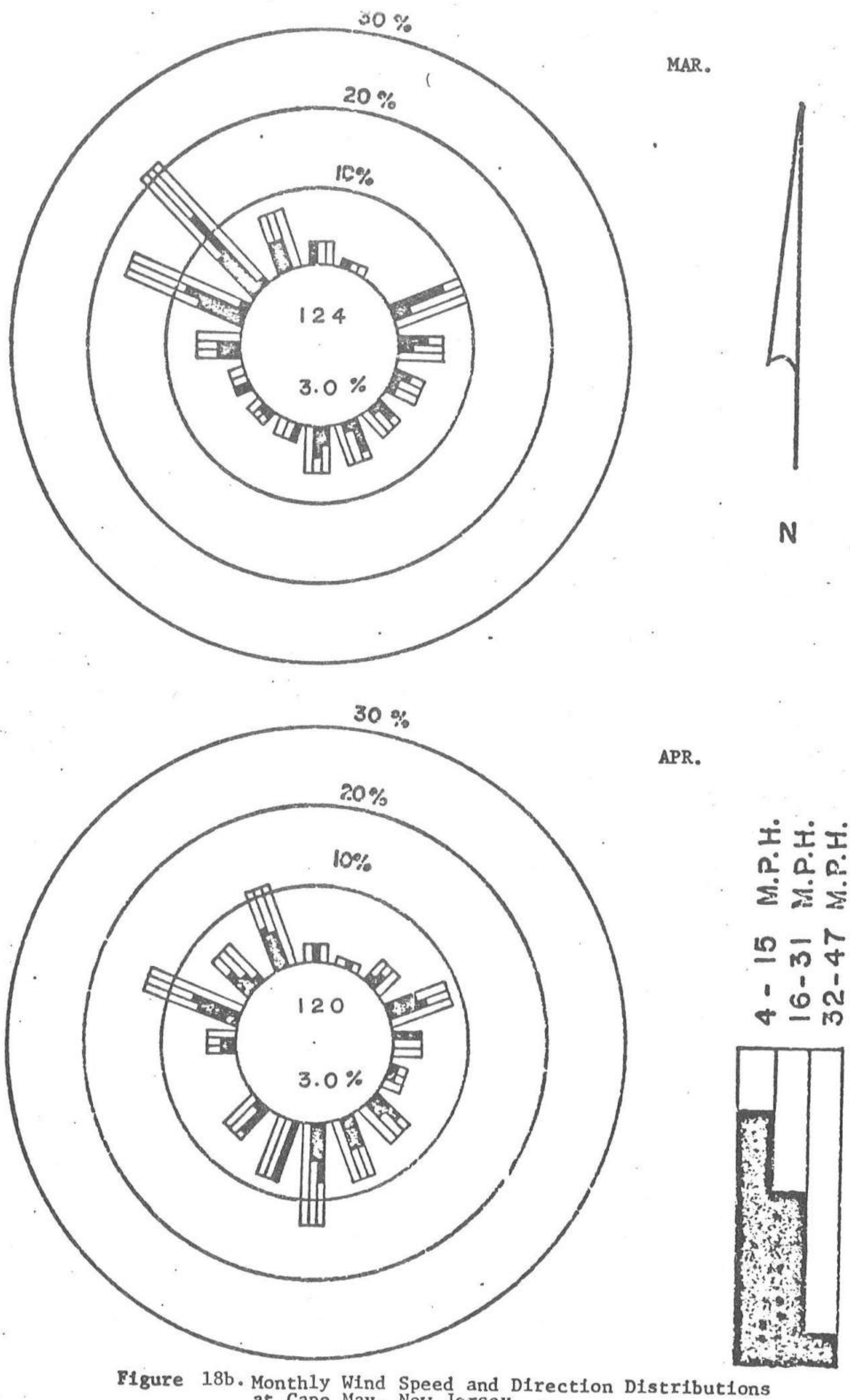


Figure 18b. Monthly Wind Speed and Direction Distributions at Cape May, New Jersey

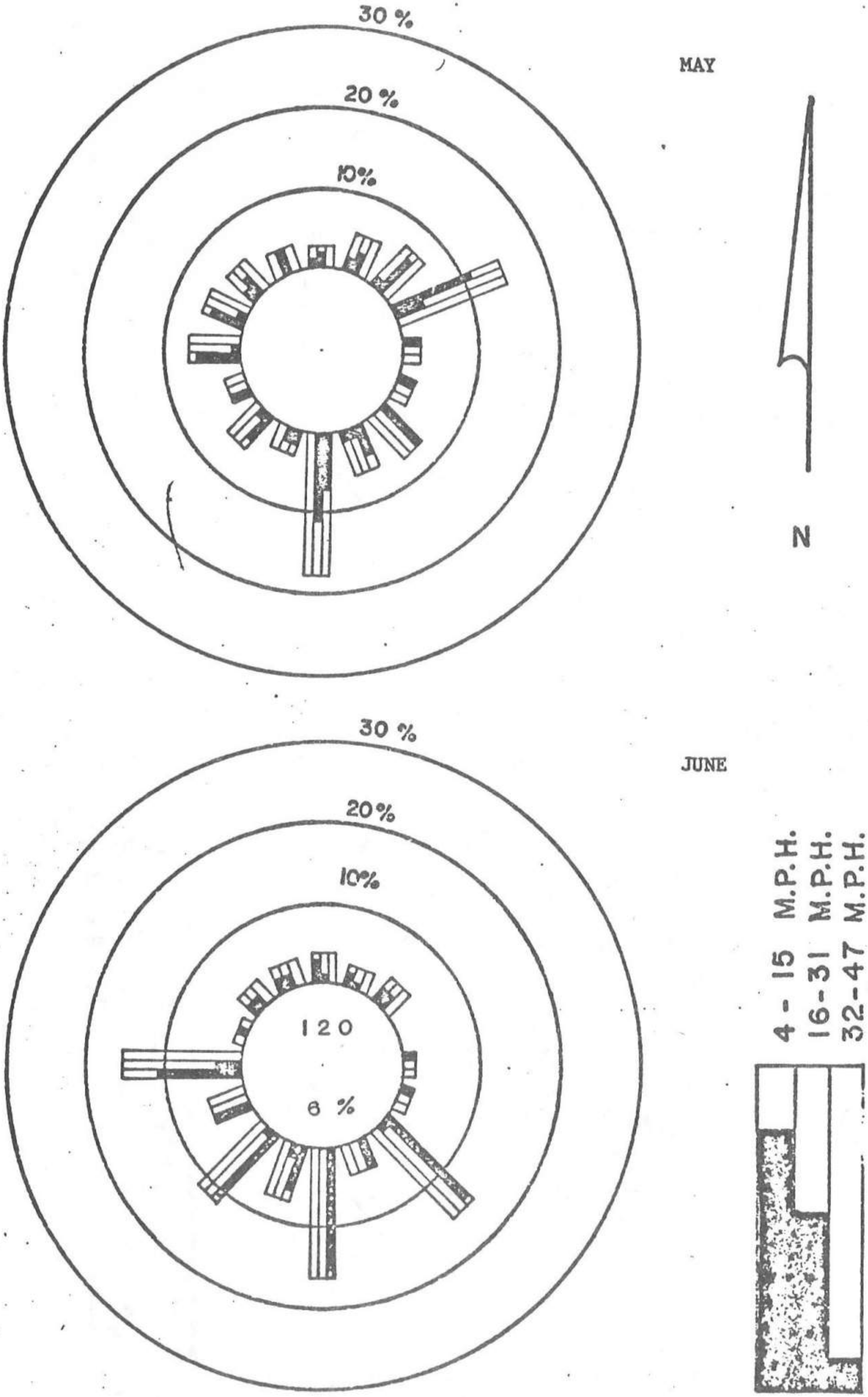


Figure 18c. Monthly Wind Speed and Direction Distributions at Cape May, New Jersey

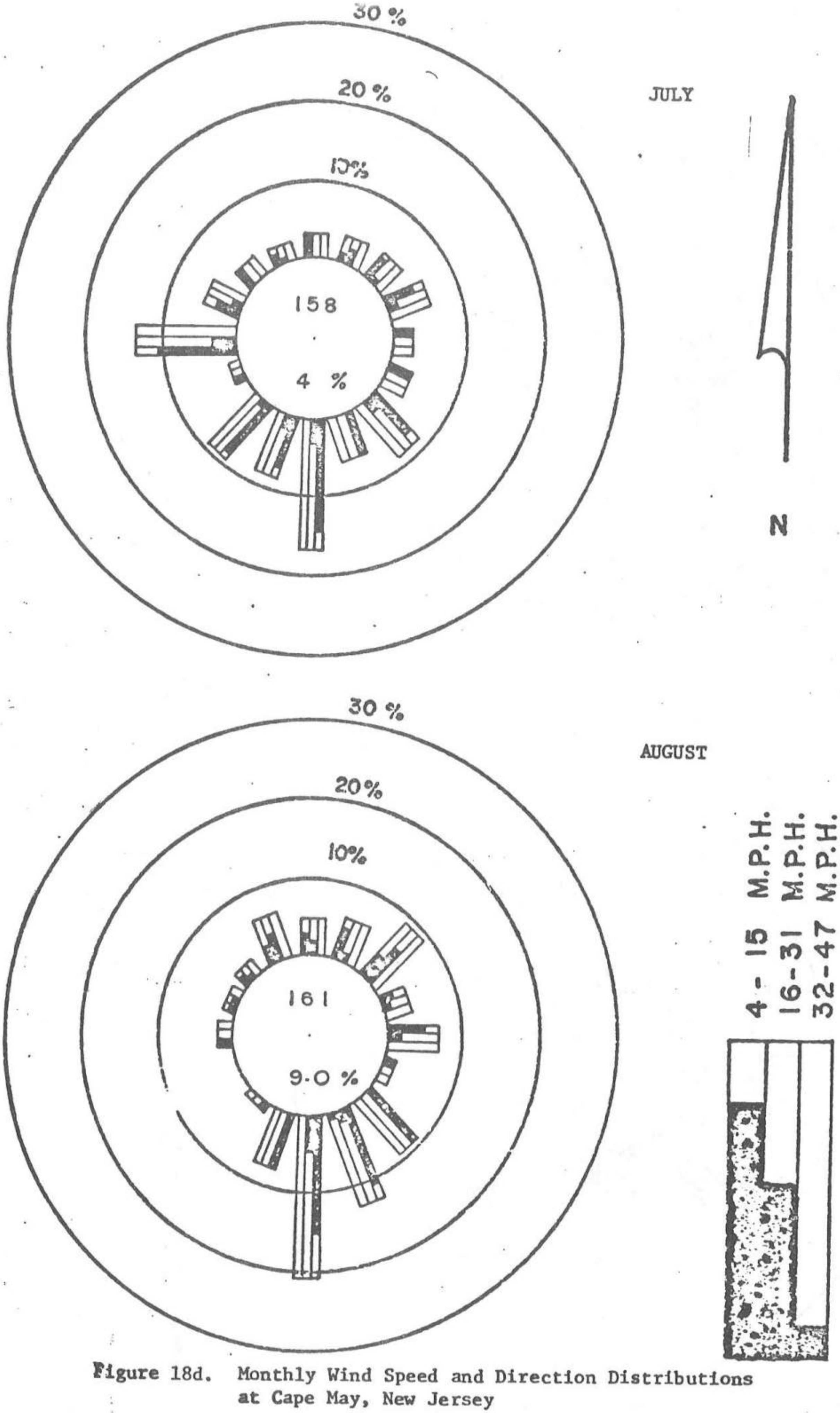


Figure 18d. Monthly Wind Speed and Direction Distributions at Cape May, New Jersey

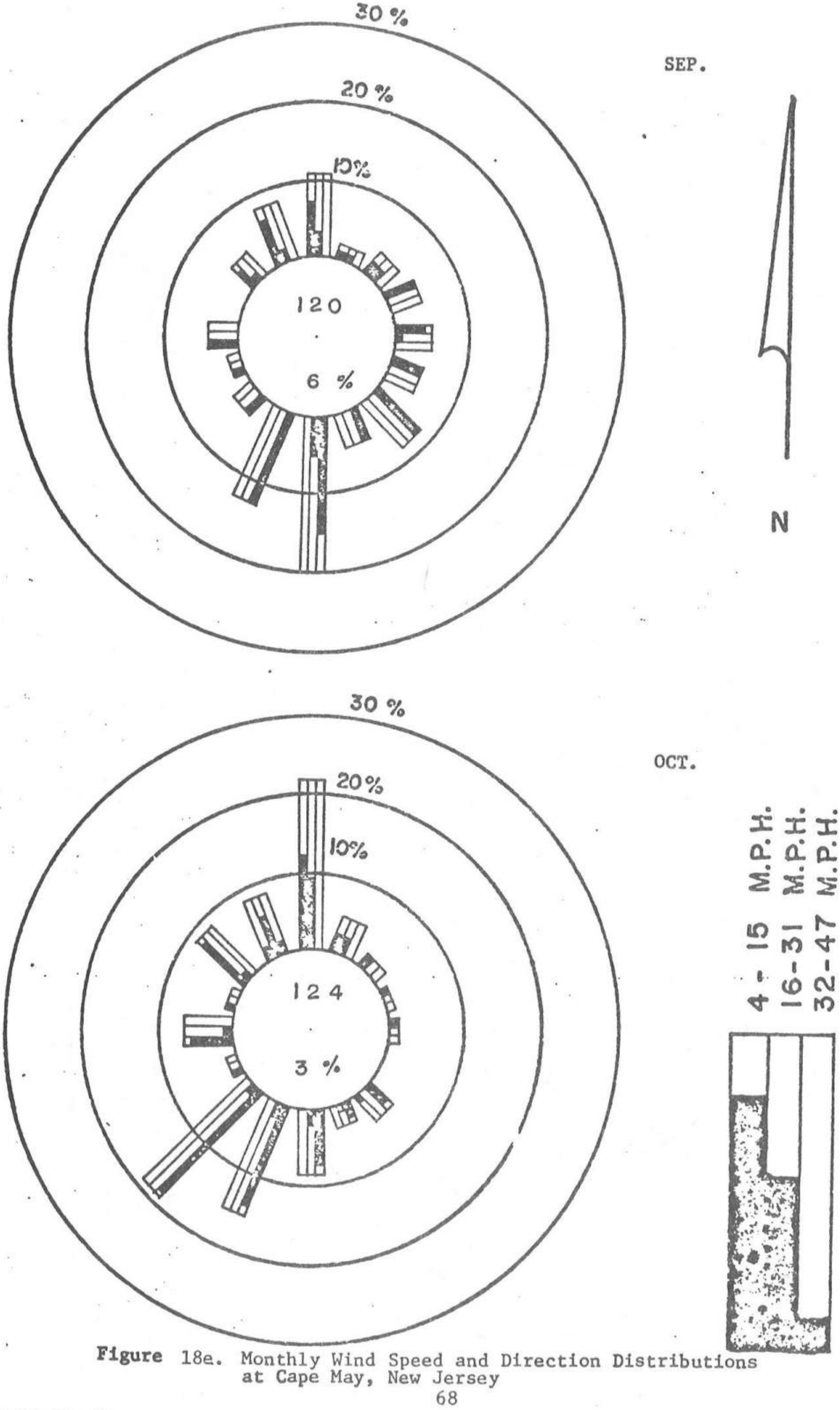


Figure 18e. Monthly Wind Speed and Direction Distributions at Cape May, New Jersey

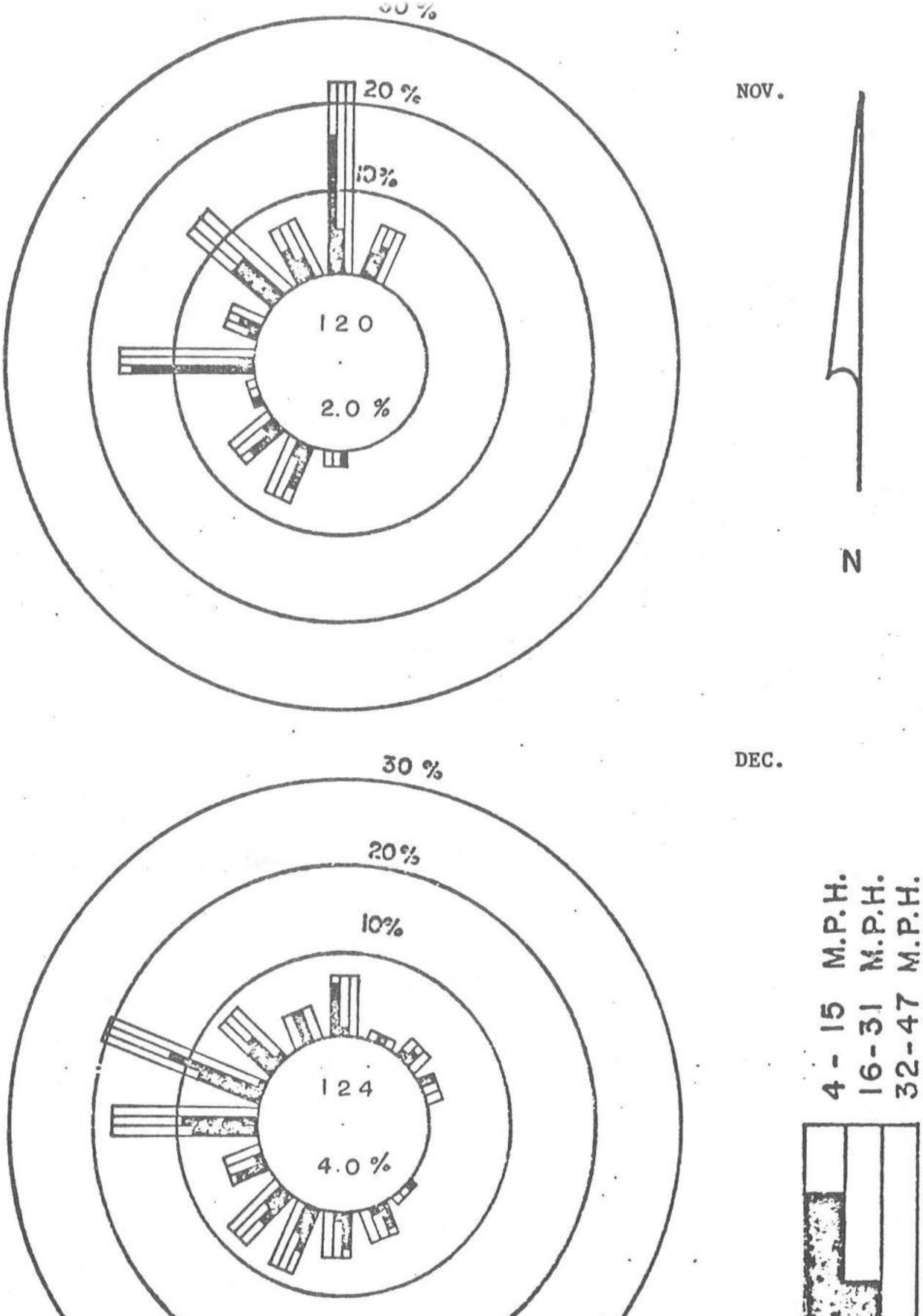
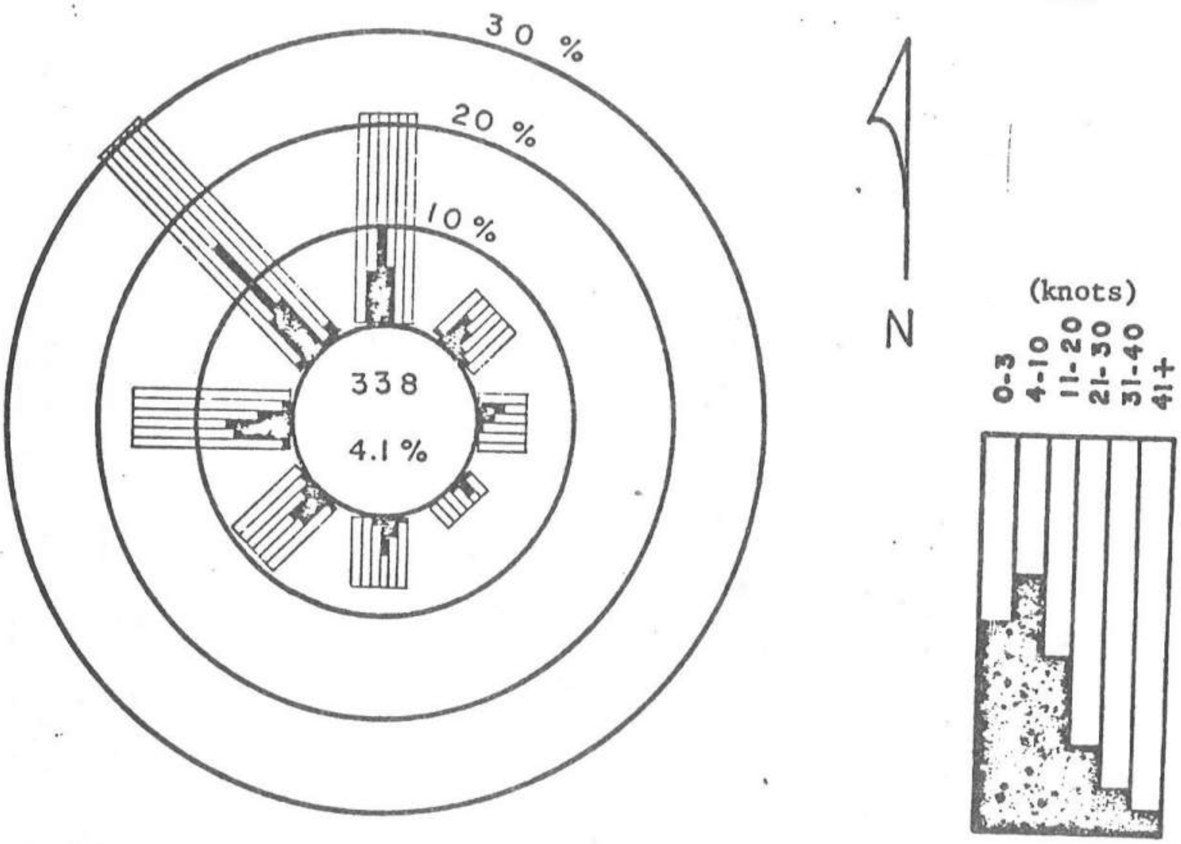


Figure 18f. Monthly Wind Speed and Direction Distributions at Cape May, New Jersey



