Evaluation of a Hard Clam Spawner Transplant Site Using a Dye Tracer Technique

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February 1978

Special Report 10

Reference 77-6

Approved for Distribution

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ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The hard clam (*Mercenaria mercenaria*) spawner transplant site of the Town of Islip, New York was evaluated using a water soluble, fluorescent dye tracer. The tracer was introduced to the site at the same time as the transplanting and was subsequently followed for 18 days. Dye concentrations were measured by continuous underway sampling using a fluorometer secured in a small boat. The resulting pattern of dispersion suggested that the site is in an undesirable location with respect to maximizing the set of spawner larvae within town waters. An alternate site in a less dispersive area in the north central part of town waters is recommended.

Four of the dye distributions were compared with turbulent diffusion theory and a mean diffusion velocity of 0.42 ± 0.024 cm sec^{-1} was determined for the area. This information was used to construct a simple model to predict the theoretical dispersion of larvae from an alternate site in town waters. The model was also used to determine ways in which Islip can maximize the setting densities of spawner larvae within town waters.

INTRODUCTION

The hard clam or quahog (*Mercenaria mercenaria*) thrives in Great South Bay, New York (Figure 1). It supports the most valuable hard clam fishery in the world with a landed value of 17 million dollars in 1976 (National Marine Fisheries Service, 1977). In addition to providing a livelihood for thousands of full- and part-time baymen, the fishery supports a large number of local marinas, shippers, processers, and restaurants (Buckner, 1976). The total retail value of the industry has been estimated at 100 million dollars (Nassau-Suffolk Regional Planning Board, 1974).

In 1976, approximately 52 percent (National Marine Fisheries Service, 1977) of the hard clams landed in Great South Bay came from the Town of Islip's waters (Figure 2). Islip has a very active shellfish management program, one segment of which is the spawner transplant program. Briefly, the spawner program consists of transplanting clams from colder waters outside the Bay to a designated site within town waters (Figure 2). It is hoped that the larvae of these spawners will significantly augment the natural set produced by native clams. The spawners themselves are of little value since they are all of the commercially least valuable chowder size class.

The transplanting is usually carried out in mid-July when Bay water temperatures are high enough to induce hard clam spawning. The spawners are brought from colder waters outside Great South Bay. Although these clams have not yet spawned, their gonads are physiologically mature and it is believed that they require only a thermal stimulus to initiate spawning.

Since *Mercenaria* larvae are essentially planktonic, their dispersion from the transplant site is governed primarily by the physical processes of advection and diffusion. To justify the spawner program from Islip's standpoint, a large percentage of the surviving larvae must be distributed over suitable areas within town waters at the time of setting. Of prime importance, therefore, is the location of the transplant site within town waters.
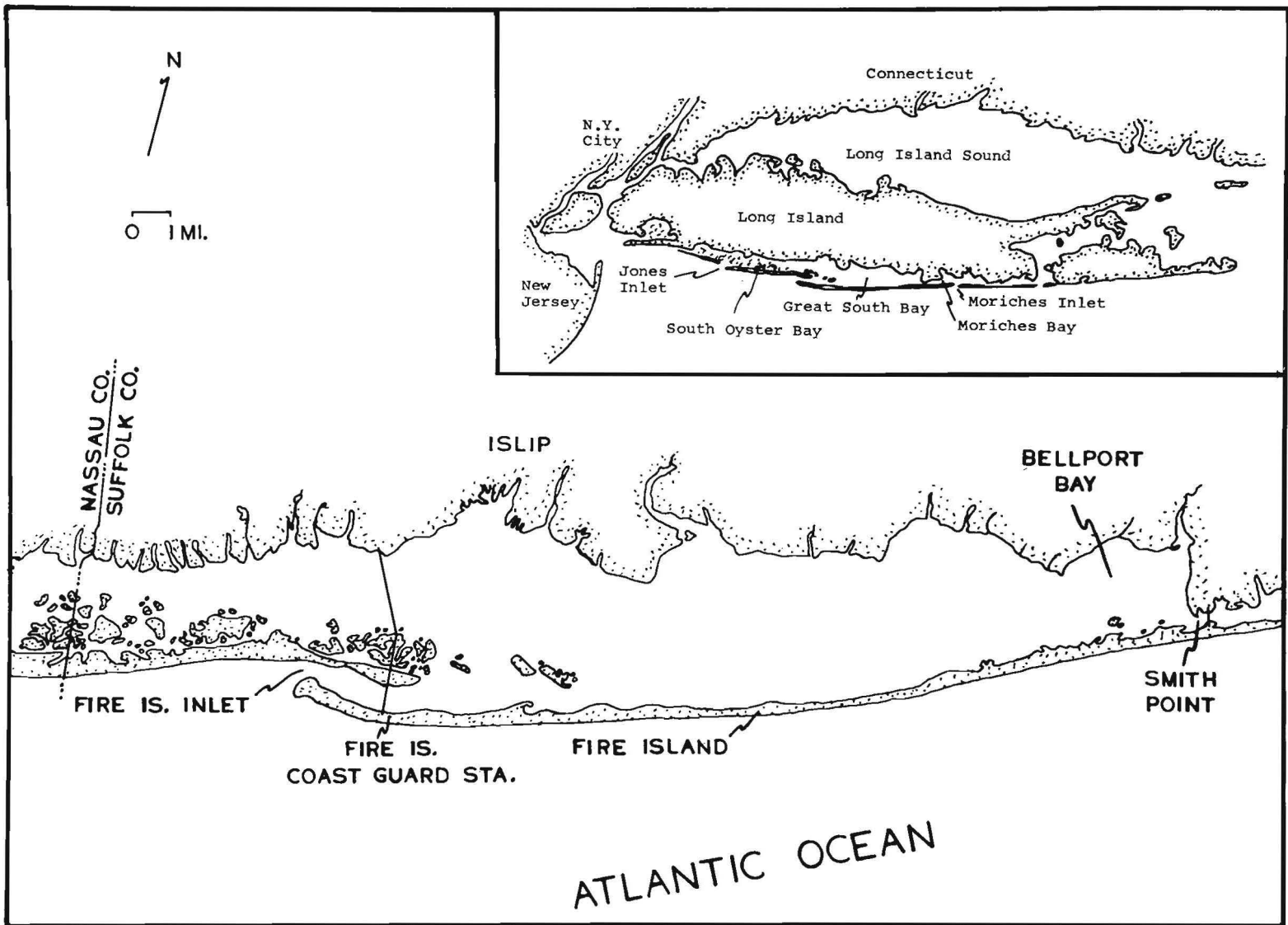
Figure 1. Location of Great South Bay.
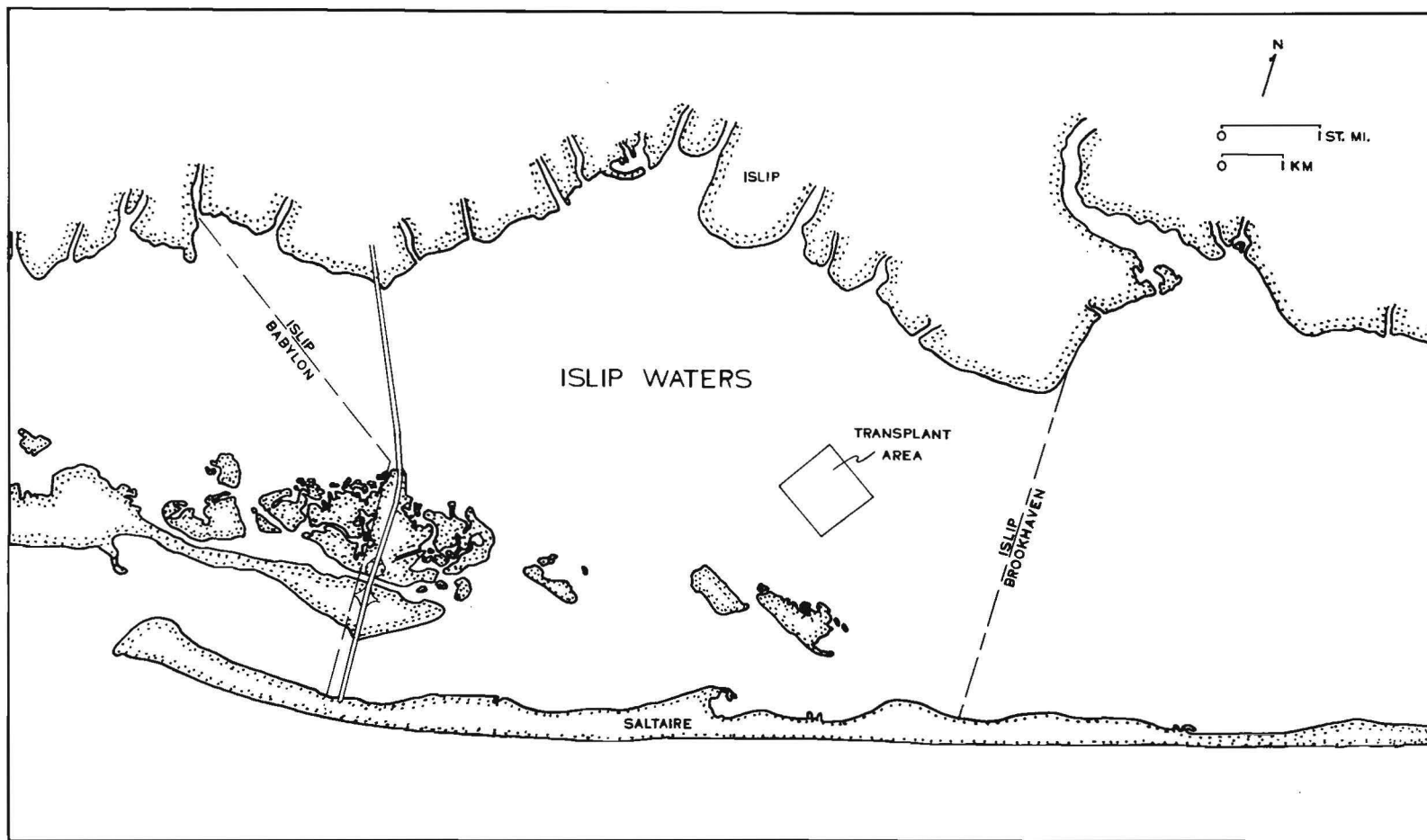
Figure 2. Location of Islip Waters and the Spawner Transplant Area.

In the last 20 years, dye tracer techniques have experienced increasing use for empirically determining the dispersive properties of various bodies of water (Carter and Okubo, 1976). The Chesapeake Bay Institute, in particular, has refined the technique of dye tracing for studying a wide variety of problems related to mixing and water circulation in coastal zones. In 1960, D. W. Pritchard first used an artificial tracer (Rhodamine B) to simulate oyster (*Crassostrea virginica*) larvae in an area of Chesapeake Bay (unpublished). In 1967, H. H. Carter used Rhodamine WT to predict the brood stock requirements for an oyster producing area in Chesapeake Bay. This study is an attempt to apply the basic techniques used by Pritchard and Carter to the study of *Mercenaria* larval dispersion from the Town of Islip's spawner transplant site.

If one assumes that *Mercenaria* larvae are more or less passively carried by water currents, it is possible to use a water soluble, passive tracer to simulate their dispersion. Then, by means of a simple comparison between dye and larval concentrations, the percentages of late-stage larvae setting in suitable areas can be estimated. These percentages were the primary criteria for evaluating the present location of Islip's spawner transplant site. In addition, the theoretical dispersion of *Mercenaria* larvae within Islip waters can be predicted by comparing the tracer results with two-dimensional turbulent diffusion theory. The theoretical analysis was used to determine ways in which Islip can maximize larval setting densities within town waters.

PHYSICAL SETTING

Great South Bay is a shallow bar-built estuary. Its major axis is 40 km in length and is oriented in an east-west direction between the Nassau-Suffolk County boundary on the west and Smith Point on the east. The Bay varies in width from 2.4 to 8.0 km and has an average depth of 1.3 m (MLW). Its surface area is approximately 235 km^2. As defined, direct connection with the ocean is through Fire Island Inlet. The Bay is indirectly connected with the ocean through South Oyster Bay and Jones Inlet on the west and through Moriches Bay and Moriches Inlet on the east. Salinity is essentially vertically homogeneous due to wind and tide mixing (Redfield, 1951) and decreases as one moves eastward from Fire Island Inlet to Bellport Bay. There also exists a lateral salinity gradient with lower salinity water on the north side and higher salinity water on the south (Redfield, 1951; Hair and Buckner, 1973). The lateral gradient is the result of freshwater inflow from the mainland of Long Island on the north, the inflow of salt water through Fire Island Inlet on the south, and possibly the effects of Coriolis force acting upon tidal movements (Redfield, 1951). The tidal range throughout the Bay is less than 0.2 m and, due to the shallowness of the system, high water occurs progressively later at points farther from Fire Island Inlet. Maximum current velocities range from 1.5 m sec^{-1} in Fire Island Inlet to less than 0.3 m sec^{-1} throughout the main part of the Bay.

Circulation in Great South Bay is extremely complicated. It is controlled primarily by tidal currents but due to the shallowness of the Bay, the small tidal range, and the relatively long and unobstructed fetch, it is also strongly influenced by the wind. In a body of water with nonuniform depth such as Great South Bay, one would expect the wind to exert a differential effect on waters of different depth. Although the surface wind stress will be essentially uniform over the Bay, the applied force per unit mass of water will be inversely proportional to depth if it is assumed that the force is uniformly distributed through the water column. Since the Bay is semi-enclosed, the net amount of water moved in the direction of

4

the wind must be zero. This requires, therefore, that motion be directed downwind in areas where depth is shallower than average and upwind in areas deeper than average. Hence, wind conditions are very important in any analysis of movement and mixing in Great South Bay. Because of the elongated shape and east-west orientation of the Bay, wind from either the east or west should exert the greatest influence on circulation.

In addition to the wind, irregular bottom topography, marsh islands, thick beds of eelgrass (*Zostera marina*), and exchange with South Oyster Bay and Moriches Bay also act to modify the tidal circulation.

On the basis of the salinity distribution, one would expect a general counter-clockwise drift throughout the Bay. There is some evidence of this type of circulation (Redfield, 1951; Jamieson, 1968), but more intensive investigations are required for confirmation.

The Town of Islip has jurisdiction over approximately 80 km^2 of the western part of the Bay, including Fire Island Inlet. The hydrography of the southern part of these waters is strongly influenced by the tidal flow through the Inlet. The deposition of sediments by the main tidal current as it moves into the Bay and dissipates has resulted in the formation of a tidal delta which covers most of this southern area (Figure 3). The delta consists of broad shoal areas interrupted by a series of scoured tidal channels (Snakehill, Dickerson, West, South, Range, and East). In addition, four groups of marsh islands (Captree, Sexton, West Fire, and East Fire) have formed on the shoals with their axes parallel to the Inlet.

