MAXIMIZING HARD CLAM SETS AT SPECIFIED LOCATIONS IN GREAT SOUTH BAY BY MEANS OF A LARVAL DISPERSION MODEL

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MAXIMIZING HARD CLAM SETS AT SPECIFIED LOCATIONS IN GREAT SOUTH BAY BY MEANS OF A LARVAL DISPERSION MODEL

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ABSTRACT

The importance of Great South Bay to New York lies in the fact that at one time it was the largest single producer of hard clams *(Mercenaria mercenaria)* in the world. In 1976 it produced more hard clams than the rest of the Atlantic coast combined. Since then, production has steadily declined to less than half of the 1976 value. One management strategy suggested has been the designation of spawner sanctuaries where large, low market value, fecund clams would be placed and protected from harvesting while serving as brood stock. In this report we have addressed the problem of specifying the locations and effectiveness of potential spawner sanctuaries in Great South Bay which, if stocked with adult clams, would produce sets on areas that have been productive in the past.

Since hard clam larvae are planktonic prior to setting, they are largely at the mercy of the physical processes of advection and turbulent diffusion during this 10-20 day period. The key to predicting larval dispersal, therefore, is a proper understanding of the circulation and mixing in Great South Bay during the summer months when hard clams spawn. To quantitate these processes, we combined the velocities generated by an existing two-dimensional, numerical, hydrodynamic, finite element model (CAFE) of Great South Bay with numerically generated random turbulent velocities based on Markov-chain properties in a particle dispersion model in order to disperse under typical summertime conditions over time ($\sim$20 days),

a cluster of neutrally buoyant particles representing hard clam larvae. However, in order to utilize the combined dispersion model for hindcasting the location of spawner sanctuaries, given the areas where setting is desired, a seven-step rationale was developed and is described in detail in the report.

The waters of Great South Bay are politically subdivided into the towns of Babylon (western part), Brookhaven (eastern part), and Islip (central part). Each has jurisdiction over the management practices carried out within its waters. Accordingly, each town designated the productive areas for which the location of potential spawner sanctuaries was required (five such areas for Babylon, six in Brookhaven, and four in Islip). Our rationale was then applied to these 15 sites. In this report, however, the entire methodology has been included for only the four sites in Islip waters together with final results for single sites in Babylon and Brookhaven. Management implications of these results are discussed in terms of total set, setting densities, and required post-setting survival rates. Our analysis suggests that a spawner sanctuary consisting of 1000 bushels of adult clams could be cost effective over several spawning seasons provided that the area in which the sets are produced is characterized by low predator densities (1 predator/m^2) or, if not, has been subjected to some form of predator reduction.

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BACKGROUND

The Great South Bay Study

In 1979 a comprehensive interdisciplinary study of the physical and biological processes of Great South Bay was begun by scientists of the Marine Sciences Research Center, SUNY, Stony Brook, NY. The plan for the study was initiated by a request in June, 1977 from the New York State Department of Environmental Conservation (DEC) to the New York Sea Grant Institute (NYSGI) to prepare a plan for a comprehensive, synoptic study of the physical and biological processes of Great South Bay (GSB). By December, 1977 a draft plan had been prepared by a panel consisting of representatives of the New York State Department of Environmental Conservation, the Nassau-Suffolk Regional Planning Board[#], and the Marine Sciences Research Center. This draft plan was then discussed with representatives of major research laboratories on Long Island and the New York Metropolitan area. In addition, 6 workshops, attended by representatives from over 30 agencies, firms, and institutions, were held during January, 1978 and provided further discussion of the study elements. The final study plan[##], consisting of 21 separate tasks, was forwarded to DEC by the NYSGI on February 10, 1978. Funding for most tasks was subsequently provided by the NYSGI during 1979, 1980, 1981, and 1982.

[#] Now known as the Long Island Regional Planning Board.

[##] A Design for a Great South Bay Study. Submitted to DEC by the NYSGI on February 10, 1978.

This report presents the results from the project which addressed task 12, the identification of hard clam brood stock areas which produce sets on known productive beds. This was a third year project since it depended critically on completion of task 10, a study of the circulation in Great South Bay. Results of that study are contained in Wong (1981) and Wong and Wilson (1983). As a part of that study, an existing vertically averaged, hydrodynamic, numerical, finite element model (CAFE) was modified and used to simulate the circulation patterns within Great South Bay. Simulations were carried out and archived for a winter period (December 13-December 24, 1979) and a summer period (September 1-September 28, 1980). This latter simulation, selected to coincide with a dye tracer study in central and eastern GSB to quantitate the diffusive processes (Carter 1981), is the basis of our analysis.

Great South Bay

Great South Bay is a shallow, coastal bay which was formed following the retreat of the most recent glacier (Wisconsin) as the headlands of the eastern end of the southern Long Island coast were eroded and the resulting sediment carried westward by the littoral currents. A barrier island was formed thereby which enclosed a series of bays intermittently connected to the ocean by tidal inlets. See Figure 1. The Bay is about 40 km in length and varies in width between 2.5 and 8 km. The average depth is 1.3 m; depths of 7.6 m occur in the channels, however.

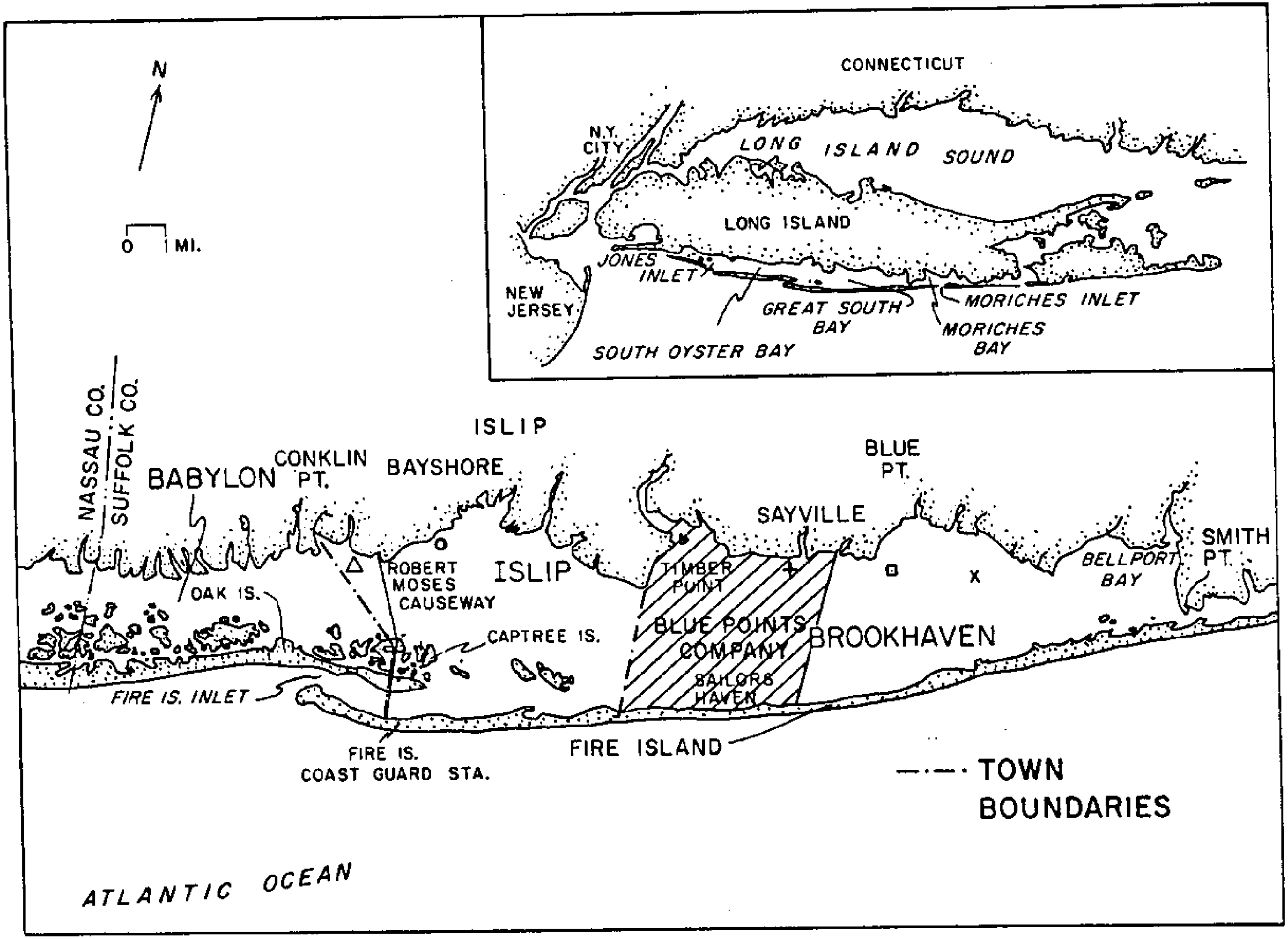

Figure 1. Chart of Great South Bay.

GSB is directly connected to the ocean by Fire Island Inlet and indirectly via Jones Inlet to the west through South Oyster Bay and Moriches and Shinnecock Inlets to the east through Narrow Bay and the Quantuck and Quogue Canals. The circulation of the Bay is influenced, therefore, by the astronomical tides but Wong and Wilson (1983) have shown that 2 additional modes of circulation are also very important. Because the axis of the Bay is parallel to the coast, a setup or setdown of coastal sea level accompanies longshore winds (249/069°T) as a result of coastal Ekman forcing. That is, westerly winds produce a drop in coastal sea level and flow *out* through Fire Island Inlet and Narrow Bay, and flow *in* from South Oyster Bay; easterly winds result in coastal setup and flow *in* through Fire Island Inlet and Narrow Bay, and flow *out* to South Oyster Bay. The predominant period of this mode is 7 days. A second and less important mode is a unidirectional, i.e., all east or all west, response to local wind at a period of approximately 3 days which is somewhat stronger in summer than in winter. Wong and Wilson (1983) note that the Ekman forced mode is important to the volume exchange between the Bay and the shelf since its period (7 days) is comparable to the time scale of mixing within the Bay (10 days). As a result, it is most effective in flushing dissolved or waterborne substances from the Bay.

The importance of GSB to New York lies in the fact that it is the single largest producer of hard clams *(Mercenaria mercenaria)*.

in the world; at one time (1976) it produced more hard clams than the rest of the Atlantic coast combined.

Behavior and Dispersal of Hard Clam Larvae

Fertilization of *M. mercenaria* ova follows the discharge of the eggs and spermatozoa from the siphons of the adult clams. Approximately 24 hours after fertilization, embryos develop into fully-shelled free-swimming larvae which are planktonic (Carriker 1961), but they lack the ability to swim against all but the weakest of horizontal currents. It appears from available data that their dispersal is wholly determined by circulation patterns. On the other hand vertical movements of the veliger larvae of bivalves have been known for many years (reviewed by Mileikovsky 1973). Both lab and field studies have quite clearly shown that these larvae respond to external stimuli and alter their vertical position in the water column. In his comprehensive review of the swimming behavior of larval marine invertebrates, Mileikovsky (1973) stated that the vertical movement rates for bivalves all fell within the same order of magnitude (1 - 60 cm $\cdot$ min^{-1}). He concluded from these data that bivalve larvae could to a limited extent control their vertical position and distribution in nearshore and estuarine waters. Carriker (1961), for example, used a plankton pump to determine the vertical profile of abundance of hard clam larvae over a tidal cycle. He reported that larvae were near the surface during periods of ebb or flood tide and during daylight hours. Carriker concluded that clam larvae maintained themselves away from the bottom during daylight hours and that they descended toward the bottom during hours of darkness. He hypothesized that the larvae were stimulated to rise in the water column by turbulence created by tidal currents.

Mileikovsky (1973) presented field data that showed a very significant upward migration of unidentified bivalve larvae during the darkness of a solar eclipse, followed by downward migration as the eclipse ended. Both this study and Carriker's work contradict the earlier laboratory studies of Turner and George (1955), who reported that hard clam larvae showed no detectable reaction to light and were generally "indifferent" in their behavior to a wide range of salinities.

It is clear from this brief review that the larvae of hard clams are capable of vertical migrations. It is important to keep in mind that such migrations will, under some circumstances, alter

rsal of these larvae relative to water circulation patterns.

o clear that the environmental factors influencing larval

and the interactions between vertical migration and water

are very poorly understood. Although the complexity of

em suggests that studies relating water movement to larval

should be viewed with some caution, three important points

kept in mind relative to the present study. First of all,

migrations have been demonstrated more clearly for oysters than for clams, and the data for hard clams are somewhat contradictory. Secondly, the situation is further complicated in a shallow, well mixed system such as Great South Bay. Great South Bay lacks the vertical salinity gradients that might be important keys to larval migration. Finally, vertical migrations notwithstanding, hard clam larvae are totally dependent upon water movement for their dispersal. Simply put, clam larvae cannot swim against even the weakest current. They will move horizontally only where the water carries them. For that reason, an understanding of the physical nature of circulation within the Bay is ultimately the key to predicting larval dispersal.

Management Strategies

According to McHugh (1983), the hard clam has long been the leading marine resource in New York State. He concludes from the hard clam landing data that the peak of production from Great South Bay was probably in 1976[#]; since that time production in Great South Bay has steadily declined to less than half of the 1976 value. A number of management practices have been and are currently being applied to the Great South Bay hard clam fishery. They include gear restrictions, a minimum legal size of 1 inch across the valves, mariculture, i.e., planting of seed clams, and bringing spawners from colder areas to extend and augment spawning. These practices have not arrested the decline in landings which some attribute to

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[#] The peak for New York State was in 1974.

overfishing, poor law enforcement, and increased salinity due to the conversion of a large area bordering on Great South Bay from cesspools and septic tanks to a centralized sewage treatment system (Southwest Sewer District). This diverted a substantial amount of ground water from the Bay to the ocean thus tending to increase the salinity. The magnitude of this increase, if any, has not been documented as yet.

Proposed but not currently in effect are restrictions on the numbers of clammers, better enforcement of the laws regulating minimum size and harvesting in closed areas (poaching), more severe sentences for violators, and the operation of spawner sanctuaries where the large, low market value, fecund, chowder-size clams would be placed and protected from harvesting while serving as brood stock. These spawner sanctuaries would presumably be located where there was a high probability that the larvae produced by them would seed specific areas which are or have been productive. Prior to the circulation study reported in Wong (1981) this approach would not have been possible since little was known of the processes of advection and diffusion in GSB which disperse the larvae between spawning and setting. As noted earlier, it is this latter strategy which we shall address in this report.

A Rationale for Maximizing Setting Densities of Hard Clams on Known Productive Areas

A determination of the origin of larvae that set some 10-20 days after fertilization on a designated site requires a step-by-step approach. We propose the following:

First, exercising the CAFE model (described later) under the combined influence of actual summertime tidal and atmospheric forcing to calculate the horizontal currents at a suitably dense array of points over the area of interest. This was done for GSB pursuant to task 10 for the period September 1-28, 1980 and the velocities archived. In a later section we will show that the wind conditions for that period were typical for GSB for June, July, and August,

Second, simulating the diffusive processes that waterborne particles are subject to by means of small, additive, random, turbulent velocities. The model which predicts and applies these turbulent velocities is described in detail in a later section,

Third, identifying the location(s) of the sites where setting is desired. This information must come from the hard clam managers,

Fourth, simulating the release of a large number of particles (2-300), evenly spaced over the entire area of interest, i.e., town waters, and subjecting them only to advection,

Fifth, analyzing the results of these releases, day by day, identifying the release point(s) of the particle(s) most frequently located in the desired site(s) between 10 and 20 days after release,

Sixth, assigning both advective and turbulent velocities to a cluster of particles (100) located at the release point(s) identified during step five and following the cluster for 20 days. These 100 particles are initially arranged uniformly over a small area (75 m × 75 m) and represent the larvae from 1000 bushels of chowder-size hard clams arranged at a density of 36 clams/m^2, and

Seventh, relating the day-by-day area within the cluster in terms of setting density and total set according to mortality.