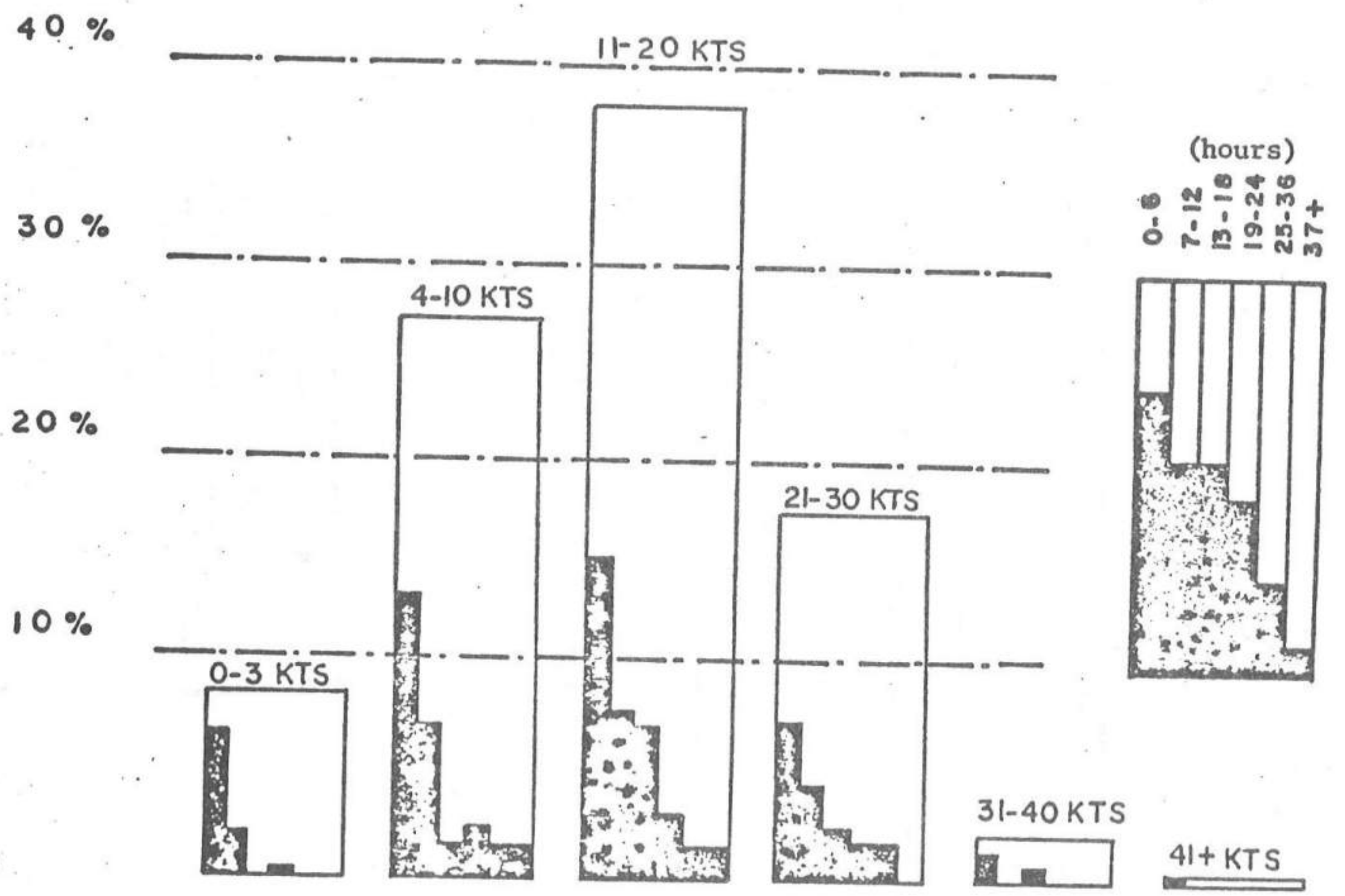


Figure 19a. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware

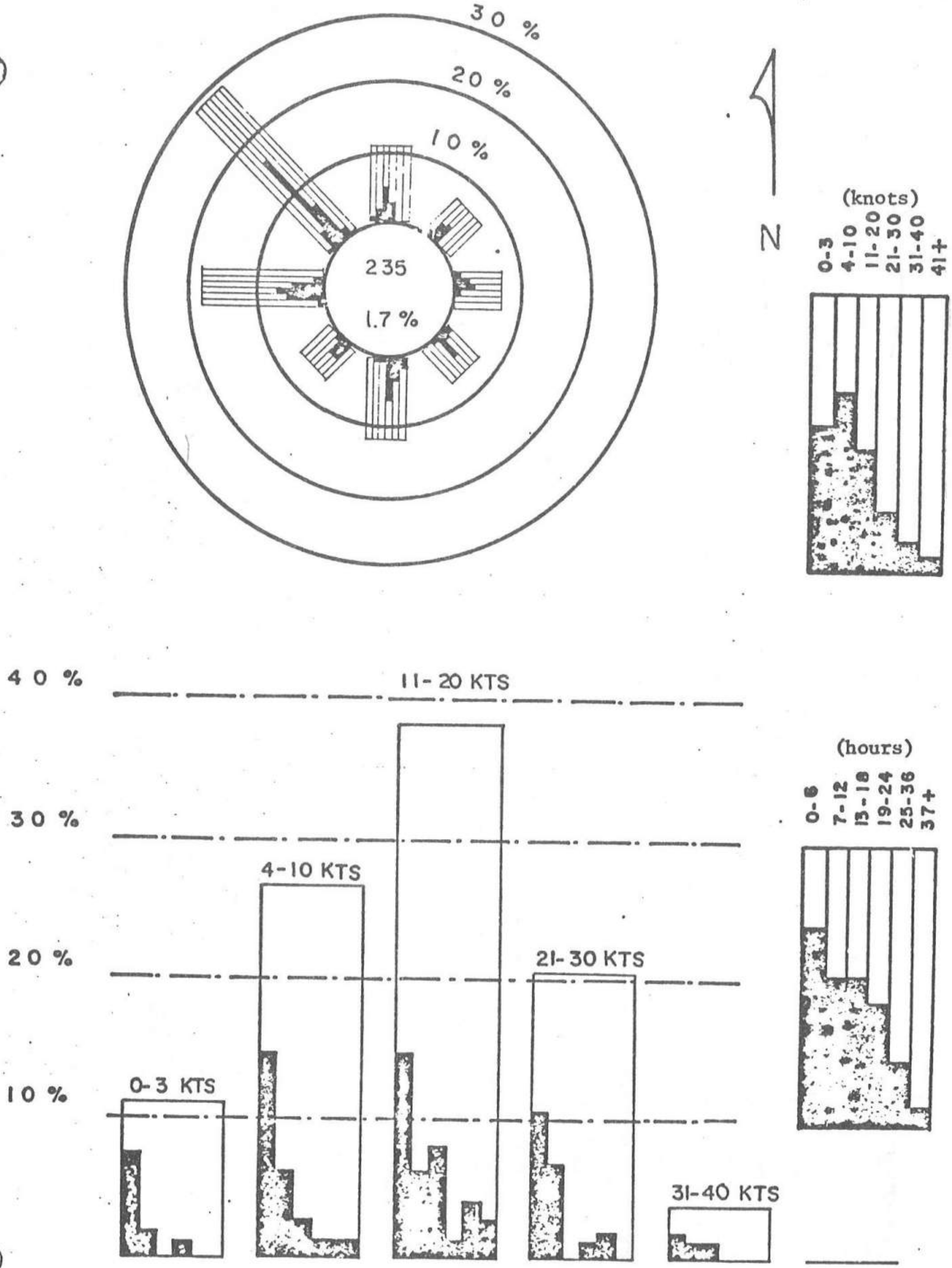


Figure 19b. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware

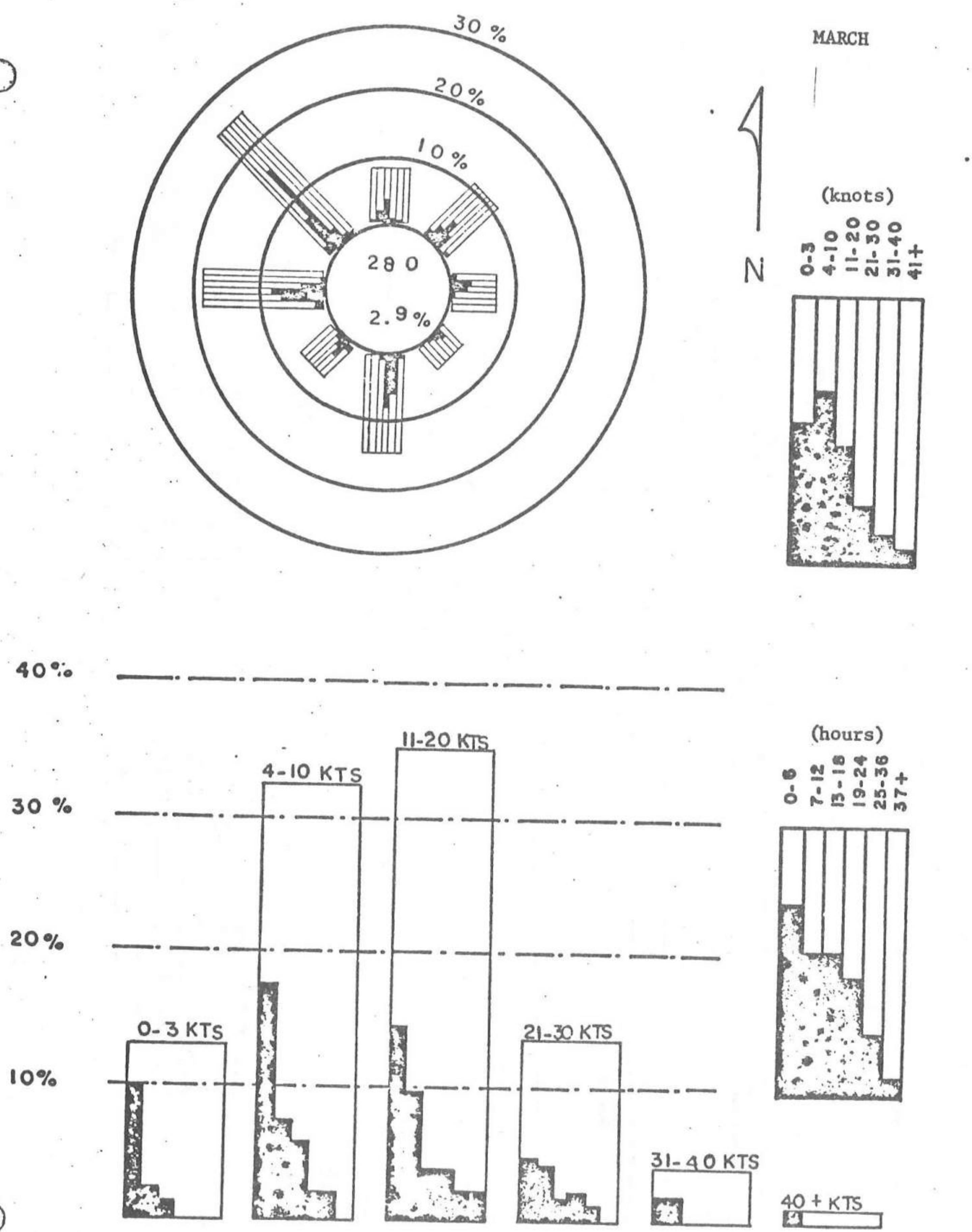
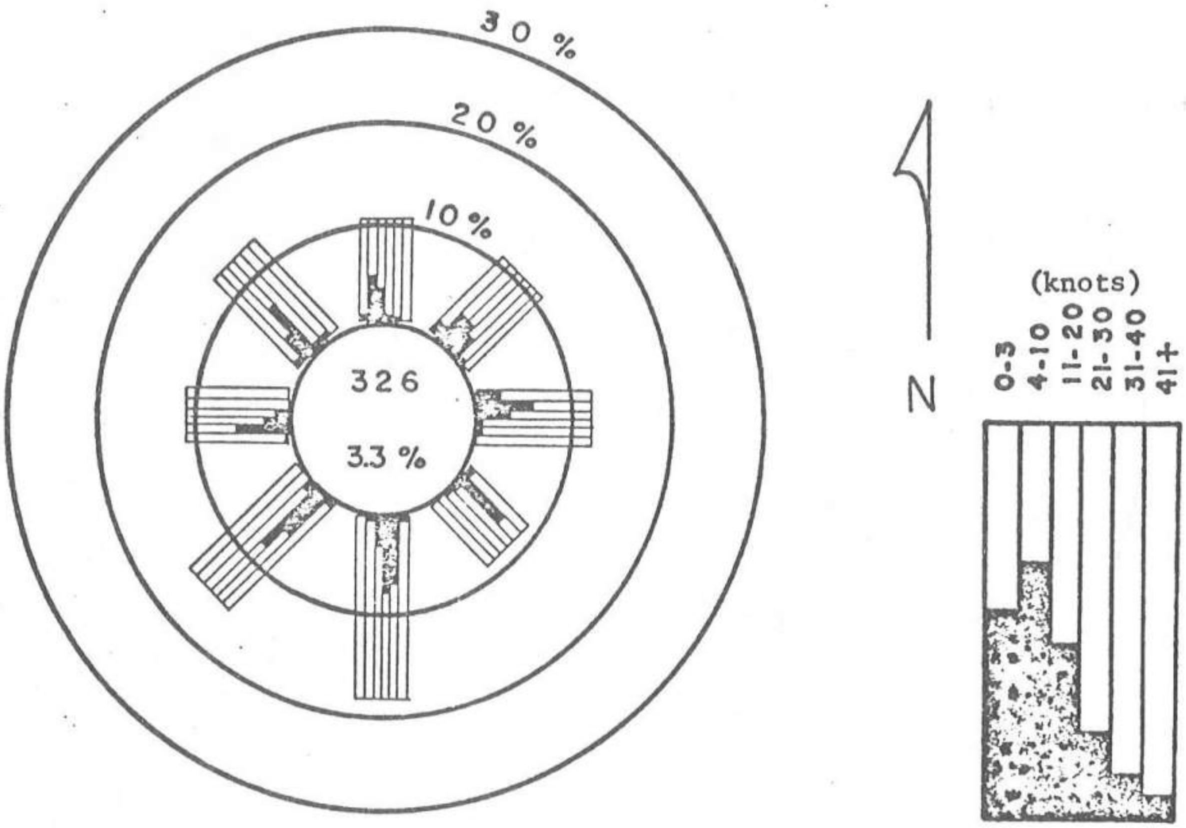


Figure 19c. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware



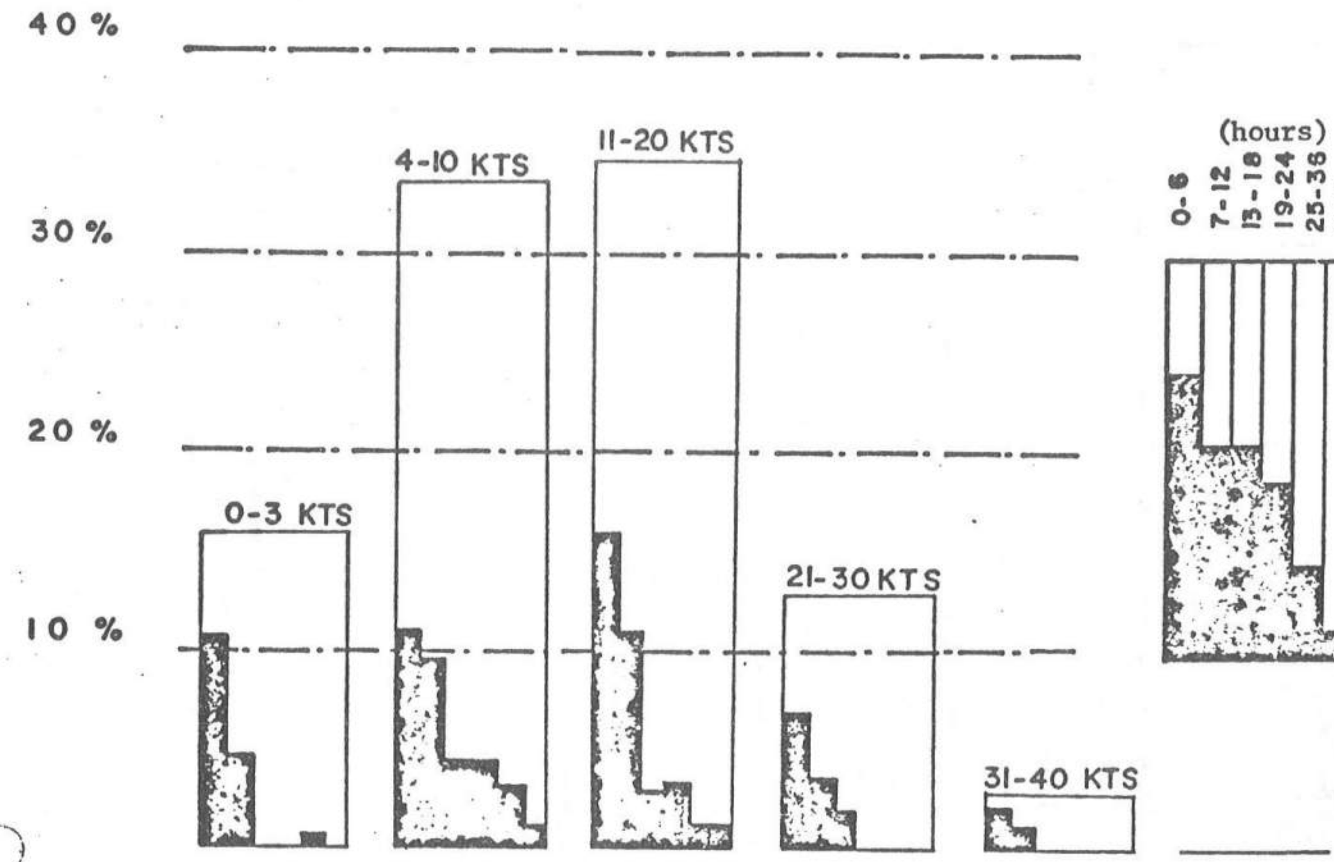
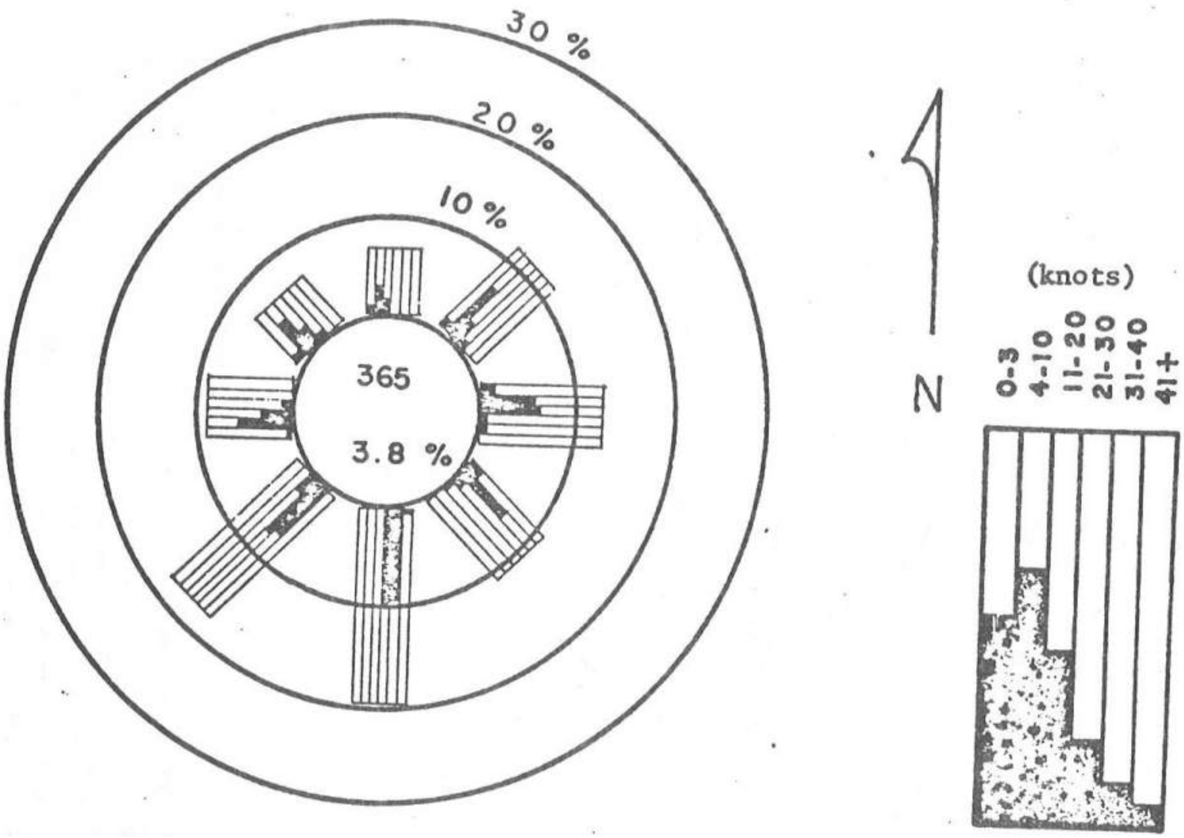