Fire Island Inlet directs the flood tide into the Bay in an easterly direction. As the main tidal current enters the Bay, the channels subdivide it into three definable flows. Two of these flows are directed north through Snakehill Channel and through Dickerson and West Channels, while the third continues in an easterly direction through South Channel. The maximum excursion of the flood tide rarely penetrates past the arc formed by the marsh islands and Fire Island except through Snakehill Channel (Robert A. Taft Sanitary Engineering Center, 1962). Exchange of ocean water with the rest of the Bay apparently results from wind- and tidally-induced turbulent mixing. During ebb tide, the channels act as tributaries to direct the water back out of the Inlet.

The northern part of Islip waters is generally deeper than 2 m and is devoid of marsh islands. Circulation in this area is neither as strong nor as well defined as that to the south. There is speculation that a weak westerly current exists as a result of the baywide counterclockwise drift previously mentioned but confirmation of this is lacking.

At present, the Town of Islip's spawner transplant site is located approximately 1.5 km north of East Fire Island on a large shoal (Figure 3). The site covers an area of approximately 1 km^2 and is located in water of between 1 and 2 m depth.

MERCENARIA LARVAL HISTORY

Since adult hard clams generally show little movement and no migration (Belding, 1931), their distribution is dependent primarily upon the factors which influence the setting and survival of the young. Any attempt to control the distribution of the resource through introduction of larvae to a system must be concerned primarily with events of the larval and early post-larval stages. Presented below are some of the more critical events, from a management standpoint, that occur during these two periods.

Fertilization in *Mercenaria* is external. It follows the discharge of eggs and spermatozoa from the excurrent siphons of the adult organisms. Approximately 24 hours after fertilization, embryos develop into fully-shelled free-swimming larvae (veligers). *Mercenaria* veligers are planktonic and cannot
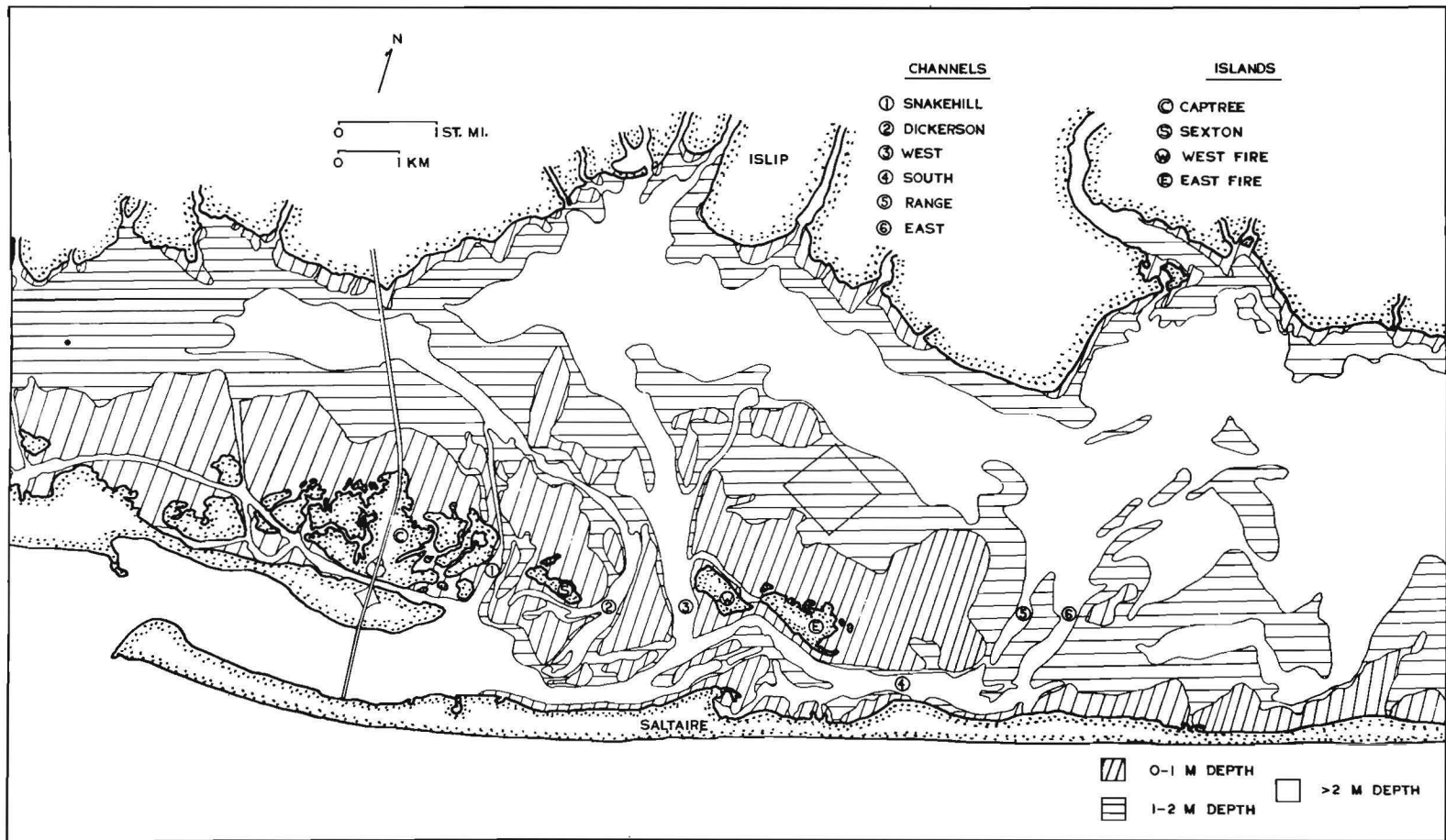
Figure 3.   Physical Geography of Islip Waters (from N.O.S. chart 120-SC, 1973).

resist horizontal dispersion (Carriker, 1961). However, the larvae are able to control their vertical position with the aid of a ciliated swimming organ, the velum. Carriker (1961) concluded, on the basis of laboratory experiments, that healthy *Mercenaria* larvae remain suspended in the water column for the entire veliger stage.

Belding (1931) suggested that the veliger stage is the most critical and important period in the life cycle of the hard clam. Veligers are essentially at the mercy of the elements. Sharp changes in temperature and salinity, "polluted waters", predators, flushing out to sea, and settling over poor substrate all contribute to the high mortality experienced during this period. The duration of the veliger stage is critical since the longer a larva remains in the water column, the lower are its chances of survival. Temperature, as it influences growth rate, is the main determinant of the length of this period (Belding, 1931; Loosanoff and Davis, 1963). Loosanoff *et al.* (1951) found that the onset of setting varied between 7 and 16 days after fertilization depending upon water temperature.

As the veliger nears the end of its planktonic existence, it develops a strong, mobile foot. The clam then enters the pediveliger stage in which it alternates between a planktonic and benthic existence by swimming and crawling in an apparent search for a suitable habitat. The pediveliger can still range over large areas of substrate by retaining the ability to swim back up into the water currents.

The velum is soon lost and a byssus gland develops in the foot. The young clam has now entered the plantigrade stage in which it alternately anchors itself with a byssus (a slender thread secreted by the byssus gland) and crawls along the bottom with its motile foot. Upon reaching this stage, the clam's ability to migrate is drastically reduced.

Finally, after siphons begin to emerge,

the clam is able to burrow into the sediment and begin an essentially stationary existence.

It can be seen from the preceding discussion that it is possible for *Mercenaria* larvae to influence their horizontal dispersion indirectly through vertical migrations and, during the pediveliger stage, by temporarily removing themselves from the water column. The results of the present study will be in error, therefore, to the extent that the larvae can modify their dispersion relative to a dissolved substance such as dye.

THE TRACER STUDY

Rhodamine WT was used as the tracer material because tests have shown it to be less adsorbent on sediments and suspended materials than other popular tracers (Carter, 1974). This property is essential for studies performed in turbid inshore waters such as Great South Bay. In addition, the tracer met the requirements of being stable, economical, harmless, and easily detectable with high sensitivity.

Dye concentrations (fluorescence) were determined with a Turner Model 111 fluorometer modified for continuous underway sampling (for details see Carter, 1974). The instrument was sensitive to concentrations as low as ± 0.02 ppb. Excitation light aperture settings of 30x, 10x, 3x, and 1x were used to detect concentrations as high as 60 ppb. The emitted fluorescence was recorded on a Rustrak strip chart recorder.

Power was supplied by a Honda Model EM400 portable generator which delivered an alternating current of 115 volts at a frequency of 64 Hz. This is within the power range at which the Model 111 fluorometer will operate satisfactorily without changing calibration (Carter, 1974). The fluorometer was calibrated at the beginning and end of the experiment to ensure that the calibration had not changed appreciably during the

course of the study.

A Jabsco ("Handy-Puppy") pump, located downstream from the fluorometer, circulated water throughout the sampling system. The pump is capable of delivering a constant flow of water at a rate of 15 l min^{-1}. Transit time between the intake and the fluorometer was approximately 8 seconds.

The fluorescence of Rhodamine WT is temperature dependent. Sample temperature must therefore be monitored continuously. The relationship between temperature and fluorescence can be expressed as,

$$F_s = F_m e^{-k(s-m)} \tag{1}$$

where F_s = the fluorescence in arbitrary units at a standard temperature s C,

F_m = the measured fluorescence of the sample in arbitrary units at temperature m C,

k = the temperature coefficient for Rhodamine WT in C^{-1}.

Feuerstein and Selleck (1963) determined a value of 0.027 C^{-1} for k.

Accordingly, temperature was monitored continuously with a portable temperature device utilizing a thermistor (Schiemer, 1962) and recorded on a Rustrak strip chart recorder. The temperature probe (thermistor) was located in a flow cell immediately downstream from the fluorometer.

An intake probe was constructed from a 2.5-meter length of aluminum tubing (2 cm inner diameter) and was mounted on a fixture about 15 cm from the starboard quarter of the sampling vessel. The fixture allowed the probe to swing in a short arc about a vertical axis to minimize lateral forces during vessel maneuvers. Polyethylene tubing was run through the entire length of the probe to an opening about 3 cm from the bottom. The tubing was bent through the opening so that samples were taken horizontally and opposite to the vessel's direction of movement. This served to minimize clogging and bubble formation at the intake.

The depth of the intake could be varied from 0 to 2 m by adjusting the probe assembly.

All sampling was performed from a 16 ft Boston Whaler equipped with a 50 hp outboard engine. A masonite housing was constructed over the bow of the vessel to protect the instruments. Sampling was accomplished by pumping water at a constant rate through the fluorometer, the flow cell, the pump, and then over the side. All piping was 1.3 cm (outer diameter) clear polyethylene (PolyFlo) tubing. Figure 4 shows a schematic representation of the sampling system aboard the vessel.

Positions of the sampling vessel were determined by running transects at constant speed and course between established navigation and/or management buoys. Occasionally, when a transect extended beyond an established buoy, the terminus was determined by horizontal sextant angles between well defined objects on shore.

From 1030 to 1042 on 14 July 1976, 139.48 kg of a 20 percent solution of Rhodamine WT (density 1.122 g cm^{-3}) was released as a small volume instantaneous point-source in the southwest part of Islip's spawner transplant area (Figure 5). The dye was poured on the surface from two 133-liter drums as rapidly as possible; however, because of the relative motion between the boat and the water it ended up as an elongated patch approximately 23 m long and 15 m wide. At the time of release, the wind was out of the west northwest at 10 knots and the stage of the tide was approximately 1 hour before high water.