MODELLING THE DISPERSION OF HARD CLAM LARVAE

Modelling the Velocity Field in Great South Bay

A modified version of a two-dimensional, hydrodynamic, numerical, finite element model known as CAFE, developed under the Sea Grant Program at the Massachusett Institute of Technology, was used to simulate the velocity field within the Bay. The model is based on the vertically integrated horizontal momentum equations and the equation of continuity. It is capable of predicting the vertically integrated horizontal currents and surface elevations at the nodal points of a two-dimensional finite element triangular grid (Figure 2) representing the solution field. Basic input information which must be supplied are the mean low water depth for each node, the time variations in surface elevation at each open boundary, and the wind stress on the sea surface. Details of the model are described by Connor *et al.* (1973), Wang and Connor (1975), Pagenkopf *et al.* (1976), and Wang (1980).

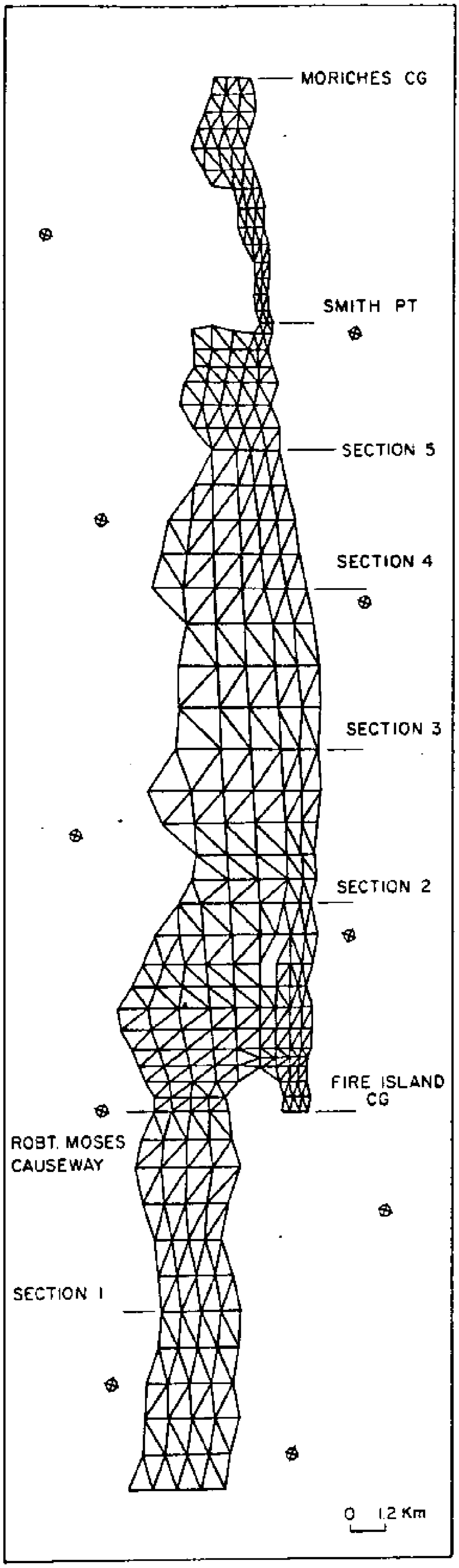


Figure 2. Finite element grid for Great South Bay.

CAFE was originally designed to handle only one tidal harmonic at the open boundaries and a constant wind stress on the surface. Since these restrictions greatly limit the usefulness of the model, it was modified so that observed sea surface elevations at each open boundary and the observed, temporally varying, wind field on the surface of the Bay could be applied. This allowed the model to simulate the velocity field within the Bay generated by the actual combination of tidal motion and subtidal atmospheric forcing. This is important since, as noted earlier, it has been demonstrated that low frequency atmospheric forcing is important in affecting the exchange processes within the Bay (Wong 1981).

That the velocities the model calculates are reasonable was verified for two separate time periods by comparing measured sea levels and currents with model simulations for nodes in close proximity to where the measurements were made. One of these periods (December 13-24, 1979) represents wintertime conditions and the other (September 1-28, 1980) late summer. Observed and simulated sea levels agreed well in both phase and amplitude at four locations during winter and three locations during summer.

Observed and simulated E-W[#] currents were also compared for the same two periods at two locations, mid-Bay between Green Harbor on Long Island and Lone Hill on Fire Island and at Smith Point. For the winter season, there was very good agreement in phase and moderately good agreement in magnitude. Agreement for the summertime period was also considered to be satisfactory.

[#] E-W is 090°M or approximately the direction of the principal axis of GSB.

A comparison of observed and simulated low frequency or subtidal currents## at Smith Point was also made for both summer and winter periods in order to check the leveling of our tide stations; no adjustment in datums was indicated.

Details of the verification comparisons are
183-198 of Wong (1981).
Having verified that the model produces real
and water levels when forced by a combination of
coastal Ekman set-up or set-down, and direct winc
show that the archived summertime period (Septemk
ocities produced by the model are typical for the
which spawning takes place in Great South Bay (Ju
Since the astronomical tides have very constant a
characteristics which do not change from one year
amounts to comparing the local winds for Septembe
historical wind records for some nearby location
For this purpose, wind records for Westhampt
years 1952-1969 were compared with the winds fron
Meteorological Tower for September, 1980. First,
averages of the rotary power spectra of the Westl
stresses were calculated for two 42 day periods
and 7 July, respectively (Figures 3A and B). Nex

ided on pages
g velocities
onomical tides,
remains to
-28, 1980) vel-
ths during
July, August).
redictable
another, this
980 with the
the summer months.
each# for the
Tiana Beach#
ear ensemble
on Beach wind
ncing on 5 June
e rotary power

Records were low pass filtered with a Lanczos
power point at 34 hours.

Westhampton Beach is located ~ 15 miles east o
of GSB and 2.6 miles inland from the coast. Ti
miles east of Westhampton Beach and is directl

er with a half
e eastern end
Beach is ~ 5.5
the coast.

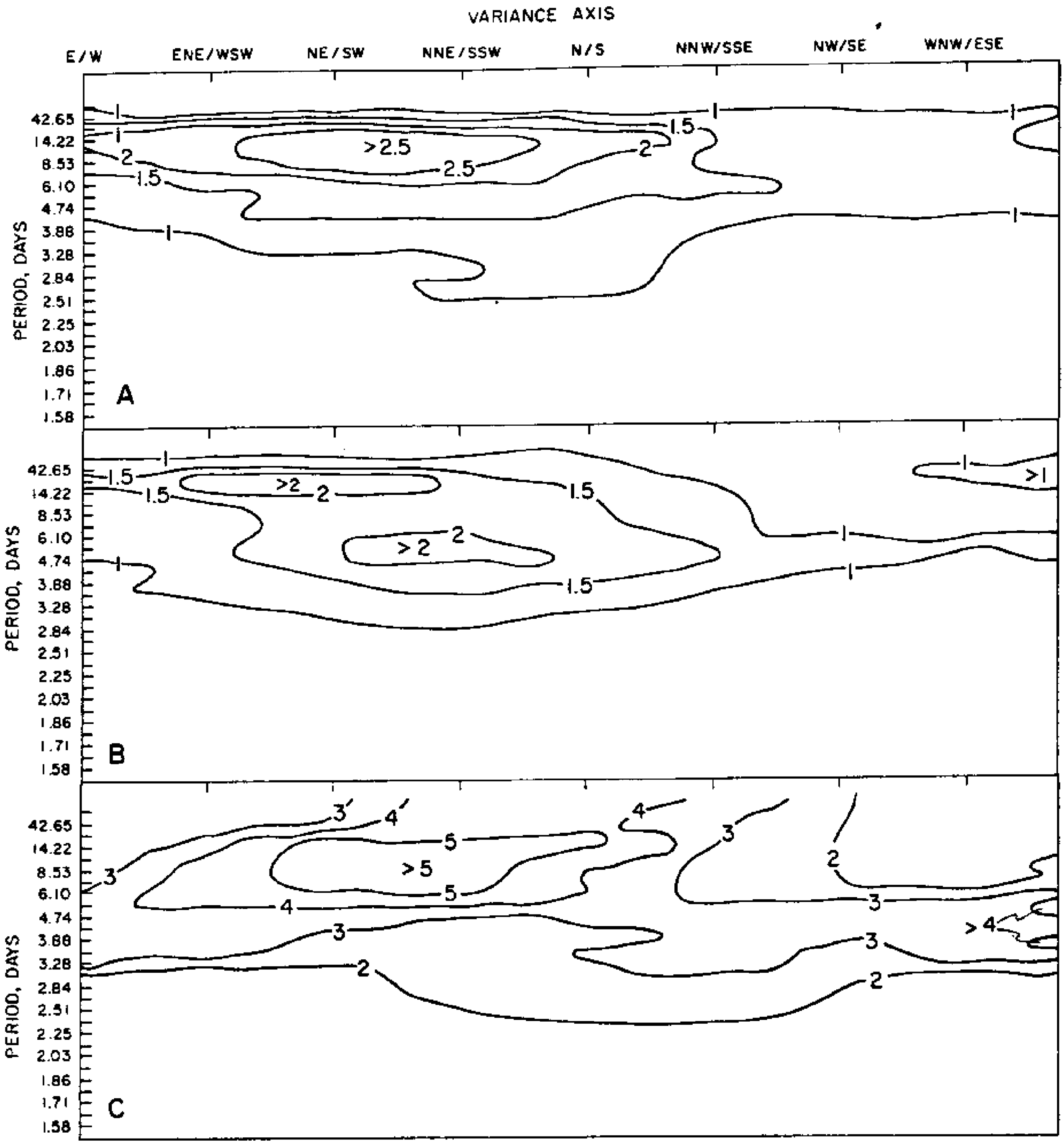


Figure 3. Eighteen year (1952-69) ensemble averages of the rotary power spectra of Westhampson Beach wind stresses (A and B) and rotary power spectra for Tiana Beach wind stress (C). A and B cover the 42 day periods commencing at 0000, June 5 and 0000, July 7, respectively; C covers the 42 day period commencing at 0000, August 25, 1980. Variance is in arbitrary units.

spectra for the wind stress components for Tiana Beach for the 42 day period commencing on August 25, 1980 was calculated and is shown in Figure 3C. A comparison of Figure 3C with Figures 3A and B shows that they are quite similar with respect to both frequency and direction. All 3 figures show that the stongest variance occurs for winds blowing along a line oriented SSW/NNE. The winds during 1980 were somewhat more energetic than the ensemble averages but there were several years as energetic in the 18 year ensembles.

Bivariate percentage frequency tabulations (speed and direction)
... at Westhampton Beach for June, July
based on hourly observations at Westhampton
and August of 1944-45 and 1951-67 were also
d to a similar
tabulation for Tiana Beach for September 19
direction mode
was SW for all 4 tables with the speed mode
6 knots for
September, 1980 and 7-10 knots for the 3 hi
ecords. This
confirms the earlier conclusion that Septem
0 was somewhat
more energetic than the average summer mont

Based on the foregoing comparisons we
ident that the
model simulated velocities for the period Se
1-28, 1980 are
typical of summertime conditions in GSB. F
H7 are examples
of the simulated velocities in Babylon and
wn waters cal
culated by the model for maximum ebb and fl
ng periods of
light westerly winds and strong easterly wi
e direct effect
of the wind may be seen by closely comparin
4 with 5 and
Figure 6 with 7.

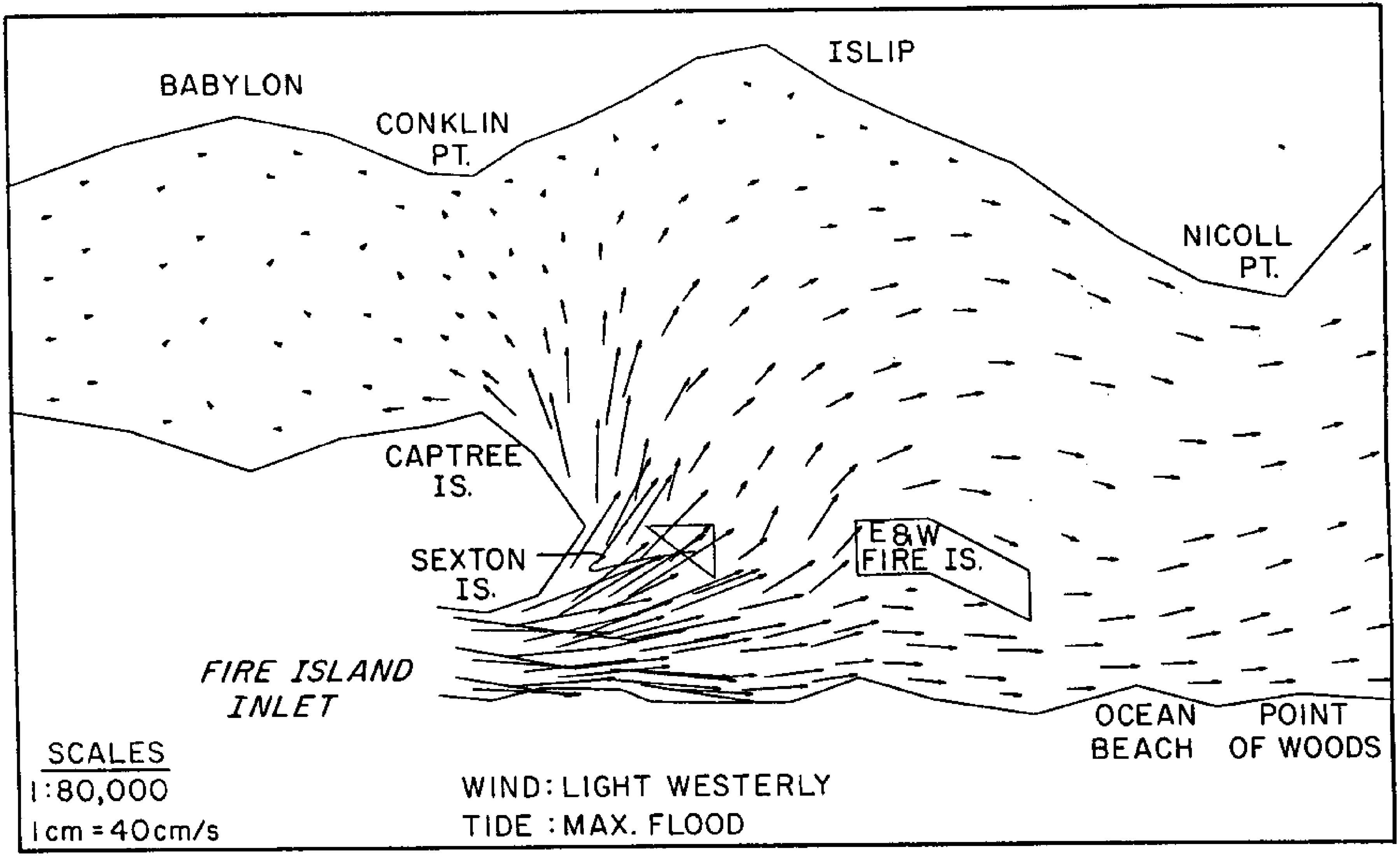


Figure 4. Typical velocity vectors for western Great South Bay. Vectors result from exercising CAFE and represent vertically averaged velocities.