Figure 19d. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware



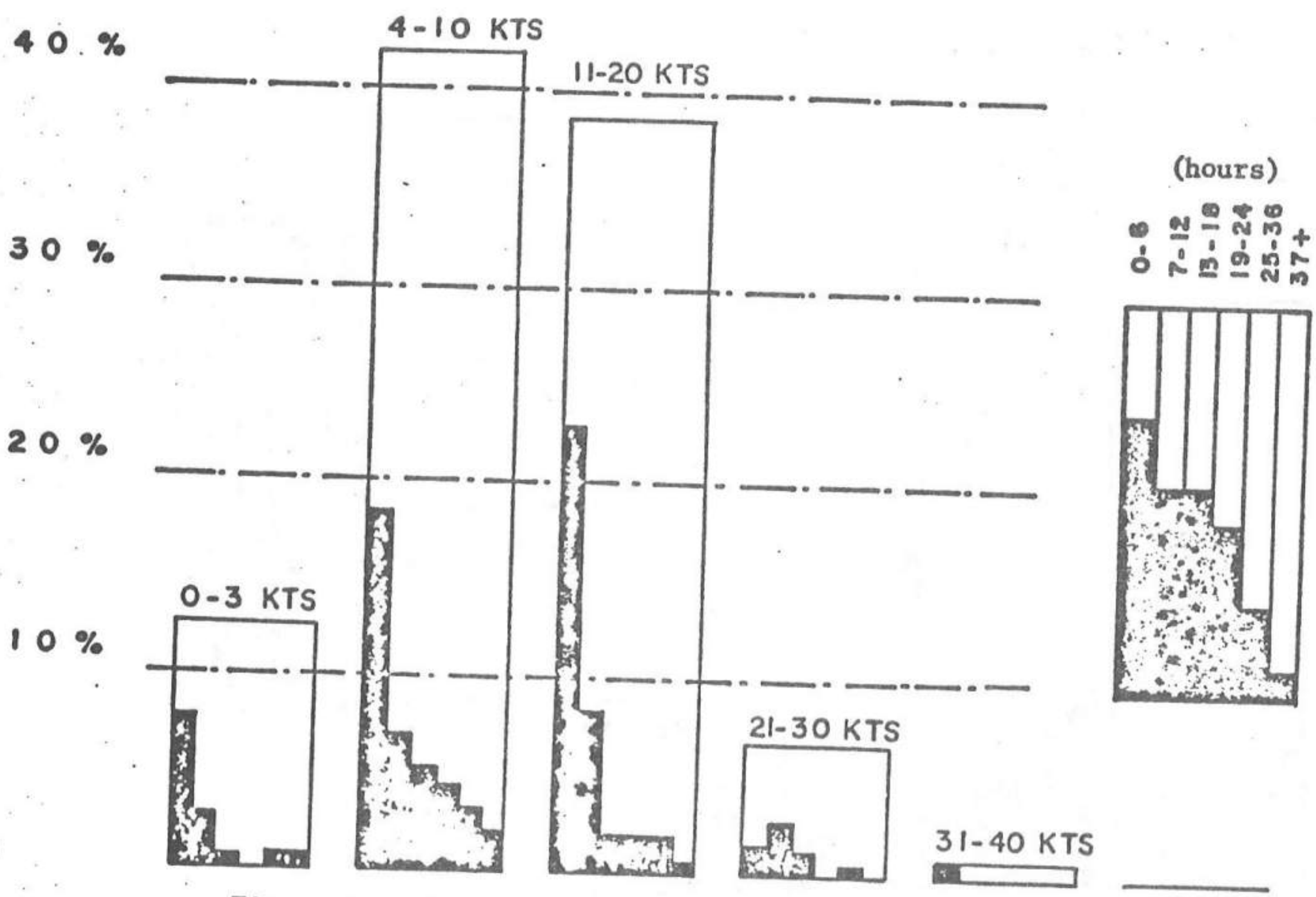


Figure 19e. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware

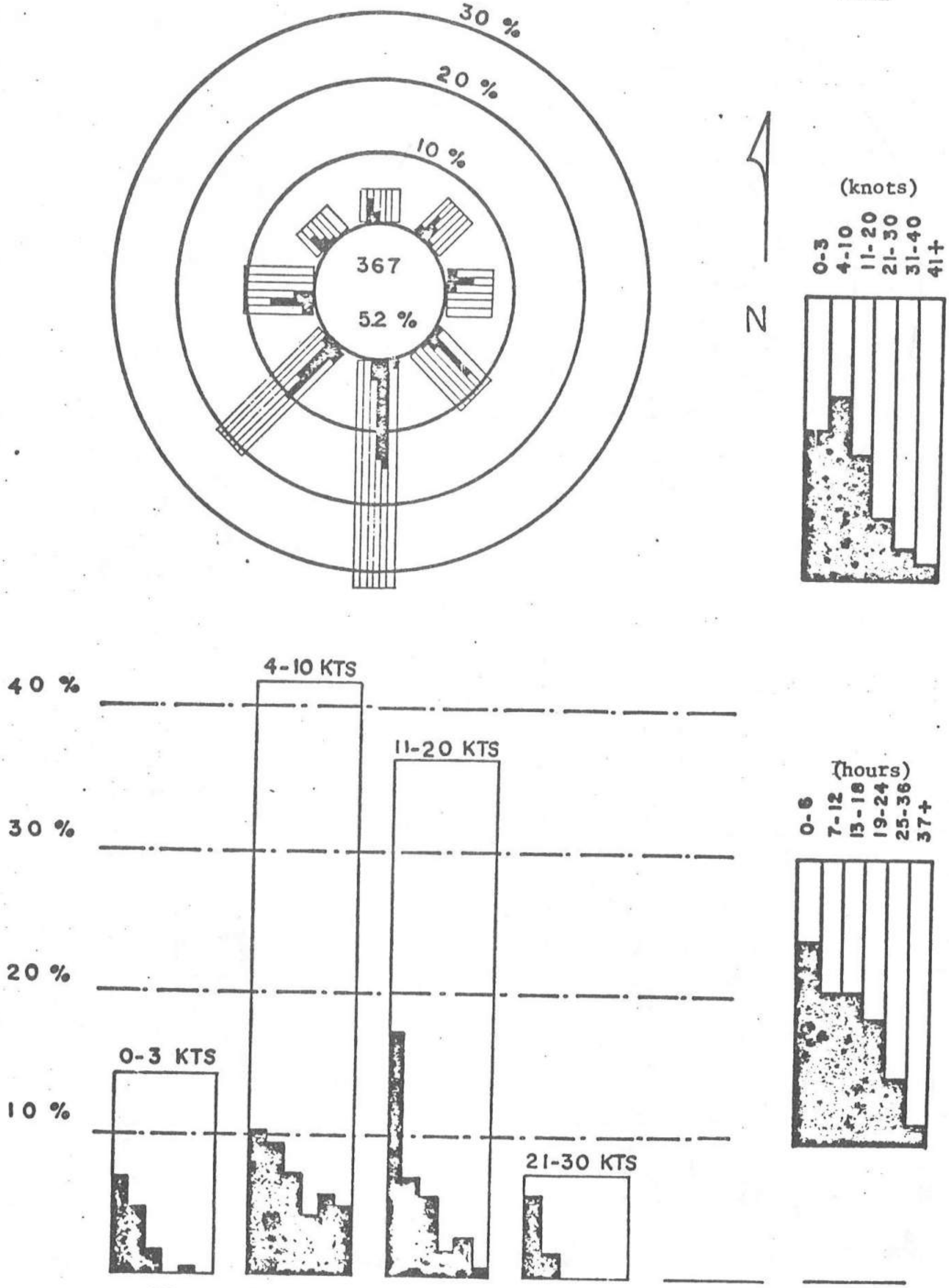


Figure 19f. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware

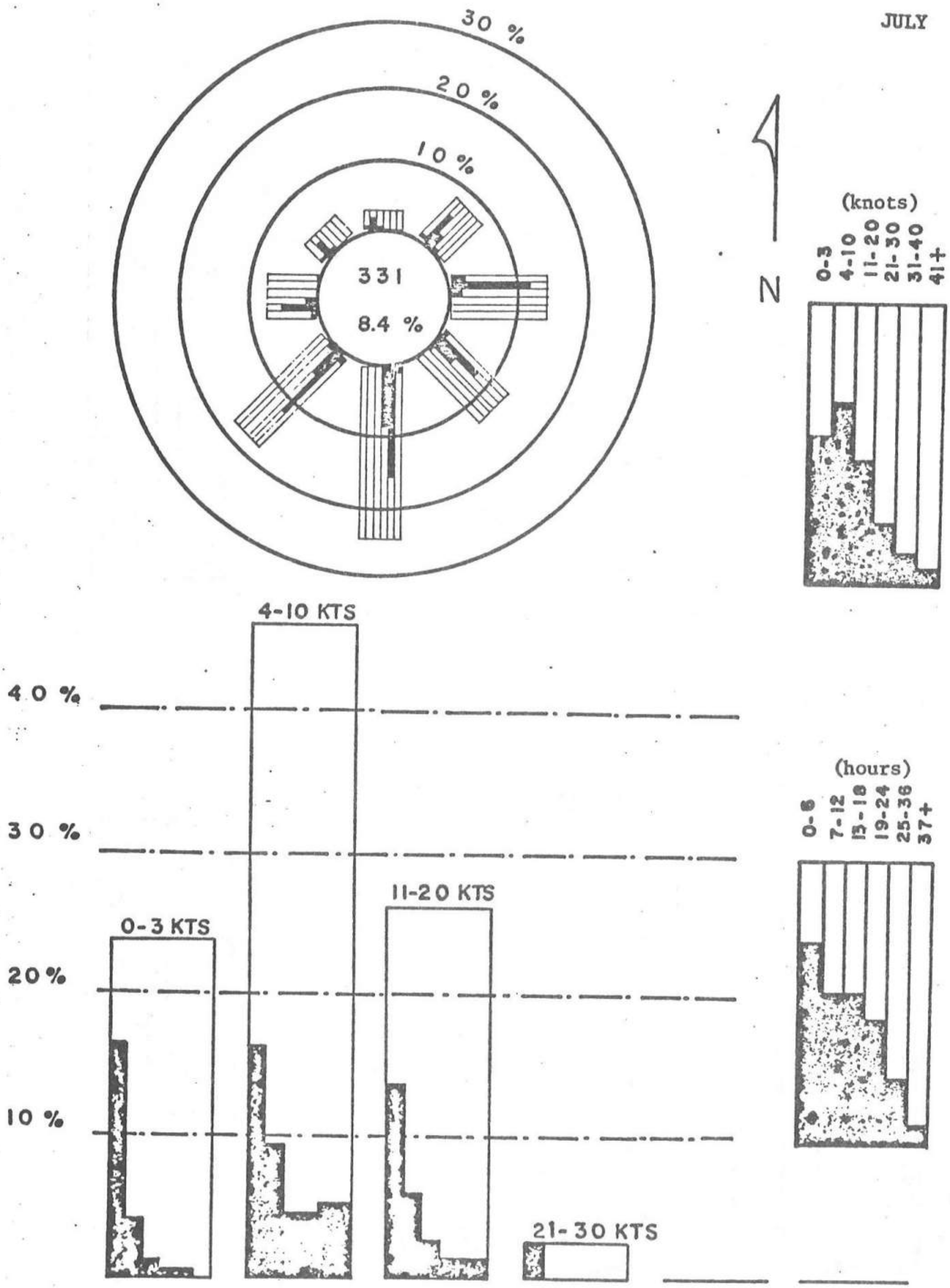


Figure 19g. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware

AUG.

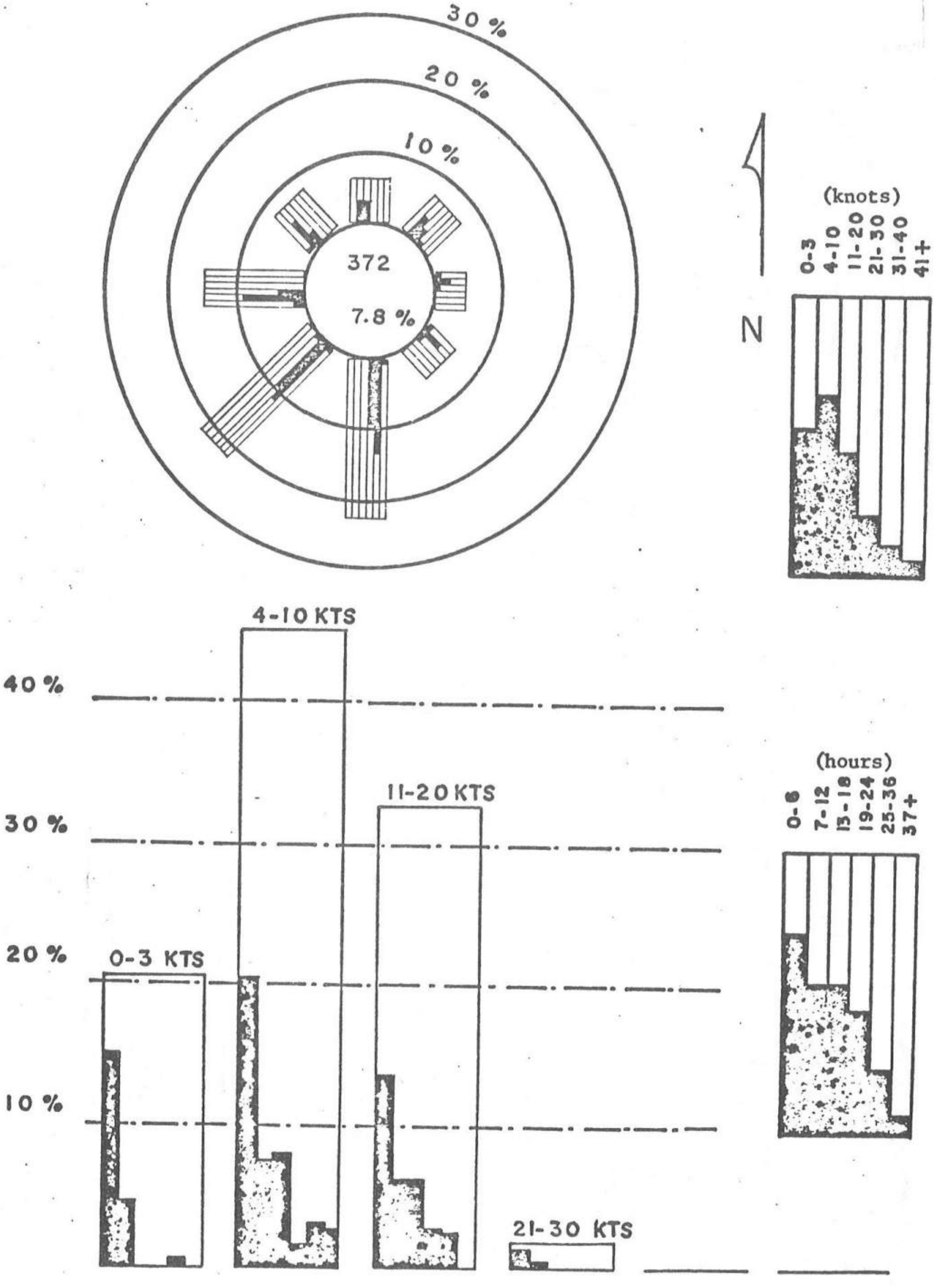


Figure 19h. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware

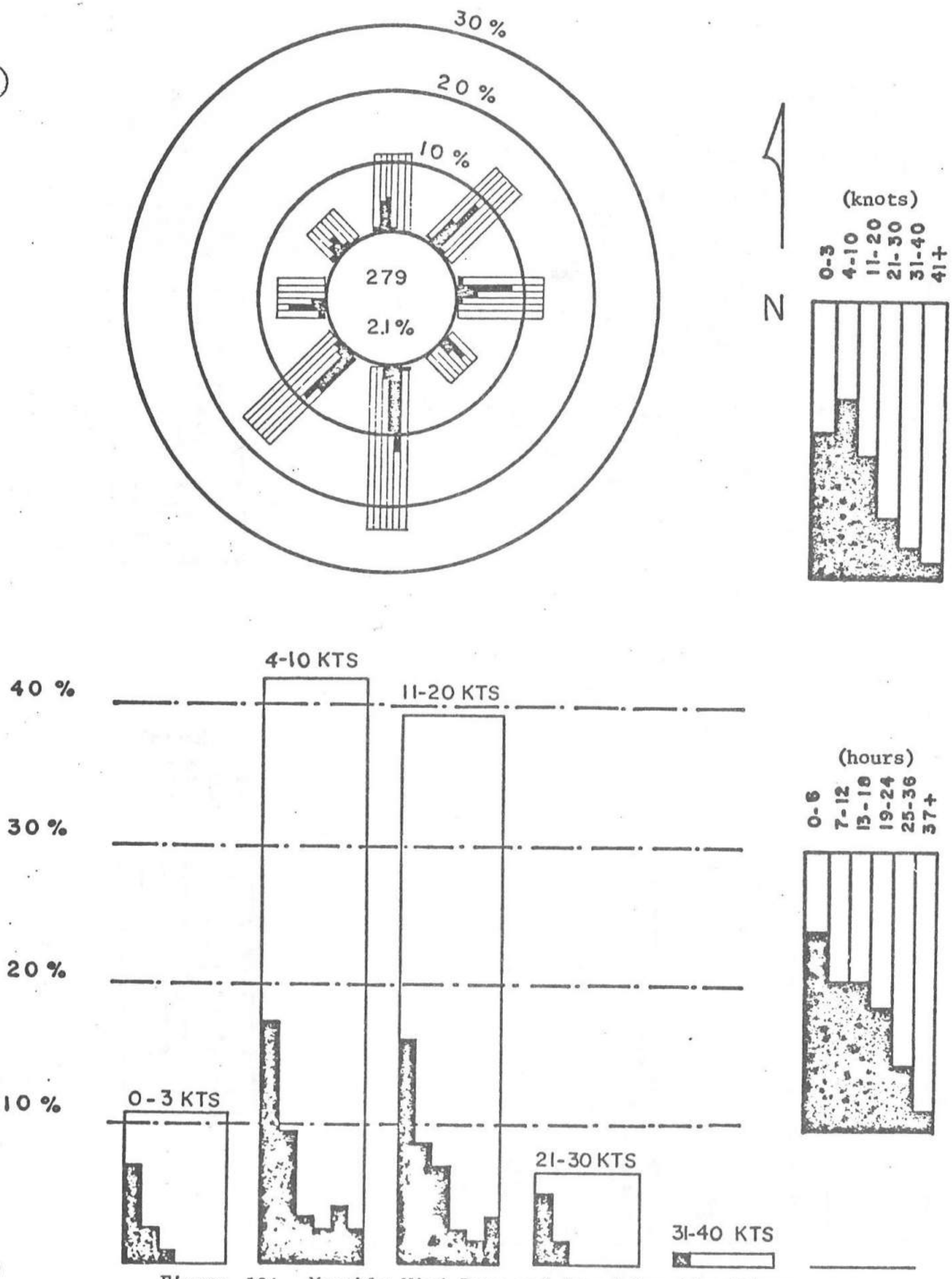


Figure 19i. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware

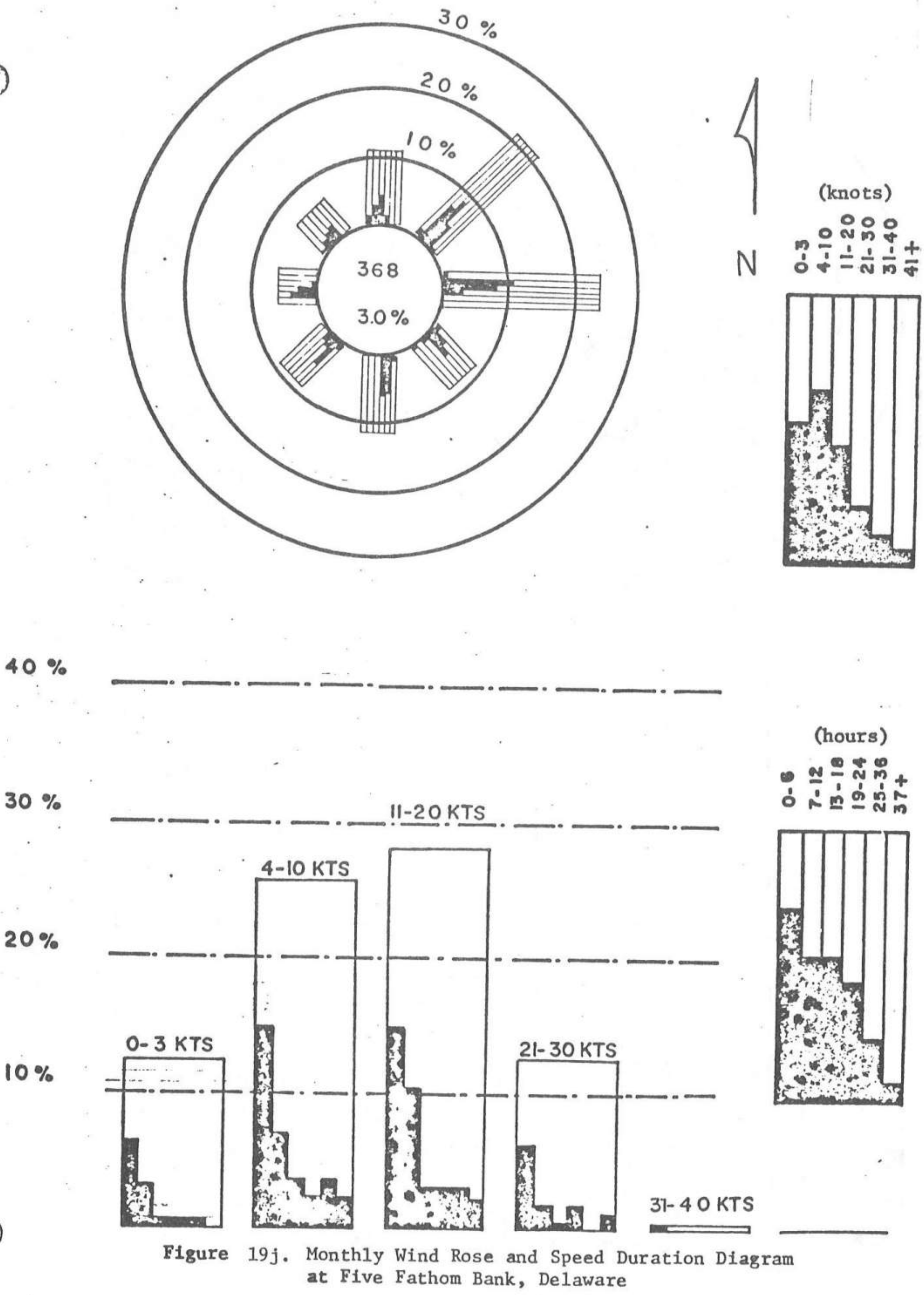
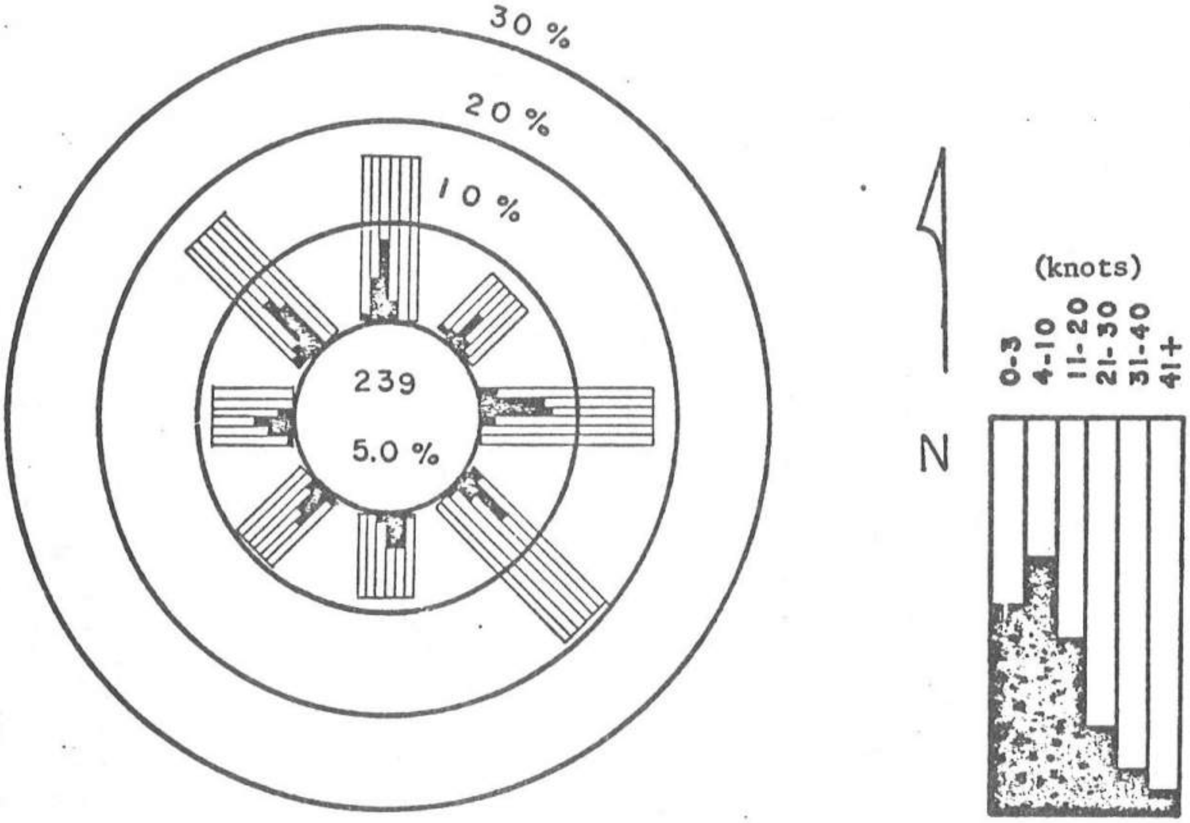


Figure 19j. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware



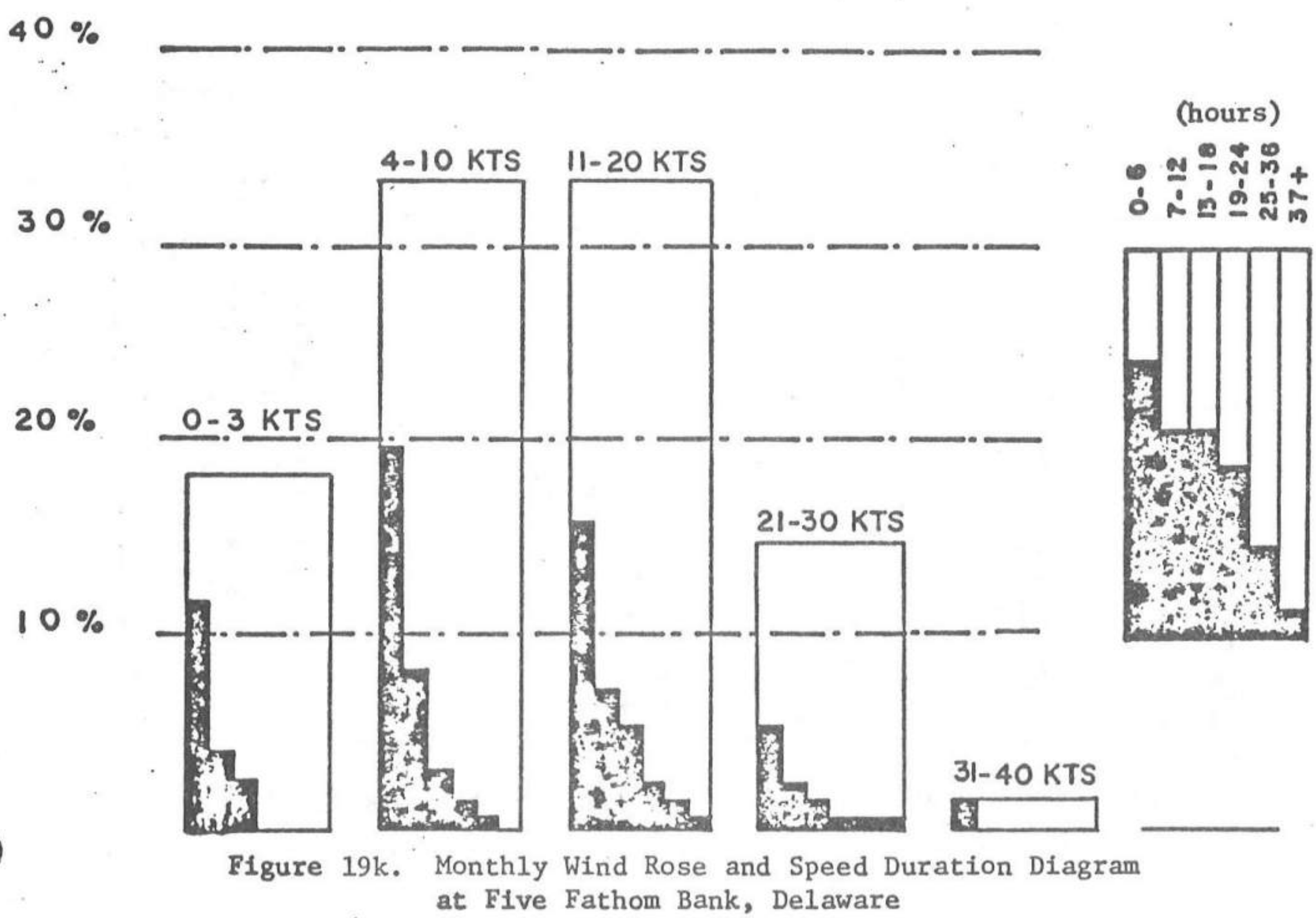
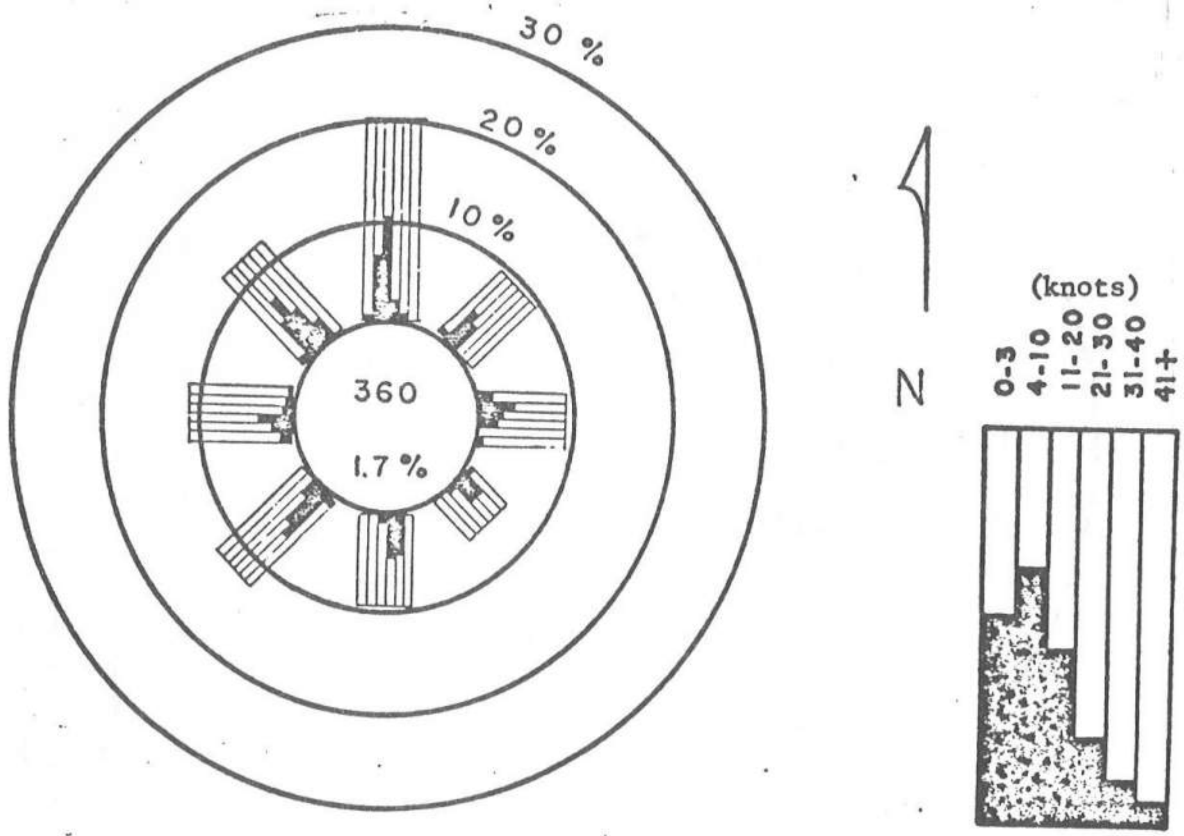