The distribution of dye as a function of time and space was measured for an overall period of 18 days. Discrete measurements were made on 11 separate occasions: Days 0, 1, 3, 5, 7, 9, 11, 13, 14, 15, and 17[1]. Parameters measured were the concentration of the tracer material, the temperature of the water, and the position of the sampling vessel. Measurements after Day 0 were made laterally by continuous underway sampling at 0.6 m depth.
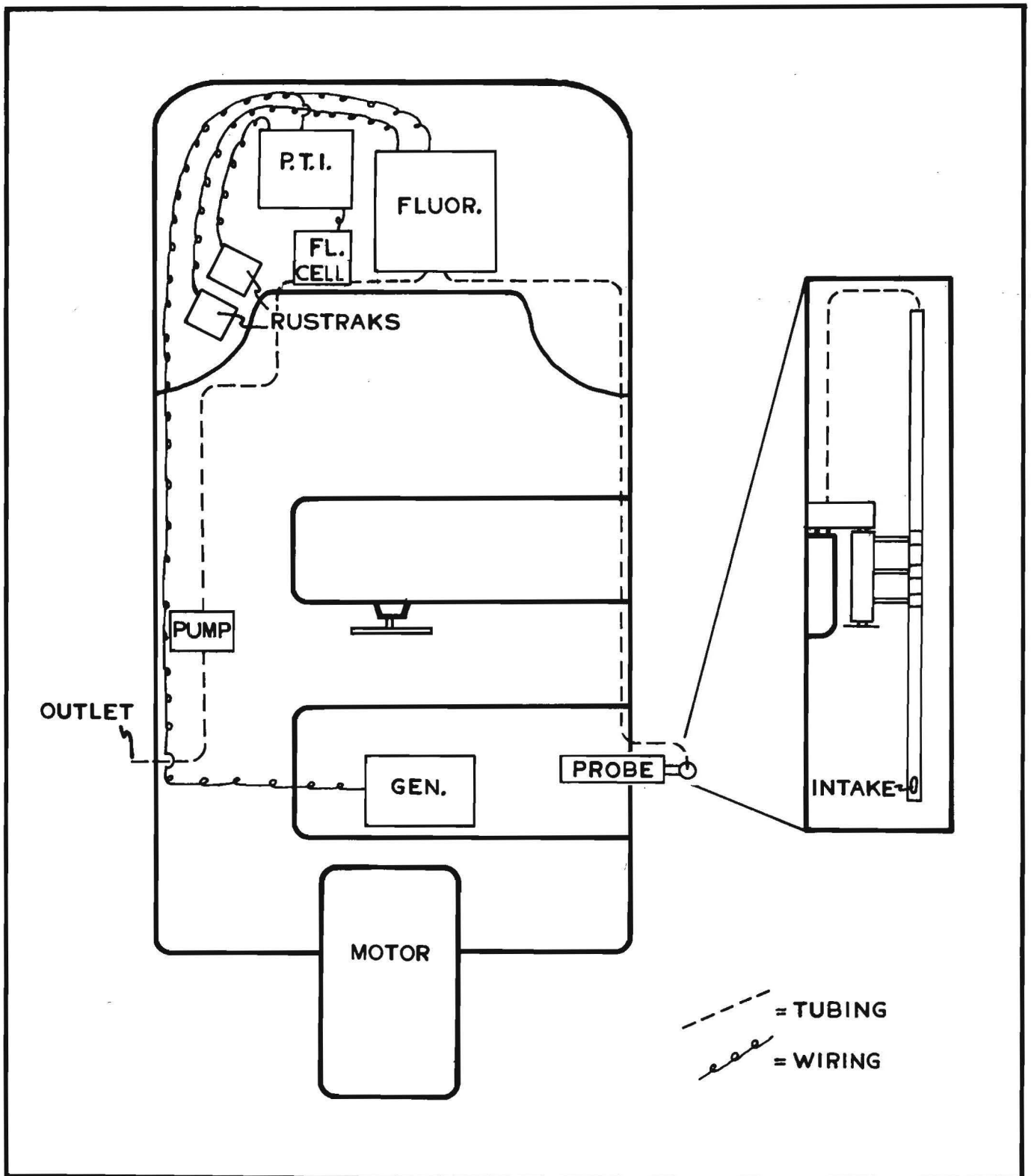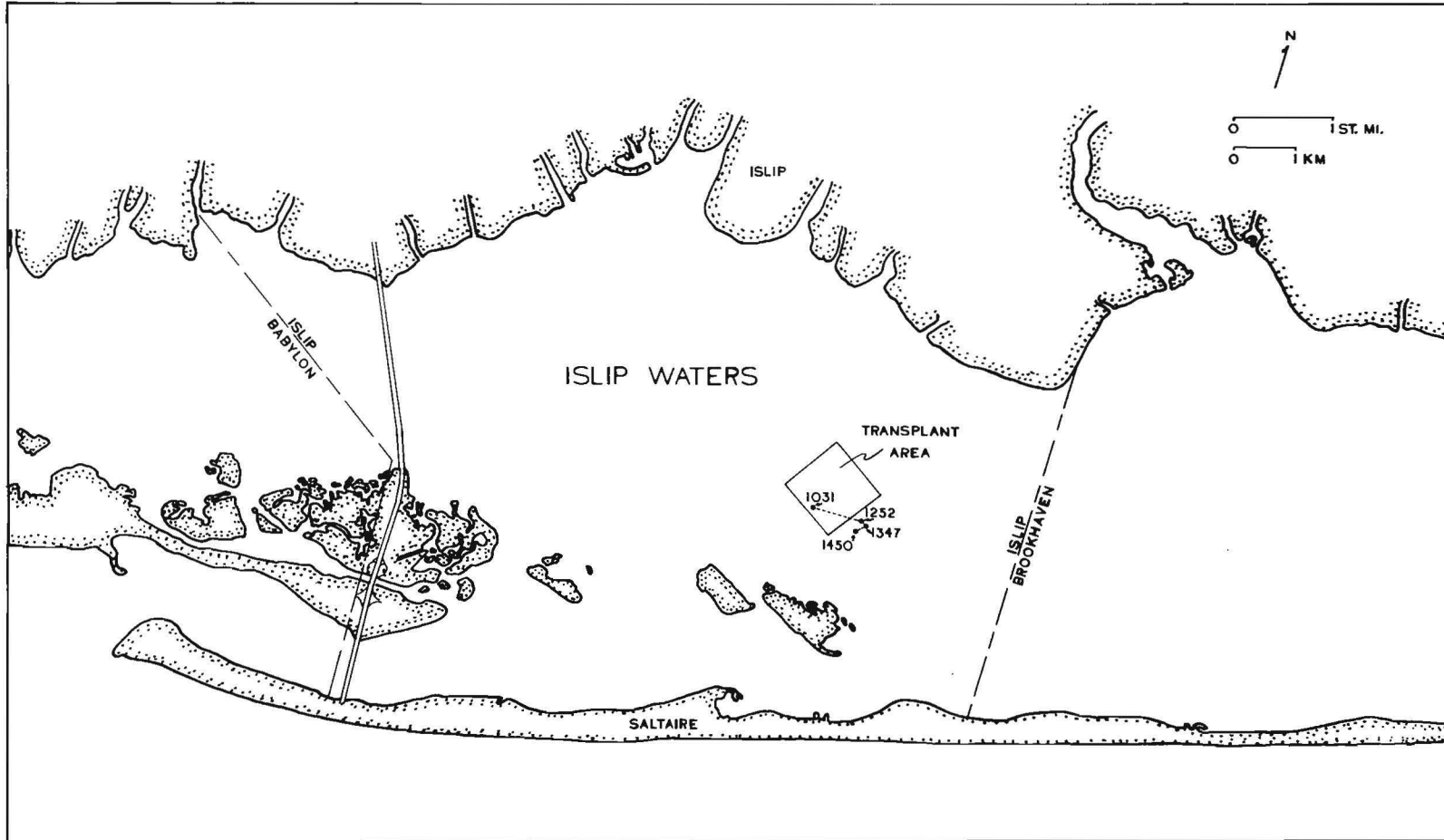
8

Figure 4. Sampling System.

Figure 5.   Initial Movement of Dye Patch (Release Time: 1031).

Periodically, the probe was lowered as deep as 2 m to determine the vertical profile of the dye.

Since initial dye concentrations were too high to register on the fluorometer's 1x scale, the movement of the patch on Day 0 was determined by following the patch in the sampling vessel and periodically taking sextant readings.

Due to limitations in equipment and personnel, it was not always possible to sample the entire distribution during a single stage of the tide. To the degree that this influenced the results, the subsequent analysis is in error. It is believed, however, that owing to the relatively small tidal excursion over much of the Bay, this type of influence was minimal.

Throughout the study, the central part of the dye patch remained on a shoal with depths as shallow as 0.2 m at low water. Depending upon the sea state and the stage of the tide, it was not always possible to sample this area adequately. Hence, the peak concentration of the distribution could not be measured with certainty on every sampling day.

On Day 11, 25 July, the tracer was distributed over too large an area to be adequately sampled in one day. It was then decided to vary daily sampling between the eastern and western halves of the distribution for the remainder of the study.

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[1]Throughout this report, the number of each day corresponds to the number of days elapsed since release of the tracer. Day 0, therefore, represents 14 July.

RESULTS

The movement of the dye patch for the first 4 hours after release is shown in Figure 5. The horizontal distributions of Rhodamine WT at 0.6 m depth for Days 1 through 17 are presented in Figures 6 through 15. Progressive vector diagrams of the wind for the period commencing with the termination of sampling on the previous sampling day and ending with the termination of sampling on the day in question are also presented in each figure.

All concentrations are expressed in terms of $(C/M_d) \times 10^{15}$, i.e. the dye concentrations in mass per unit volume (g cm^{-3}) normalized by the mass (g) of dry dye released. The units are cm^{-3}. The rationale for this procedure is that most rhodamine solutions are produced primarily for industrial use as dyes and hence, the solution strength may not be known to sufficient accuracy for scientific purposes. Since it is possible to calibrate the fluorometer in terms of C/M_d knowing only the initial solution volume or mass released, variations in solution strength are not a factor. For further details concerning this procedure see Carter (1974).

Monthly summaries of local climatological data for July for the years 1966 to 1975 were compared with that of July 1976 (Table 1). The data were obtained from the John F. Kennedy International Airport, approximately 50 km west of the study area. Comparison of monthly mean conditions (i.e. average temperature, total precipitation, resultant wind direction, and resultant wind speed) using a t-test for comparing a single observation with the mean of a sample (Sokal and Rohlf, 1969) showed that the mean conditions of July 1976 did not differ significantly ($P<0.05$) from those of July for the past 10 years. With respect to meteorological influence on Bay circulation, the results of this study, therefore, can be considered as representative of a typical or "average" July.