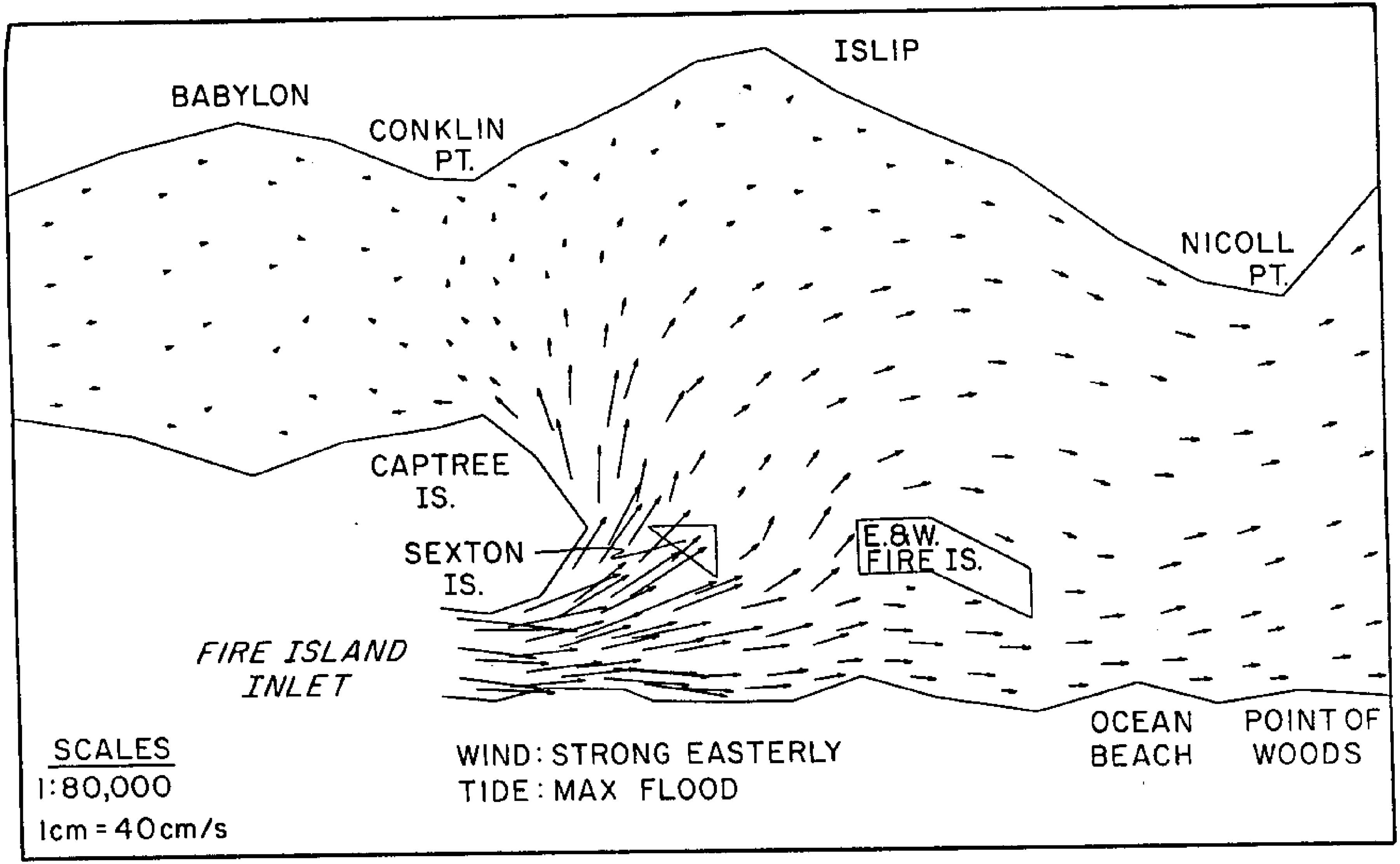


Figure 5. Typical velocity vectors for western Great South Bay. Vectors result from exercising CAFE and represent vertically averaged velocities.

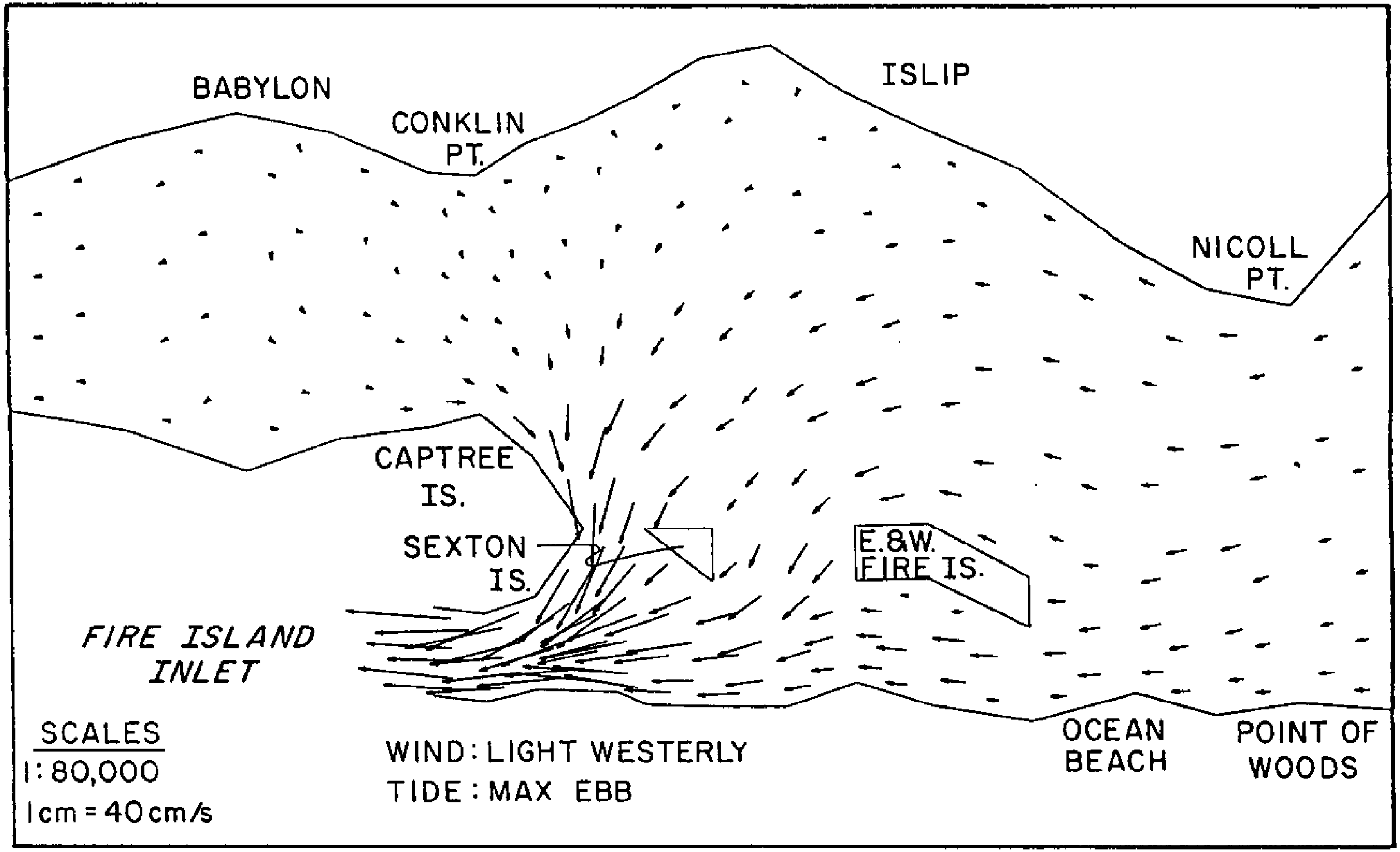


Figure 6. Typical velocity vectors for western Great South Bay. Vectors result from exercising CAFE and represent vertically averaged velocities.

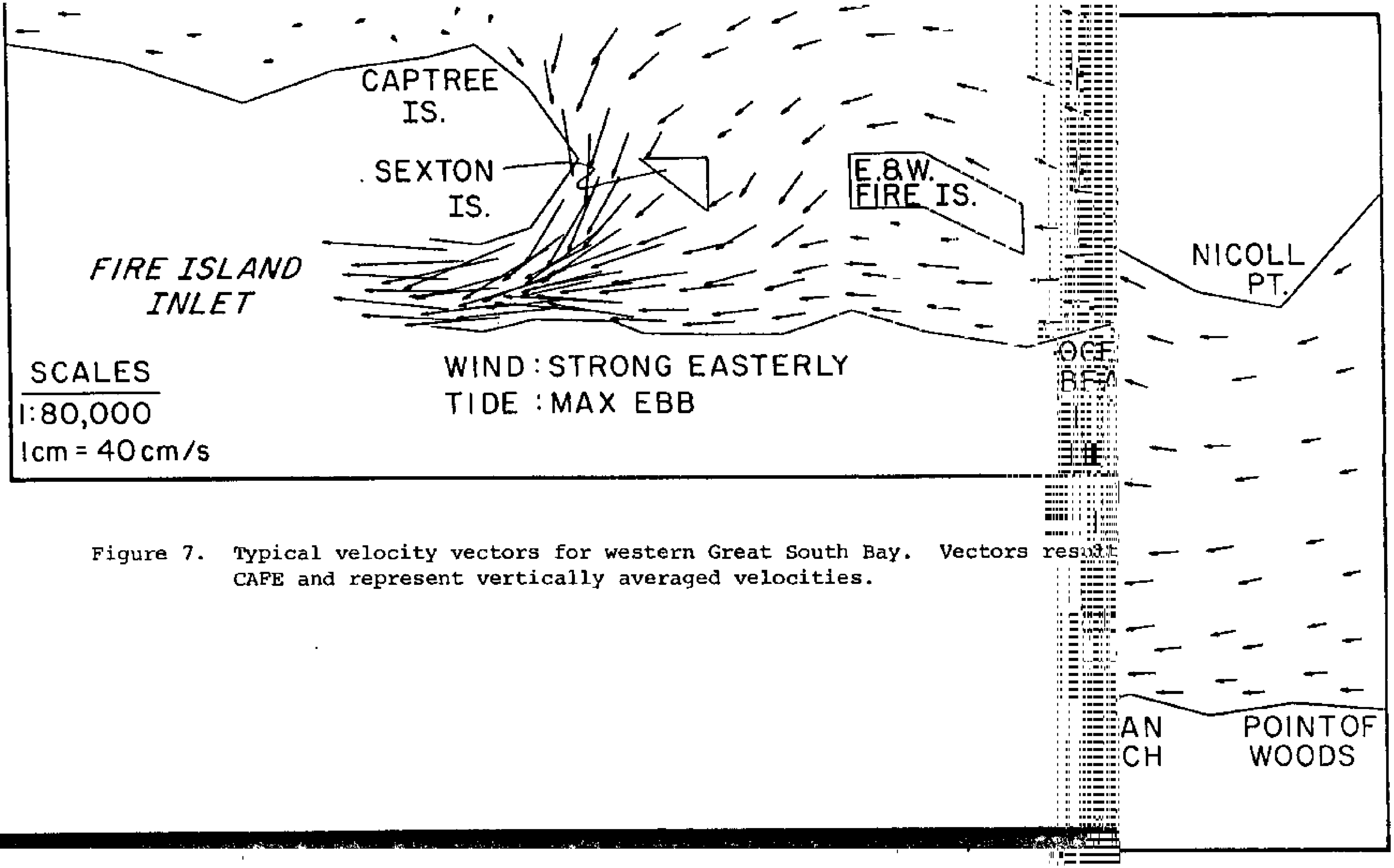
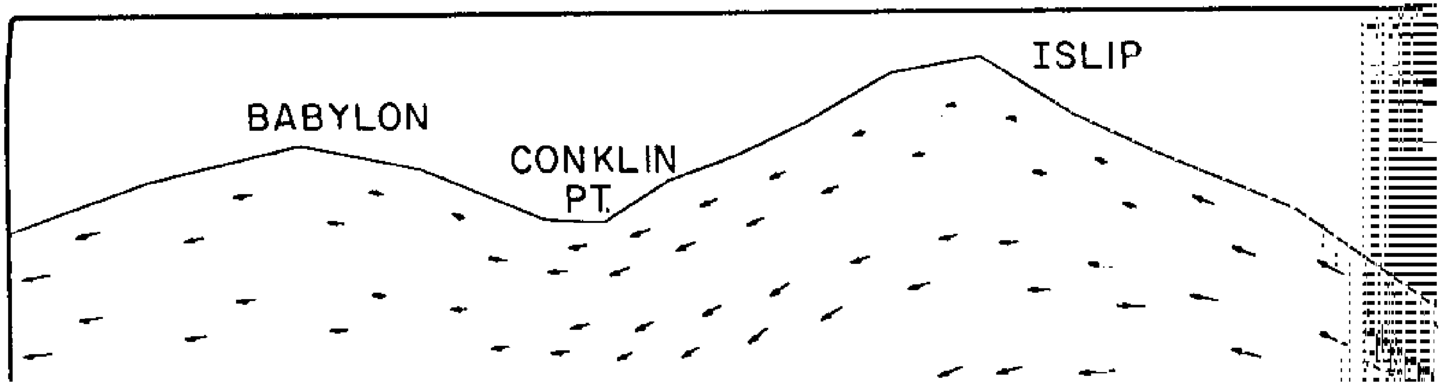


Figure 7. Typical velocity vectors for western Great South Bay. Vectors result CAFE and represent vertically averaged velocities.



from exercising

Modelling the Processes of Diffusion in Great South Bay

Two entirely different methods were considered for modelling the diffusion processes in Great South Bay. Our first approach was to numerically solve the mass transport equation for the concentration of any dissolved constituent at the nodal points of the two dimensional finite element grid used in the circulation model CAFE. The velocity field output of CAFE was used as an input to the diffusion model. This technique was tested against the 1980 dye study (Carter 1981) and was generally successful in describing the gross features of the dye patch over time but failed to provide the desired spatial resolution in the concentration field since the distance between nodal points was generally greater than 800 m.

A second method, and the one used in this study, simulates the turbulent diffusion processes by subjecting a cluster of particles to random turbulent velocities and then tracing the spread of the particle cluster with time. The turbulent diffusion velociti experienced by particles were numerically generated by the Markov-Ch model developed by Awaji (1982). One component of the turbulent velocity vector, $u'(t_i)$, experienced by a particle during a time step Δt (from time t_i to t_{i+1}) is given by

$$u'(t_i) = \rho \, u'(t_{i-1}) + \gamma(t_{i-1}) \tag*{1)}$$

where ρ is a constant. $v'(t_i)$, the other turbulent component, has a similar form. The correlation between turbulent velocities separated by m time steps of Δt is ρ^m according to Eq. (1) since $\gamma(t_i)$ is independent of $u'(t_i)$. For a single time step, i.e., $m = 1$, ρ^m may be approximated by $1 + \ell n\rho$ if we can neglect terms higher order than $\frac{(\ell n\rho)^2}{2!}$. Approximating ρ by $\exp(-\Delta t/T_L)$ meets this condition if $\Delta t << T_L$. Here T_L is the Lagrangian integral time scale, a measure of the longest time during which, on the average, a particle persists in a motion in a given direction. From the definition of ρ, it is clear that

$$T_L = \int_0^\infty \rho \, d\,\Delta t \tag{2}$$

or that ρ is the velocity autocorrelation coefficient. Our model time step is 5 m; therefore, we have taken T_L as 2 h a number sufficiently larger than 5 m. The first term in Eq. (1) is then calculated using $u'(t_{i-1})$ from the previous time step.