Figure 19k. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware



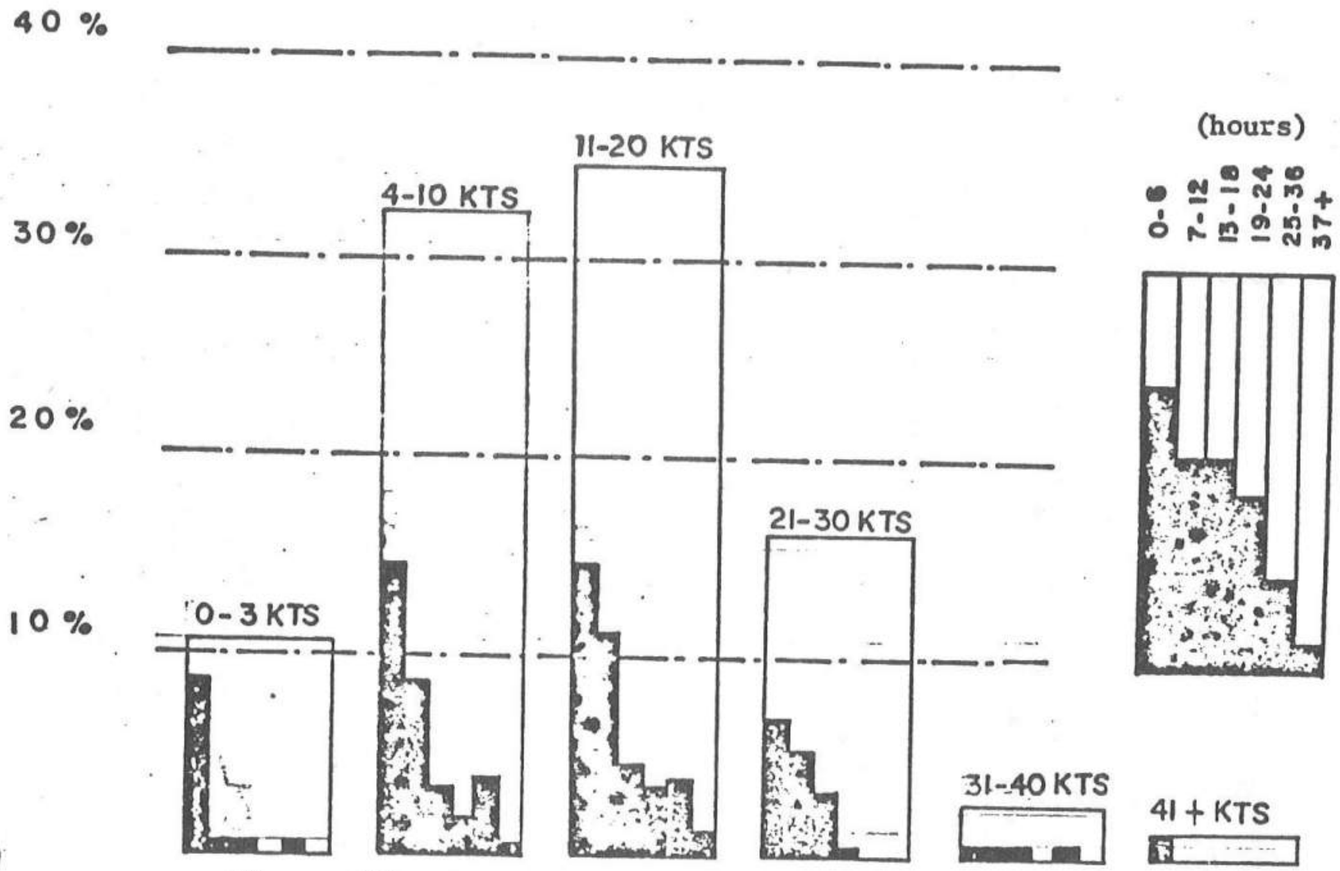
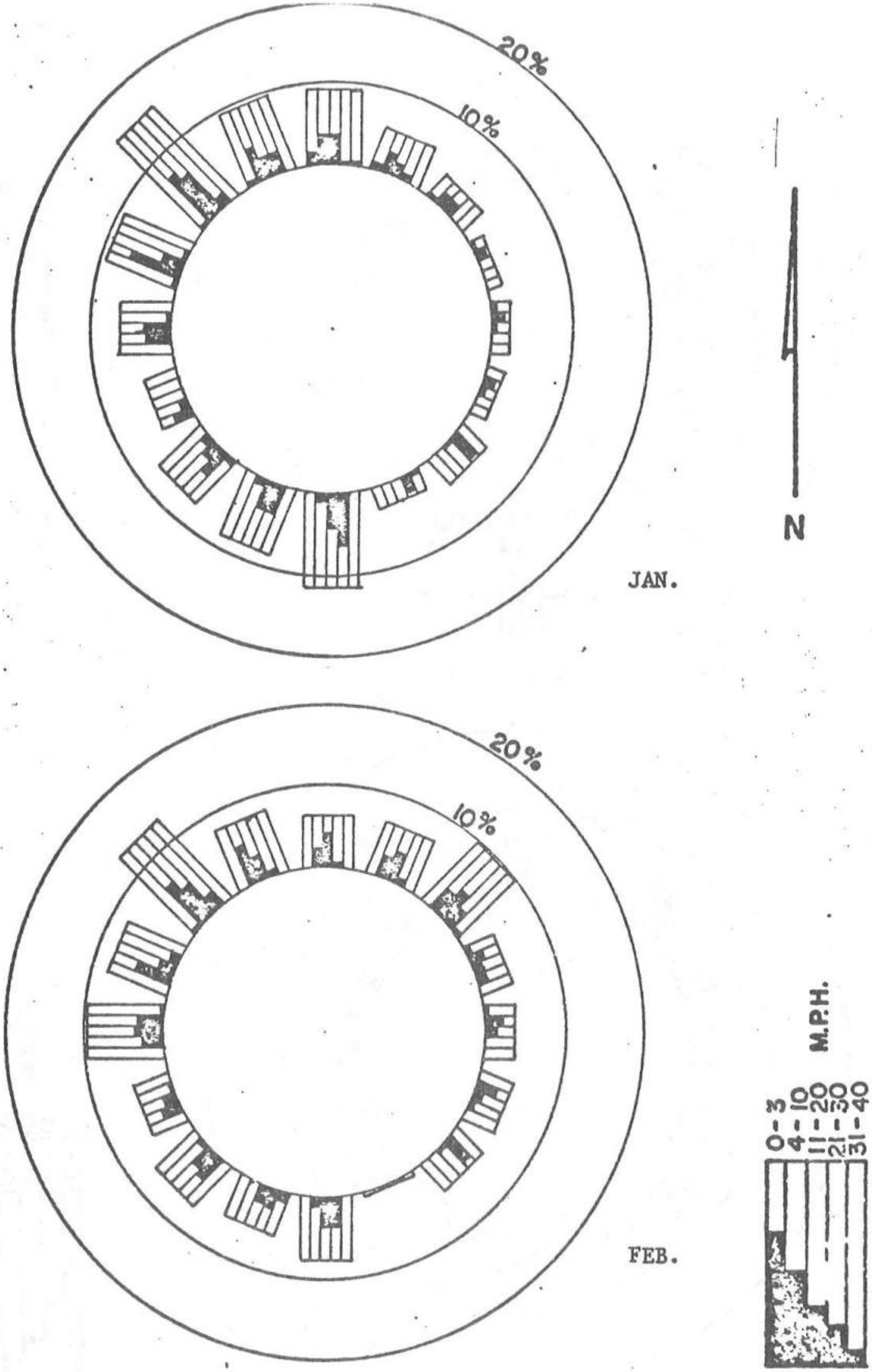
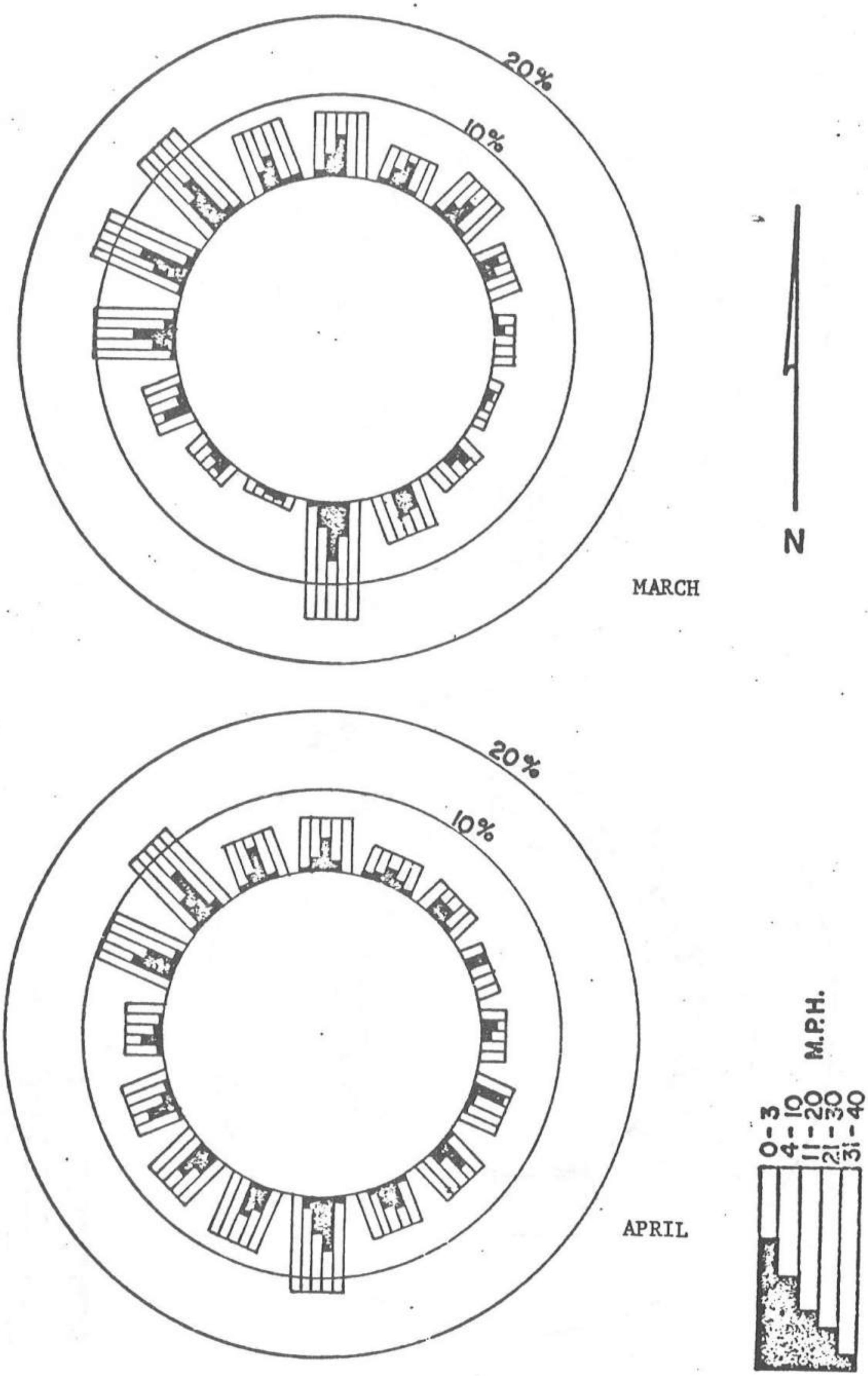


Figure 191. Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware



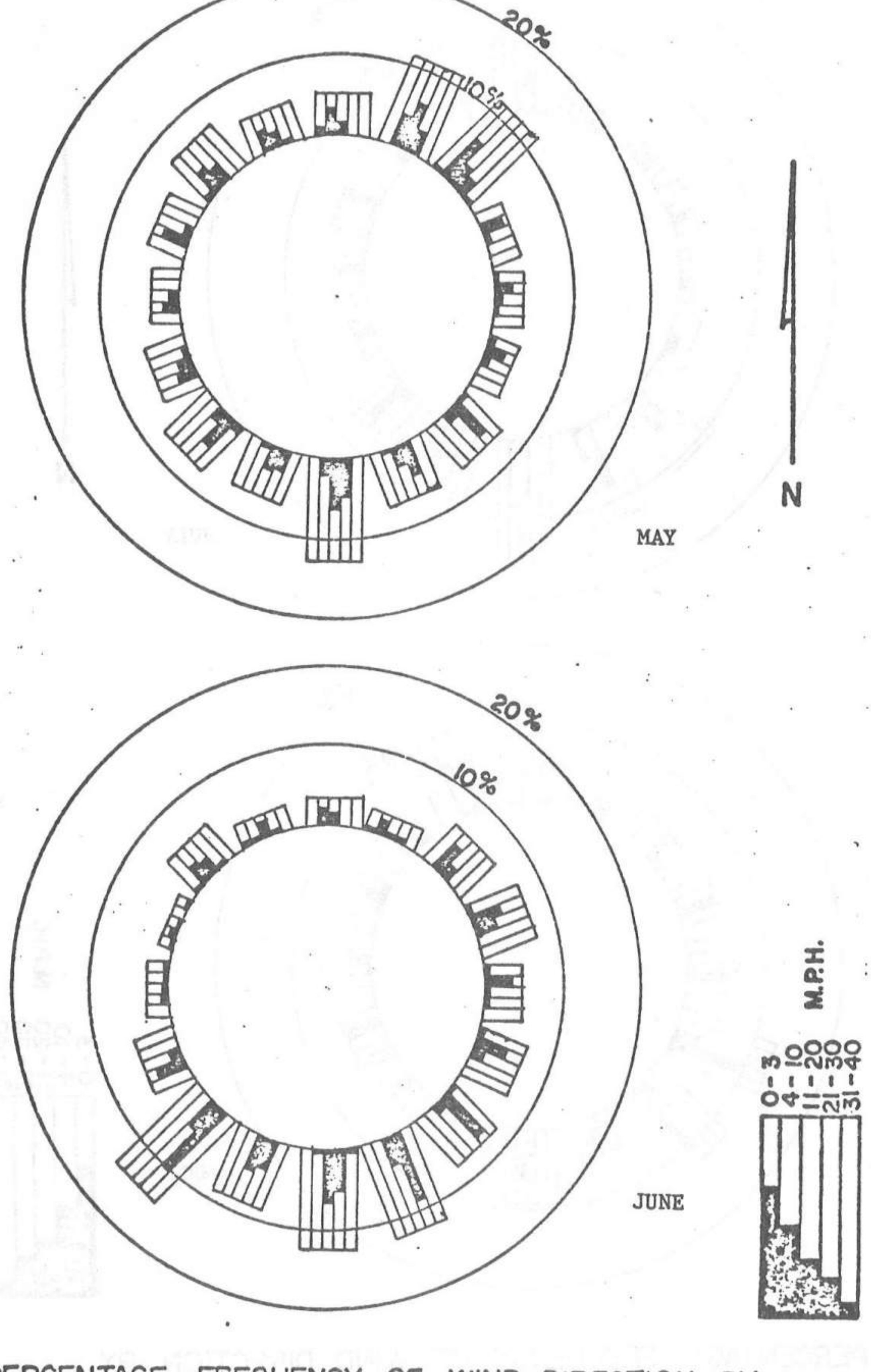
PERCENTAGE FREQUENCY OF WIND DIRECTION BY SPEED INDIAN RIVER INLET, DELAWARE

Figure 20a.



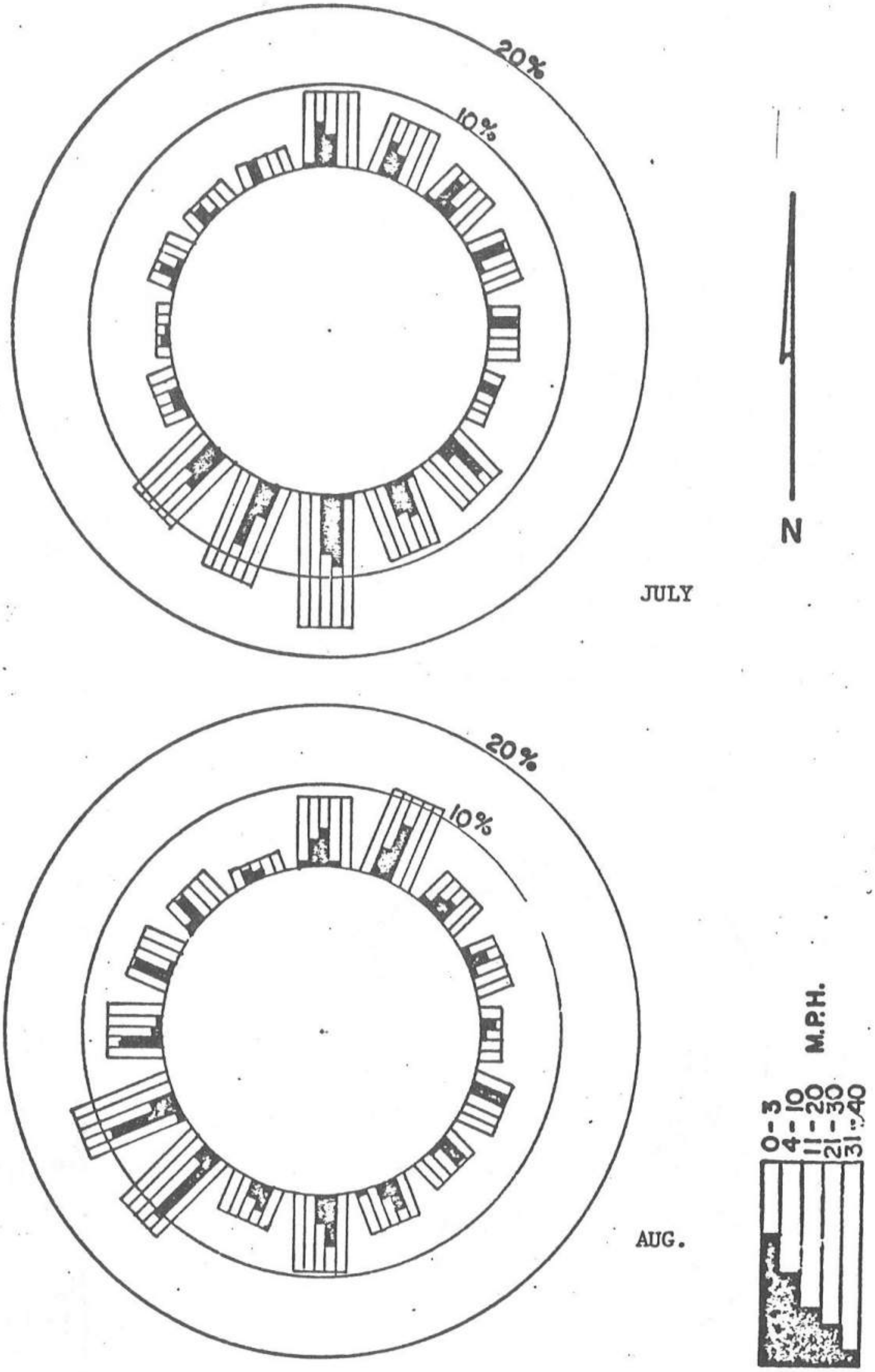
PERCENTAGE FREQUENCY OF WIND DIRECTION BY SPEED INDIAN RIVER INLET, DELAWARE

Figure 20b.



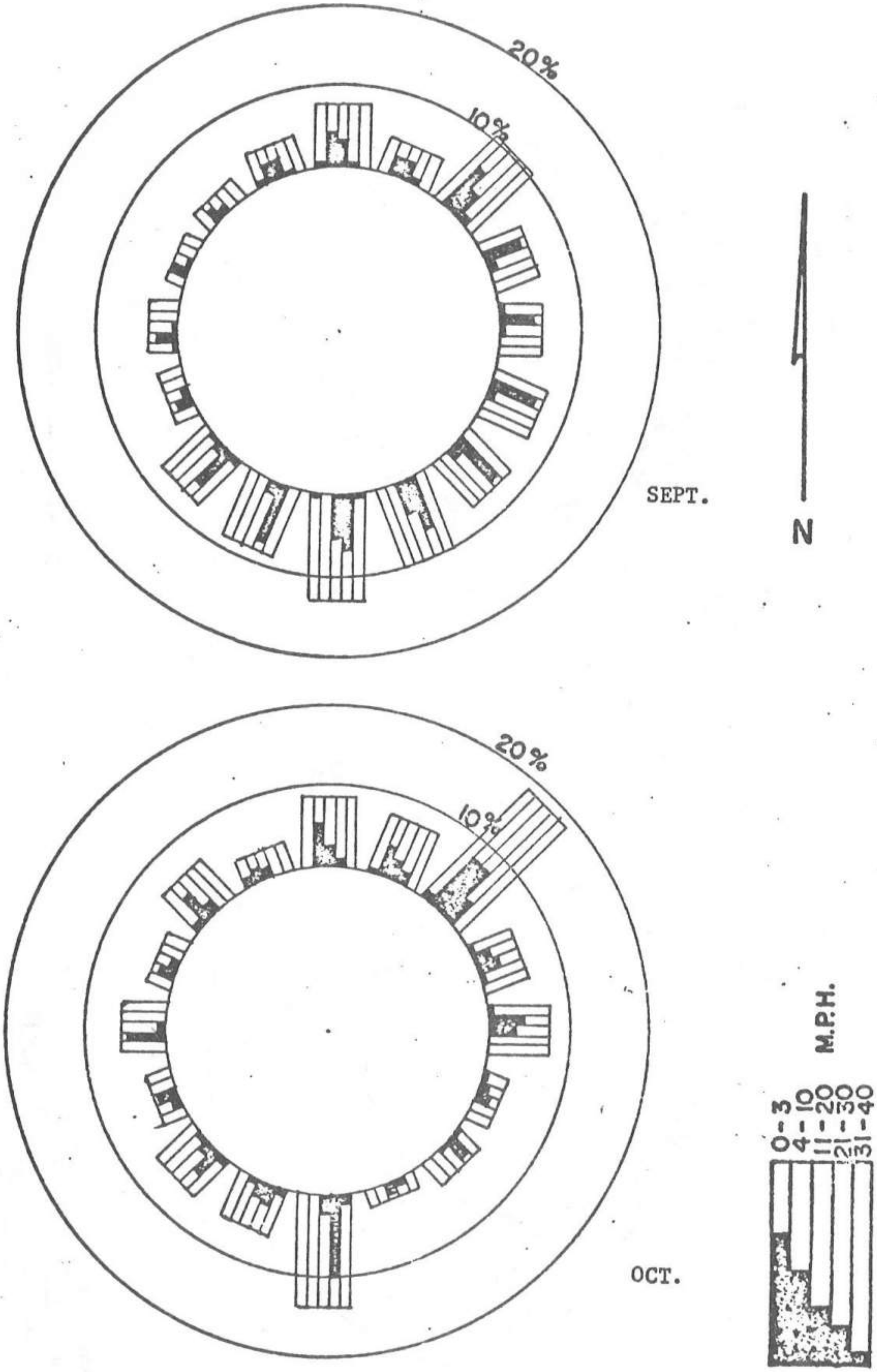
PERCENTAGE FREQUENCY OF WIND DIRECTION BY SPEED INDIAN RIVER INLET, DELAWARE

Figure 20c.