Wind data for the overall sampling period were obtained from the National Weather Service. They consisted of wind speed and direction measurements (Table 2) made every 3 hours at the Fire Island Coast
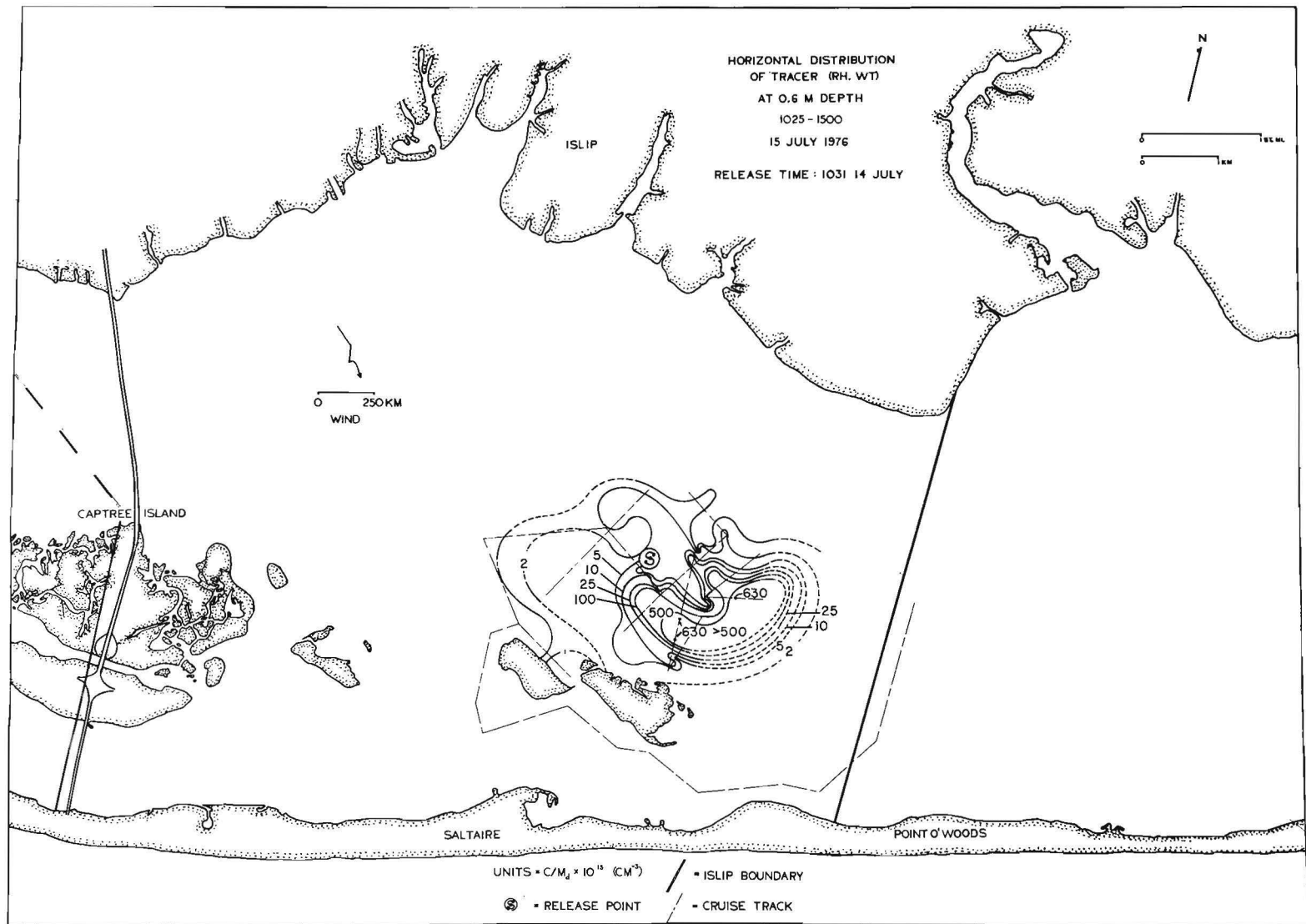
Figure 6. Horizontal Distribution of Tracer on Day 1.
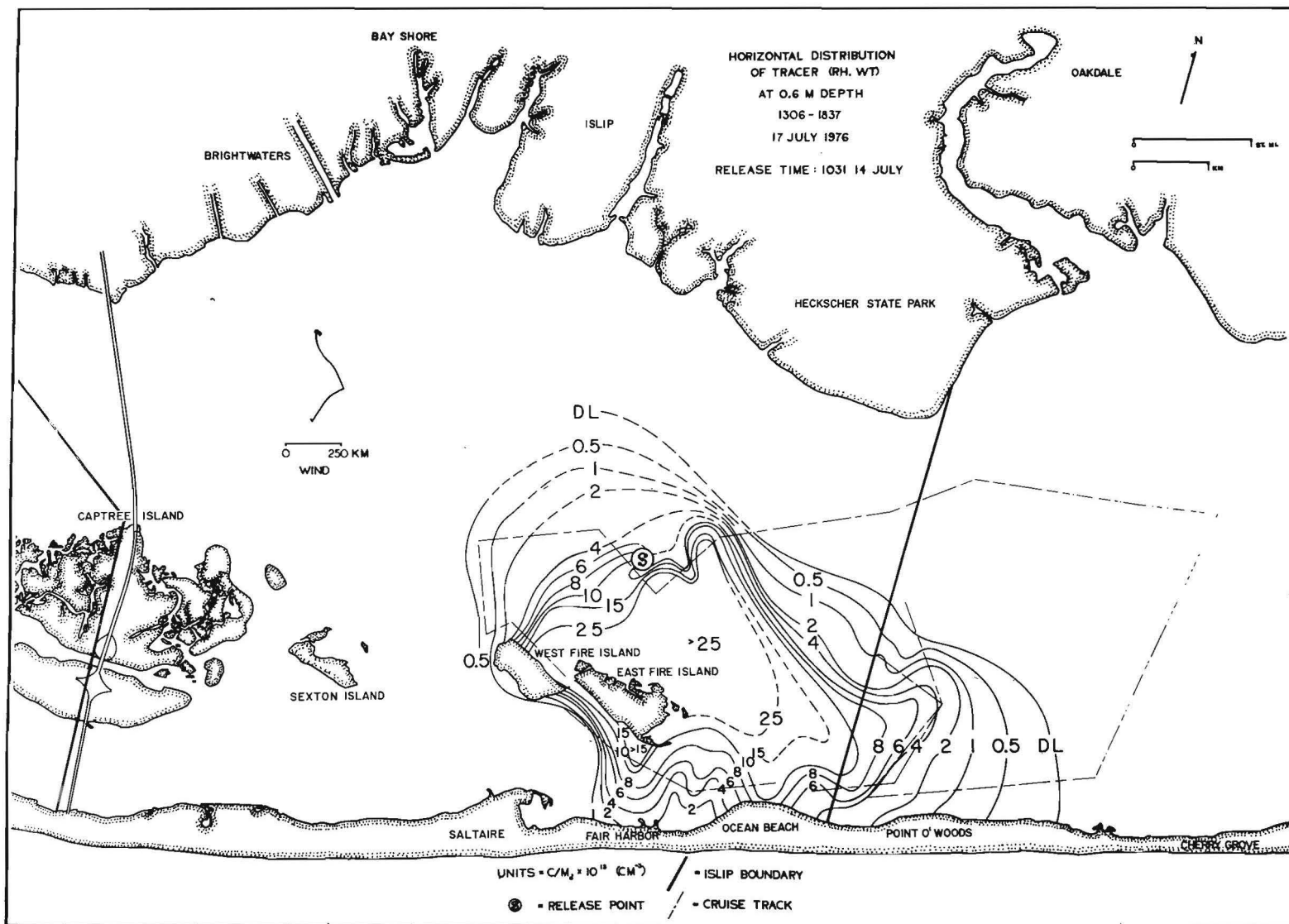
Figure 7. Horizontal Distribution of Tracer on Day 3 (DL = Detection Limit).
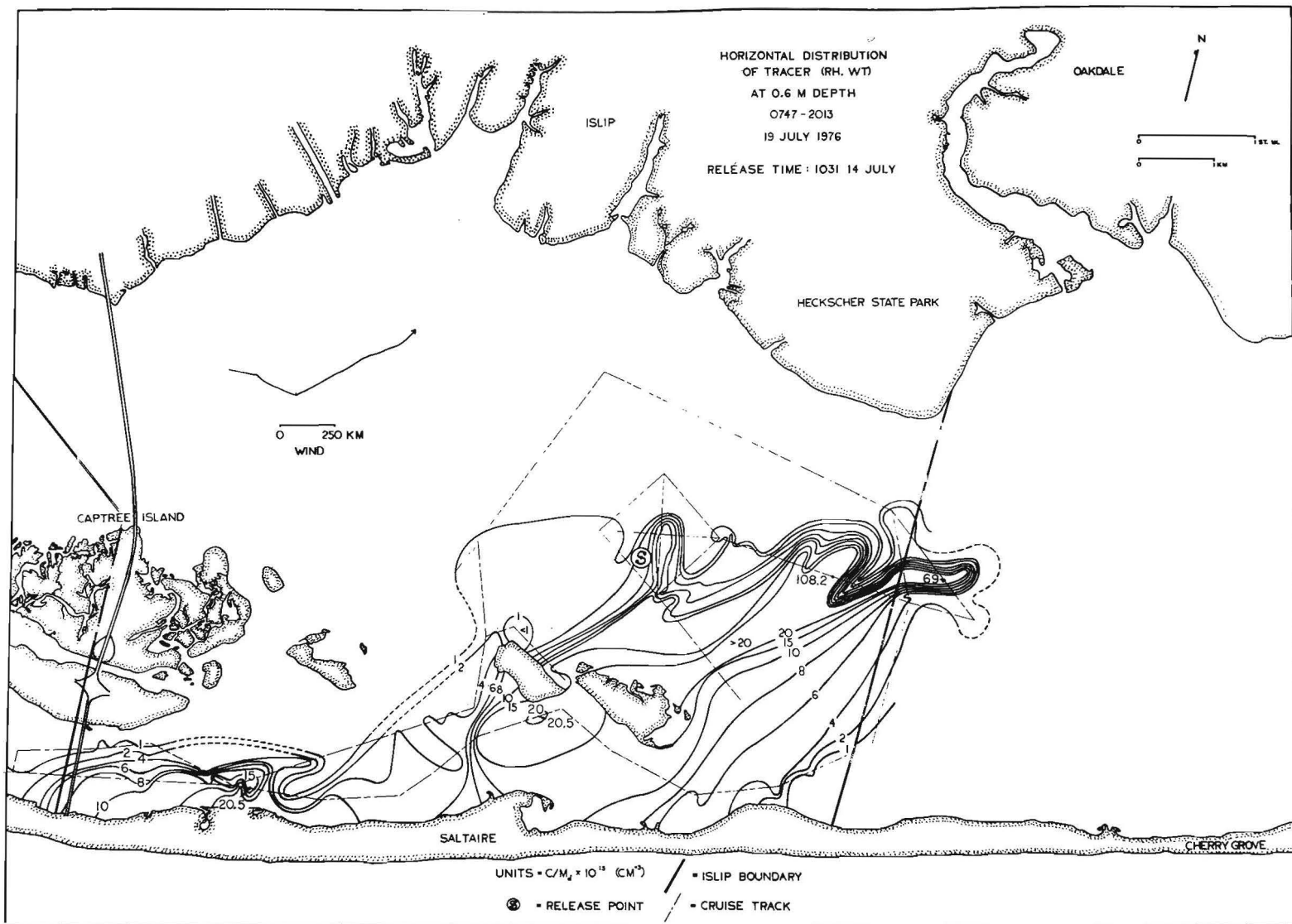
Figure 8. Horizontal Distribution of Tracer on Day 5.
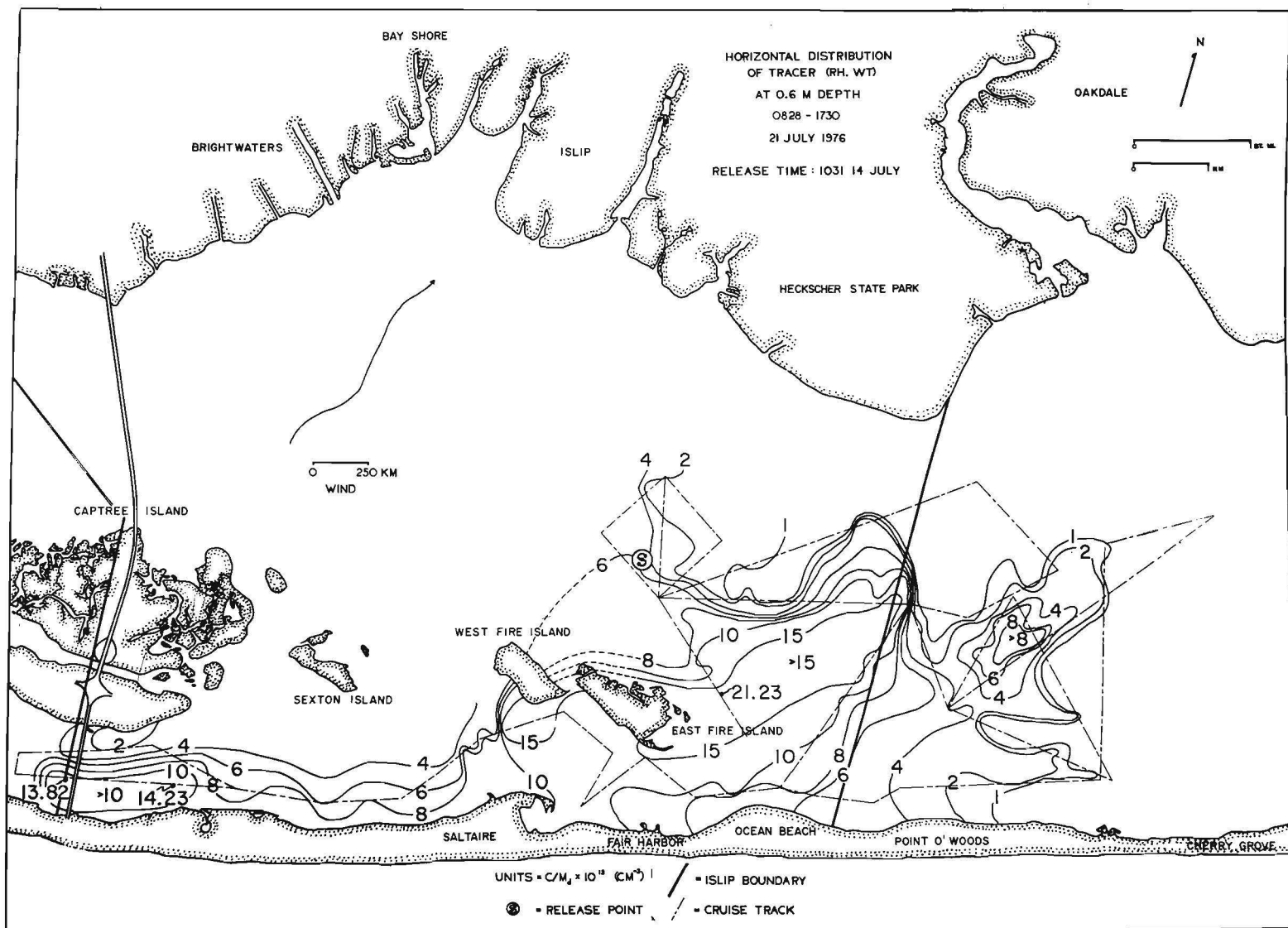
Figure 9. Horizontal Distribution of Tracer on Day 7.
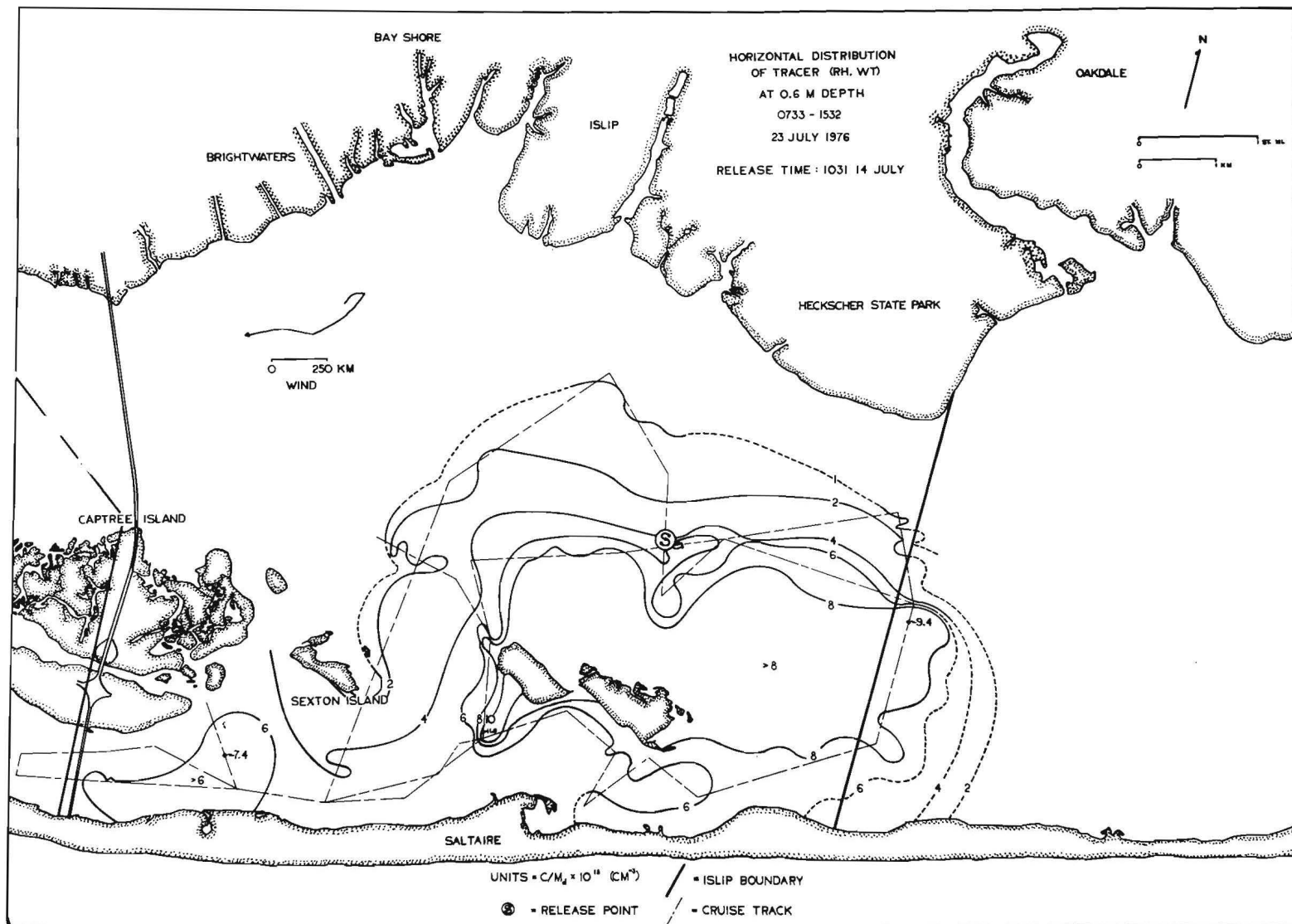
Figure 10. Horizontal Distribution of Tracer on Day 9.