To calculate the second term in Eq. (1), $\gamma(t_{i-1})$, we proceed as follows. For diffusion times large compared to T_L it can be shown that K, the coefficient of eddy viscosity, is given by

$$K = \sigma_v^2 \, T_L \tag{3}$$

where σ_v is the variance of the turbulent velocities. Rearranging (3) we have

$$\sigma_v = \sqrt{K/T_L} \tag{4}$$

from which σ_v may be estimated for GSB if K can be specified. For this purpose, we utilized the results of two dye tracer studies carried out in GSB in 1976 and 1980 and reported in Carter (1981). Carter's analysis of these 2 dye studies resulted in the following expression for K

$$K = 2.1 \times 10^{-2}\ t^{1.08} \tag{5}$$

Since T_L was previously assumed to be 2 hours, a value of σ_v appropriate for GSB can now be calculated at every time step using Eqs. (4) and (5). Returning now to Eq. (1), taking the variance of both sides and noting that $\gamma(t_i)$ and $u'(t_i)$ are uncorrelated, we obtain the following relation for σ, σ_v, and ρ

$$\sigma = \sigma_v(1-\rho^2)^{\frac{1}{2}} \tag{6}$$

σ is now calculated from Eq. (6) at each time step, and for each particle to be followed, a sequence of random numbers is generated from a Gaussian distribution with a mean of 0 and a standard deviation of σ. A random selection is made from this sequence which becomes γ. $u_i(t_i)$ is then calculated from Eq. (1); $v'(t_i)$ is generated in the same way. By applying these turbulent velocities at each time step to each particle of a cluster the effect of the processes of turbulent diffusion on the cluster are simulated.

The Complete Larval Dispersion Model

As noted earlier, the larval dispersion process in Great South Bay is simulated by assigning both advective and turbulent diffusive velocities to a large number of particles (100) and then tracking these particles in time. Since CAFE provides the advective velocity field at the nodal points of the finite element grid, the initial advective velocity of each particle at time T_o can be computed through interpolation once the initial position of each particle within a triangular element has been assigned. The turbulent diffusion velocity for each particle is then determined by means of the model described in the previous section. When all components of both the advective and diffusive velocities of the particles are known, they are summed and multiplied by the time step Δt to obtain the position the particle will assume at time $T_o + \Delta t$. Once these new positions are determined, a new set of appropriate advective and diffusive velocities is computed for the particles and is used to transport them from time $T_o + \Delta t$ to $T_o + 2\Delta t$. By repeating this procedure, the cluster of particles is transported forward in time thus simulating the larval dispersive processes within the Bay.

THE COMPLETE LARVAL DISPERSION MODEL APPLIED TO GREAT SOUTH BAY

General

Although the numerical model boundaries are Seaford on the west and Moriches CG Station on the east, our area of interest is the waters of GSB within the towns of Babylon, Islip, and Brookhaven. It is important to note that we have not been asked to address the question of the hard clam brood stock locations that provide sets on the known productive beds within GSB but instead for the waters of each town *separately*. Since the biological and physical processes which determine the dispersal and setting locations of hard clam larvae in GSB are not subject to political considerations, each town benefits to some degree from its neighbors but as will be shown there are also losses which, in some cases, are more than offsetting.

There is also a privately managed area located in the western part of Brookhaven waters (Blue Points Company) which is not a part of this study. The boundary locations of the 3 towns and the Blue Points Co. are shown on Fig. 1.

Given a brood stock location, the areas within which larvae will set can be estimated very simply by exercising our complete larval dispersion model forward in time. Our problem, however, is somewhat more difficult. We wish to identify those brood stock locations which will maximize the probability of setting on specified areas which are known to be productive. For this purpose, shellfish managers from each of the three towns provided locations of the productive areas within their waters in which they were specifically interested. 4 such areas were identified in Islip, 6 in Brookhaven, and 5 in Babylon.

Since our methodology was essentially the same for each town, we shall use Islip to illustrate the methodology. Initially a large number of evenly spaced (∿600 m apart), labelled particles (143 for Islip, 383 for Babylon, and 251 for Brookhaven) were released and *advected*# forward in time for 20 days. The initial particle distribution for Islip is shown in Figure 8. The four areas on which sets are to be maximized are also shown on Figure 8. After 20 days, the starting position of those particles which were located in any of the preferred areas between 10 and 20 days after release were considered to be first order estimates of the proper brood stock areas. Table 1 shows the numbers of the labelled particles that were located in any of the 4 specified areas between 10 and 20 days after release. According to Table 1, only 3 particles, #'s 135, 136, and 142, were located in at least one of the four areas on all days between 10 and 18. Accordingly, the centroid of the triangle formed by 135, 136, and 142 (see Fig. 8) was selected as the initial location of the brood stock area for Islip.

At this point diffusion was not applied at each time step in order to minimize computer costs.

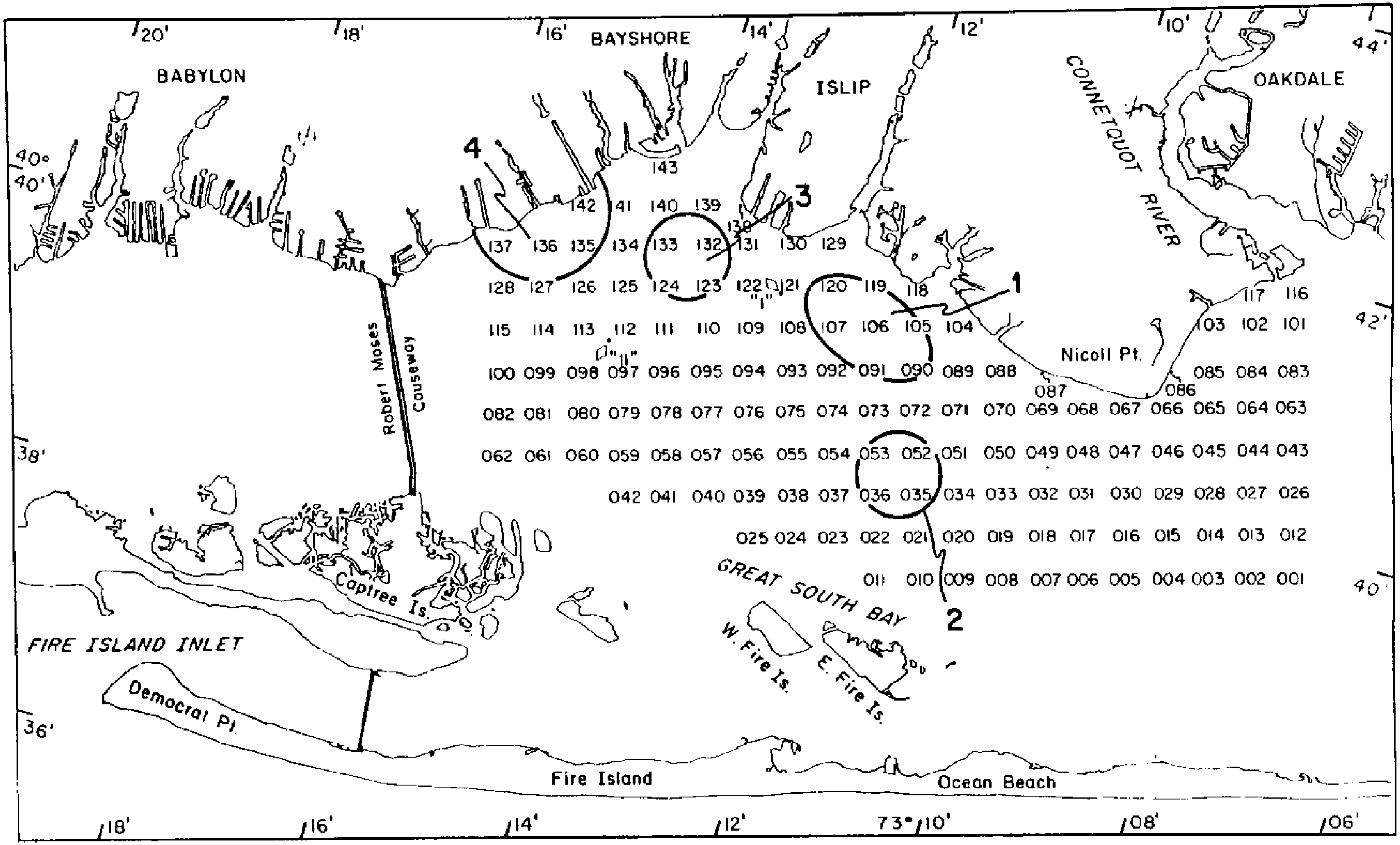


Figure 8. Initial (t = 0) distribution of particles (143) for Islip waters.

Table 1

Numbers of Labelled Particles by Location and Age for Islip Waters

Age, days	Area 1	Area 2	Area 3	Area 4
10	69	36,33	133,134,135, 136,142	110,123
11	69	33,36,51	124,133,134, 135,136,142	110,122,123, 131,137
12	71,88,89		110,123,124, 133,134,135, 136,142	94,109,121, 122,125,137
13	55,71,88, 89,135,136, 142	58	94,105,109, 110,121,122, 123,125,131, 132,137	
14	135,136,142	34,35,55, 57,75,76, 107,120	109,121,125, 132	
15	110,135,136 142	56,57,75, 76,107,120	91, 92,105, 106,109,121, 125,132	
16	41,55,58, 80	130	94,110,122, 123,131,135, 136,137,142	105,109,132
17	59		55, 80, 71, 88, 89	135,136,137 142
18			41, 55, 58, 71, 80, 88, 89	35, 56,135 142
19	19,20,32, 33,35,51, 70			41, 59
20	49		19, 20, 50, 51, 70	

Once a release point had been identified in this manner for a particular area(s), 100 evenly spaced particles, representing the larvae from 1000 bushels of chowder-size clams arranged 36 clams/m^2, were released from a small area (75 m × 75 m) centered on the selected point. These particles were then moved forward in time for 18-20 days with *both* advective and diffusive velocities. As noted earlier, the advective velocities used for this purpose were obtained previously by exercising CAFE for the period September 1-28, 1980. Results for each of the towns are given in the following Sections.

Results

The results from exercising the complete larval dispersion model are presented separately for each town as a series of charts. As noted earlier, each release was assumed to take place at 0000, September 9, 1980 (t = 0). This was selected as the release time because the strength of the longshore component (069/249°T) of wind stress was significantly weaker during the first 9 days of September than during the remainder of the month (Figure 43, Wong 1981). Between September 9 and 28, there was significant variance in both the longshore and crossbay components of the windstress which, according to Wong (1981) and our Figure 3, is more typical of the summer wind field over GSB.

The phase of the astronomical tide at the time of release was not considered to be critical except possibly for the easternmost release in Brookhaven. According to Cheng (1983), the time during the tidal cycle that the particles are released is very important when mixing processes are estimated with Lagrangian tracers. Some numerical experiments performed by K.C. Wong and R.E. Wilson (personal communication) for Great South Bay suggested that the time of release was important, however, only in those areas where there were significant gradients in the phase and amplitude of the tidal signal. According to their experiments, such areas would be the Smokehill Channel just east of Captree Island (phase and amplitude), Narrow Bay which connects Great South Bay with Moriches Bay (amplitude) and Bellport Bay in eastern Great South Bay (phase). Accordingly, over much of the interior of Great South Bay the time of release should not materially affect the results.

In general, the velocities were easterly (8-11 cm s^{-1}) in Babylon and Islip and westerly (3-4 cm s^{-1}) in Brookhaven at the time of release.

It will be shown later that the envelopes of the 100 particle clusters may be viewed as good approximations to lines of constant equal relative larval concentration, i.e., relative to the peak concentration, and the centroids labelled "C" on the figures as the location of the peak concentrations. In a later section we will scale the envelopes to larval concentrations and estimate the total set within them.

Islip

Figures 9-17 show the positions of the 100 particles at days 10 through 18. The figures show an eastward drift of the particles

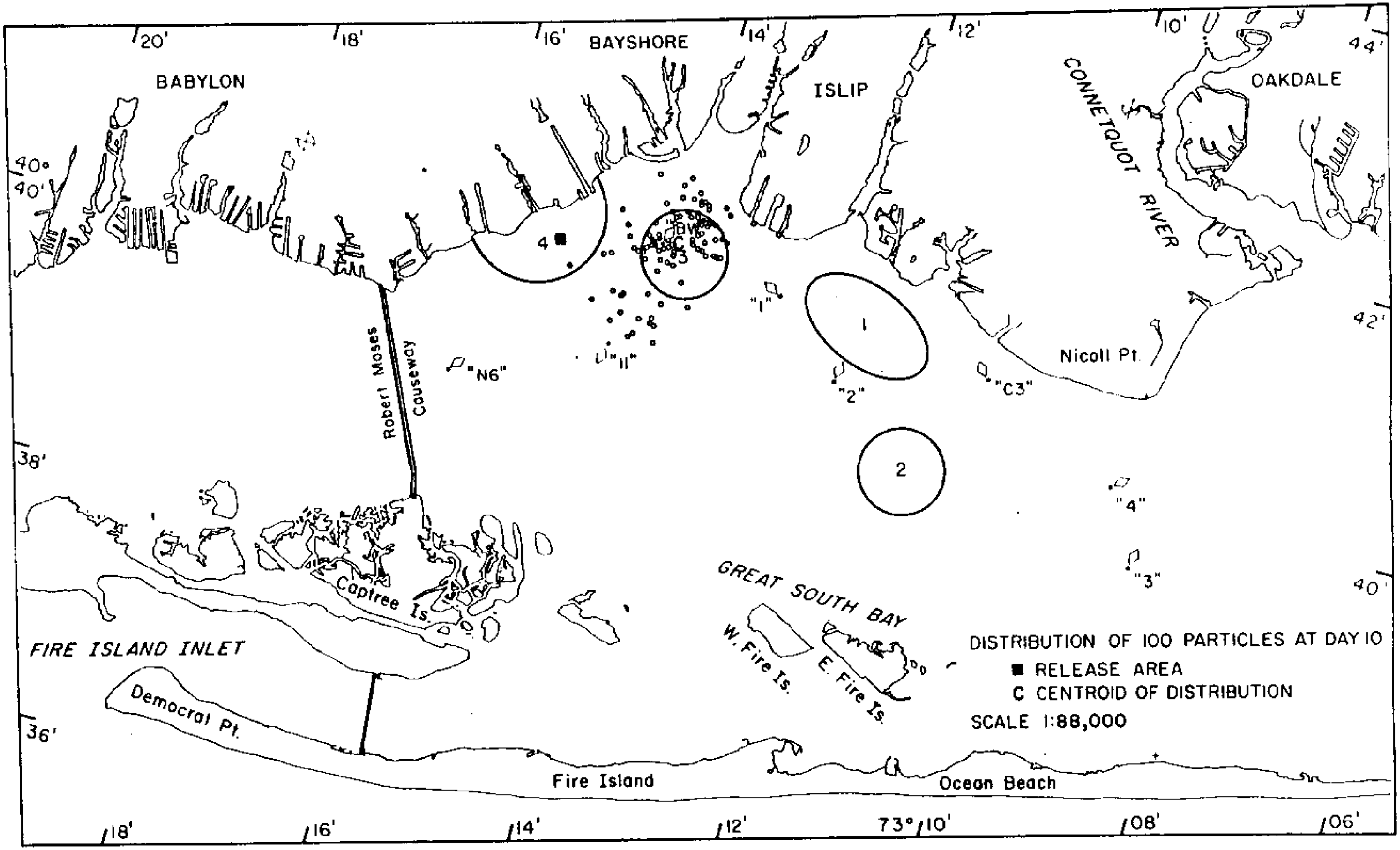


Figure 9. Particle distribution 10 days after release relative to productive areas. t = 0 was 0000, 9 September 1980.