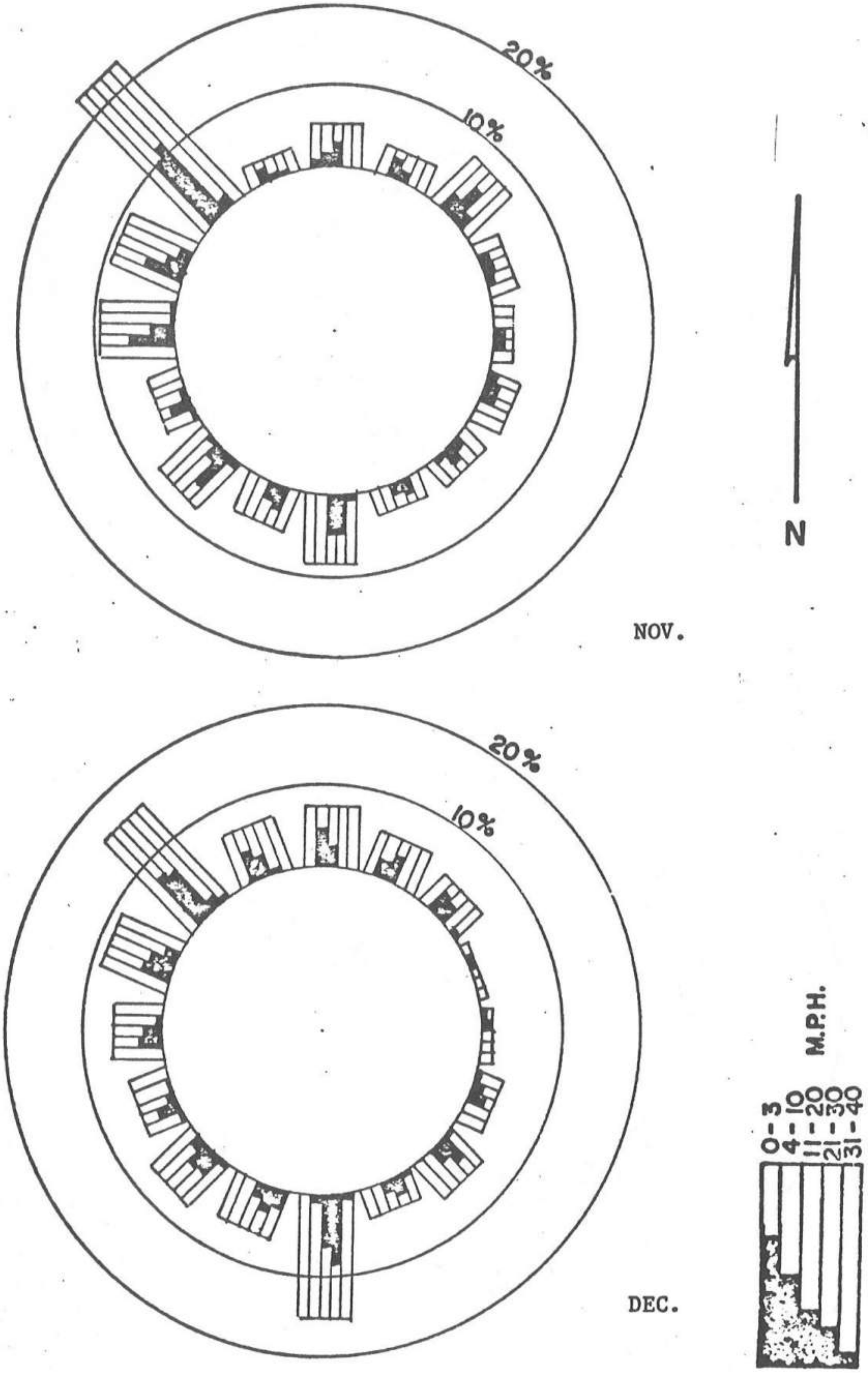
PERCENTAGE FREQUENCY OF WIND DIRECTION BY SPEED INDIAN RIVER INLET, DELAWARE

Figure 20d.



PERCENTAGE FREQUENCY OF WIND DIRECTION BY SPEED INDIAN RIVER INLET, DELAWARE

Figure 20e



PERCENTAGE FREQUENCY OF WIND DIRECTION BY SPEED INDIAN RIVER INLET, DELAWARE

Figure 20f.

E. Wave Climate Data

Wang and Maurer (9) have studied wave data from the Five Fathom Lightship station and reported wave rose data for swell height and frequency and swell period and frequency on a monthly basis. They also present significant wave height and direction and frequency of occurrence tables, as well as statistical estimates of extreme winds and waves for the offshore Delaware Bay area. While these data have not been used for the transport and mixing studies for the environmental assessment of the proposed outfalls, such data are necessary and available for studies of any structure, such as a submerged outfall pipe, in these coastal waters.

III. Mixing Analyses - General View

A. Scope of Mixing Analyses

The sections IV and V of this report summarize the results of several analyses of the mixing of waste water effluents discharged into the near-shore coastal waters of the State of Delaware. These analyses have been perfomed to assist in the assessment of the potential environmental impact of and siting of ocean disposal systems in the area of Hen and Chickens Shoal and in the area offshore of South Bethany Beach. The maximum waste water discharge at the Hen and Chickens Shoal (HCS) site is to be 30 mgd and at the South Bethany Beach (SBB) site is to be 25 mgd.

Analysis of the physical mixing of waste water effluent with the receiving coastal waters was the primary focus of these studies. Aside from the density of the effluent, the chemical and biological constituents of the effluent are not considered here. Thus, any interactions of effluent and seawater or beneficial die-off of bacteria have not been considered at this point. Analyses have been performed to determine the mixing and dilution attainable at various site regions and for various submerged multi-port diffuser configurations and geometries. Because the mixing characteristics of a given outfall scheme depend on the configuration and geometry of the diffuser section, as well as the ambient receiving water environment, many functional designs of the diffuser system have been determined. These various diffuser options were found by establishing certain minimum dilution requirements at various sites and were subjected to a number of receiving water conditions to obtain a measure of their mixing performance. Each outfall option, therefore, was analyzed in some detail to assure that its mixing characteristics could be realized and to assure that realistic design constraints were made. However, it is important to note that the design options included in this report are in no way intended to be final diffuser designs. While all designs are feasible from a mixing and hydraulic standpoint (Section IV), detailed diffuser design encompasses factors unique to the particular specific site chosen. The options presented herein are for site screening for the purpose of environmental impact.

The following sections include an overview of the mixing problem and analyses, the limitations and assumptions underlying the analyses for mixing, summaries of the characteristics of several outfall options at both general site regions, and discussions of these options.

B. Description of Analyses of Mixing Characteristics

The primary questions concerning the mixing characteristics of a submerged multi-port diffuser outfall are the following:

(1) What dilution of the effluent is achieved in the surface waters directly above the diffuser?

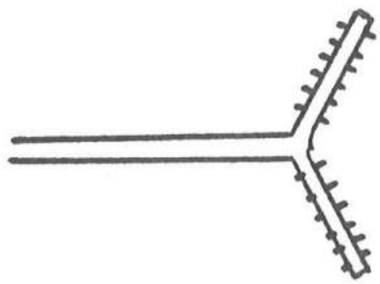
(2) What dilution of the effluent is achieved after the surface plume of effluent has drifted and mixed toward the beach or some other point of interest removed from the diffuser location?

These two questions are addressed directly in this report with regard to several diffuser locations and configurations. Other questions of interest may include the amount of bottom space required to accommodate the diffuser and outfall pipe, the size of the effluent plume, the buoyant jet trajectories and the effects of density stratification.

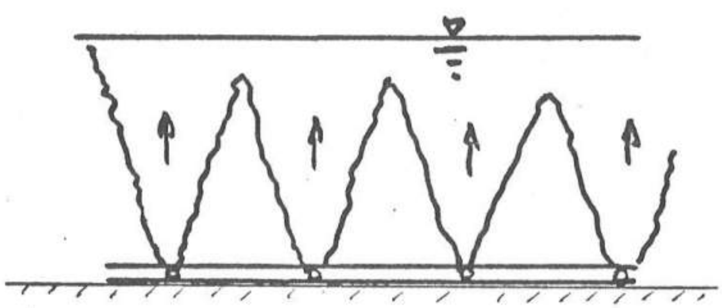
A brief description of the mechanics of the mixing processes is given here as an introduction to the analyses and results summarized in this report. Generally, the most effective means of mixing an effluent with seawater is to jet it into the receiving water near the bottom by means of a multi-port diffuser. This diffuser section to the outfall is a closed-end pipe, often of different diameter than the carrier pipe, with many carefully spaced and sized discharge ports. Usually, ports are located on both sides of the pipe at the springline (see Figure 21). The diffuser section may be a single straight pipeline (Fig. 21a) or a wye pipeline with two legs (Fig.21b). Both configurations are considered in this report.

FIGURE 21

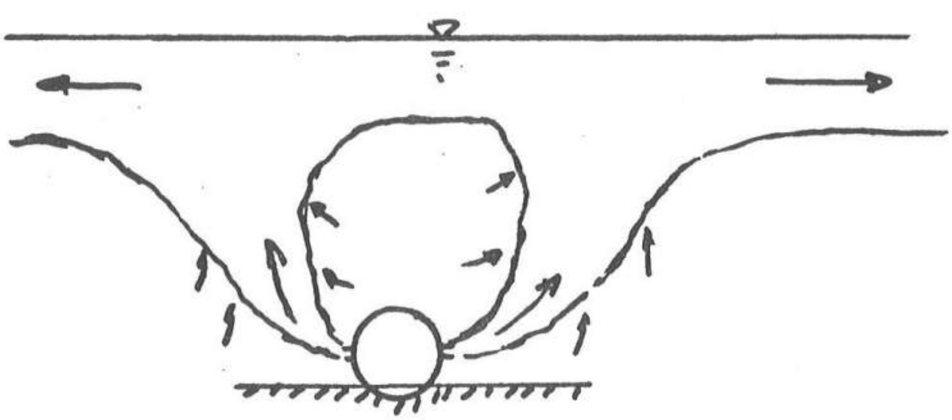
a) Straight Diffuser



b) Wye Diffuser



c) Side view



d) End View

The effluent, generally less dense than seawater (as in this case), is discharged from the ports forming buoyant jets. The buoyant jets rise and entrain seawater, thus diluting the effluent. The mixture of effluent and seawater rises to the surface, except in cases where ambient density stratification is sufficiently strong, and the jets remain neutrally buoyant below the water surface. Diffusers are often designed so that adjacent jets do not interfer with each other before the surface is reached (Fig. 21c).

When the diluted effluent reaches the water surface, it forms a surface plume which has little horizontal momentum of its own. Thus, a short distance from the diffuser site, the effluent no longer moves relative to the receiving water but drifts at the speed of the surface current and mixes due to the ambient turbulence of the receiving water.

In the report, the buoyant jet mixing region is referred to as the near-field and the surface drift and mixing as the far-field. The diffuser designer has some control over the near-field mixing, although the depth of water available for mixing is a constraint. Mixing in the far-field, however, depends largely on natural processes, although the diffuser configuration has some effect.

The approach employed in this screening study is outlined here in summary fashion:

(1) Near-field analysis -

For a particular depth of water available, analyses of the buoyant jet with a given port size produce a series of possible dilutions at the water surface, each dictating a particular number of ports, port spacing, and total diffuser length. Such studies produced several diffuser options, both single legs and wye diffusers, with various trade-offs between maximizing dilution and minimizing the length of the diffuser section.

(2) Internal hydraulics analysis -

Although the near-field analysis produces a particular diffuser option, it presupposes that the discharge leaves the diffuser equally distributed among the ports. This, of course, can only happen for the appropriate manifold design. The internal hydraulic analysis determines the diffuser diameter, the distribution of discharge among the ports, and the head loss in the diffuser. This analysis is essential to guarantee that options selected by near-field analysis will actually work.

(3) Far-field analysis -

The extent of the surface plume over the diffuser is determined by the near-field analysis. How this field spreads as it drifts with the current is determined using data on the surface current speed and direction and large-scale mixing processes. This analysis produces the additional dilution achieved by the effluent plume after it has drifted to some new location.

IV. Near-Field Analysis and Results

Initially, a variety of water depths existing at each site region and a variety of port sizes were used to generate over one hundred possible buoyant jet discharges for several surface dilutions. These characteristics were given a rough screening to rule out obviously over- or under-sized designs. The remaining options were analyzed carefully to determine mixing and diffuser characteristics.

A. Assumptions

The following assumptions were made to enable near-field analysis. They are basically conservative with regard to estimating surface dilutions and follow general diffuser design. However, as mentioned previously, a final design might well alter some of these assumptions for a specific site.

(1) The ports are aligned to discharge horizontally.

(2) For a given diffuser, all ports are the same diameter ($\geq$3" to prevent clogging), spaced uniformed, and one exists on each side of the diffuser. (A designer may wish to add a port at the end).

(3) The depth of water refers to the depth above the ports.

(4) The receiving water environment is initially assumed to be of uniform density (as exists during most of the year at both site regions). The effect of vertical density stratification of the receiving water is considered in detail,

although it appears to be of secondary importance for the initial screening. The effect of currents is neglected initially as they usually increase jet mixing and slack tide is the critical condition.

(5) The maximum discharge for each site is assumed, and the density difference between effluent and sea water is chosen from field data to assure design on a "worst-case" basis (see Table 11). Generally, lesser discharges and other possible density differences result in dilutions greater than design values. The focus here is on the maximum discharges and their impact; designers may desire to propose other designs to handle start-up or phased effluent discharges.

(6) No interference between adjacent jets is permitted (see Fig. 22a).

(7) Dilutions values are based on centerline concentration values, Figure 22b, (although average dilutions are slightly greater), using the analyses of Ref. 2,3,4,6,7, and 10.

Table 11

Density Difference Data, $\Delta\rho$

(difference between receiving water density surrounding the discharge and effluent density)

Effluent Density

-assuming near "fresh" water conditions

Temperature	Density(g/ml)
10°C (50°F)	0.9997
18°C (65°F)	0.9993
21°C (70°F)	0.9988

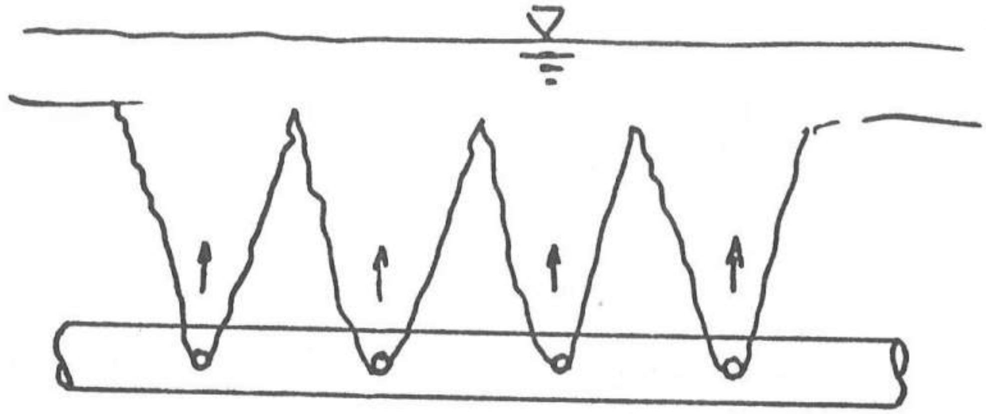
Receiving Water Density

(see Tables 1 and 2)

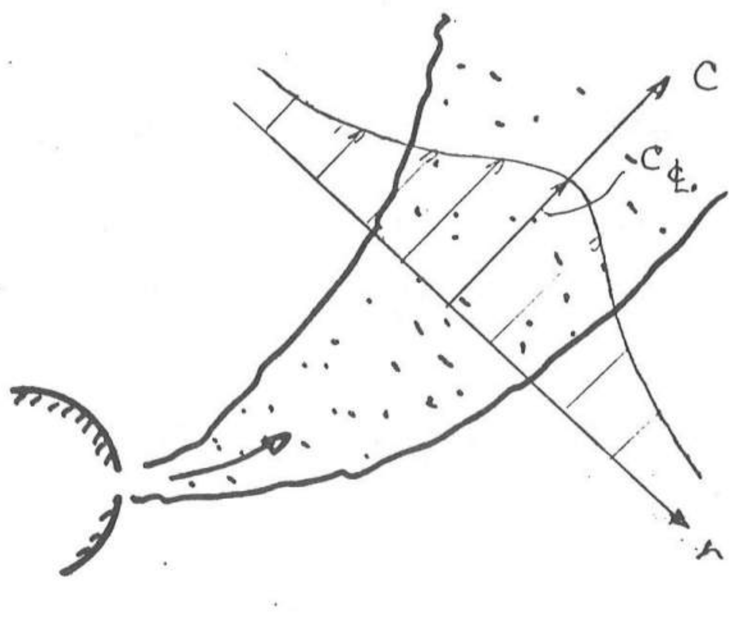
Site	Season	Typical Bottom Temp(°C)	Typical Bottom Salinity ‰	Density g/ml
HCS	Summer	17-20	27-29	1.0180-1.0195
	Winter	10	29-30	1.0222
SBB	Summer	19-21	30-31	1.0230
	Winter	10	29-31	1.0200-1.0208

Use $\Delta\rho \approx 0.02$ g/ml for option calculations

FIGURE 22



a) No Interference



b) Concentration Profile

B. Hen and Chickens Shoal Site Results

The results of the near-field analyses are summarized in Table 12. The maximum discharge is 30 mgd. The water depths used are for 25', 50', 60'. and 90'. Zones for which these depths exist are shown in Figure 23 and are

25' - inside H & C Shoal about 1500 feet offshore. This area is too confined and active with regard to sediment transport to be a suitable diffuser site, but calculations are presented to give an idea of the dilution obtainable there. Also, a region similar depth exists on the outside of the south tip of the shoal.

50' - offshore of the shoal about 4,500 feet from the beach.

60' - offshore of the shoal about 6,000 feet from the beach.

90' - depression confirmed by field studies about 13,500 feet offshore.

The dilutions considered range from 50:1 to 200:1, with the greater dilutions at the surface over the diffuser realized in deeper water with a shorter diffuser. Note that dilutions of 200 cannot be guaranteed at depths less than 60'. Diffusers with one and two legs are considered. Wye diffusers offer the advantage of an alternative discharge should one leg have to be taken out of service temporarily and can provide better far-field mixing depending on their orientation (see Section V). Larger port diameters, although usually resulting in increased diffuser length and diameter for a given dilution, may ensure greater protection against clogging and fouling than a small one.

TABLE 12

Summary: Near-Field and Internal Hydraulics Analyses Results

"Hen and Chickens Shoal" Site

Option No.	Depth of Water	Minimum Dilution	No. of Legs	Diff. Leg Length	Diffuser Pipe Diam.	Port Diam.
1	25 ft.	50:1	1	610 ft.	4 ft.	3 in.
2	"	50	2	305	3	3
3	"	70	1	1472		3
4	"	70	2	736	4	3
5	"	100	2	1392	6	3
6	50	100	1	600	3	3
7	"	100	2	300	2	3
8	"	100	1	912	4	4
9	"	100	2	456	3	4
10	60	100	1	500	2*	3
11	"	100	2	250	2*	3
12	"	100	1	616	3	4
13	"	100	2	308	2	4
14	"	150	1	1292		3
15	"	150	2	646	3	3
16	"	150	1	1278		4
17	"	150	2	639	4	4
18	"	200	1	2200		3
19	"	200	2	1100	4	3
20	"	200	1	2160		4
21	"	200	2	1080	5	4
22	90	200	1	1353		4
23	"	200	2	677	3	4
24	"	200	1	728		6
25	"	200	2	364	3	6

*Flow distribution marginal

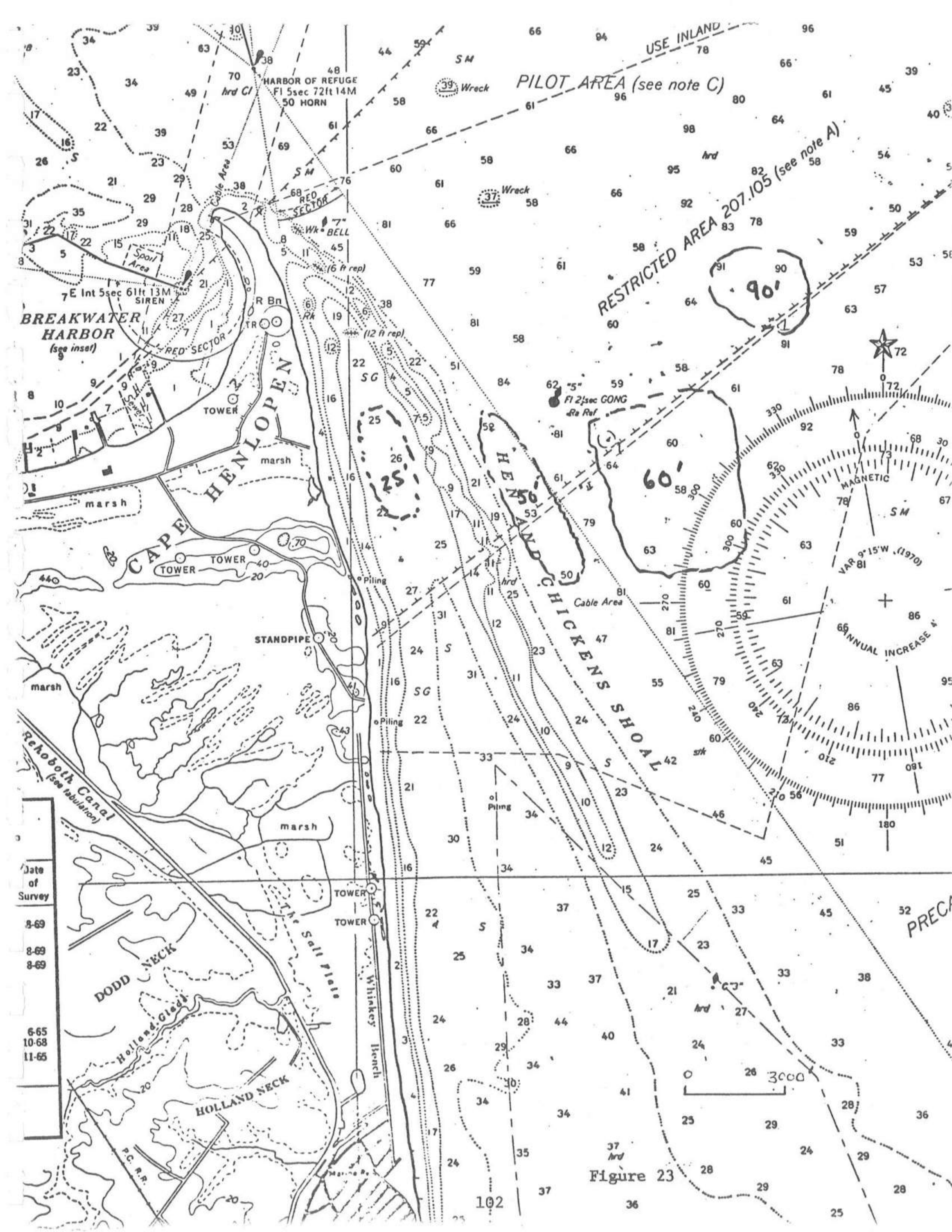

USE INLAND
PILOT AREA (see note C)
RESTRICTED AREA 207.105 (see note A)
HARBOR OF REFUGE
Fl 5sec 72ft 14M
50 HORN
Wreck
Wreck
RED SECTOR
"7" BELL
(6 ft rep)
(12 ft rep)
E Int 5sec 61ft 13M
SIREN
BREAKWATER HARBOR
(see inset)
Spoil Area
Cable Area
RED SECTOR
R Bn
TOWER
CAPE HENLOPEN
marsh
marsh
marsh
TOWER
TOWER
STANDPIPE
Piling
Piling
"5"
Fl 2½sec GONG
HEN AND CHICKENS SHOAL
Cable Area
90'
60'
25'
56'
MAGNETIC
VAR 9°15'W (1970)
ANNUAL INCREASE
Rehoboth Canal
(see tabulation)
The Salt Pond
Whiskey Beach
DODD NECK
Holland Glade
HOLLAND NECK
P.C. R.R.
Date of Survey
8-69
8-69
8-69
6-65
10-68
11-65
PRECA
3000

Figure 23

The effects of vertical density stratification of the receiving water was studied for several of the options considered above. As discussed in Section II. A., a composite vertical density profile was developed which incorporated the primary characteristics of density stratification at the site areas during the most "stratified" conditions found during the field studies. This density profile is shown in Figure 5. The computations focused on the behavior of an individual buoyant jet discharged from a diffuser port. This approach is valid, since the outfall configuration options were developed on the basis of no interference between adjacent jets. The buoyant sewage effluent discharged into a uniform density environment always rises to the water surface as indicated in Figure 24. However, when the receiving water environment is density-stratified, the possibility exists the discharge will entrain enough of the dense bottom waters that it will become neutrally buoyant at some depth below the water surface as shown in Figure 24.