HORIZONTAL DISTRIBUTION
OF TRACER (RH, WT)
AT 0.6 M DEPTH
1004 - 1539
25 JULY 1976

RELEASE TIME : 1031 14 JULY

ISLIP

HECKSCHER STATE PARK

CAPTREE ISLAND

250 KM
WIND

SALTAIRE

UNITS = C/M$_d$ x 10^{18} (CM^{-3})   —— = ISLIP BOUNDARY

Ⓢ = RELEASE POINT   —·· = CRUISE TRACK
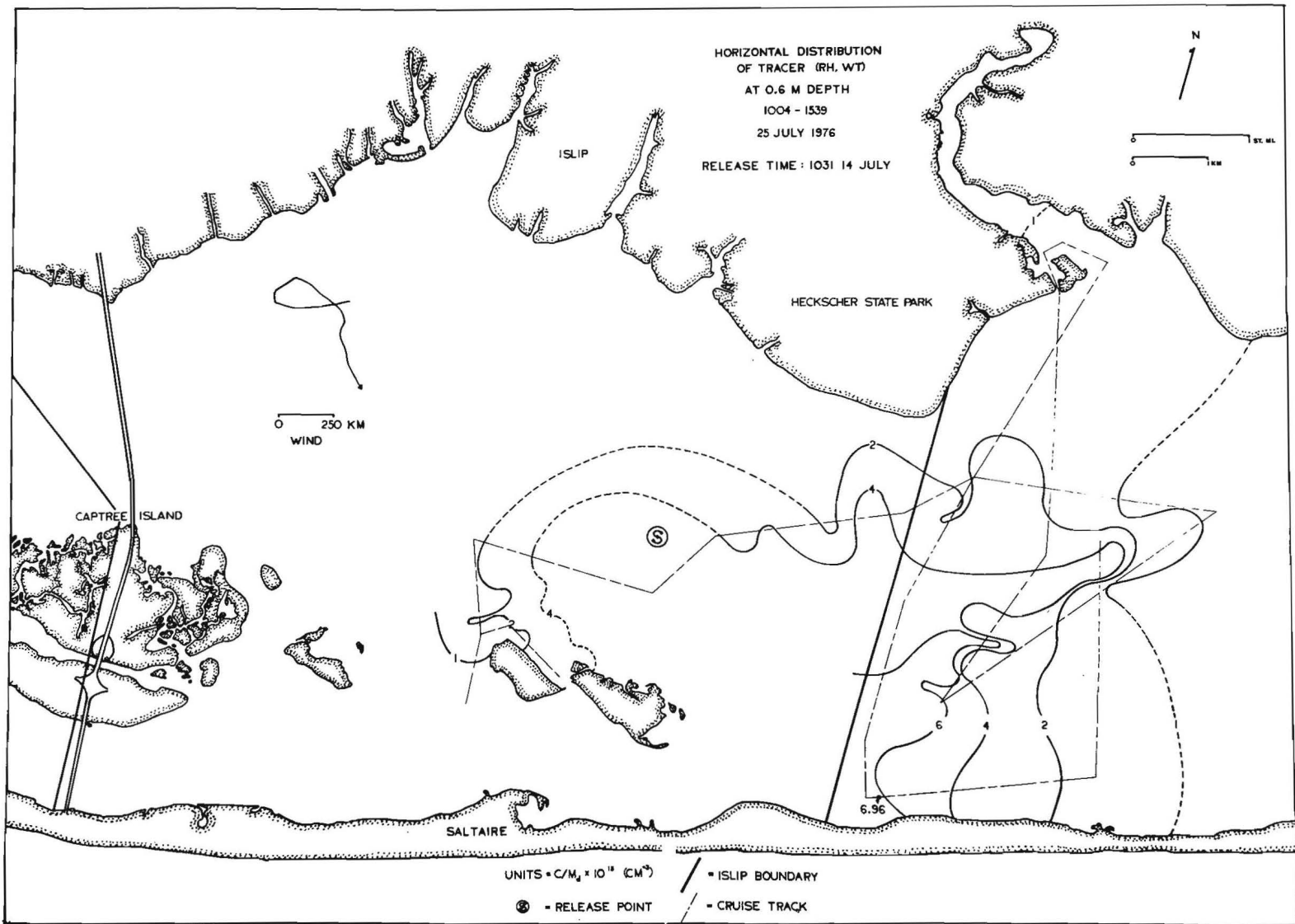
Figure 11.   Horizontal Distribution of Tracer on Day 11.
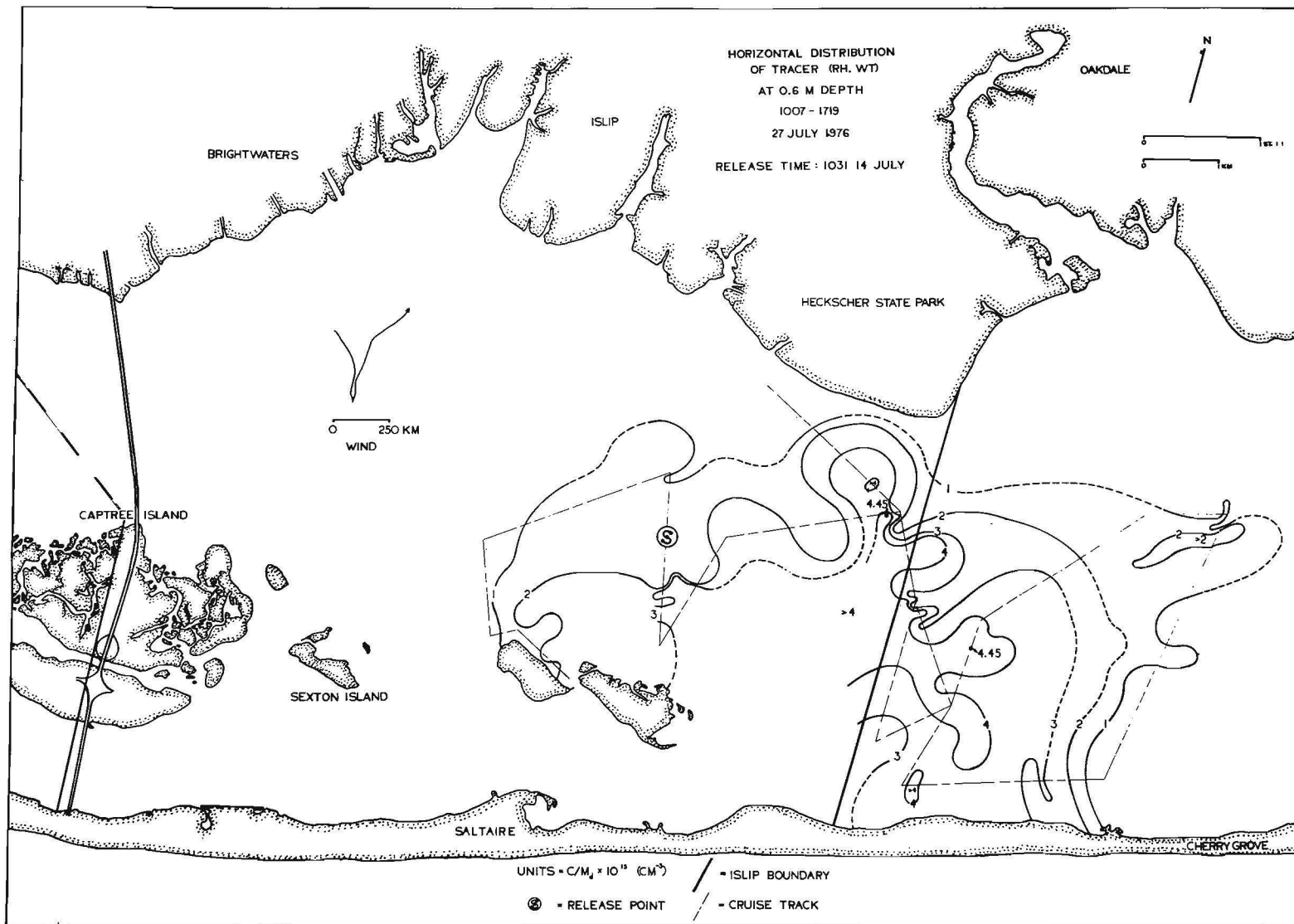
Figure 12. Horizontal Distribution of Tracer on Day 13.
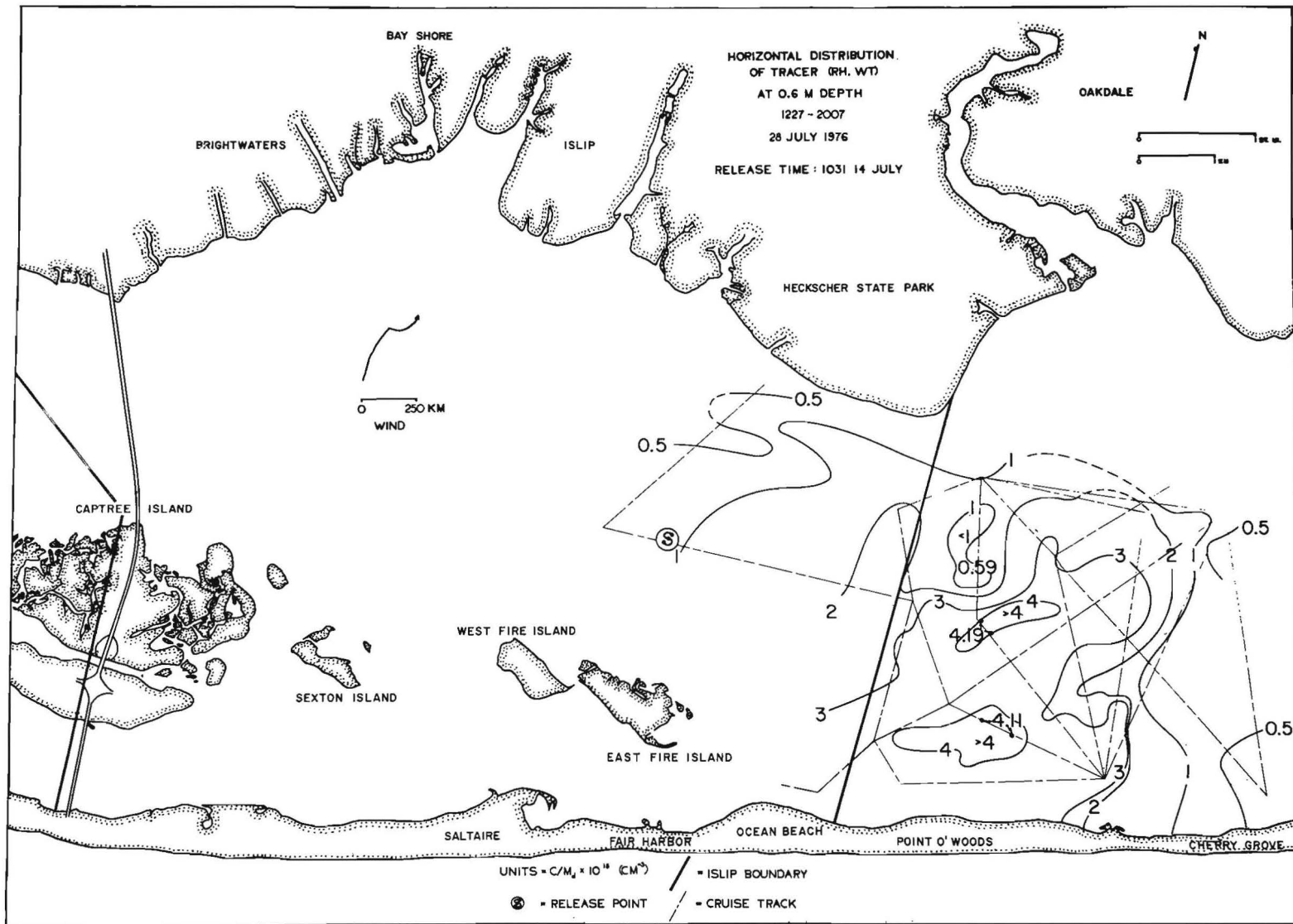
Figure 13. Horizontal Distribution of Tracer on Day 14.
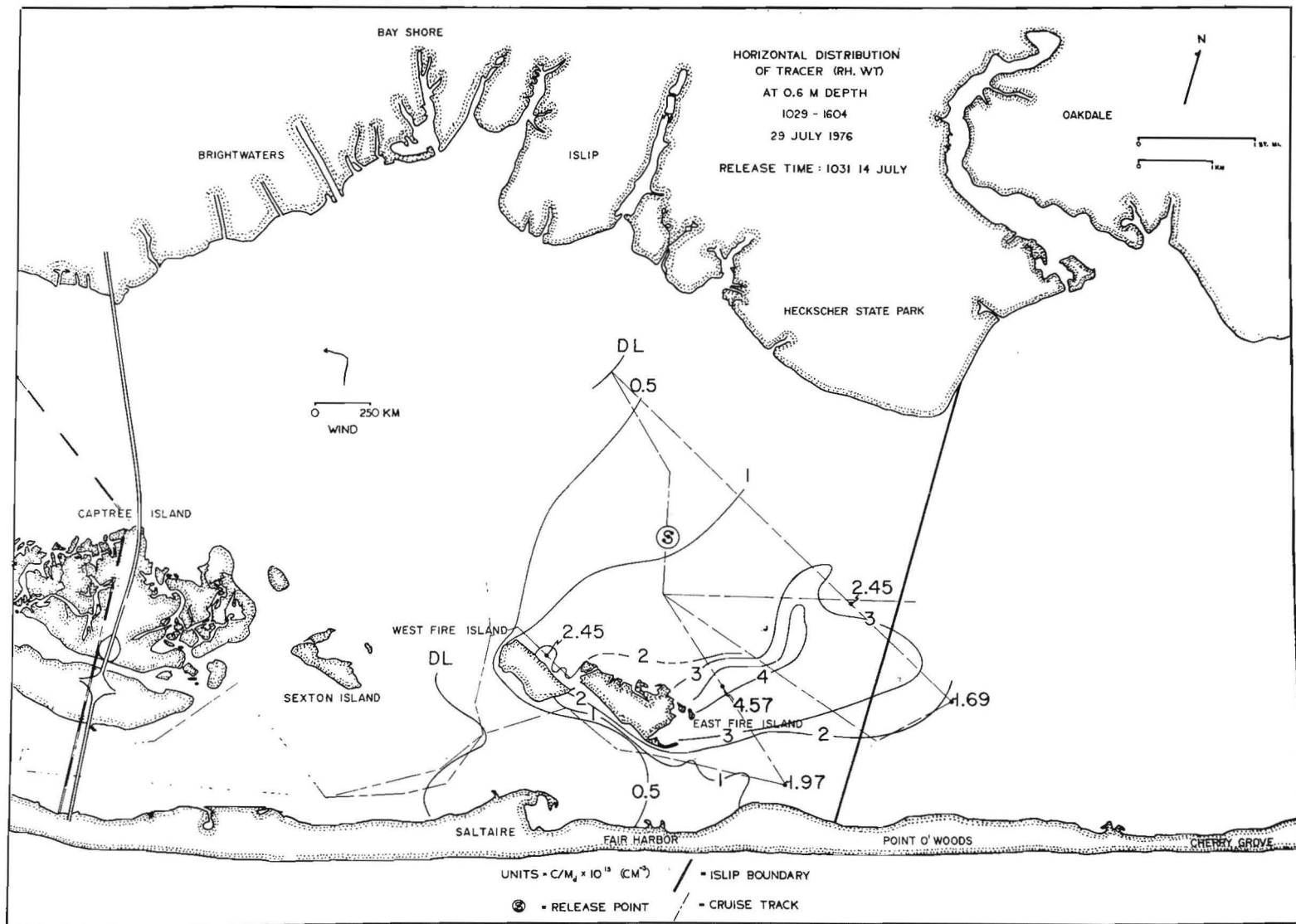
Figure 14. Horizontal Distribution of Tracer on Day 15 (DL = Detection Limit).
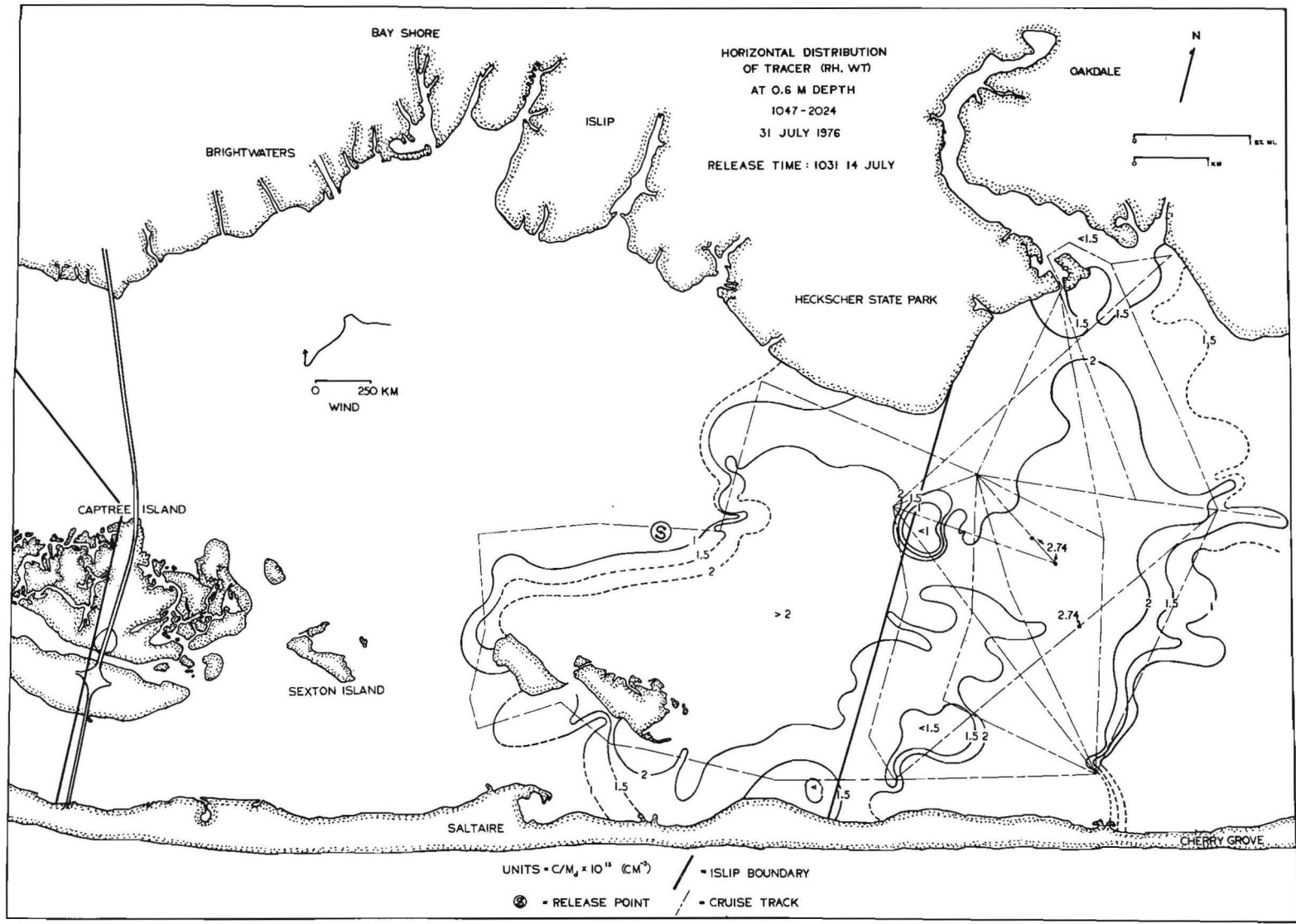
Figure 15. Horizontal Distribution of Tracer on Day 17.