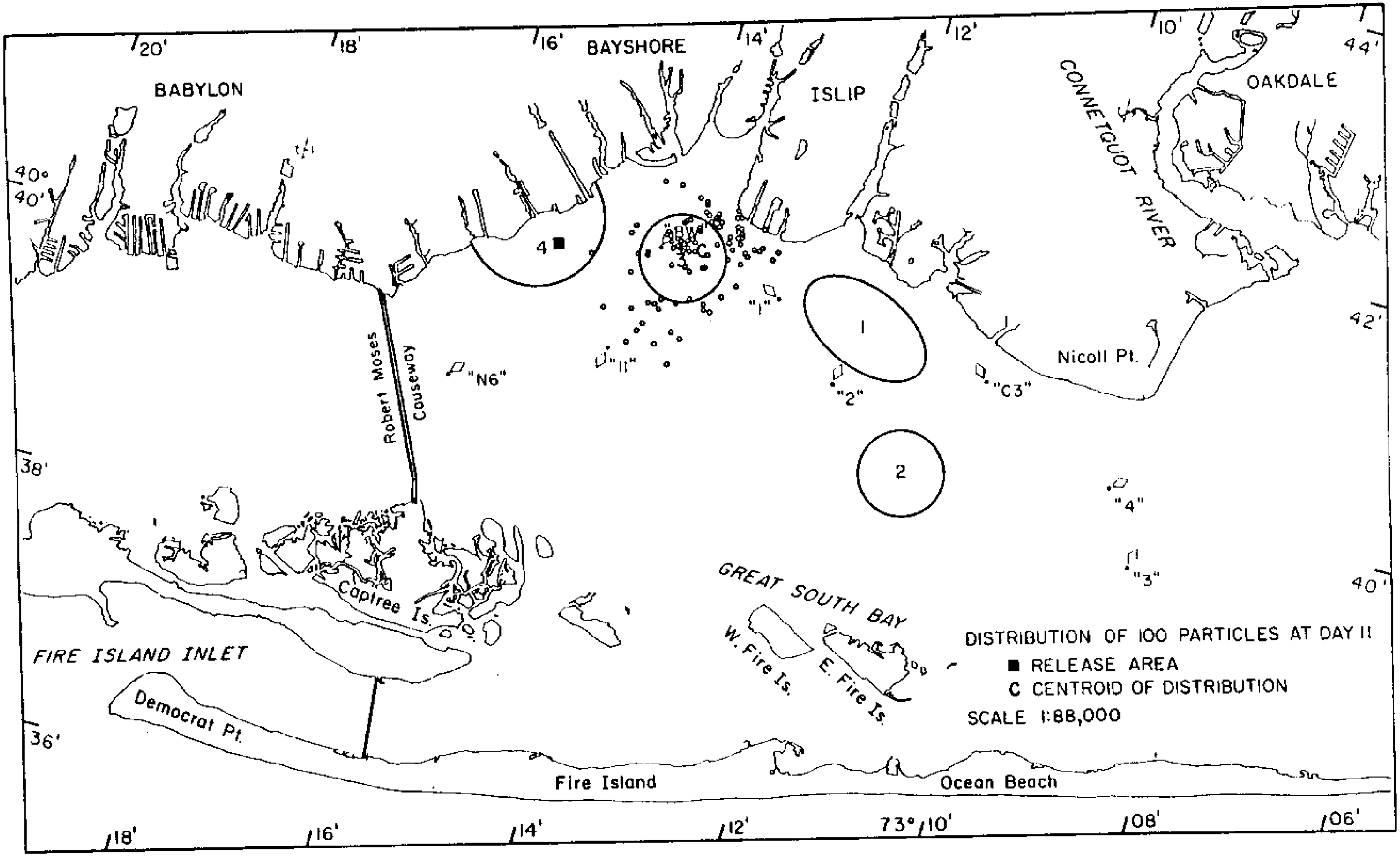


Figure 10. Particle distribution 11 days after release relative to productive areas. t = 0 was 0000, 9 September 1980.

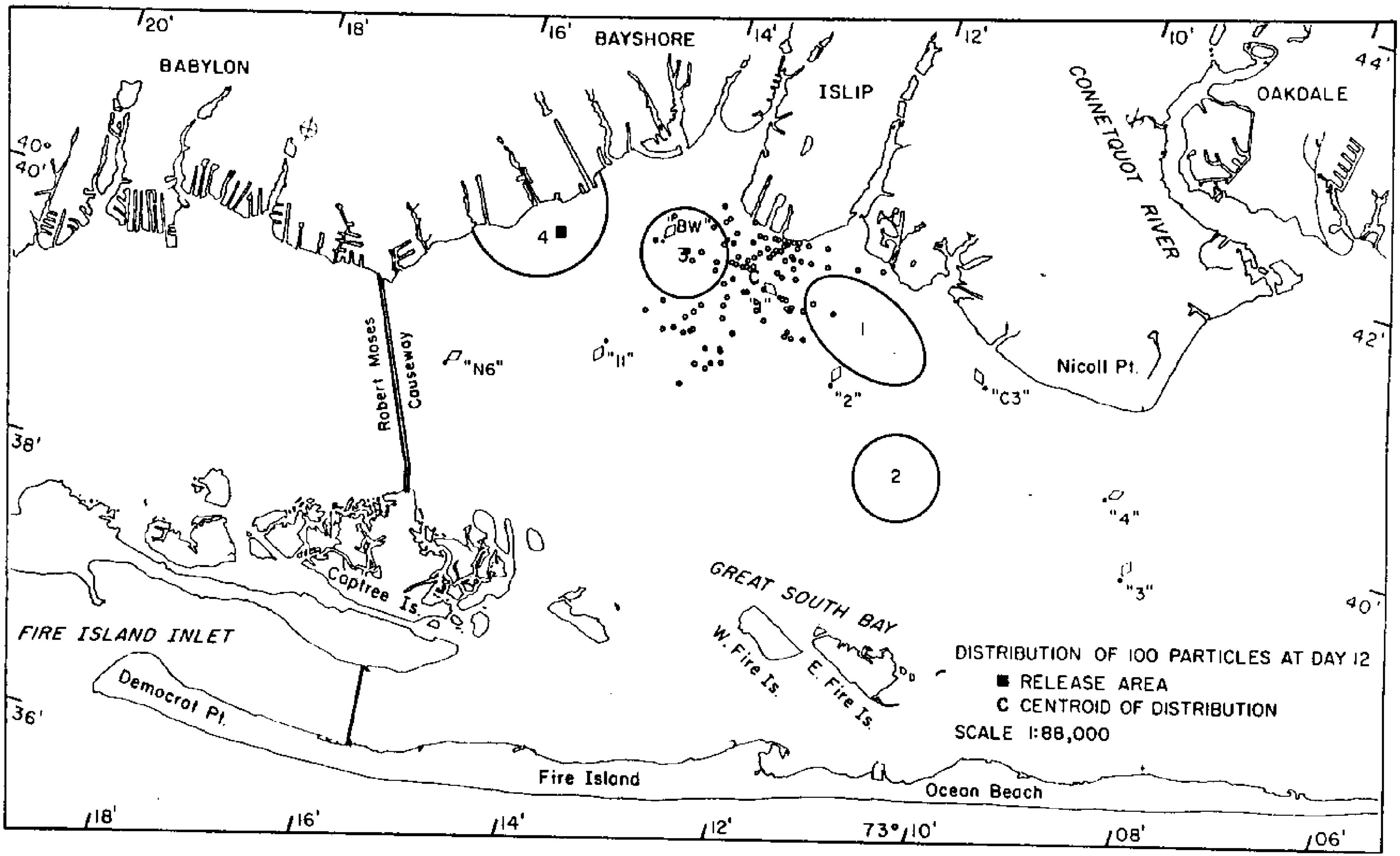


Figure 11. Particle distribution 12 days after release relative to productive areas. t = 0 was 0000, 9 September 1980.

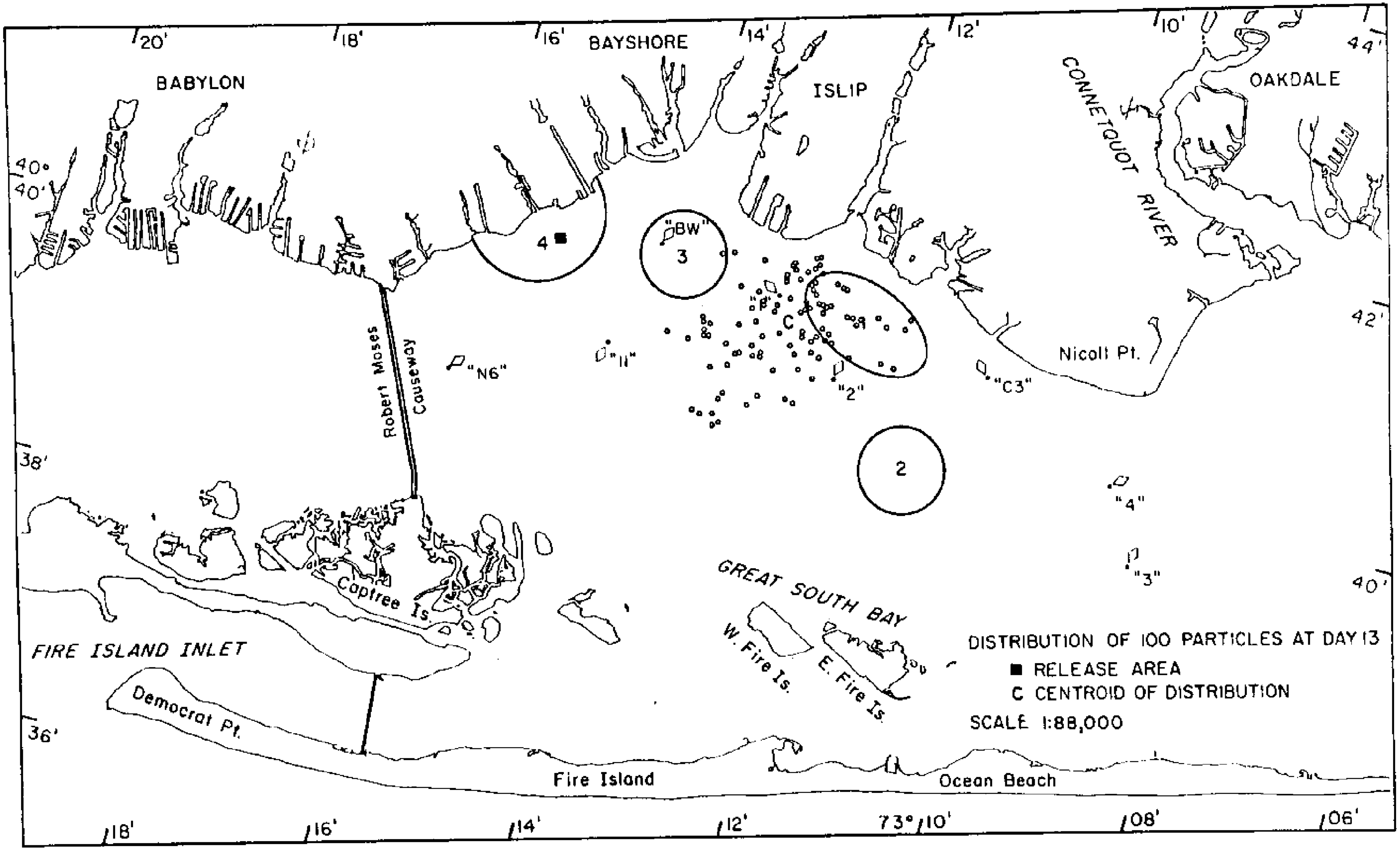


Figure 12. Particle distribution 13 days after release relative to productive areas. t = 0 was 0000, 9 September 1980.

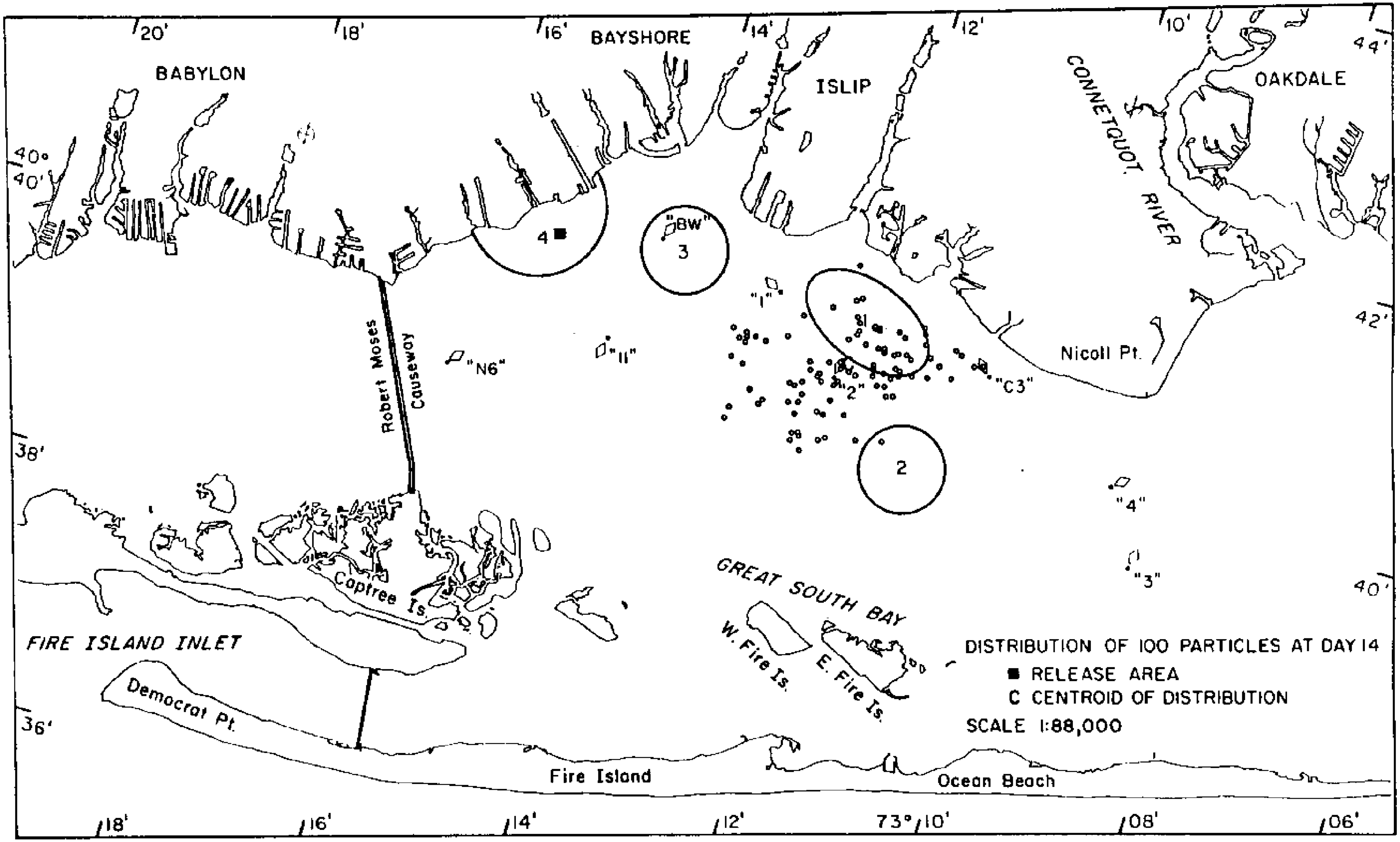


Figure 13. Particle distribution 14 days after release relative to productive areas. t = 0 was 0000, 9 September 1980.