The analysis of a buoyant jet in a stagnant environment of arbitrary stratification followed that of Reference 2. Given the discharge characteristics and the receiving water stratification, the analysis predicts the centerline trajectory of the buoyant jet, the jet width, velocities, and the dilution achieved. The analysis is valid until the jet loses all vertical momentum and can rise no further. The elevation at which this occurs is known as the "terminal or maximum height of rise" of the jet. In Figure 25, the plot of jet trajectory and width ends at this point. At the terminal height of rise the effluent is slightly negatively buoyant relative to its surrounding and may sink to the "level of neutral buoyancy." The level of neutral buoyancy is indicated in Figure 25 by the dot on the centerline trajectory. The analysis does not predict the thickness of the horizontal spreading effluent or the

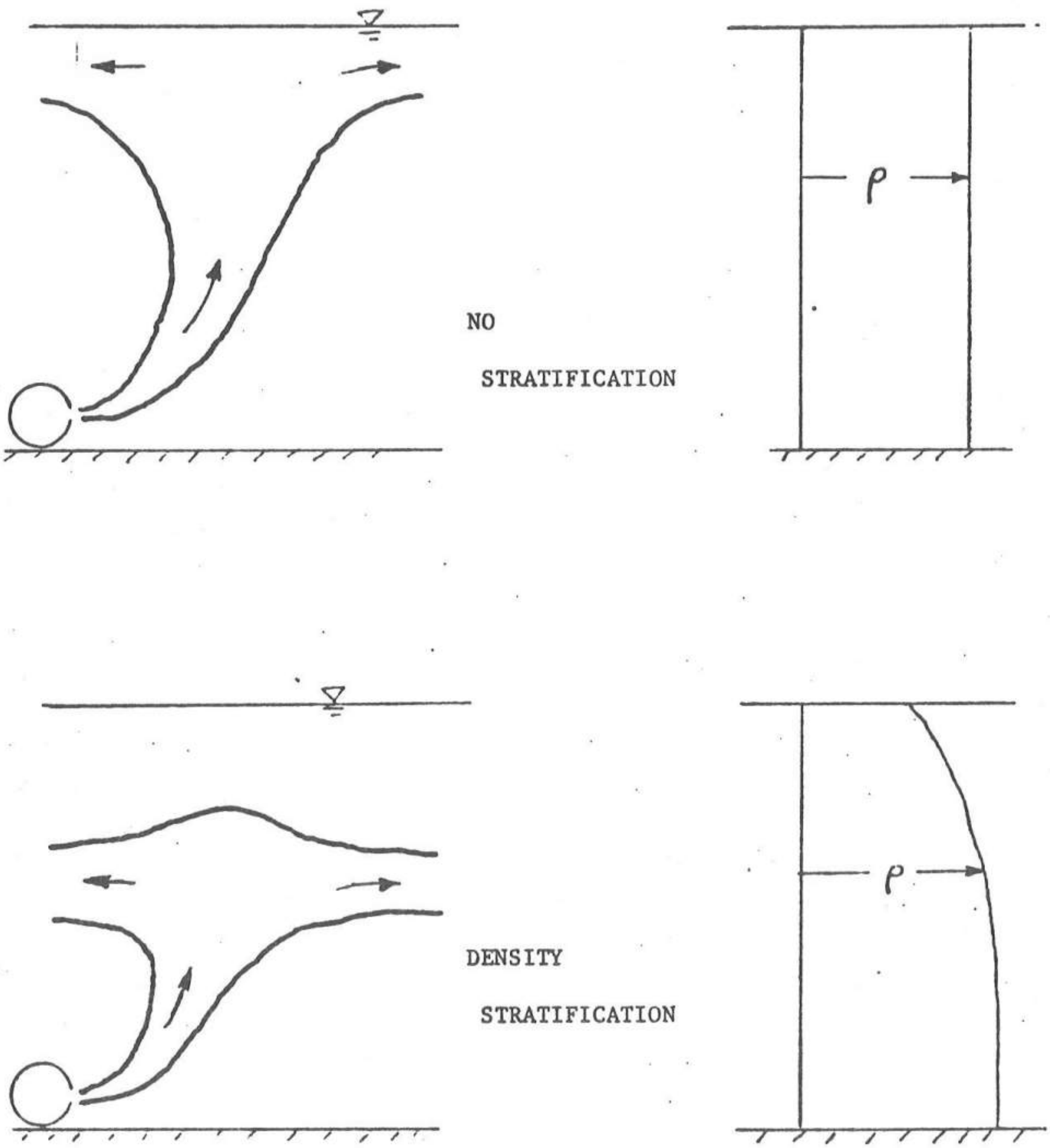


FIGURE 24

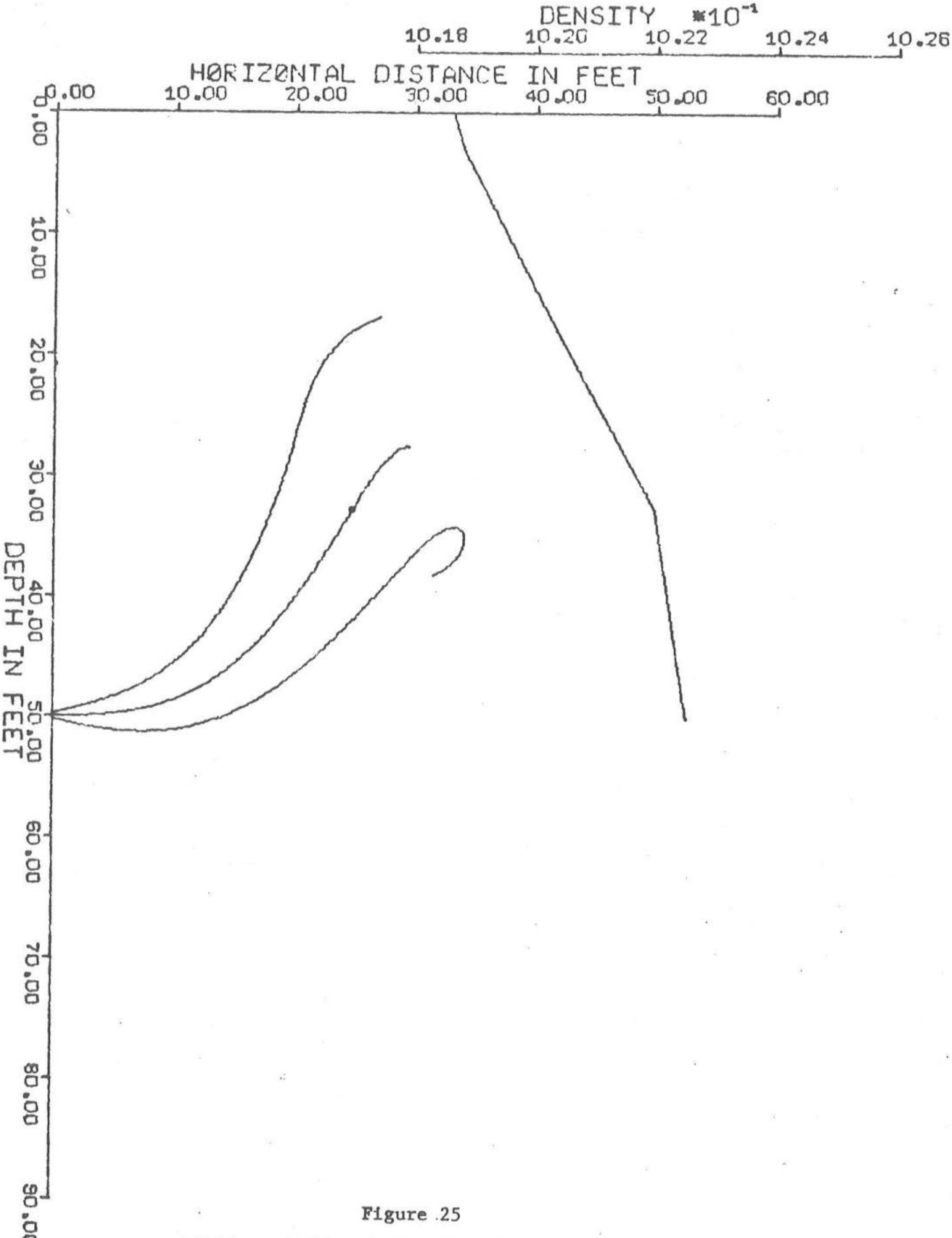


Figure 25

HEN & CHICKENS SHØAL - ØPT 7

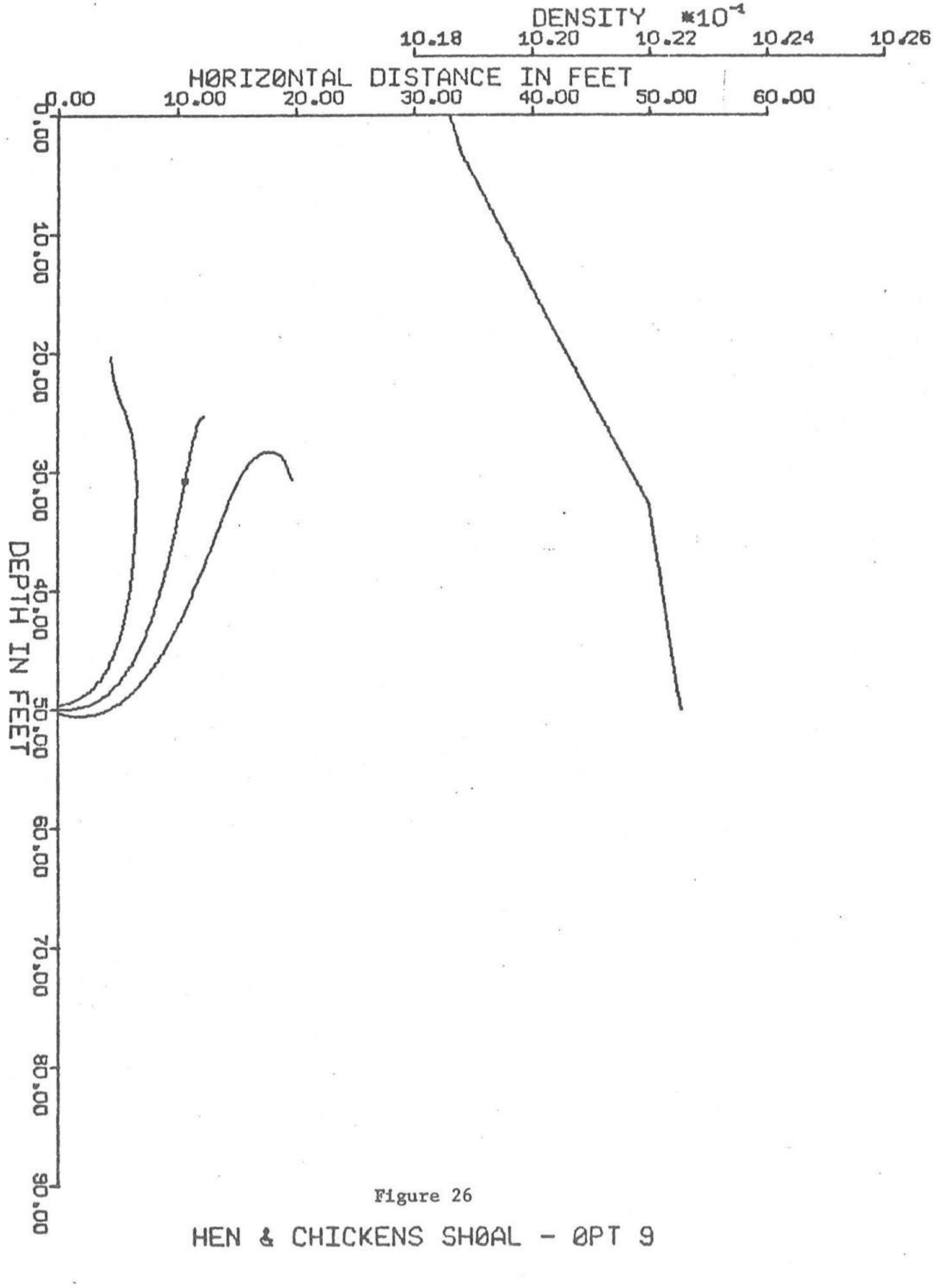


Figure 26

HEN & CHICKENS SHOAL - OPT 9

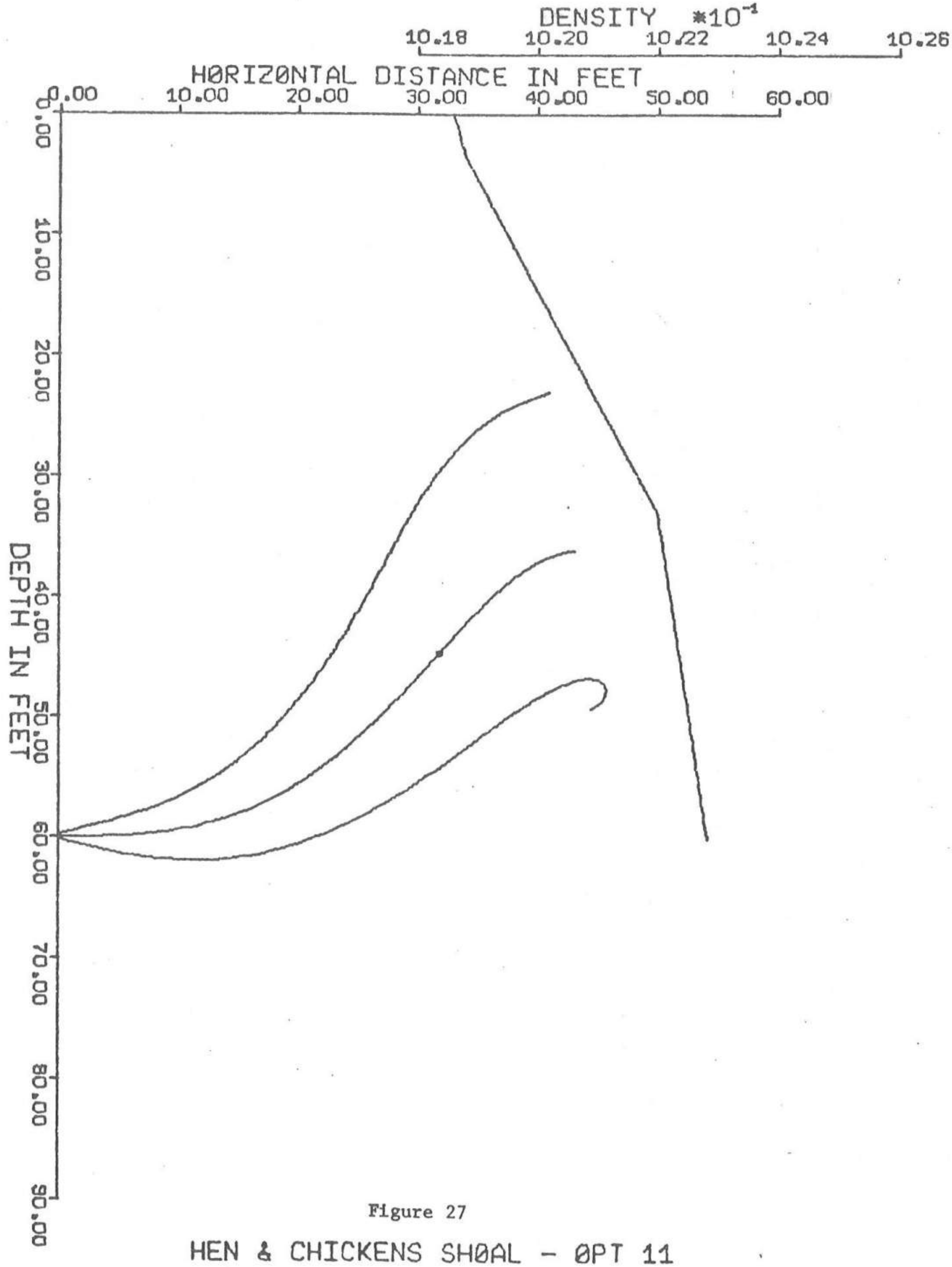


Figure 27

HEN & CHICKENS SHØAL - ØPT 11

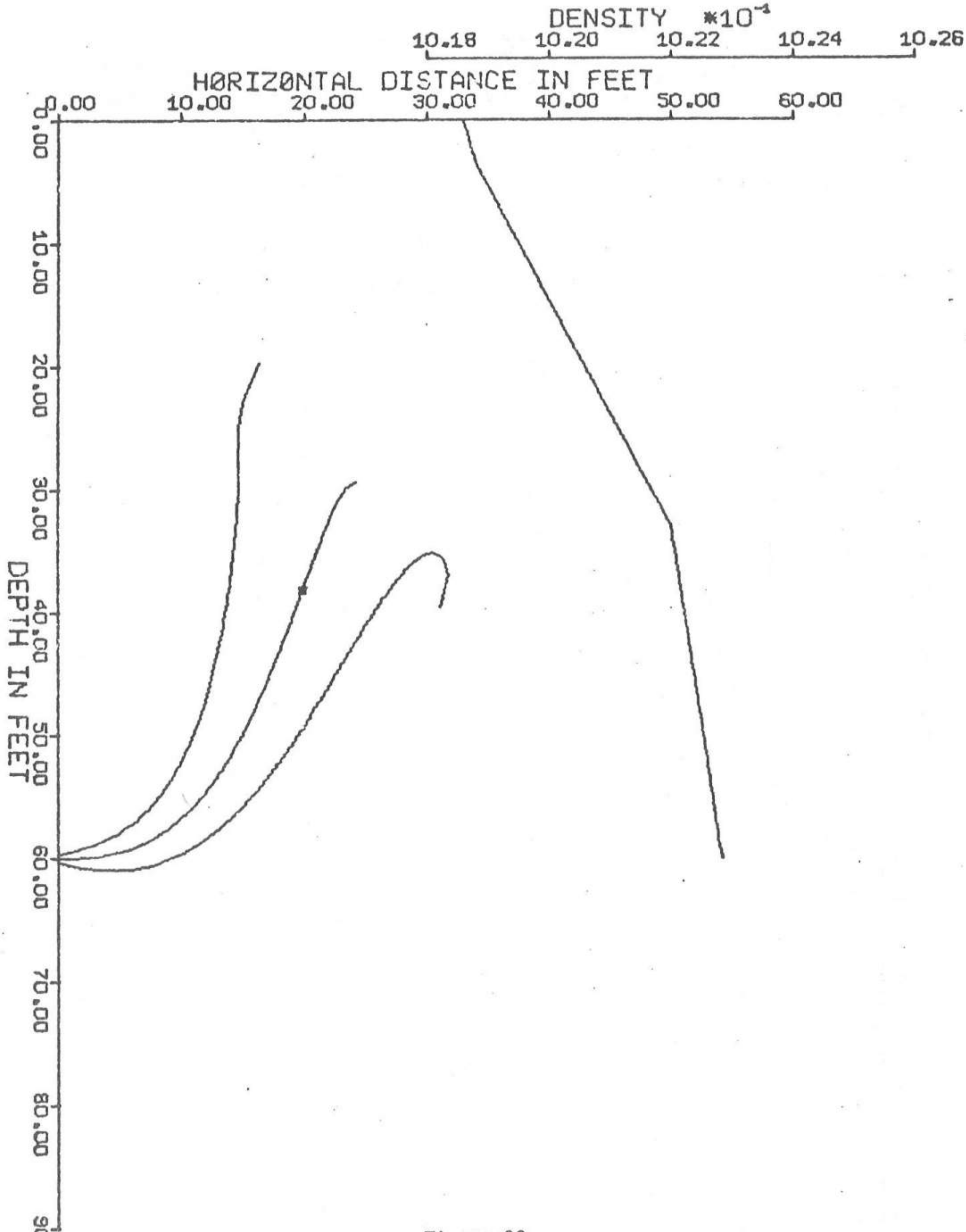


Figure 28

HEN & CHICKENS SHØAL - ØPT 13

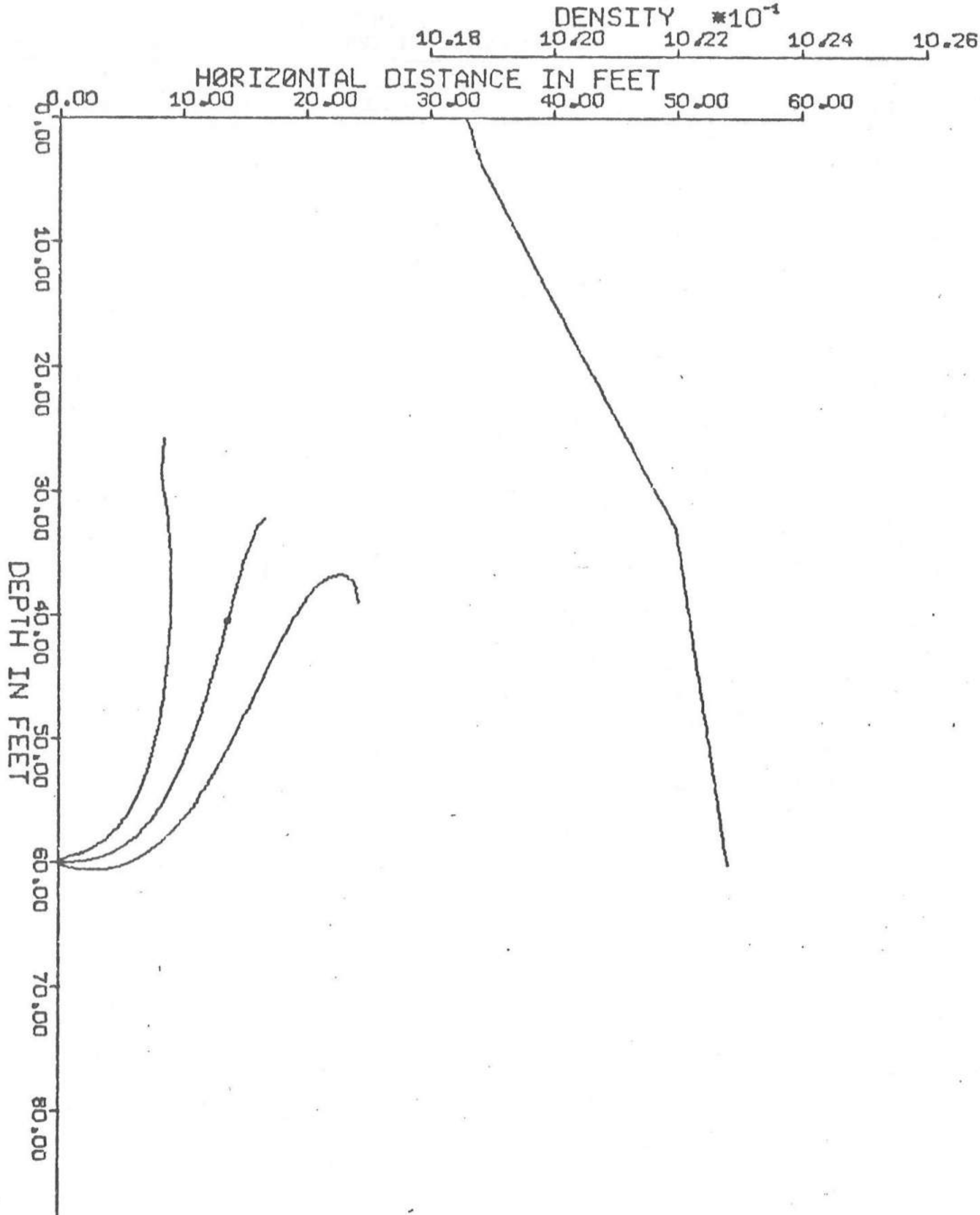


Figure 29

HEN & CHICKENS SHØAL - ØPT 15

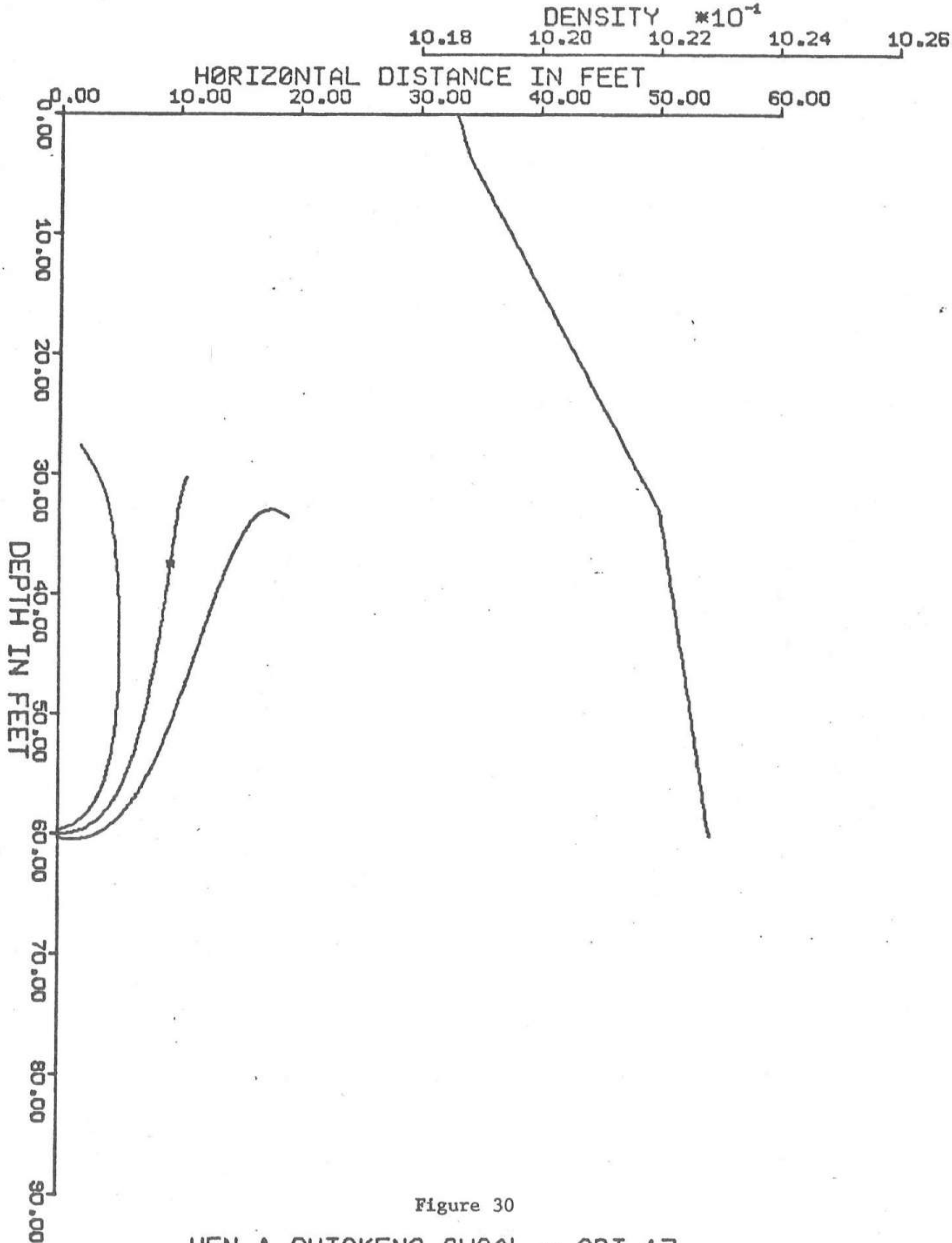


Figure 30

HEN & CHICKENS SHØAL - ØPT 17

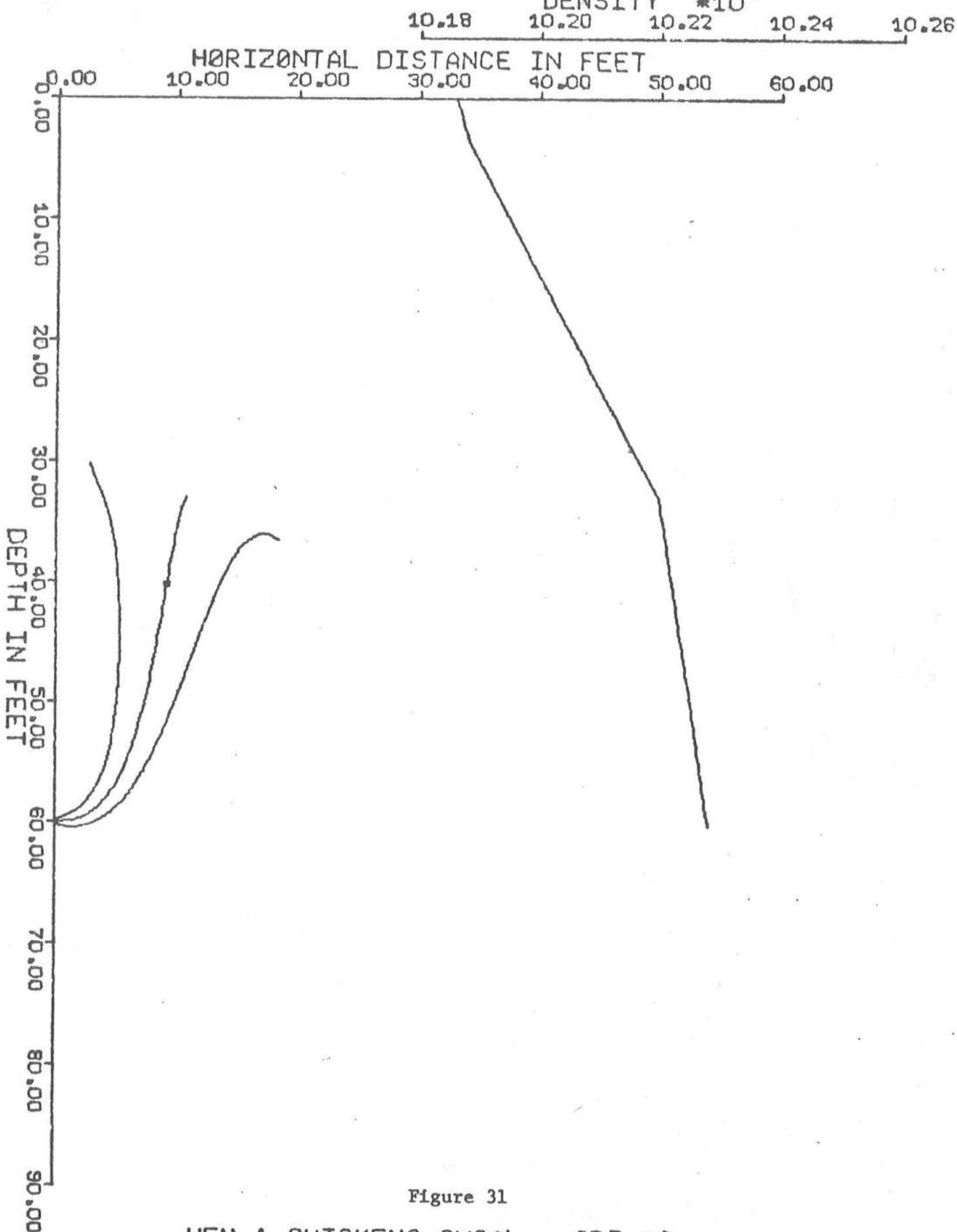


Figure 31

HEN & CHICKENS SHØAL - ØPT 19

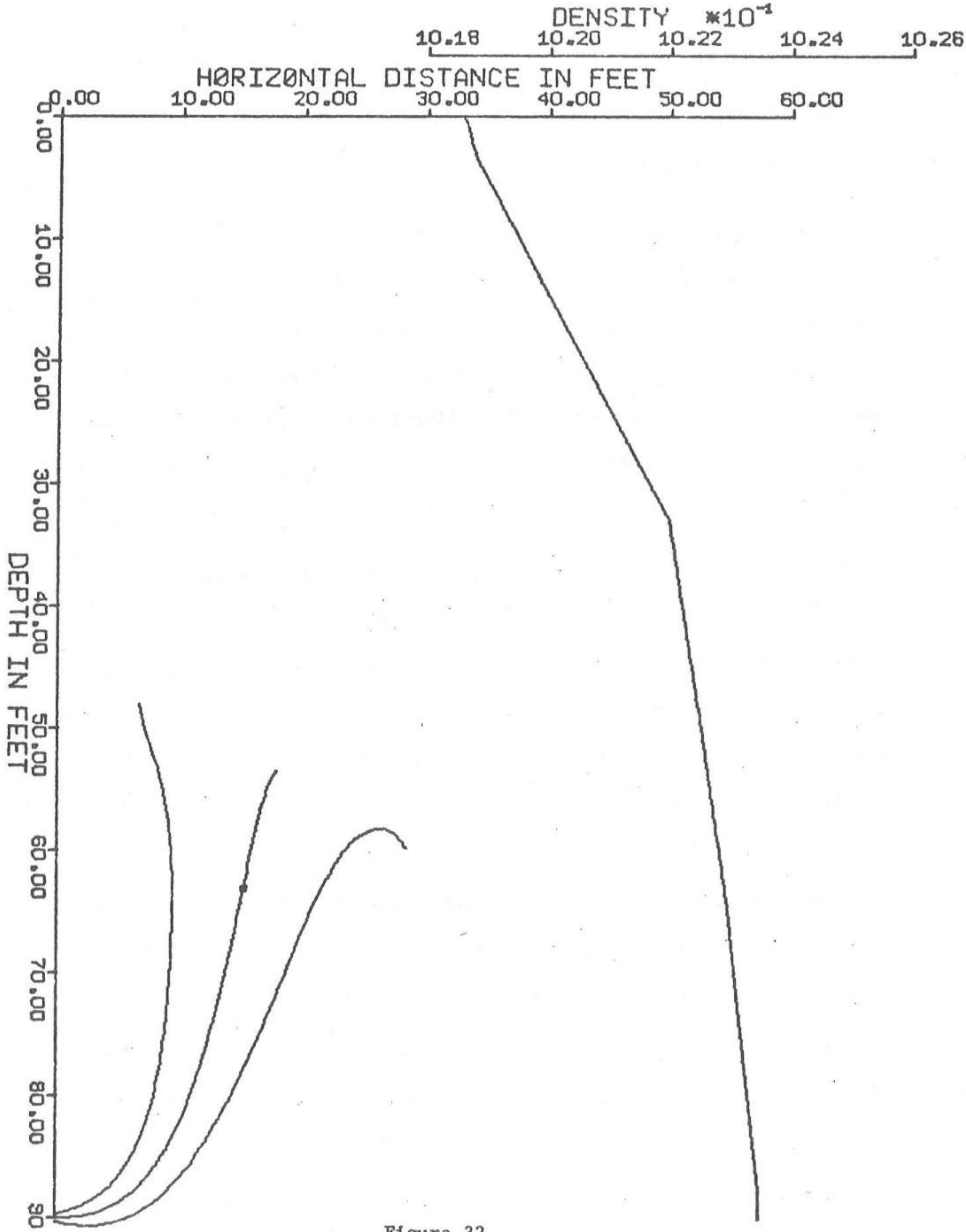


Figure 32

HEN & CHICKENS SHØAL - ØPT 23

additional mixing that occurs during sinking from the terminal height of rise to the level of neutral buoyancy.

The analysis for a stratified receiving water environment at the Hen and Chickens Shoal site was undertaken for eight of the options considered in Table 12. These eight options are representative of several locations and configurations. Plots of the jet centerline trajectories, nominal widths, and the density stratification are given for these eight options in Figures 25 through 32. Table 13 describes the dilution performance of these options under stratified conditions.

The results of the analyses show that under well-developed density stratification conditions the rising effluent from the diffuser will not penetrate to the water surface directly. In addition, the dilutions achieved at the terminal height of rise are less than those which would occur at the surface when density stratification does not exist or is "weaker" than the conditions assumed for analysis. The implications of these possible submerged effluent fields are:

1) Since the effluent field is submerged, it is not as likely to be subjected to surface wind-driven currents, particulary those which might transport the effluent shoreward.

2) Since drift of the submerged effluent is likely slower than at the surface, longer drift times probably result in greater far-field dilutions by turbulent diffusion.

3) The lesser dilutions above the diffuser in the submerged cloud may be of some concern should the concentrations appear large, and the build-up of submerged effluent cloud concentrations depends on local

Table 13

Performance of Hen and Chickens Shoal Options Under Stratified Conditions

Option	Depth of Water (ft)	Max. Height of ℄ Below Surface (ft)	Design (Unstratified) Surface Dilution	Dilution at Max. Height
7	50	27	100:1	51:1
9	50	25	100	43
11	60	36	100	62
13	60	30	100	49
15	60	32	150	60
17	60	30	150	57
19	60	33	200	66
23	90	53	200	63

transport away from the site.

The existence of strong current shears near the surface or thermocline can generate enough vertical diffusive transport that, although the terminal height of rise is below the surface, vertical transport of effluent may in fact result in effluent reaching the surface with additional dilution. Of course, the breakdown of stratification due to strong wind conditions will also permit the submerged cloud to reach the water surface, but it will be further mixed before reaching the surface.

C. South Bethany Beach Site Results

The results of the initial near-field analyses (no stratification) are summarized in Table 14. The maximum discharge is 25 mgd. The water depths considered were 30', 35', 40', and 45' which are approximately 2000', 4000', 6000', and 8000' offshore, respectively. These areas are shown in Figure 33. The South Bethany Beach Site is uniformly shallower than the Hen and Chickens Shoal site and has much greater uniformity in bottom topography parallel to the coastline.

The dilutions considered range from 50:1 and 100:1. The shallow nature of this site makes the achievement of a dilution of 100 more difficult, and such dilution is produced only by going relatively far offshore and using a relatively long diffuser section. Again, both one and two legged diffusers are considered. Trade-offs between diffuser pipeline length and diameter and port size exist as for the Hen and Chickens Shoal site.

The effects of density stratification (described in detail above) for six representative options at South Bethany Beach were studied. Plots of the jet centerline trajectories, nominal widths, and the density stratification are given for these six options in Figure 34 through 39. Table 15 describes the dilution performance of the options under stratified conditions. The implications of the effect of stratification to prevent the jet rising to the surface were discussed above (Section IV. B). However, it should be noted that the composite density profile used for the calculation provides a stratification which is slightly stronger than any measured during the field studies at the South Bethany Beach site (although not an unreasonable one for an upper bound). Also, the evidence of greater vertical mixing and uniformity at this site duesto its shallowness suggests that stratification may not exist throughout the entire summer.