TABLE 1

Monthly Mean Conditions for July 1966 to 1976

Year	Average temperature (^{O}F)	Total precipitation (inches)	Resultant wind direction (^{O}T)	Resultant wind speed (knots)
1976	72.9	3.50	240	3.6
————	————	————	————	————
1975	75.0	7.86	200	4.8
1974	76.6	1.29	250	2.7
1973	74.0	2.64	210	4.3
1972	77.0	2.60	220	3.6
1971	77.2	3.19	200	3.9
1970	77.0	0.54	200	5.5
1969	75.0	8.48	170	1.6
1968	77.0	2.58	210	4.8
1967	73.3	4.98	210	4.7
1966	77.0	0.69	220	3.6
mean =	75.9	3.49	209	4.0
stan. dev. =	1.45	2.79	20.2	1.1
t_{s} value =	-1.98 ns[1]	0.01 ns[1]	1.46 ns[1]	-0.4 ns[1]

[1]All t_{s} values were not significant when compared with the critical value of $t_{0.05(9)}$ = 2.26 (Rohlf and Sokal, 1969).

TABLE 2

Wind Speed and Direction During the Study Period

Date	Hour	Wind Direction	Wind Speed (knots)	Date	Hour	Wind Direction	Wind Speed (knots)
14 July	0000	WNW	10	23 July	0000	E	12
	0300	NW	15		0300	ENE	10
	0600	WNW	10		0600	ENE	10
	0900	WSW	10		0900	ENE	10
	1200	WNW	12		1200	ENE	11
	1500	NW	16		1500	ENE	12
	1800	NW	12		1800	ENE	12
	2100	SSW	2		2100	E	9
15 July	0000	N	13	24 July	0000	E	11
	0300	NNW	3		0300	SE	5
	0600	SW	7		0600	S	8
	0900	NNW	7		0900	SW	5
	1200	NW	6		1200	SW	10
	1500	N	7		1500	SW	10
	1800	SSW	10		1800	NW	14
	2100	SSW	7		2100	WNW	18
16 July	0000	S	8	25 July	0000	WNW	18
	0300	SW	8		0300	N	12
	0600	SW	8		0600	NE	7
	0900	W	3		0900	NW	12
	1200	SE	2		1200	NNW	10
	1500	SE	10		1500	NNW	10
	1800	SSE	10		1800	NW	14
	2100	ESE	9		2100	NW	10
17 July	0000	SE	12	26 July	0000	NW	9
	0300	SE	7		0300	NW	10
	0600	SSW	6		0600	NW	10
	0900	S	6		0900	N	14
	1200	NNE	10		1200	N	18
	1500	SSW	5		1500	SW	7
	1800	WNW	10		1800	SSE	10
	2100	WSW	15		2100	S	10
18 July	0000	NW	7	27 July	0000	SSW	12
	0300	WNW	12		0300	S	16
	0600	W	10		0600	SSW	10
	0900	WNW	10		0900	SW	10
	1200	WSW	8		1200	SW	9
	1500	SW	10		1500	SW	10
	1800	SW	10		1800	S	11
	2100	SW	15		2100	S	15
19 July	0000	WSW	8	28 July	0000	SSW	18
	0300	SSW	9		0300	SSW	10
	0600	WSW	10		0600	NW	4
	0900	SW	12		0900	W	7
	1200	WSW	8		1200	SW	3
	1500	SW	10		1500	SW	5
	1800	SW	10		1800	SW	10
	2100	SSW	13		2100	SSE	7
20 July	0000	SSW	10	29 July	0000	S	5
	0300	SW	10		0300	S	6
	0600	SW	12		0600	S	5
	0900	WSW	10		0900	SSE	7
	1200	SW	10		1200	ENE	8
	1500	SW	10		1500	ESE	8
	1800	SSW	10		1800	ENE	5
	2100	S	15		2100	E	7
21 July	0000	SSW	20	30 July	0000	E	5
	0300	S	15		0300	ENE	10
	0600	SSW	20		0600	SE	10
	0900	SW	10		0900	SE	5
	1200	SW	10		1200	NNE	12
	1500	SW	10		1500	SSW	8
	1800	SSW	10		1800	N	10
	2100	SSW	5		2100	N	8
22 July	0000	W	5	31 July	0000	NE	10
	0300	WSW	6		0300	NE	5
	0600	N	2		0600	NE	10
	0900	NNE	15		0900	N	8
	1200	NE	18		1200	NE	8
	1500	NE	18		1500	S	3
	1800	E	5		1800	SSE	8
	2100	E	15		2100	S	8

Guard Station. A progressive vector diagram was constructed from these data (Figure 16) to determine the pattern of wind movement during the sampling period. It can be seen that the prevailing winds during the period were out of the southwest, which is consistent with the average wind conditions expected in July.

As shown in Figure 5, the initial movement of the patch was to the east southeast, corresponding to the direction of the wind. After 2 hours, it had drifted approximately 0.8 km. Its drift then began to slow and its course changed to southwest apparently under the influence of the ebbing tide. After another 2 hours, the patch had drifted only another 0.3 km.

Figure 6 shows that the patch continued to move in a southeast direction in response to the prevailing northwest winds which were blowing at speeds of between 3 and 16 knots. The shape of the patch began to elongate in the direction of net drift with highest concentrations near the leading edge. At the end of sampling on Day 1, 28 hours after release, the center of the patch had travelled approximately 1.7 km from the release point.

Several hours after termination of sampling on Day 1, the wind shifted to the south southwest and prevailed from a general southerly direction at speeds of between 2 and 12 knots for the next 2 days.

The distribution of Day 3 (Figure 7) shows that the southerly winds apparently transported some of the tracer back in a northwesterly direction. It also shows that the leading edge of the patch moved within the influence of the tidal currents flowing through South, Range, and East Channels and was elongated in an east-west direction. The lateral boundaries of West and East Fire Islands as well as Fire Island had also influenced the distribution by this day. The central part of the patch remained on the shoals northeast of West and East Fire Islands.

At the end of sampling on Day 3, the wind began to shift to the west northwest and prevailed from that direction for the next 18 hours. It then shifted to the southwest where it prevailed at speeds of between 8 and 20 knots for 3.5 days.

The dye distribution of Day 5 (Figure 8) shows the combined effects of the strong southwest winds and the tidal currents. The eastern part of the patch was elongated in the direction of the wind with its center remaining over the shoals northeast of East Fire Island. The western part of the patch was elongated in a westerly direction under the influence of the strong tidal currents in South Channel.

The shape of the distribution of Day 7 (Figure 9) is similar to that of Day 5 except that the eastern part has spread farther east under the influence of Range and East Channels.

By Day 9 (Figure 10), the eastern part of the patch had become more evenly distributed. On this day, dye was first measured moving out to sea. The dilution by ocean water continued and on Day 15 (Figure 14), the concentration of dye west of West Fire Island was below the detection limit. On this same day, the dye concentrations of the eastern part of the patch were still detectable with highest concentrations remaining over the shoals northeast of East Fire Island.

The main feature of interest in the distribution of Day 17 (Figure 15) is the tongue of diluted water moving through South, Range, and East Channels.

In summary, then, the dispersion of the tracer had the following characteristics:

1. Initially, the patch was moved primarily by the wind. The downwind transport of the dye was probably enhanced by the shallowness of the area.
2. Once the patch moved within the influence of the tidal channels, it was rapidly elongated in the direction of the channels. Due to the orientation of South,
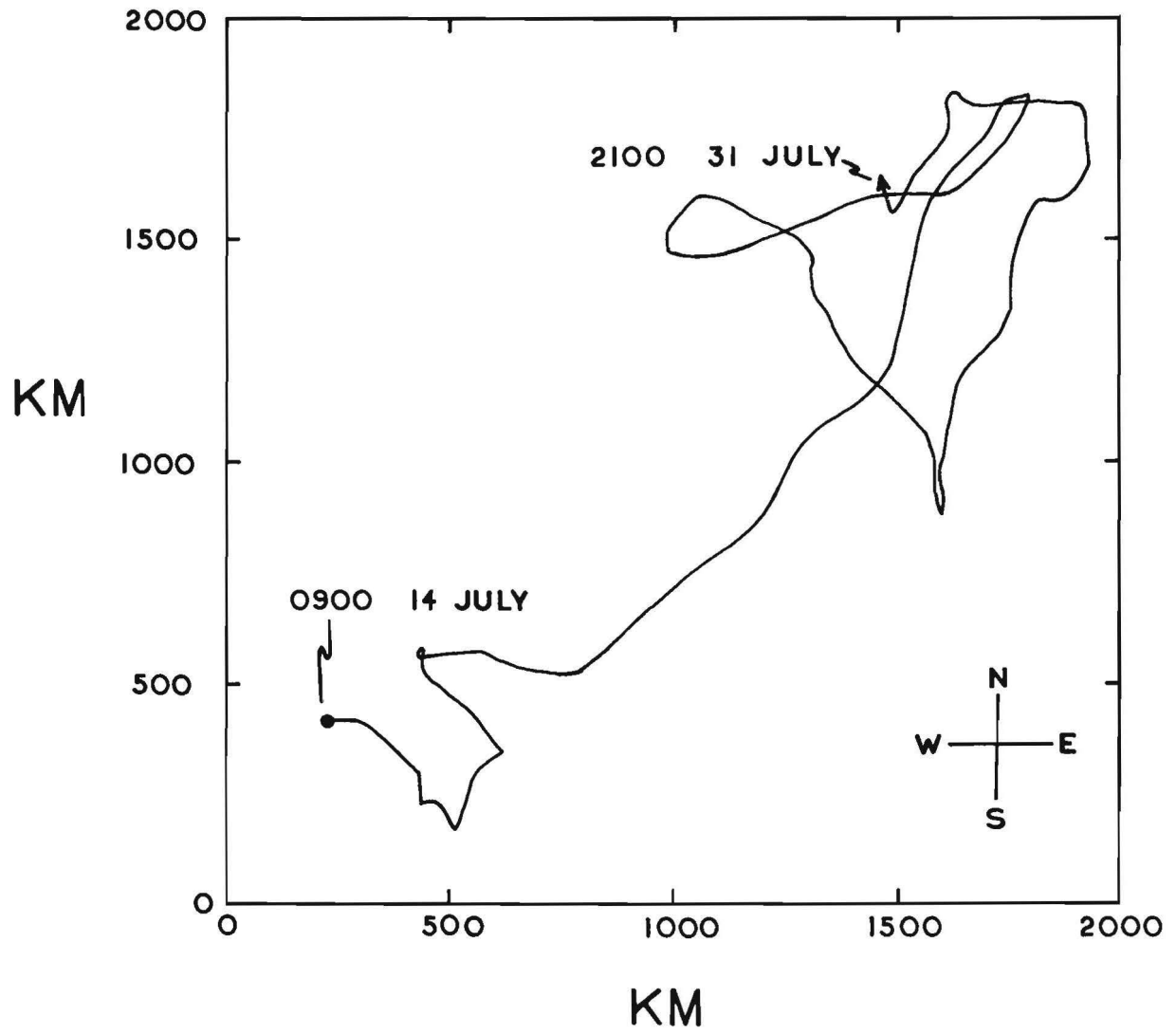
Figure 16.   Progressive Vector Diagram of the Wind During the Study Period.

25

Range, and East Channels, a large amount of dye was transported eastward to Brookhaven waters and westward to Fire Island Inlet and the ocean.

3. The center of mass of the dye distribution showed little advective movement. Throughout the main part of the study it remained on the shoals northeast of East Fire Island.

4. The eastern part of the patch became relatively evenly distributed over a large area while the western part was diluted to concentrations below the detection limit by tidal exchange with the ocean.

ANALYSIS AND INTERPRETATION OF RESULTS

Evaluation of the Transplant Site

To evaluate the Town of Islip's spawner transplant site, a first order estimate of the percentage of surviving larvae distributed over suitable setting areas was made in the following manner.

First, areas considered suitable for *Mercenaria* larval setting (Figure 17) were selected using the following criteria:

1. The area must be within town waters,
2. The area must be open to shellfishing, and
3. Major channels were not considered desirable areas.

It was assumed that young clams could survive, with varying degrees of success, in any part of the selected areas.

Next, the percentages of tracer remaining over the selected areas on Days 7 and 15 were determined. These days were used because they approximate the range of *Mercenaria* setting times determined in the laboratory.

The percentage of tracer remaining over suitable setting areas on each day was determined as follows:

1. Only dye concentrations, (C/M_d) x 10^{15}, greater than 1 cm^{-3} were counted.

2. Isolines that were not continuous on the charts were joined subjectively in the most probable manner.

3. Depth distributions were divided into 4 ranges; 0 to 1, 1 to 2, 2 to 3, and 3 to 4 m. The depth of each range was represented by the respective mean value.

4. The mean concentration of adjacent dye isolines was used as the concentration of dye in the volume of water between the isolines.

5. The area formed by adjacent dye isolines and depth contours was measured with a planimeter.

6. The areas determined in step 5 were converted to volumes by multiplying by the mean depth.

7. The mass of dye in each volume was then calculated by multiplying the mean concentration by the volume.

8. Finally, all masses were summed and the total was compared with the initial mass of tracer released.

The calculations performed for Days 7 and 15 showed that the percentages of dye remaining over suitable setting areas were 11.8 and 4.1, respectively. If it is assumed that *Mercenaria* larvae were dispersed in the same manner as the tracer, then between 11.8 and 4.1 percent of the surviving spawner larvae settled over suitable areas. These percentages do not appear large enough to justify the present location of Islip's spawner transplant site.