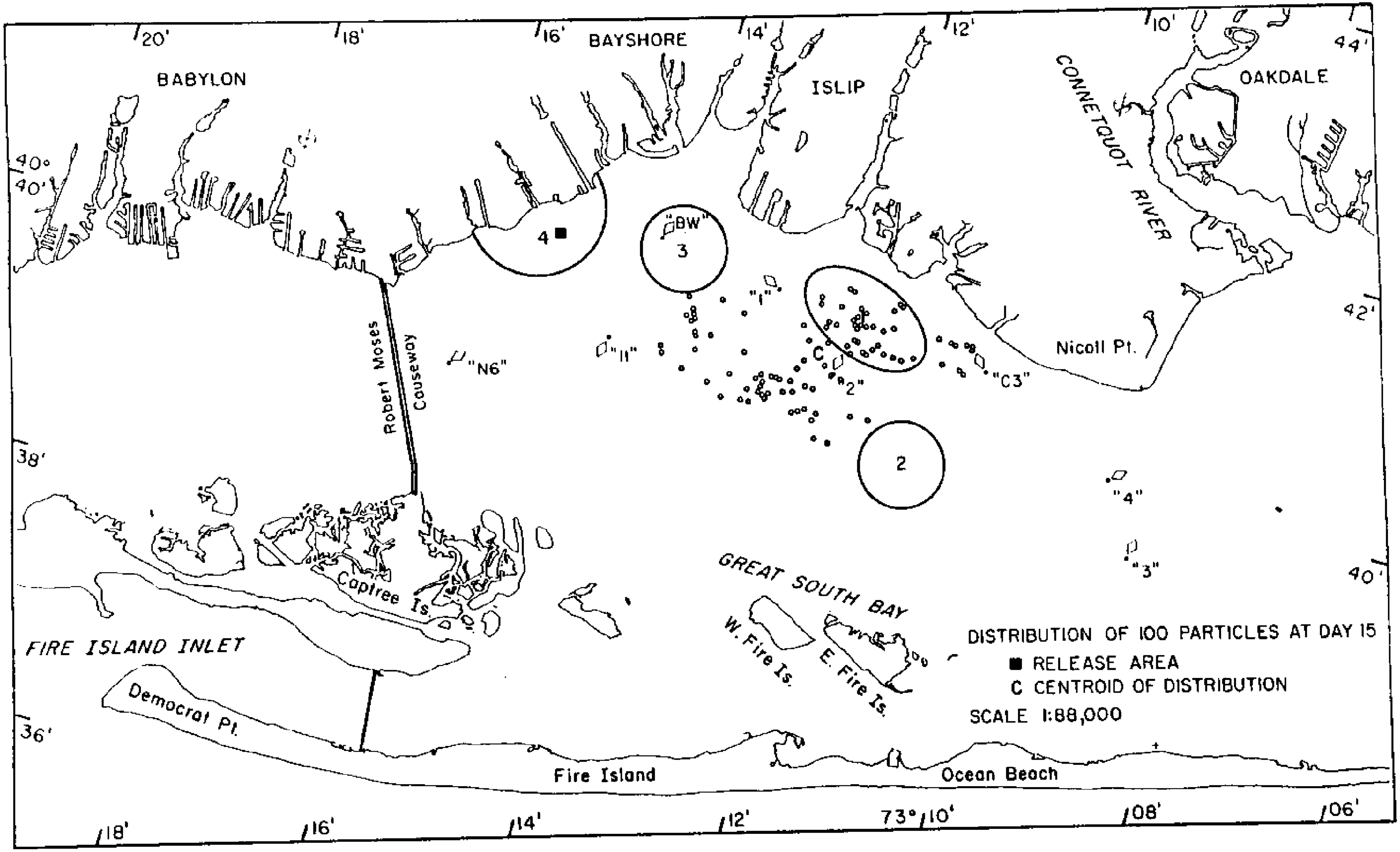


Figure 14. Particle distribution 15 days after release relative to productive areas. t = 0 was 0000, 9 September 1980.

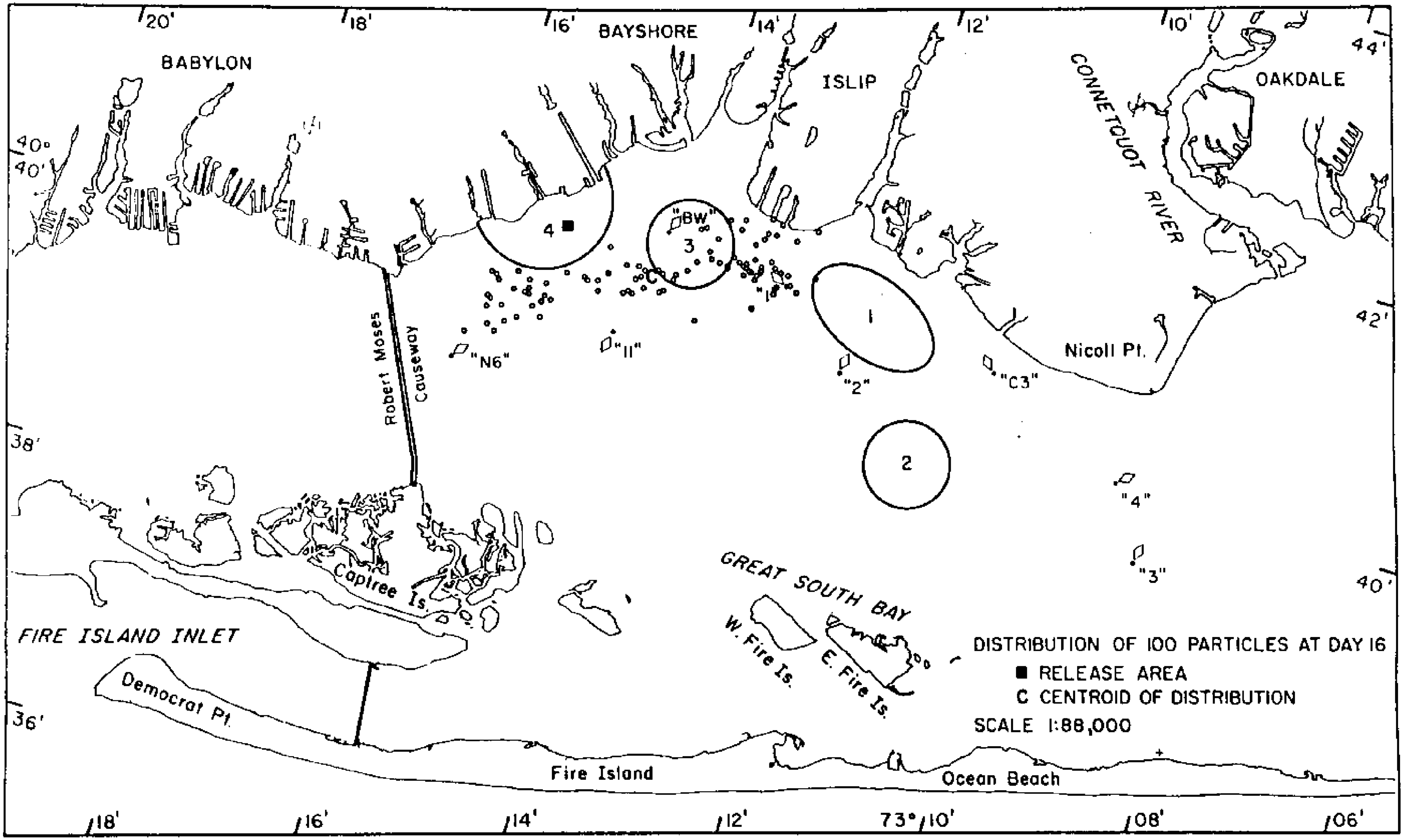


Figure 15. Particle distribution 16 days after release relative to productive areas. t = 0 was 0000, 9 September 1980.

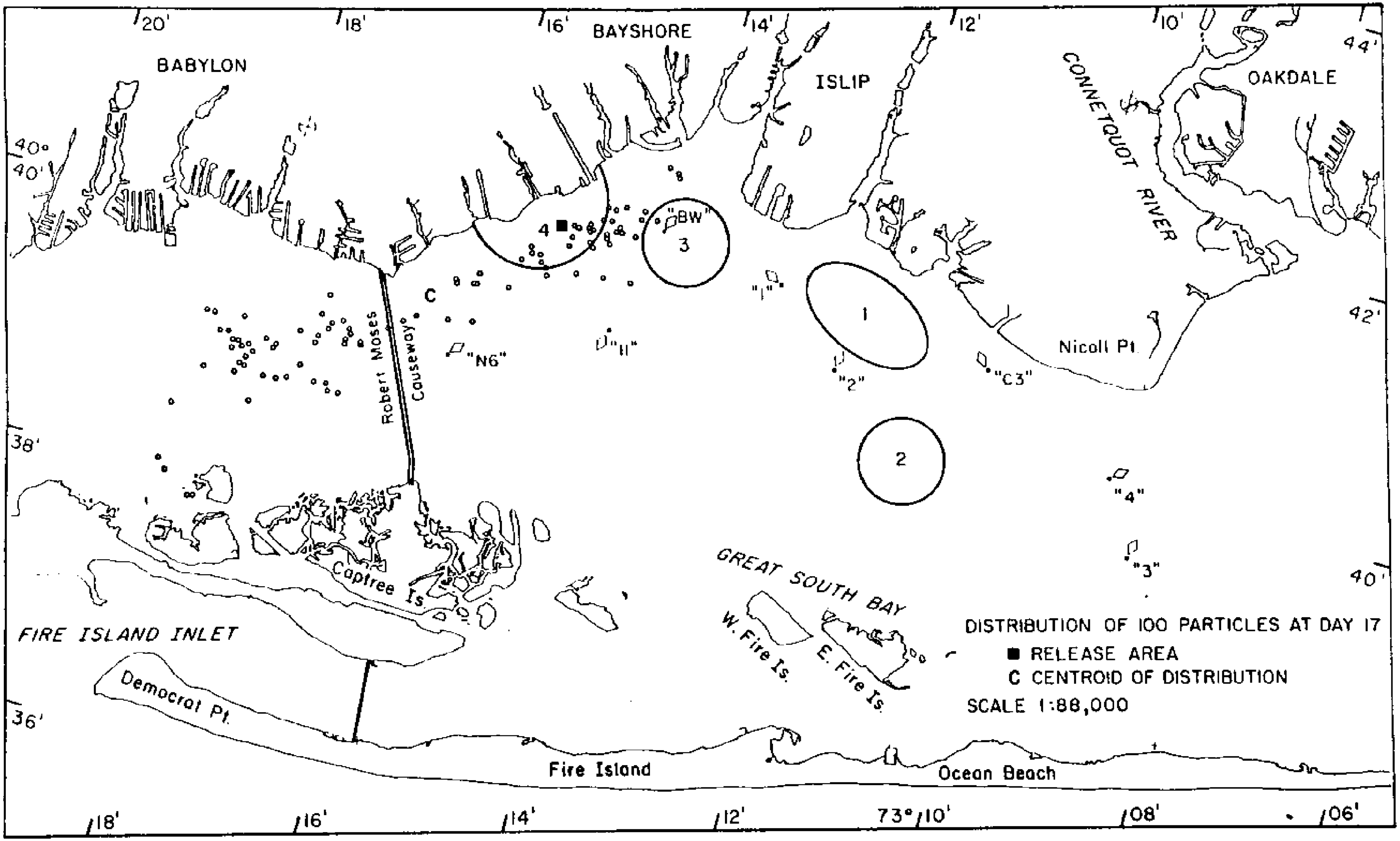


Figure 16. Particle distribution 17 days after release relative to productive areas. t = 0 was 0000, 9 September 1980.

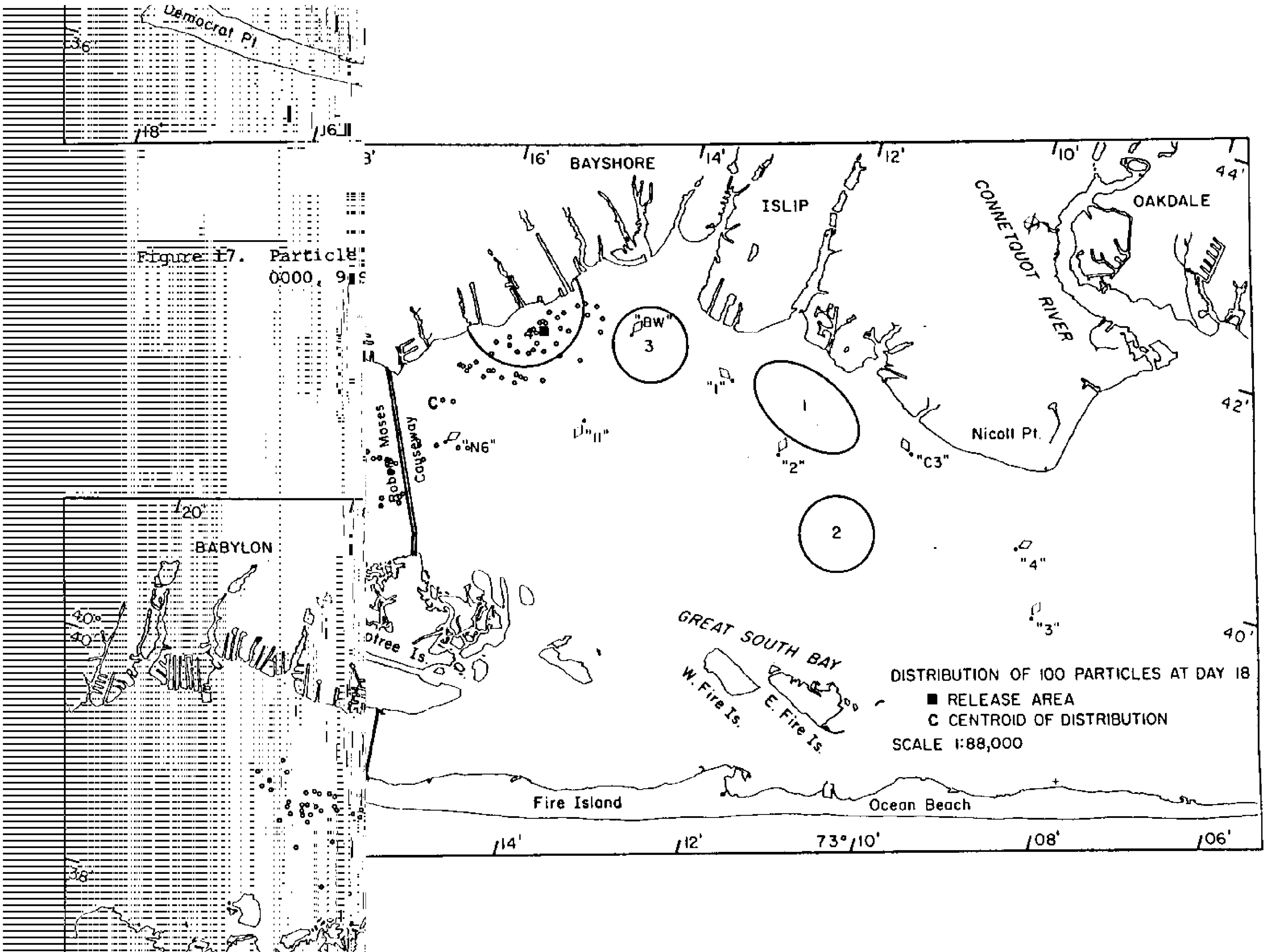


Figure 17. Particle distribution 18 days after release relative to productive areas. t = 0 was 0000, 9 September 1980.

through day 15 followed by a reversal between day 15 and 18 with a substantial number of the particles actually penetrating Babylon waters at day 17. The peak concentration remained near the northshore of GSB for the entire period. The area enclosed within the particle envelope expanded continuously, of course, while elongating in the alongshore direction. The foregoing is consistent with Figure 5 of Wong and Wilson (1983) which shows a wind reversal from southeast to southwest late on day 14 (September 23, 1980).