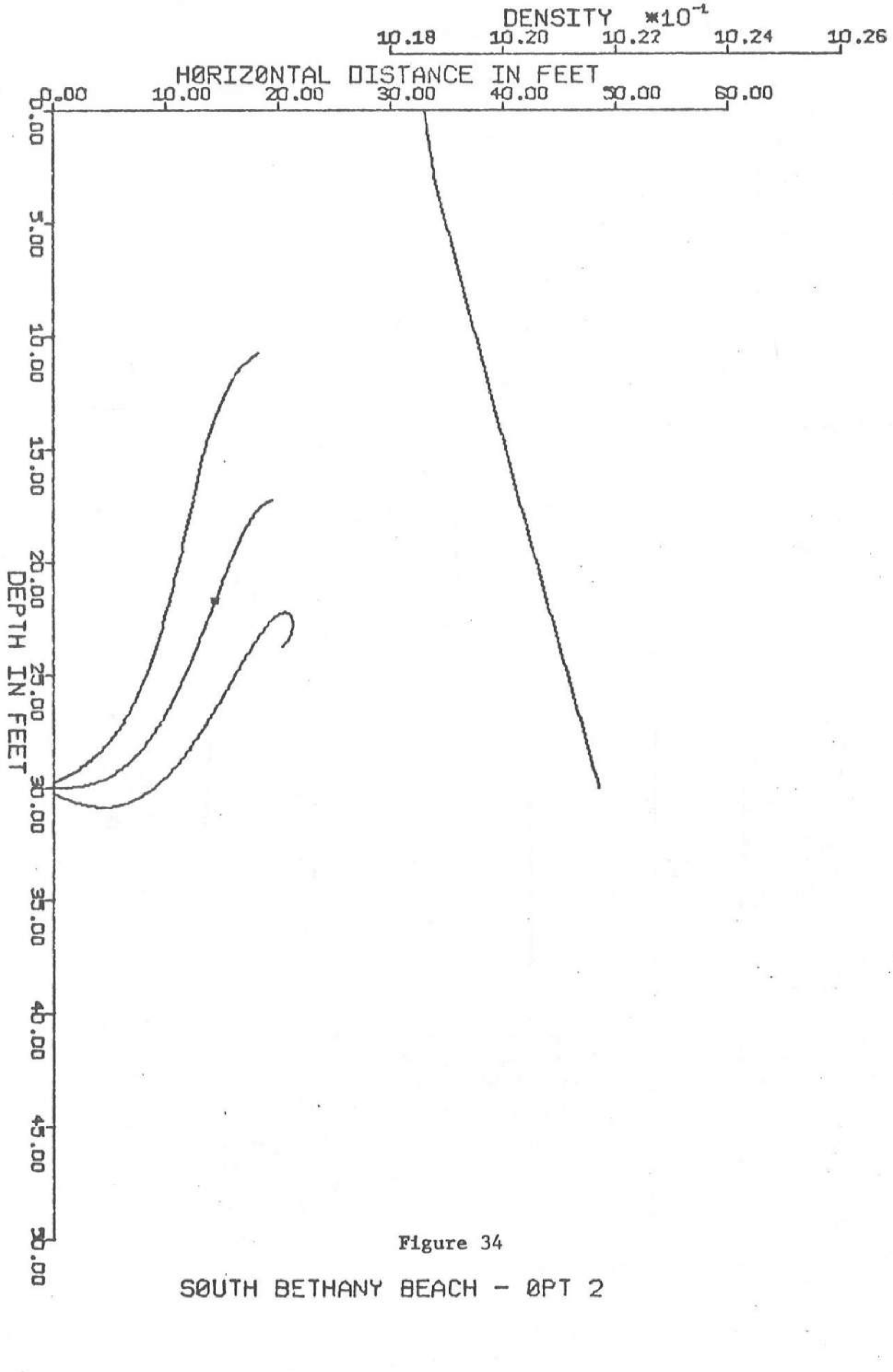


Figure 34

SØUTH BETHANY BEACH - ØPT 2

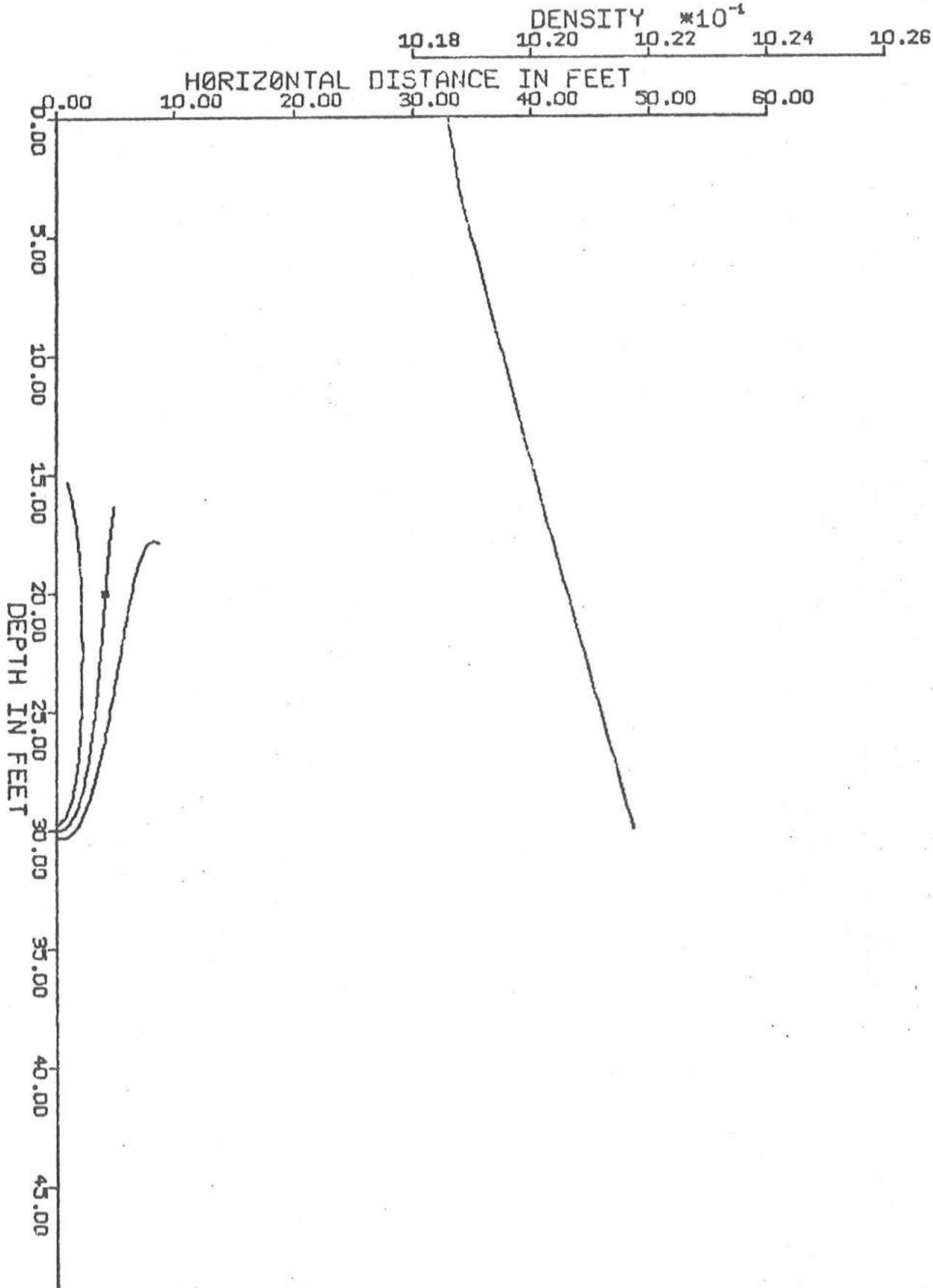


Figure 35

SØUTH BETHANY BEACH - ØPT 4

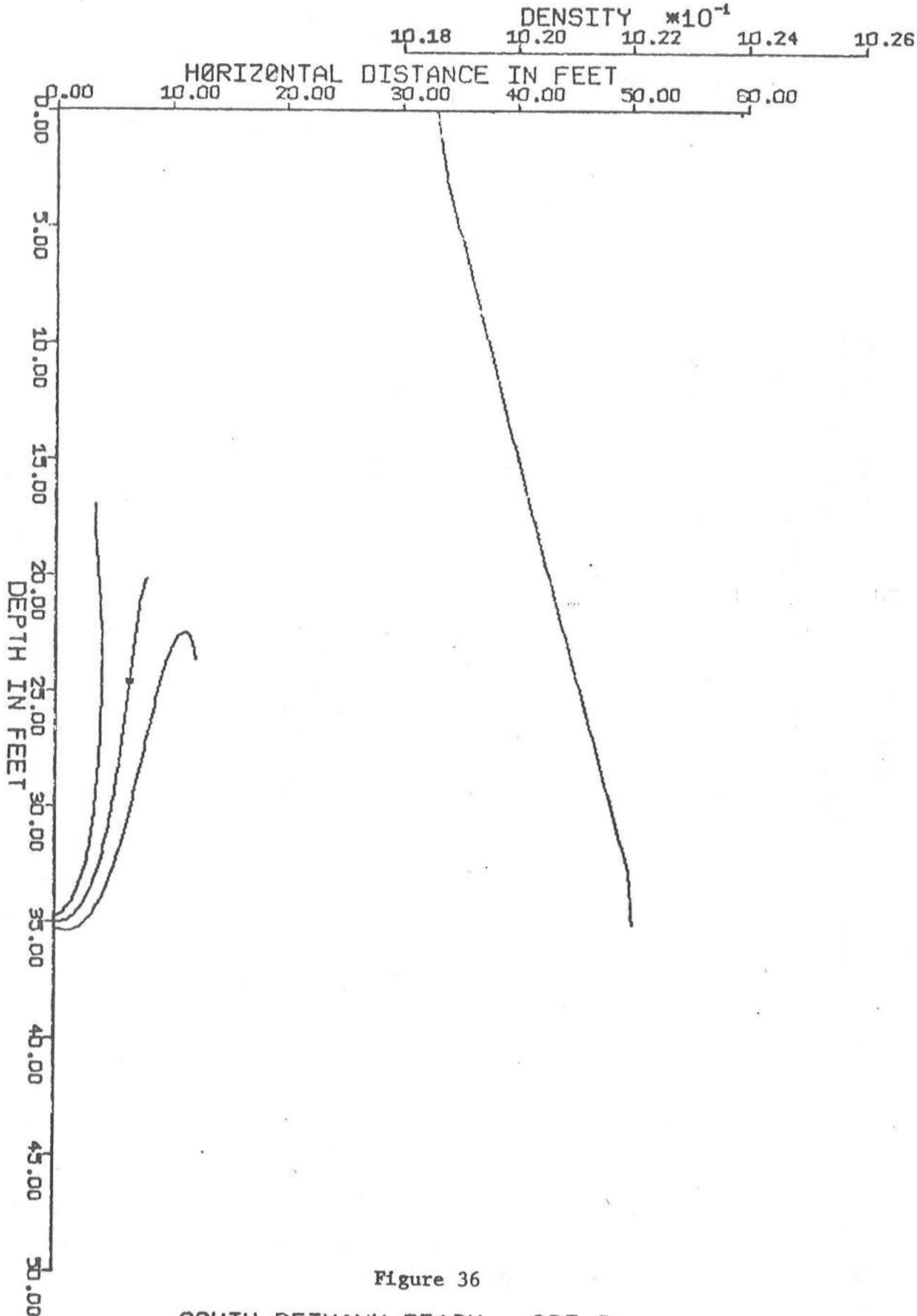


Figure 36

SØUTH BETHANY BEACH - ØPT 8

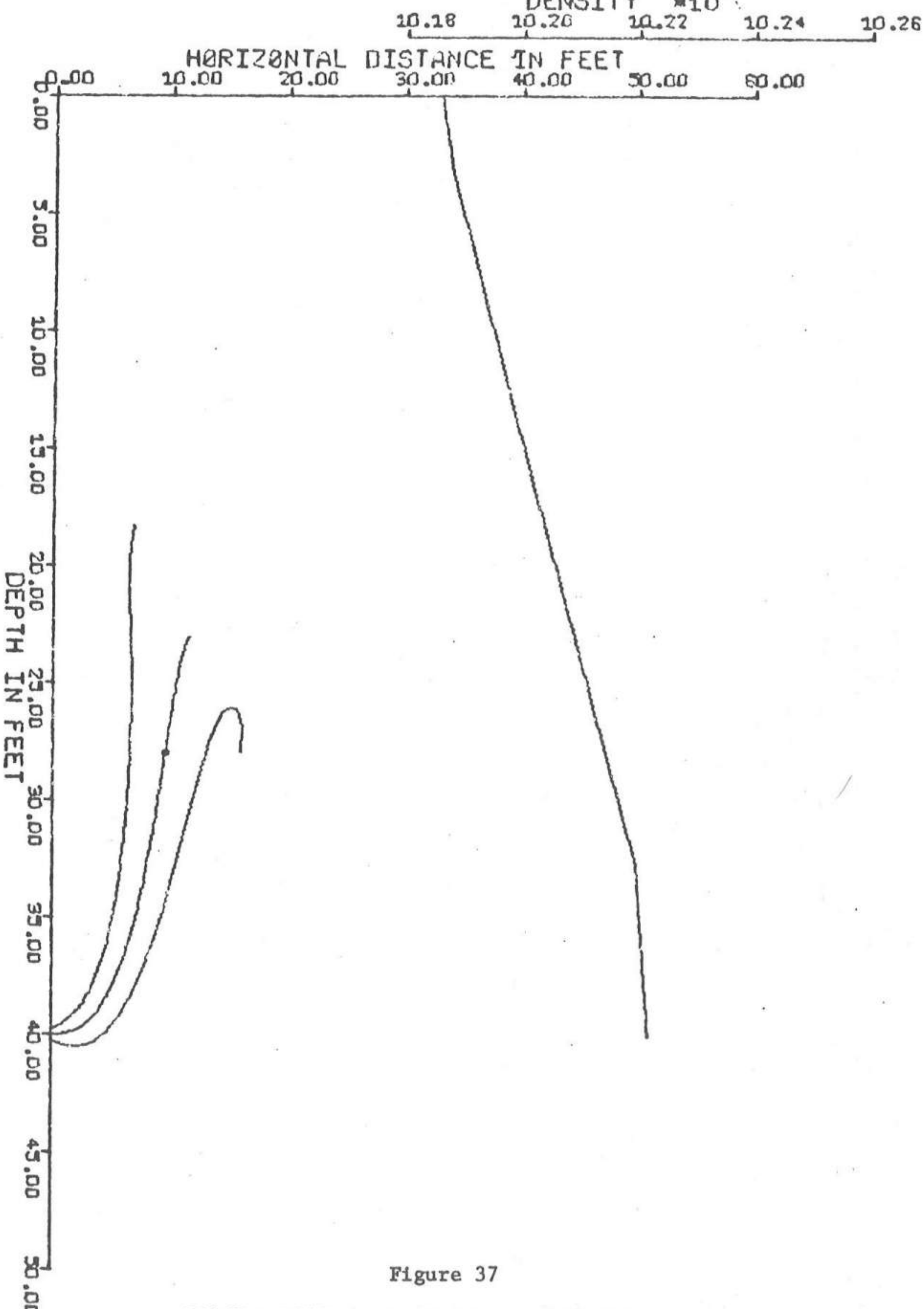


Figure 37

SOUTH BETHANY BEACH - OPT 12

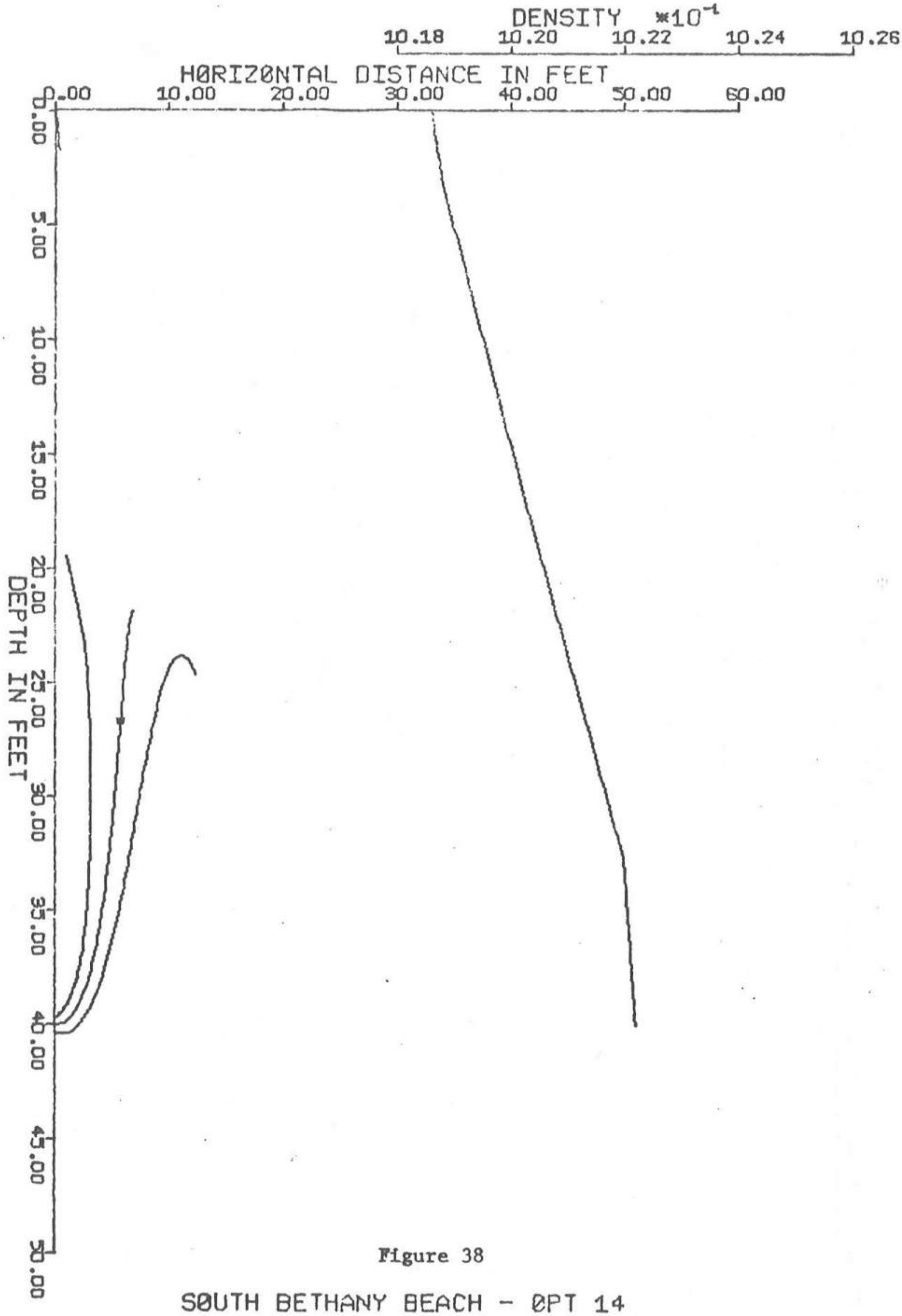


Figure 38

SØUTH BETHANY BEACH - ØPT 14

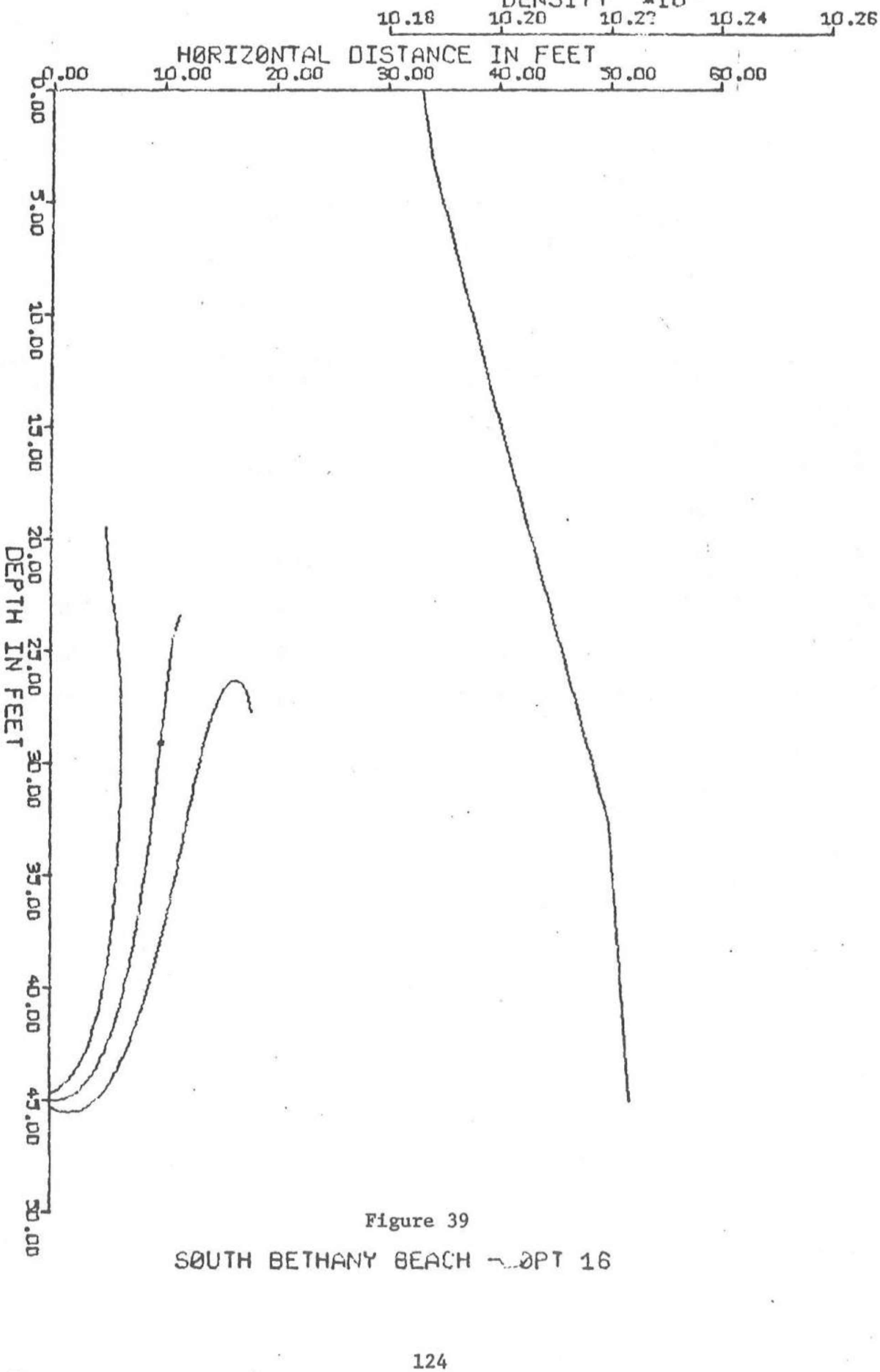


Figure 39

SOUTH BETHANY BEACH — OPT 16

Table 15

Performance of South Bethany Beach Options
Under Stratified Conditions

Option	Depth of Water (ft)	Max. Height of ℄ Below Surface (ft)	Design (Unstratified) Surface Dilution	Dilution at Max. Height
2	30	16	50:1	31:1
4	30	16	100	34
8	35	20	100	33
12	40	23	100	37
14	40	22	100	34
16	45	23	100	37

D. Internal Hydraulics Analysis

The analysis of the internal hydraulics of the diffuser section for specification of pipe diameter and for calculation of flow distribution from the ports and head loss in the diffuser section require the following assumptions. (Again, these are made to obtain a realistic measure of diffuser size and feasibility. They may change, and, thus, change the diffuser characteristics some in a more specific design).

(1) The diffuser pipeline is assumed to be horizontal or have very small slope.

(2) The ports are circular and sharp-edged.

(3) The pipe material is assumed to be concrete.

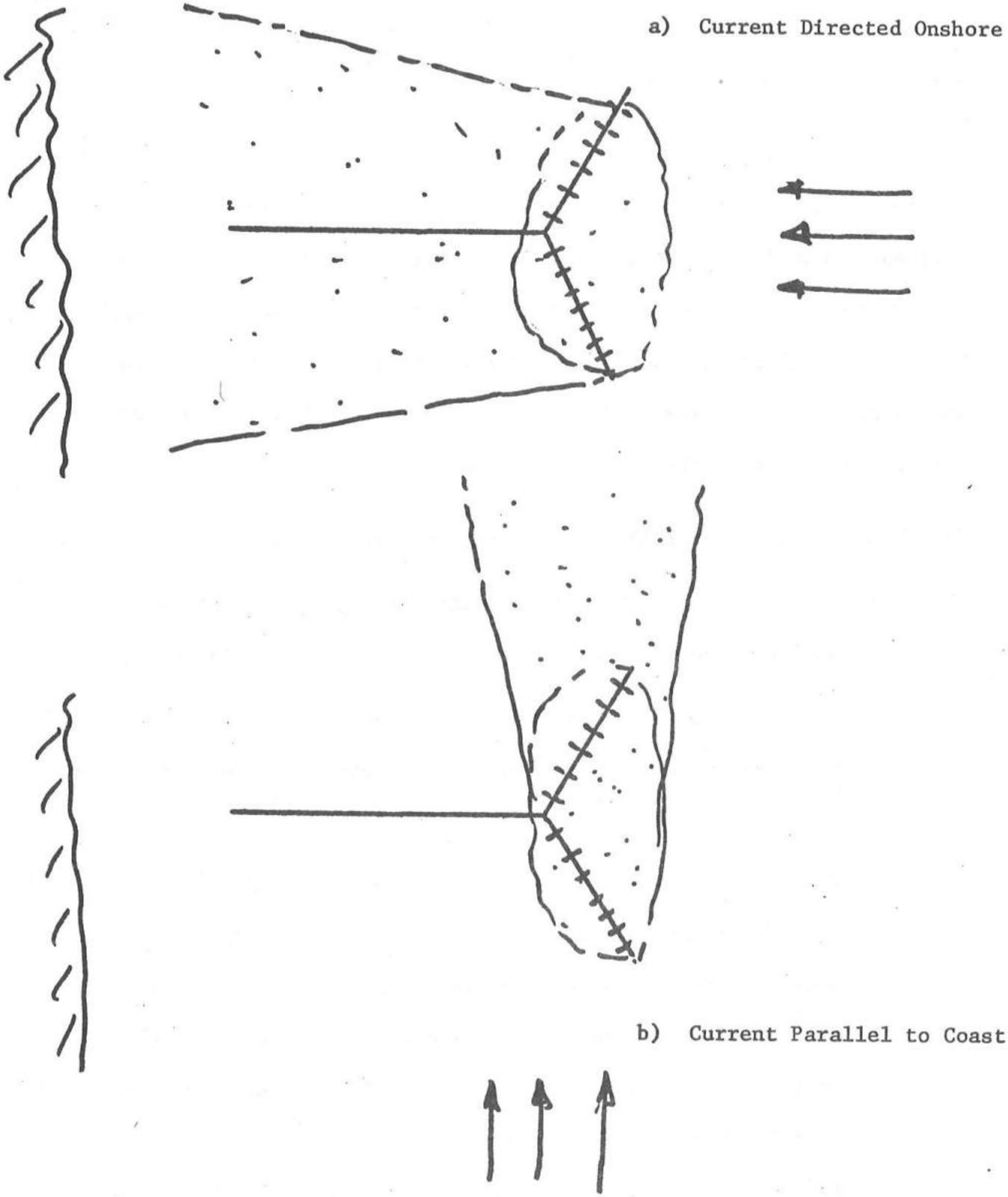
(4) The total part area is required to be less than the cross-sectional area of the pipe.

Using these assumptions, the analyses (10,5) produced the inside pipe diameter for the diffuser section as recorded in Tables 12 and 14. The distribution of discharge among the ports on any diffuser leg varies at maximum about 7% except as noted. The head loss due to the diffuser section is usually less the 10' except as noted.

V. Far-Field Analysis and Results

Mixing in the far-field is due to passive turbulent diffusion. As the surface effluent plume is carried along by the surface current, it spreads laterally and to a lesser extent vertically (see Figure 40). This mixing process usually does not result in mixing or dilution to the same degree as the submerged buoyant jets. Characteristically, the additional dilution achieved by far-field mixing is much smaller in the vicinity of the outfall (unless the current transporting the plume is very small and thus keeps the plume nearby for a long time).

FIGURE 40



A. Analysis

In this report, the far-field is viewed from the "worst-case" point-of-view. That is, the minimum dilutions available due to far-field mixing are calculated for some relatively infrequent conditions.

The two kinds of far-field drift conditions considered here are shown in Figure 40. The first (Figure 40a) is the case of a current carrying the effluent plume directly onshore from the diffuser site. The second (Figure 40b) is the case of a current carrying the effluent plume approximately parallel to the coastline. The wye diffuser has the advantage of providing for relatively good mixing in either case without forcing the jets to interfere greatly with one another.

The far-field analysis (11) employed incorporates the following assumptions:

(1) A wye diffuser is considered with the two legs 120° apart and oriented relative to the coast as shown in Figure 40.

(2) The effect of vertical mixing is neglected, and all spreading is lateral. Lateral diffusion coefficients for shallow coastal waters are assumed (11).

(3) For the case of an onshore current, a surface drift velocity of 1 ft/sec was assumed. This is approximately what might be generated by a 20 knot wind blowing toward shore in the fall on the Delaware coast. This is a measure of a "worst-case" in that the effluent will be brought to the beach much more quickly than "normal" and thus have little opportunity for additional dilution. The largest winds experienced during the field studies were about 12 knots. The onshore drift at Hen and

Chickens Shoal during these conditions was small as the currents there were primarily composed of tidal components and motion parallel to the coastline. At South Bethany Beach, because tidal currents were weak, onshore drift was significant but measured currents never exceeded 0.5 ft/sec used in these studies, while perhaps not the "worst case," is an event of rather restricted occurence. (See Sections II B. and D for detailed current and wind data.)

(4) The case of a current parallel to the coast was considered only at the HCS site regarding a plume drifting toward Cape Henlopen and Delaware Bay. In this case, a maximum tidal velocity of 2.5 ft/sec was used (although this could have been augmented by wind to come closer to a "worse-case"). As a point of reference, the maximum sustained currents found at this site during condition of a flood tide and parallel wind (13 mph) driven currents averaged about 2.6 ft/sec (See Section II B.).

(5) The initial far-field width of the surface effluent plume was assumed to be that of the diffuser projection in the direction of the current.

B. Hen and Chickens Shoal Site Results

The results of far-field analyses for all two-legged diffuser options are given in Table 16. The diffusers are assumed located in the regions indicated previously by depth (Figure 23). The minimum dilution at the shore due to an onshore drift and mixing is given and varies from 1 to 2.2. The numbers in parentheses refer to the total dilution of effluent at the beach due to both near- and far-field mixing, and range from 50 to 440. Even with more moderate onshore drift, far-field dilution from a diffuser on the land side of HCS would be very small. The minimum dilution at the Bay mouth (approximately 10,000' from HCS site) is given and ranges from 1.07 to 3.3 for far-field mixing and maximum tidal drift. Total dilution figures are given also. Far-field mixing toward the Bay is based on conservative mixing coefficients given the level of fluid motion in that area and of course increases as the diffuser is located further to the south of the entrance to Harbor of Refuge.

Current and dye studies indicate that ebb flows from the Bay mouth tend to move in an E to SE direction and would probably not carry the diluted effluent from the entrance of Harbor of Refuge directly back to the diffuser site. Ebb currents in the general site areas studied are about parallel to the Shoal and after slack would move diluted effluent back over the diffuser site. However, the tidal currents (plus wind currents) switch rather quickly and the return flow of diluted effluent should not be persistent.

TABLE 16

Summary: Results of Far-Field Mixing Analyses

"Hen and Chickens Shoal" Site

Option No.	Depth of Water	Dist. to Shore	Minimum Dilution @ Shore	Min. Dilution Toward Cape @ 10,000'
1	25 ft.	∿ 1500 ft.		
2	"	"	1:1 (50)	2.5:1 (125)
3	"	"		
4	"	"	1 (70)	1.07 (75)
5	"	"	1 (70)	1.15 (115)
6	50	∿ 4500		
7	"	"	1.1 (110)	2.5 (250)
8	"	"		
9	"	"	1.1 (110)	1.4 (140)
10	60	∿ 9000		
11	"	"	1.5 (150)	3.3 (330)
12	"	"		
13	"	"	1.5 (150)	2.5 (250)
14	"	"		
15	"	"	1.5 (225)	1.15 (173)
16	"	"		
17	"	"	1.5 (225)	1.15 (173)
18	"	"		
19	"	"	1.2 (240)	1.05 (210)
20	"	"		
21	"	"	1.2 (240)	1.05 (210)
22	90	∿ 13,500		
23	"	"	1.5 (300)	1.15 (230)
24	"	"		
25	"	"	2.2 (440)	1.8 (360)