It can be argued that the foregoing was based upon a single experiment performed under one set of oceanographic conditions and, therefore, may not be representative of all possible realizations. While this is indeed true, the general patterns of circulation in the area suggest that, under most conditions, a large percentage of
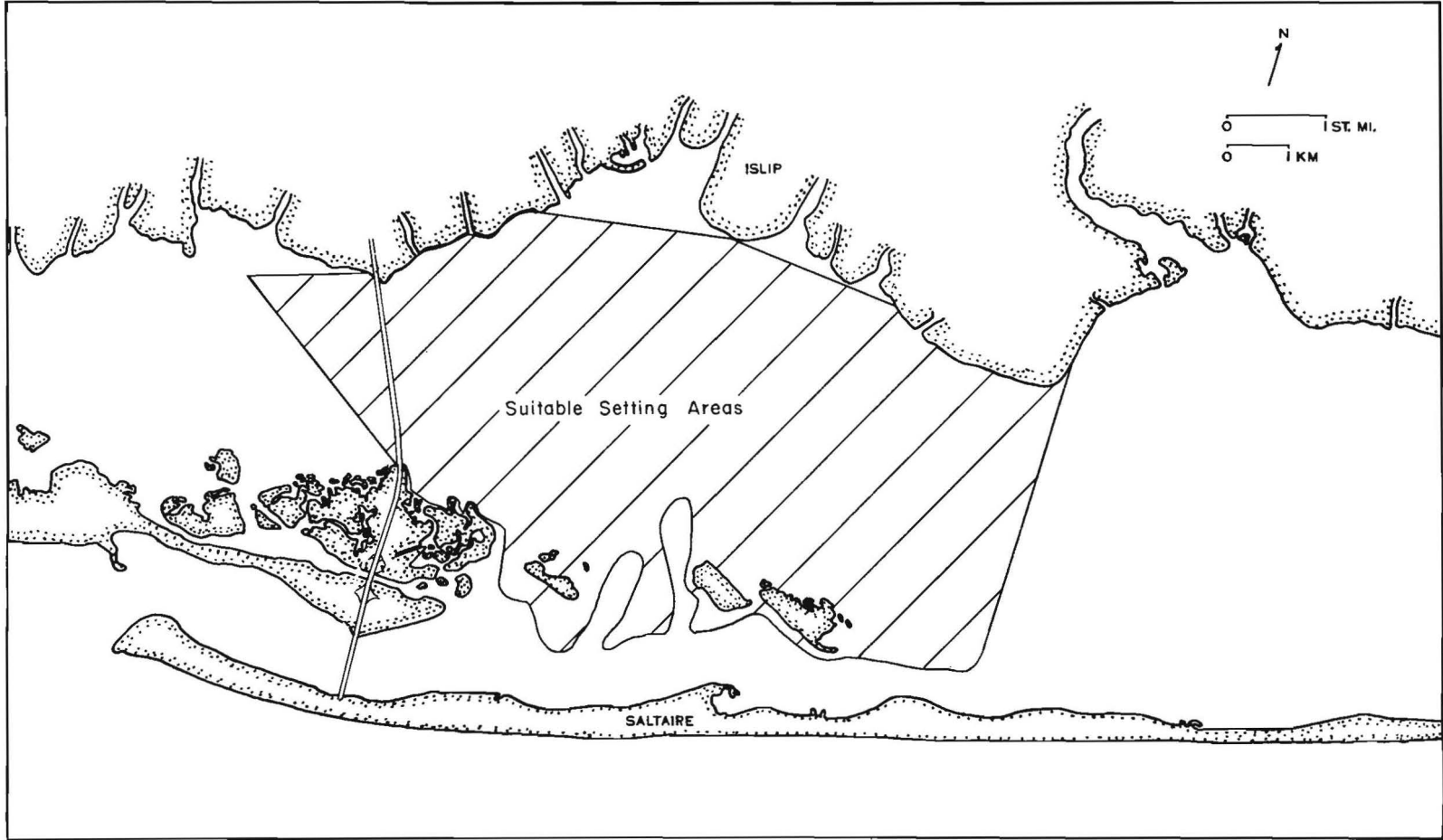
Figure 17. Suitable Setting Areas.

larvae originating at the present transplant site would be lost from Islip waters.

Based on the mean resultant wind direction for July for the years 1966 to 1976, one would expect the wind to be blowing from the southwest during the initial stages of dispersion. The initial movement of the larval patch would therefore be in a northwest direction, parallel to Range and East Channels. As the larvae disperse about the center of mass, the eastern section of the patch will eventually move to within the influence of these channels and be transported eastward to Brookhaven waters.

Winds blowing from the west, north, or east during the initial stages of dispersion would probably result in the greatest loss of larvae since the patch would move into shallow water where wind-induced transport is greatest. Winds from any of the above directions would move the patch closer to a major tidal channel and, consequently, result in the loss of a large percentage of larvae from Islip waters.

Based on this study, it seems that the main thing to be avoided in selecting a transplant site is the possibility that a large percentage of larvae will be moved to within the influence of the major tidal channels along the southern and eastern boundaries of Islip waters. Since winds from over half the points on the compass will tend to move the patch from the present transplant site toward one of these channels, it does not appear that the site is located in a desirable area.

The northern part of Islip waters, as mentioned earlier, is generally deeper than 2 m and has a relatively weak tidal circulation. These factors would probably act to reduce the transport of a larval patch as well as the rate of dispersion about the center of mass. That is, larvae would spread over a smaller area but in greater densities. In addition, the northern area is farther away from the major tidal

channels than is the present location of the transplant site. By releasing the spawner clams in the central part of this area it seems probable that a large percentage of the dispersing larval patch would remain within town waters regardless of initial wind conditions. On this basis, it is recommended that the Town of Islip relocate their spawner transplant site in the north central part of their waters.

Prediction of Mercenaria Larval Dispersion

In addition to evaluating the present location of Islip's spawner transplant site, it is also possible to use the results of this study to predict the theoretical dispersion of *Mercenaria* larvae from an alternate site in Islip waters and to quantify the effect of the overall program in augmenting the natural set.

Horizontal dispersion in an estuary is controlled by a continuous spectrum of scales of motion ranging from the molecular free path to the order of the dimensions of the system. The effect that each scale of motion has upon a dispersing patch is a function of the size of the motion relative to the diameter of the patch. Those motions much larger than the patch tend to advect the entire patch while those of comparable or smaller size tend to deform and spread the patch through turbulent diffusion.

The theoretical form that a dispersing patch should acquire on a purely two-dimensional plane due to horizontal isotropic motions is radially symmetric about the center of mass. In estuaries, however, large scale motions are usually anisotropic; i.e. the characteristic length scale is larger in the direction of mean flow than in the lateral direction. This anisotropy usually results in an elongation of the dye patch in the direction of mean flow. In addition, lateral boundaries as well as local inputs of energy from wind, tides, and bottom friction further influence and

complicate the dispersion of a patch within an estuary.

It is evident that no single theory can fully describe the dispersion of a substance within an estuary. However, it is possible for generalized theories to approximate this dispersion and, until a deeper understanding of the processes that control estuarine dispersion is achieved, these simplified theories must suffice.

Since Great South Bay is essentially a shallow semi-enclosed basin with a well-mixed water column, one would expect the dispersion of a substance within the system to conform to a two-dimensional model of turbulent diffusion. That is, a contaminant released as an instantaneous point-source should be rapidly mixed to the bottom and thereafter be dispersed primarily by horizontal mixing. In particular, the results of this study were compared with the Okubo-Pritchard (OP) solution (Okubo and Pritchard, unpublished note in Pritchard, 1960) for two-dimensional radially symmetric diffusion, i.e.

$$\frac{C_{(r,t)}}{M_d} = \frac{1}{\pi \omega^2 t^2 D} \, e^{-\frac{r^2}{\omega^2 t^2}} \qquad (2)$$

where C = the mean concentration for a diffusing patch released as an instantaneous point-source,

M_d = the mass of diffusing substance released,

ω = the diffusion velocity,

t = the time elapsed since release of the diffusing substance,

D = the depth of vertical mixing, and

r = the radial distance from the center of mass.

In using a solution based upon radial symmetry, the effect of shear on enhancing dispersion was not ignored. In the OP solution, the diffusion velocity (ω)

combines the effects of vertical and lateral shears and diffusivities. Diffusion velocity in the present case should therefore be considered the result of all physical processes which produce dispersion. Since a combined parameter was sufficient for the purposes of the present analysis, a radially symmetric solution was used.

To compare the observed dispersion with theory, the variance (σ_{rc}^{2}), i.e. the mean square distance from the center of mass, of each of the distributions of 15, 17, 19, and 21 July was computed.

To determine the value of the variance it was assumed that the tracer was distributed in a two-dimensional Gaussian manner (Okubo, 1968), i.e.

$$\frac{C_{(r_e,t)}}{M_d} = \frac{1}{\pi \sigma_{rc}^{2}(t) D} \, e^{-\frac{r_e^{2}}{\sigma_{rc}^{2}(t)}} \qquad (3)$$

where C = the concentration of tracer,

M_d = the mass of dye released,

σ_{rc} = the standard deviation of the distribution,

D = the depth of vertical mixing, and

r_e = the radius of a circle with equivalent area.

This assumption was tested for each distribution by plotting the natural logarithm of the concentration[1] of each isoline against the square of the radius of a circle with an area equal to that enclosed by the isoline. A Gaussian distribution, when treated in this manner, will describe a straight line. That is, rearrangement of (3) to a linear form gives:

$$\ln\left(\frac{C_{(r_e,t)}}{M_d}\right) = -\frac{1}{\sigma_{rc}^{2}(t)} \, r_e^{2} + \ln\left(\frac{1}{\pi \sigma_{rc}^{2}(t) D}\right) \qquad (4)$$

which in terms of new variables, $\ln(C/M_d)$ and r_e^{2}, is the equation of a straight line with slope $-1/\sigma_{rc}^{2}(t)$ and intercept

$\ln (1/\pi \sigma_{rc}^2 (t) D)$. Accordingly, the area enclosed by each isoline was measured with a planimeter and the radius of a circle with equivalent area was calculated from $\sqrt{area/\pi}$ (Table 3). Least squares linear regression fits to the data of 15, 17, 19, and 21 July (Figure 18) gave coefficients of determination (r^2) of 0.95, 0.98, 0.99, and 0.99, respectively. On this basis, it was concluded that all of the distributions approximated a Gaussian form. The variance of each distribution was then estimated from the slope of each respective regression line (Table 4).

Knowing the variance of a distribution and the diffusion time (t), i.e. the time elapsed since release of the tracer, it is possible to calculate the standard deviation (σ_{rc}), the scale of diffusion (ℓ), and the apparent diffusivity (K_a) (Table 4).

According to the OP solution, the variance should increase with the diffusion time as t^2 and the apparent diffusivity should increase with the scale of diffusion as ℓ^1. Log-log plots of the diffusion characteristics determined in this study (Figure 19) showed that the variance increased as $t^{1.93}$ while the apparent diffusivity increased as $\ell^{0.99}$. The close fit of the observed data to the predictions of the OP solution is apparent. On this basis, the diffusion velocity for each distribution was calculated from the expression,

$$\omega = \frac{\sigma_{rc}(t)}{t} \qquad (5)$$

which was obtained by comparing (2) and (3).

The diffusion velocities so determined, 0.38, 0.40, 0.41, and 0.49 cm sec^{-1} (Table 4), fall within the range of those reported for other estuaries. Diffusion velocity ranges in the Banana River, Florida (Carter and Okubo, 1965) and the Manokin River, Maryland (Carter, 1967) were 0.17 to 0.67 and 0.38 to 0.41 cm sec^{-1}, respectively.

If it is assumed that the mean diffusion velocity determined in this study, 0.42 ± 0.024 cm sec^{-1}, is representative of Islip waters in general, the theoretical dispersion of *Mercenaria* larvae from an alternate site within town waters can be calculated. Since it was previously recommended that Islip relocate the spawner transplant site in the north central part of town waters, the subsequent calculations will be based upon a site located in this area.

It will further be assumed that *Mercenaria* larvae are dispersed in the same manner as a dye tracer, thus allowing the use of the OP solution to predict their dispersion from the transplant site. Although the model is based upon radial symmetry, it does not require the actual distribution of tracer to follow such a form. It requires only that the area bounded by each isoline be equal to the area the isoline would circumscribe in a radially symmetric distribution.

Since the OP solution assumes that the tracer is distributed in a two-dimensional Gaussian manner, the distribution will, in theory, extend to infinity. It is therefore necessary to select an arbitrary isoline as the threshold of the patch. Accordingly, the isoline, $(C/M_d) \times 10^{15}$, of 1 cm^{-3} was selected and the area covered by a patch so defined was then determined for Days 7 through 16 (Table 5), corresponding to the setting times of *Mercenaria* larvae.

The area of each distribution was determined by first solving the Gaussian expression for r_e, the radius of the isoline with concentration $C_{(r_e,t)}/M_d$, i.e.

$$r_e = \sqrt{\left(\ln \frac{1}{\pi \sigma_{rc}^2 (t) D} - \ln \frac{C_{(r_e,t)}}{M_d}\right) \sigma_{rc}^2 (t)}$$

$$(6)$$

TABLE 3
Equivalent Radii of Isolines

Date	Elapsed time (sec)	Concentration $(C/M_d) \times 10^{15}$	Equivalent radius (cm)
15 July	9.39×10^4	500	5.13×10^4
		100	6.56×10^4
		25	7.44×10^4
		10	8.63×10^4
		5	9.66×10^4
17 July	2.78×10^5	25	1.15×10^5
		15	1.35×10^5
		10	1.56×10^5
		8	1.72×10^5
		6	1.86×10^5
		4	2.02×10^5
		2	2.28×10^5
		1	2.68×10^5
19 July	4.33×10^5	20	7.48×10^4
		15	1.15×10^5
		10	1.65×10^5
		8	1.88×10^5
		6	2.10×10^5
		4	2.40×10^5
		2	2.66×10^5
21 July	6.13×10^5	15	1.01×10^5
		10	1.69×10^5
		8	2.08×10^5
		6	2.47×10^5