Brookhaven

As noted previously, the Town of Brookhaven identified 6 areas as productive. Their centroids are shown on Figures 18-21 by a $\boxed{X}$. Figures 18-21 also show the positions of the 100 particles at days 10 through 18 for a release area (■) which maximizes the probability of sets on an area in Patchogue Bay just east of the Patchogue River. The figures show little movement of the centroid of the 100 particles, i.e., the peak concentration between days 10 and 18. However, the envelope grew in a north-south direction as well as spreading out to the east. This easterly spreading of material along the northshore of Patchogue Bay is confirmed by the results of the 1980 dye study. In this study, a release of 123 pounds of Rhodamine WT dye solution was made in GSB in September 1980 midway between Green Harbor on Long Island and Lone Hill on Fire Island. By the 3rd day after release, the patch had spread northeastward into Patchogue Bay. Results on days 8, 10 and 13 show quite clearly the tendency

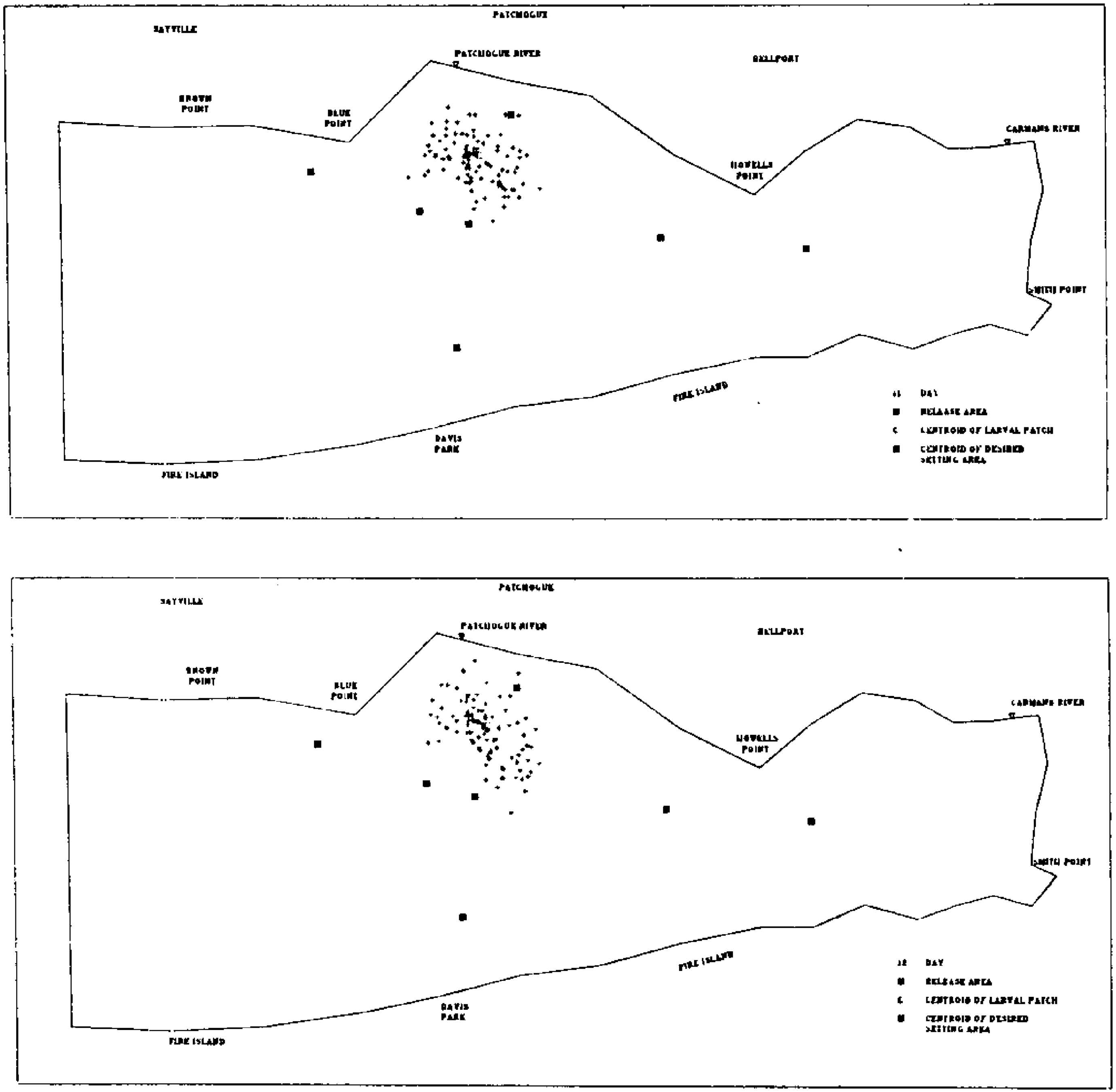


Figure 18. Particle distribution 11 days (upper) and 12 days (lower) after release relative to

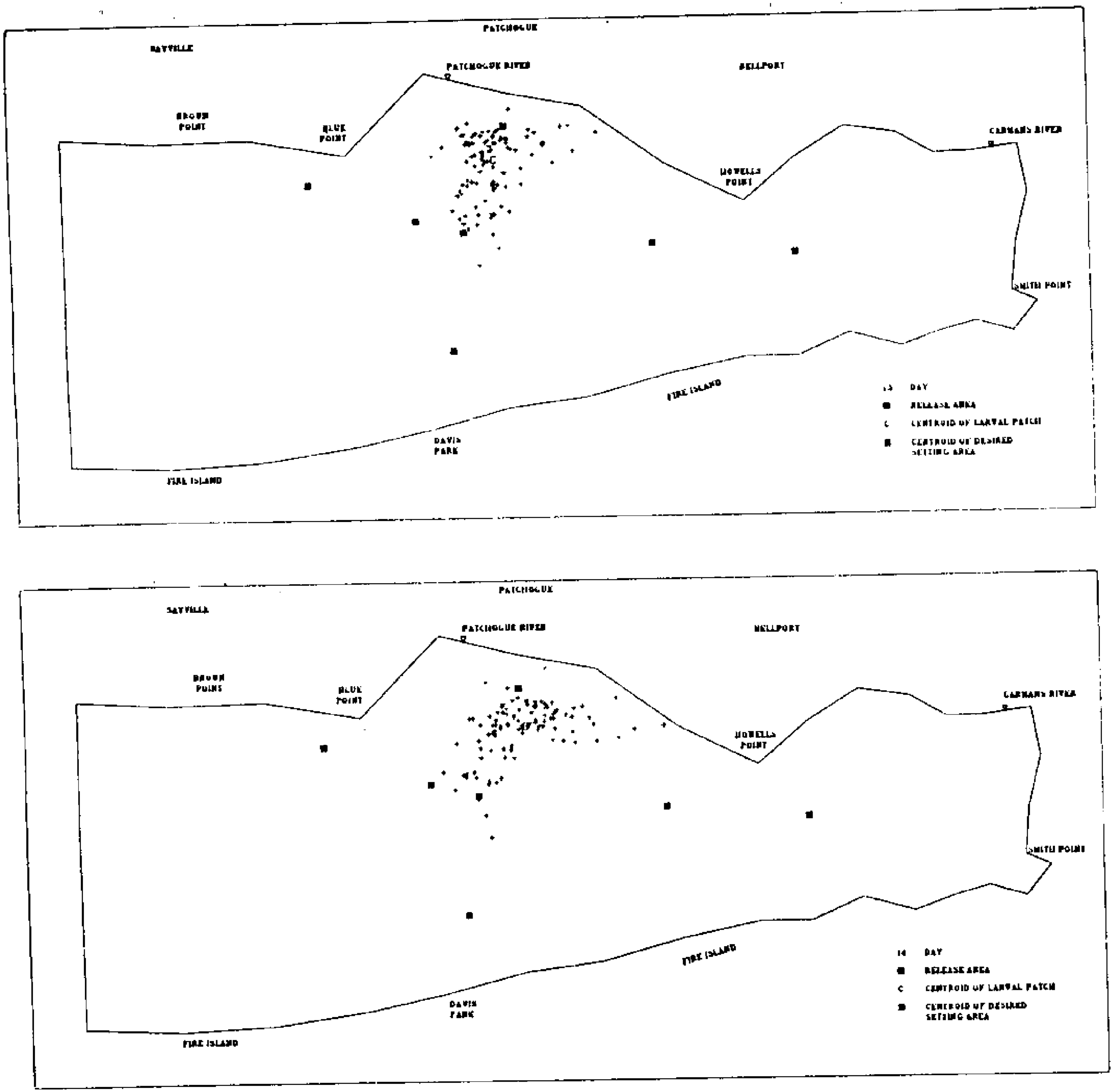


Figure 19. Particle distribution 13 days (upper) and 14 days (lower) after release relative to centroids ($\boxed{X}$) of productive areas. t = 0 was 0000, 9 September 1980.

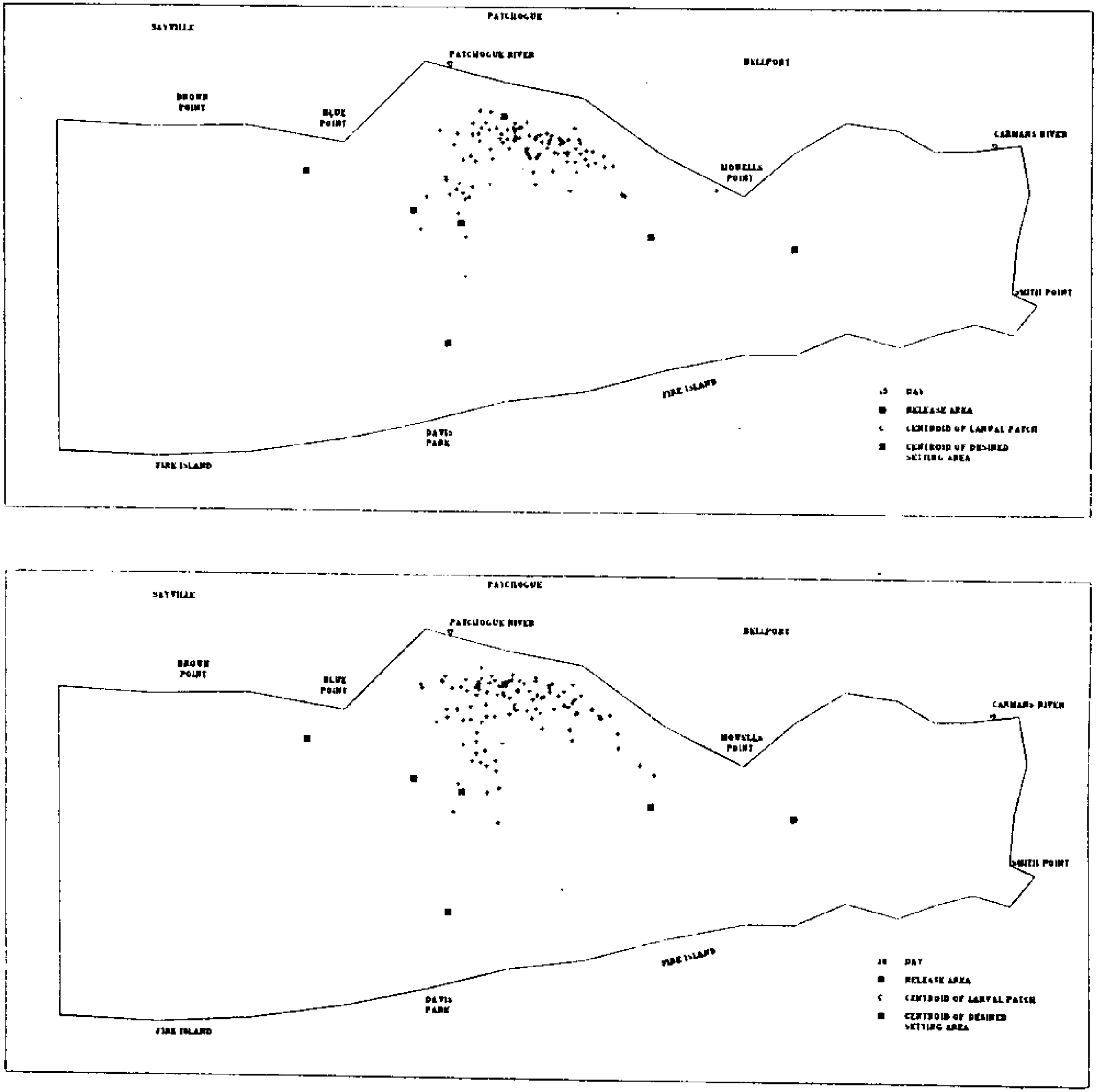


Figure 20. Particle distribution 15 days (upper) and 16 days (lower) after release relative to

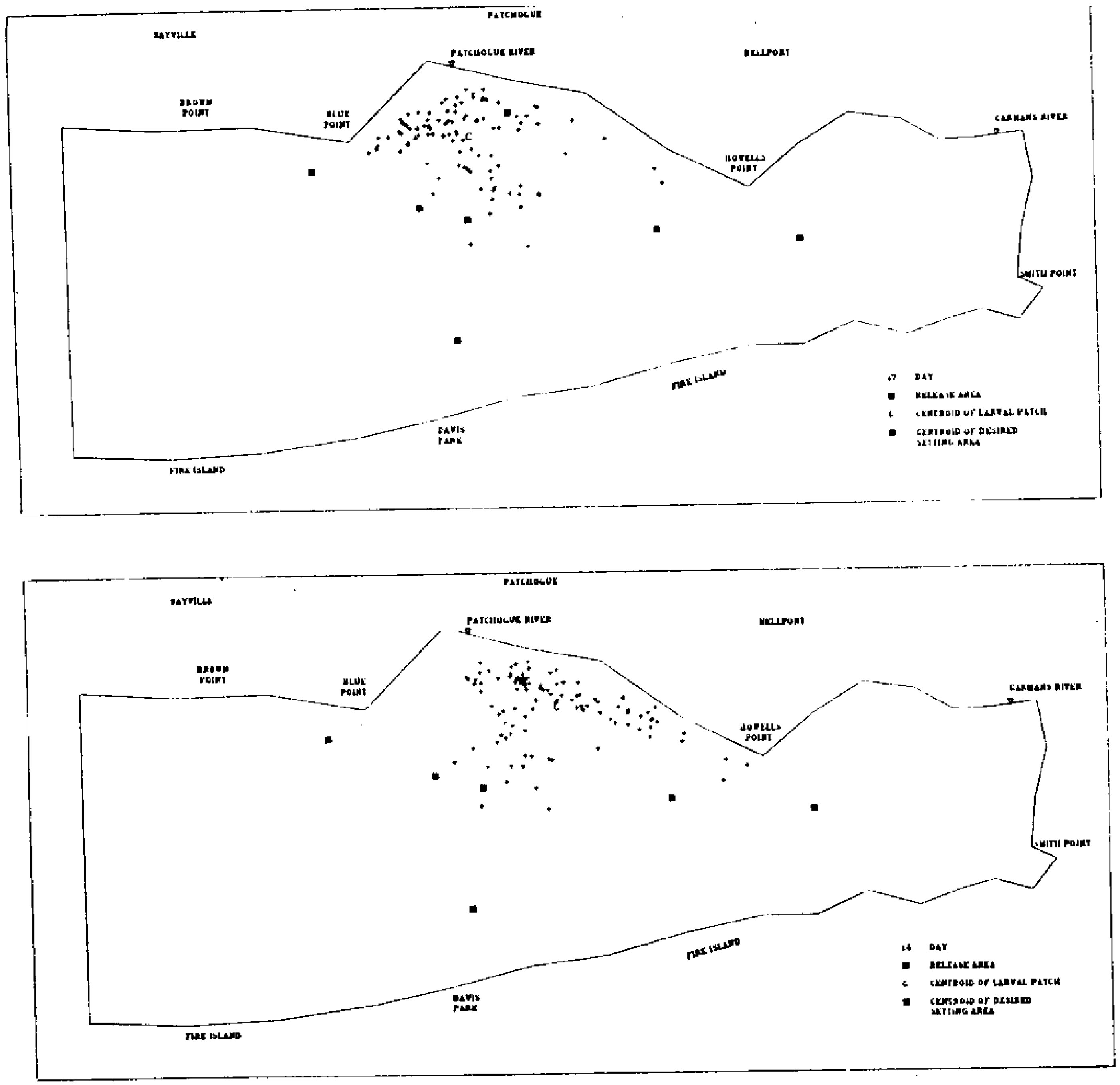


Figure 21. Particle distribution 17 days (upper) and 18 days (lower) after release relative to centroids ($\boxed{X}$) of productive areas. t = 0 was 0000, 9 September 1980.

for waterborne substances to move eastward along the north shore (Figures 5-9, Carter 1981).