( ) refers to total dilution i.e., near + far-field

C. South Bethany Beach Site Results

The results of far-field analyses for all two-legged options are given in Table 17. The diffusers are assumed located offshore distances corresponding to the water depths (Figure 33). The minimum dilution at the shore due to an onshore drift and far-field mixing is given, as well as, total dilution at the shore. Total dilution values range from 65 to 200 for the range of diffuser options. "Normal" dilutions at the shore would clearly be larger, as "normal" shoreward drift is less than the 1.0 ft/sec used in these calculations.

The current studies at the South Bethany Beach site indicate that the tidal currents are weak and of the rotary type. Thus, they tend to be influenced by wind and result in tidal excusions along the coast on the order of 2 miles. Because this site lacks the clearly distinguished tidal flushing of Hen and Chickens Shoal, the possibility for the diluted effluent to remain in the general site area for longer periods exists.

TABLE 17

Summary: Results of Far-Field Mixing Analyses

"South Bethany Beach" Site

Option No.	Depth of Water	Dist. to Shore	Minimum Dilution @ Shore	Total Dilution @ Shore
1	30 ft.	∿2000 ft.		
2	"	"	1.3:1	65:1
3	"	"		
4	"	"	1	100
5	35	∿4000		
6	"	"	1.8	126
7	"	"		
8	"	"	1.3	130
9	40	∿6000		
10	"	"	2.1	147
11	"	"		
12	"	"	2.0	200
13	"	"		
14	"	"	1.7	170
15	45	∿8000		
16	"	"	1.7	170
17	"	"		
18	"	"	2.4	192

VI. Implications of the Physical Studies for Ocean Outfall Location and Design

The purpose of these studies was not to pick "the design" for ocean outfalls at the Hen and Chickens Shoal site or the South Bethany Beach site. Rather, they are intended to serve as guidelines and a screening tool to the designer in the selection of the outfall locations and specific designs. However, the studies have provided evidence of the impacts of various designs and locations. Conclusions based on those results are provided in this section.

A. Hen and Chickens Shoal Site

The studies indicate that this site area possesses characteristics which allow for a relatively high level of mixing of the discharged effluent with the receiving waters for a wide range of expected receiving water conditions. Tables 12, 13, and 16 summarize the performance characteristics of the location and configuration options considered. The following general conclusions can be drawn regarding the outfall location and design:

General Dilution Characteristics - Minimum dilutions of 100:1 of the effluent in the surface waters above the diffuser can be achieved at the 50', 60', or 90' site areas offshore of the Shoal. Outfall discharge inside the Shoal is clearly not recommended because of the reduced circulation within that zone and its proximity to the beaches. Current measurements indicate that there exists sufficient transport of water into the 50', 60', and 90' zone areas to accomplish dilutions of at least 100:1. Generally speaking, the deeper the diffuser location, the larger the surface dilution possible. Of course, far-field mixing will further increase the dilution as the effluent drifts from the diffuser site.

Distance Offshore - While the distance offshore required is primarily a function of the degree of near-field mixing (and therefore depth) desired and of the far-field mixing to be accomplished before the effluent drifts to the beach, there is another consideration at the Hen and Chickens Shoal site. The 50' zone of Figure 23 lies just offshore of the Shoal. Studies of the growth and development of Cape Henlopen show that the Cape has grown toward the Bay and cut landward while the Shoal has moved seaward over most of its length (16,17) In view of the transient nature of the Shoal, it would appear that particular caution should be exercised in locating the diffuser section of the outfall in this 50' zone off the edge of the Shoal. It would appear reasonable to locate the diffuser section in roughly a 60' zone, as these exist generally seaward of the Shoal and as good mixing can be achieved there. (The 60' depth zone is clearly not uniquely confined to the area shown in Figure 23, but such areas can be found to the north and south of it.)

Alongshore Location - The location of the diffuser section of an outfall in the alongshore sense is, from a mixing viewpoint, primarily a function of the degree of mixing achieved by far-field processes as the effluent drifts toward the Harbor of Refuge on flood tide. Table 16 indicates the additional dilutions occurring due to drift from about "Gong 5" (the NW corner of the 60' zone) to the Harbor of Refuge. The further south of the Cape, the longer the travel time to the Cape on flood tide. While the studies indicate that flushing at the Harbor entrance during ebb tide appear efficient, location of the diffuser in 60' of water NW of "Gong 5" would mean less dilution and larger quantities of diluted effluent entering the Harbor area on flood tide.

B. South Bethany Beach Site

The studies indicate that this site possesses physical mixing characteristics different from the Hen and Chickens Shoal site; however, the proposed maximum discharge of effluent is less and may receive a higher degree of treatment. This site is characterized by the relative uniformity of its bottom topography from Bethany Beach to Fort Miles, with a gentle slope offshore. Tables 14, 15, and 17 summarize the performance characteristics of the location and configuration options considered. The following general conclusions can be drawn regarding the outfall location and design:

General Dilution Characteristics - Because of the relative shallowness of the site areas, minimum dilutions of 100:1 of the effluent in the surface waters above the diffuser can be achieved in the 30' and 35' depth zones only if large diffuser pipes and long diffuser lines are used. In 40' of water or deeper, small diffuser systems can achieve dilutions of 100:1.

Distance Offshore - The distance offshore required is primarily a function of the degree of near-field mixing (and therefore depth) desired and of the far-field mixing to be accomplished before the effluent drifts to the beach. Because of the relatively flat bottom topography in the zone from one to two miles from shore in the South Bethany Beach area, little additional near-field dilution is achieved by being further from shore. However, the far-field mixing and dilution at the shore is enhanced by being further offshore. Moreover, the nature of the currents at this site area indicates less rapid flushing of the diluted effluent from the area as a whole relative to the Hen and Chickens Shoal site. Thus, sites within one mile of the shore result in little far-field mixing and, given windless or winds from the E conditions, could result in dilutions at the beach at near-field levels or below due to little transport of the diluted effluent from the area during the tidal cycle. However, sites further offshore provide for greater far-field mixing and greater opportunity for transport by tides from the general area without as great probability of impingement on the beaches.

Alongshore Location - These studies indicate no preferred location along the shore from Bethany Beach to Fort Miles for outfall siting.

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