TABLE 4
Diffusion Characteristics

Date	t (sec)	σ_{rc}^2 (cm^2)	σ_{rc} (cm)	K_a (cm^2 sec^{-1})	ℓ (cm)	ω (cm sec^{-1})
15 July	9.39×10^4	1.46×10^9	3.82×10^4	3.89×10^3	1.15×10^5	0.41
17 July	2.78×10^5	1.83×10^{10}	1.35×10^5	1.65×10^4	4.05×10^5	0.49
19 July	4.33×10^5	2.97×10^{10}	1.72×10^5	1.71×10^4	5.16×10^5	0.40
21 July	6.13×10^5	5.58×10^{10}	2.36×10^5	2.28×10^4	7.08×10^5	0.38

where $K_a \equiv \dfrac{\sigma_{rc}^2}{4t}$

$\ell \equiv 3\sigma_{rc}$

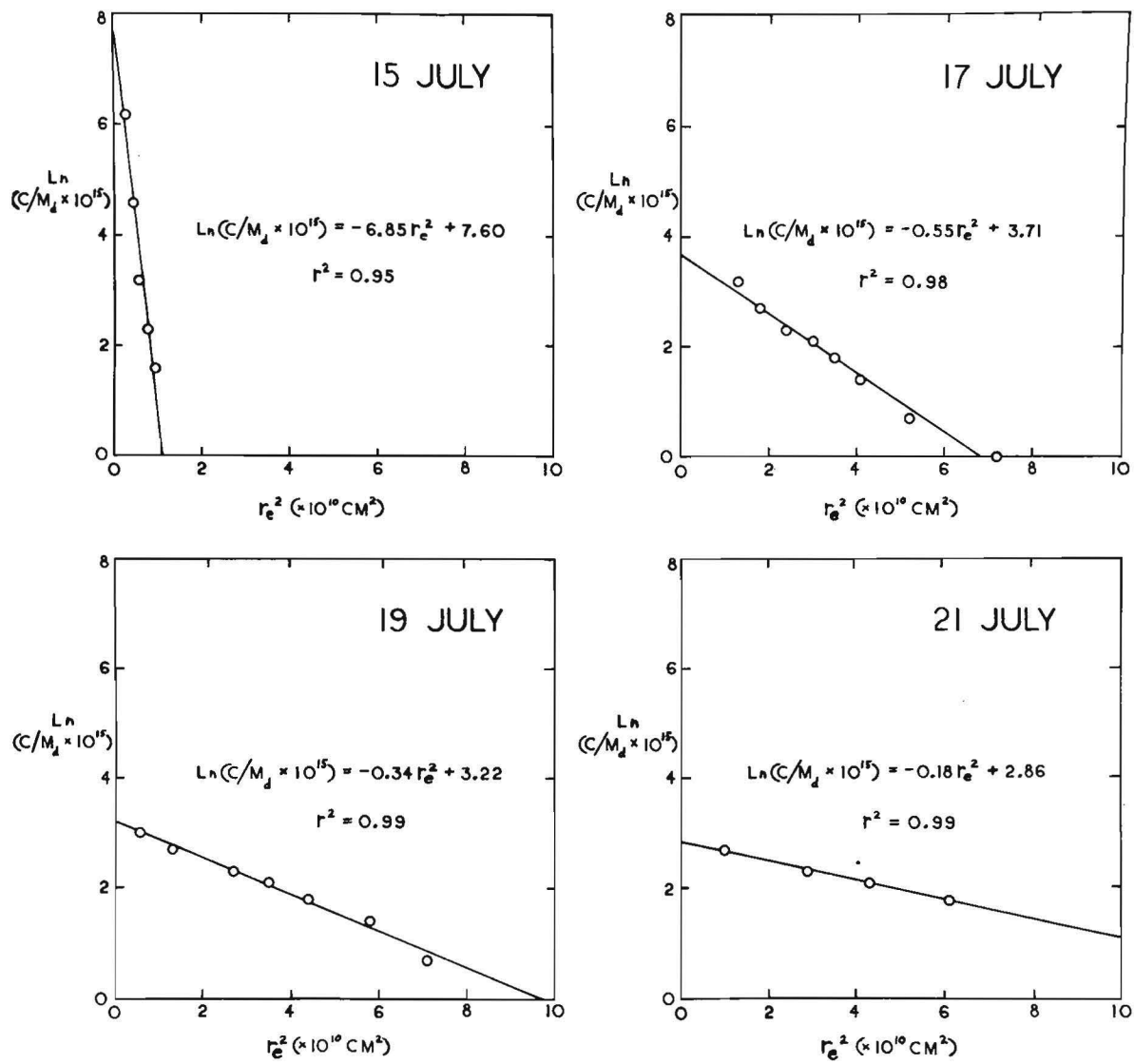$\omega = \dfrac{\sigma_{rc}}{t}$

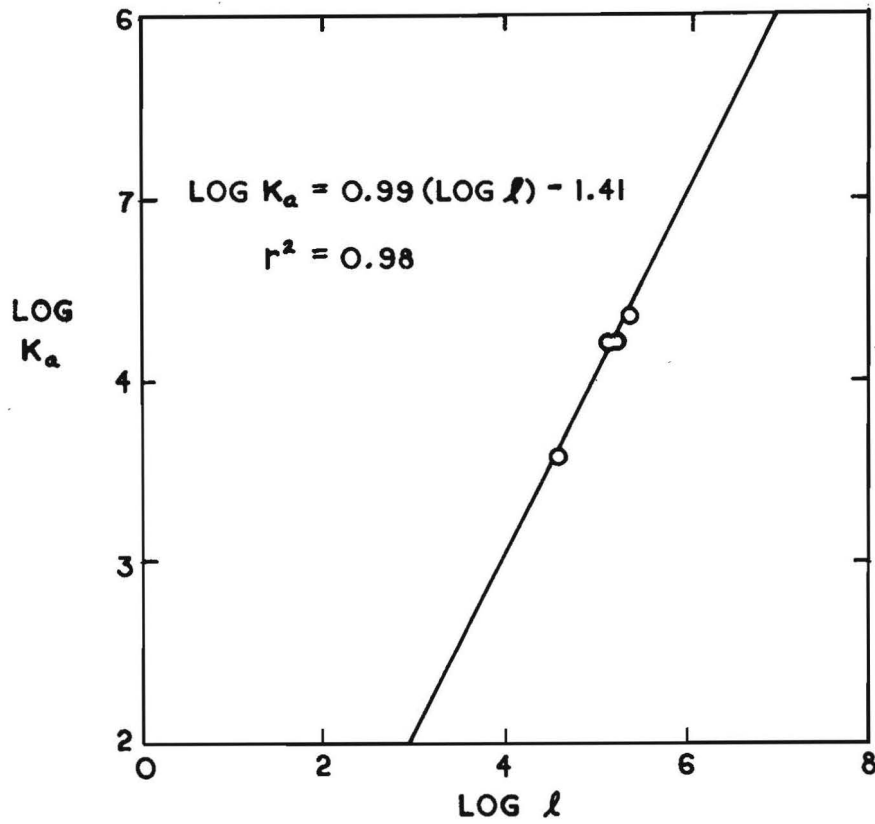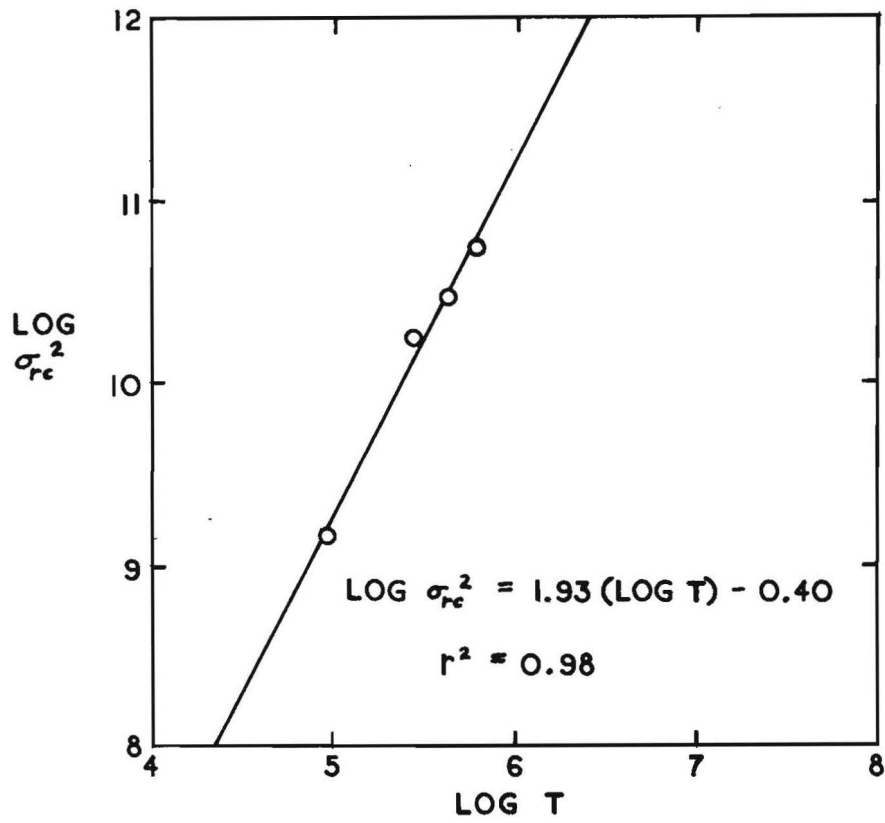Figure 18.   Plots to Verify Gaussian Distributions.

Figure 19. Plots of Diffusion Characteristics.

TABLE 5
Predicted Areas of the Dispersing Patch

Day after release	Variance (cm^2)	Patch area (km^2)
7	6.5×10^{10}	60.7
8	8.4×10^{10}	71.7
9	1.1×10^{11}	84.6
10	1.3×10^{11}	93.2
11	1.6×10^{11}	104
12	1.9×10^{11}	114
13	2.2×10^{11}	121
14	2.6×10^{11}	130
15	3.0×10^{11}	136
16	3.4×10^{11}	141

The variance on each day was estimated (Table 5) from the expression,

$$\sigma_{re}^2(t) = \omega^2 t^2 \qquad (7)$$

which was derived from (5). The diffusion velocity was assumed to be 0.42 cm sec^{-1} and a value of 2.5 m was used to represent the depth of this part of Islip waters. In this manner, the radius of the threshold isoline was determined for each day. The areas covered by the patch were then determined by squaring each radius and multiplying by π.

From Table 5 it can be seen that the dispersing patch will cover an area slightly greater than that of Islip waters as early as Day 9. Hence, it is theoretically possible for the spawner larvae to be distributed over all of Islip waters during most of the setting period.

To estimate the density of larval setting within the areas predicted by the tracer, larval concentrations were related to those of the dye in a manner similar to that employed by Carter (1967). If differences in the amount of dye released and the number of larvae spawned, the depth of vertical mixing, and larval mortality are accounted for, it is possible to scale larval densities to the observed dye concentrations. This relationship can be expressed as,

$$\frac{C_d \times D_d}{M_d} = \frac{C_l \times D_l}{N_0 e^{-kt}} \qquad (8)$$

where C_d and C_l = concentrations of tracer and larvae at time t after release,

M_d and N_0 = initial mass of tracer released and number of larvae spawned,

D_d and D_l = vertical extent of tracer and larvae, and

k = larval mortality rate.

The expression $N_0 e^{-kt}$ arises from the assumption that the rate of change of the larval population as the result of natural mortality is proportional to the size of the population. That is,

$$\frac{dN_{(t)}}{dt} = -kN_{(t)} \qquad (9)$$

or

$$N_{(t)} = N_0 e^{-kt} \qquad (10)$$

34

Little is known about the mortality of *Mercenaria* larvae in the field. Carriker (1961) assumed a mean mortality of 97.6 percent for *Mercenaria* larvae in Little Egg Harbor, New Jersey. This corresponds to a k of approximately 0.466 or a mortality rate of about 37 percent day^{-1}. Since Carriker cautions that this is a very rough approximation, a range of k values was used in this analysis. The value determined by Carriker was used as the reference point and values of 0.693 (50 percent day^{-1}) and 0.288 (25 percent day^{-1}) were used as arbitrary boundaries.

N_0 was estimated by multiplying the number of bushels of spawner clams released (1000), the number of females per bushel (approximately 75), and the average number of eggs released per female (24.6×10^6; Davis and Chanley, 1956). The resulting value of N_0 was 1.8×10^{12} larvae.

The foregoing assumes that all of the eggs were fertilized and that all 1000 bushels were released at approximately the same time. Although Islip is not always able to obtain 1000 bushels of spawners, this value was used since it is their projected goal (Buckner, 1976). In addition, the tracer and larvae were assumed to be uniformly distributed to a

depth of 2.5 m.

Concentrations of larvae m^{-2} were scaled for the peak and the threshold concentrations for Days 7, 11, and 16 (Table 6). These times correspond to the beginning, middle, and end of the range of setting times determined in the laboratory. Peak concentrations were determined from the expression,

$$\frac{C_{(0,t)}}{M_d} = \frac{1}{\pi \sigma_{rc}^2 (t) D} \qquad (11)$$

which was derived from the OP solution. The variance on each day was obtained from Table 5 and the depth of vertical mixing was assumed to be 2.5 m.

As shown in Table 6, the number of surviving larvae is critically dependent upon the value of k. It can also be seen that as time progresses, larval densities diminish as a result of mortality and physical dilution caused by dispersion. Densities range from a maximum of 12,000 larvae m^{-2} on Day 7 to a minimum of 0.069 larvae m^{-2} on Day 16. If the distribution on Day 11 with a k of 0.466 is considered "average", one would expect the patch to cover an area of approximately 104 km^2 (24 km^2 more than Islip waters) and have

TABLE 6

Predicted Larval Setting Densities

Days after release	Concentration $(C/M_d) \times 10^{15}$	Patch area (km^2)	Larval density (larvae m^{-2})		
			$k = 0.693$	$k = 0.466$	$k = 0.288$
7	19.6	0.0	690	3400	12,000
	1.0	60.7	35	170	600
11	7.96	0.0	18	210	1,500
	1.0	104	2.2	27	190
16	3.74	0.0	0.26	9.7	170
	1.0	141	0.069	2.6	45

larval densities ranging from 27 larvae m^{-2} at the perimeter to 210 larvae m^{-2} at the center of mass.

Since mortality and setting time are essentially uncontrollable in the field, the most practical ways that a manager can alter the setting densities within an area are by varying N_0 or by indirectly influencing the dispersion of the patch.

Using the present model, an increase in N_0 by a certain factor while holding other conditions constant will result in a corresponding increase in larval setting densities. Hence, if Islip were to release 10,000 bushels of spawner clams, the "average" larval densities would range from 270 to 2,100 larvae m^{-2}.

The dispersion of the larval patch can be indirectly influenced by releasing the spawner clams in less dispersive areas. That is, halving the diffusion velocity to 0.21 cm sec^{-1} would result in a larval patch that covered approximately 43 km^2 on Day 11 and had "average" densities ranging from 27 to 855 larvae m^{-2}. This was one justification for the recommendation made earlier to relocate Islip's transplant site in the north central part of town waters.

It is apparent that a better understanding of larval mortality, development, and behavior is essential for more accurate predictions of larval setting densities. It is also important to obtain dispersion data on more than one part of an area to be able to make better evaluations of prospective transplant sites. In light of these deficiencies, the present model should be considered only a first order approximation. The model can, however, be used to make certain general recommendations as to how the Town of Islip can maximize the setting density of spawner larvae within town waters. Accordingly, they are:

1. Maximize N_0 by releasing as many spawner clams as the program budget allows.

2. Relocate the transplant site in a less dispersive area. Since a diffusion velocity of 0.42 cm sec^{-1} will result in a patch that exceeds the total area of Islip waters as early as 9 days after release, an alternate site in a less dispersive area would be more desirable.

3. Relocate the site in an area where the probability of a large percentage of the dispersing larval patch remaining in town waters is high.

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[1]Concentrations in this analysis were expressed in terms of $(C/M_d) \times 10^{15}$. The factor 10^{15} was used to facilitate the handling of the data.

CONCLUSIONS

The Town of Islip's present spawner transplant site is considered to be poorly located with respect to maximizing the set of spawner larvae within town waters. The shallowness of the area combined with its proximity to major tidal channels and the Islip-Brookhaven boundary reduce the probability of a large percentage of spawner larvae being retained in town waters.

It is recommended that the spawner transplant site be relocated in the north central part of Islip waters where depths are greater and mixing is believed to be less intense.

It is further recommended that the number of spawner clams released be maximized within the limits of the program budget to increase the probability that the program results in a significant augmentation of the natural set.

36

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DUE DATE