Positions of the release areas which maximize the probability of sets on the other 5 productive areas in Brookhaven are not shown but were located and chart[#] scale (1:40,000) results similar to Figures 18-21 provided to the Town of Brookhaven.

Babylon

The situation in Babylon waters is quite different from either Islip or Brookhaven. Recalling the two wind-driven modes of circulation described in a previous section, westerly winds (the predominant summertime condition) cause coastal sea level to drop and strong flows *out* through Fire Island Inlet and *in* from South Oyster Bay. This means there is a vigorous exchange of most of Babylon water with the ocean through Fire Island Inlet. Based on an analysis of 383 labelled particles which were released throughout Babylon waters and then followed advectively for 20 days (step 4 in our rationale), it is clear that most of the area south of the east-west navigational channel[##] participates in this exchange with the area north of the channel[##] sloshing back and forth between either South Oyster Bay and Babylon or Babylon and Islip. Therefore,

---

[#] NOS chart 12352.

[##] The 11 foot channel running westerly from Buoy "1" to Buoy "15" on NOS Chart 12352.

there is no area south of the navigation channel which will, with a high probability, provide sets in Babylon waters since most of this region seems to exchange regularly during summertime conditions with the ocean through Fire Island Inlet on a time scale shorter than the time for setting to commence, i.e., 7-8 days. On the other hand, the area north of the navigation channel will provide good sets in eastern and central Islip between days 16-18 and a late set (days 17-20) in Babylon. This is shown in Figures 22-26 for a brood stock locations just east of Babylon Cove.

Some late sets (16-18 days) from Islip brood stock will also occur in eastern Babylon. See Figures 16 and 18.

Discussion

The computed distributions of the 100 particle releases (Figures 9-26) may be used to estimate the distributions of hard clam larvae as a function of age (step 7) if we take into account the following factors:

i) the mortality of the larvae, and

ii) the absence of vertical velocity shear in the model.

Mortality can be taken into account if we assume that the rate of change of larval population at any time t, because of death, predation, and other unspecified causes (not dilution), is proportional to the population at the same time t. That is

$$\frac{dN_\ell}{dt} = -k_m N_\ell \qquad \text{or} \tag{7}$$

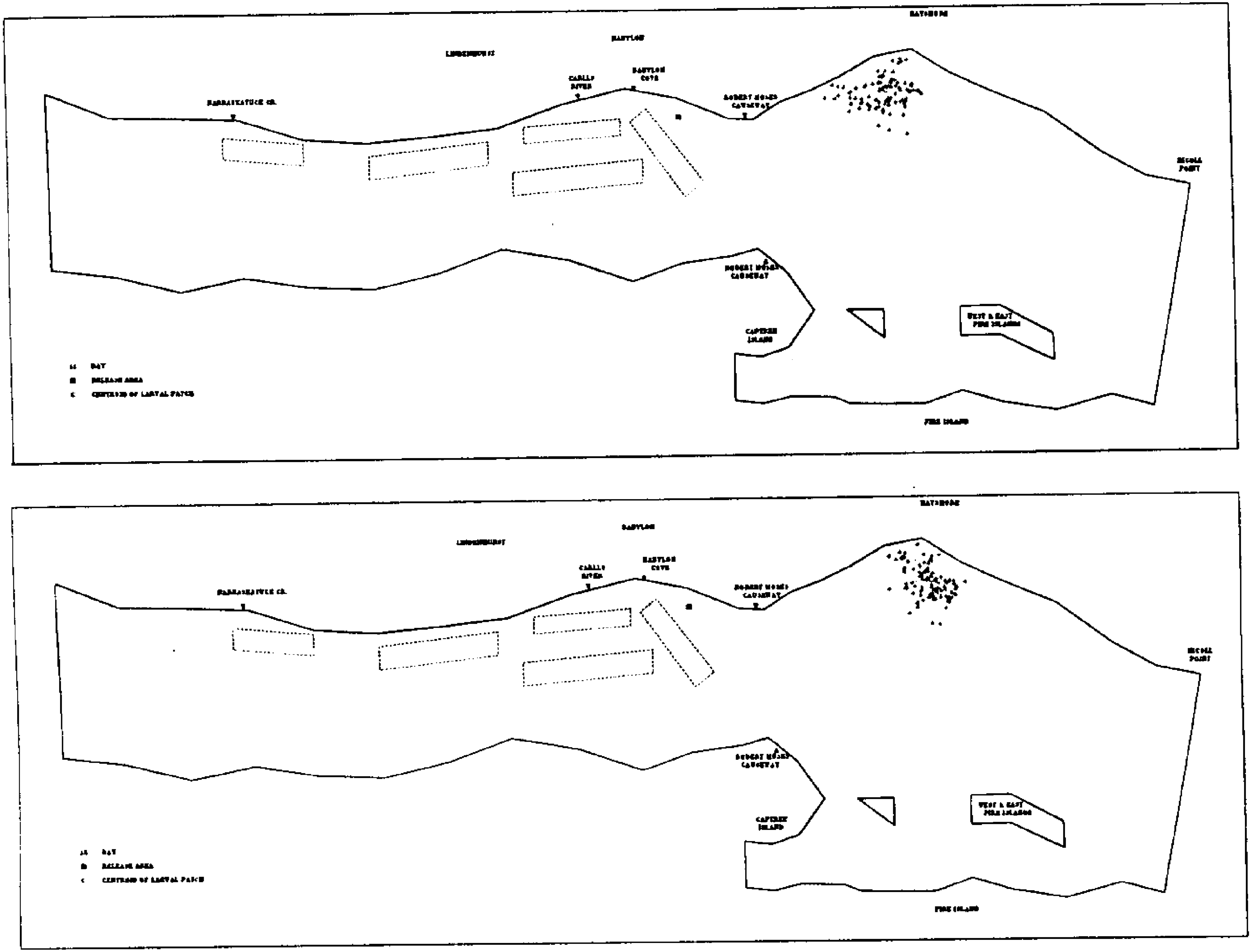


Figure 22. Particle distribution 11 days (upper) and 12 days (lower) after release relative to productive

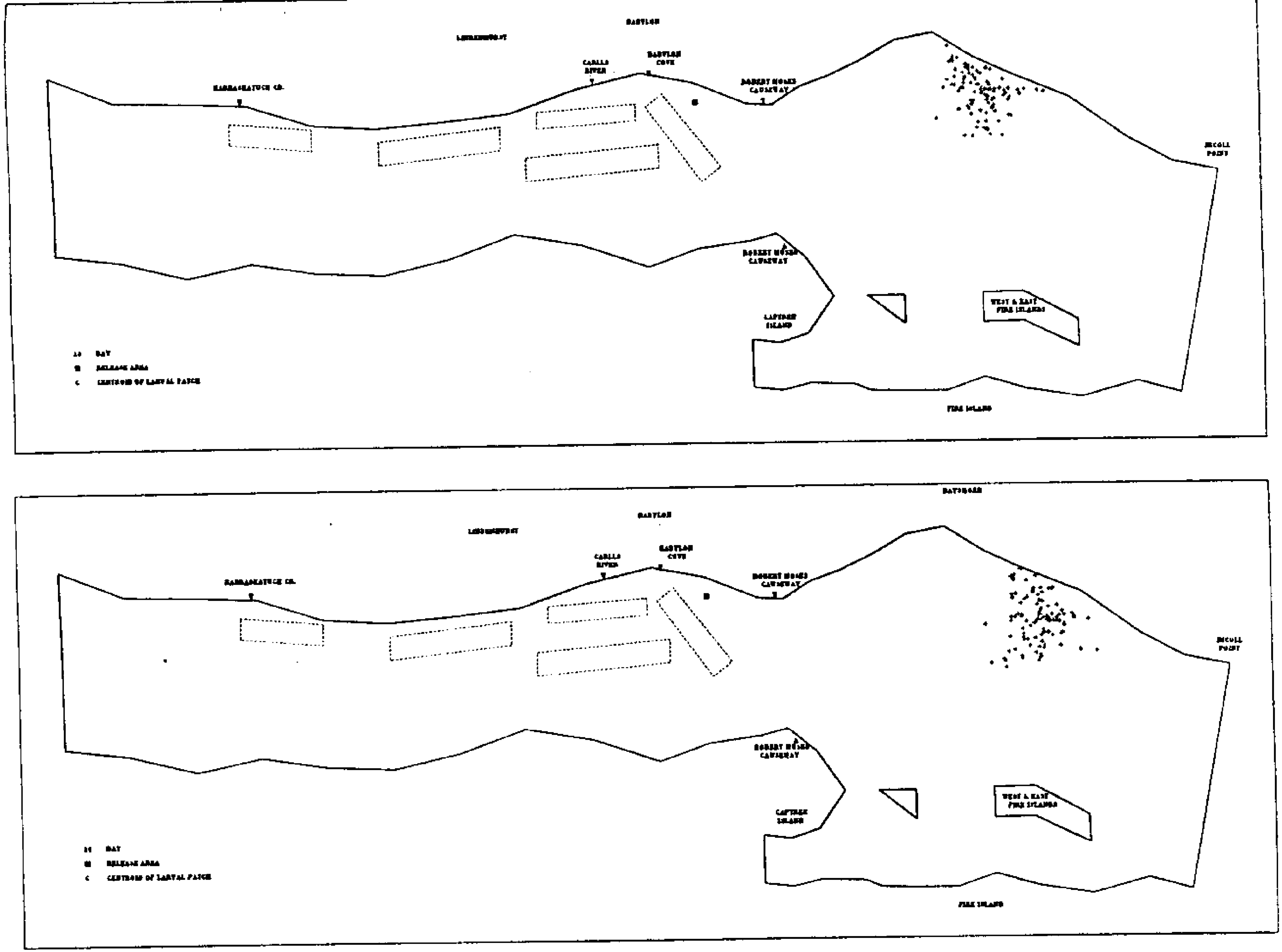


Figure 23. Particle distribution 13 days (upper) and 14 days (lower) after release relative to productive areas (----). t = 0 was 0000, 9 September 1980.

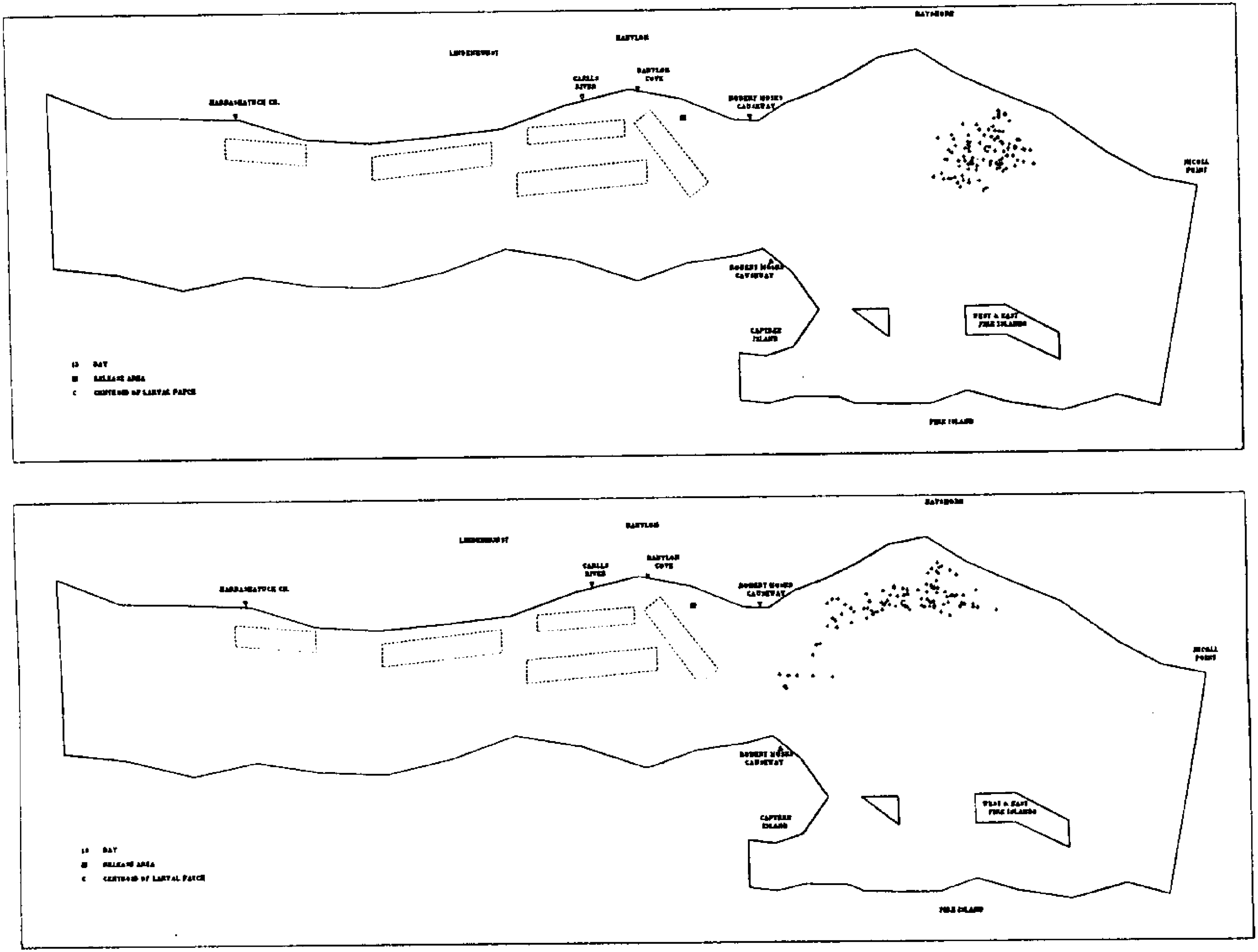


Figure 24. Particle distribution 15 days (upper) and 16 days (lower) after release relative to productive areas (----). t = 0 was 0000, 9 September 1980.

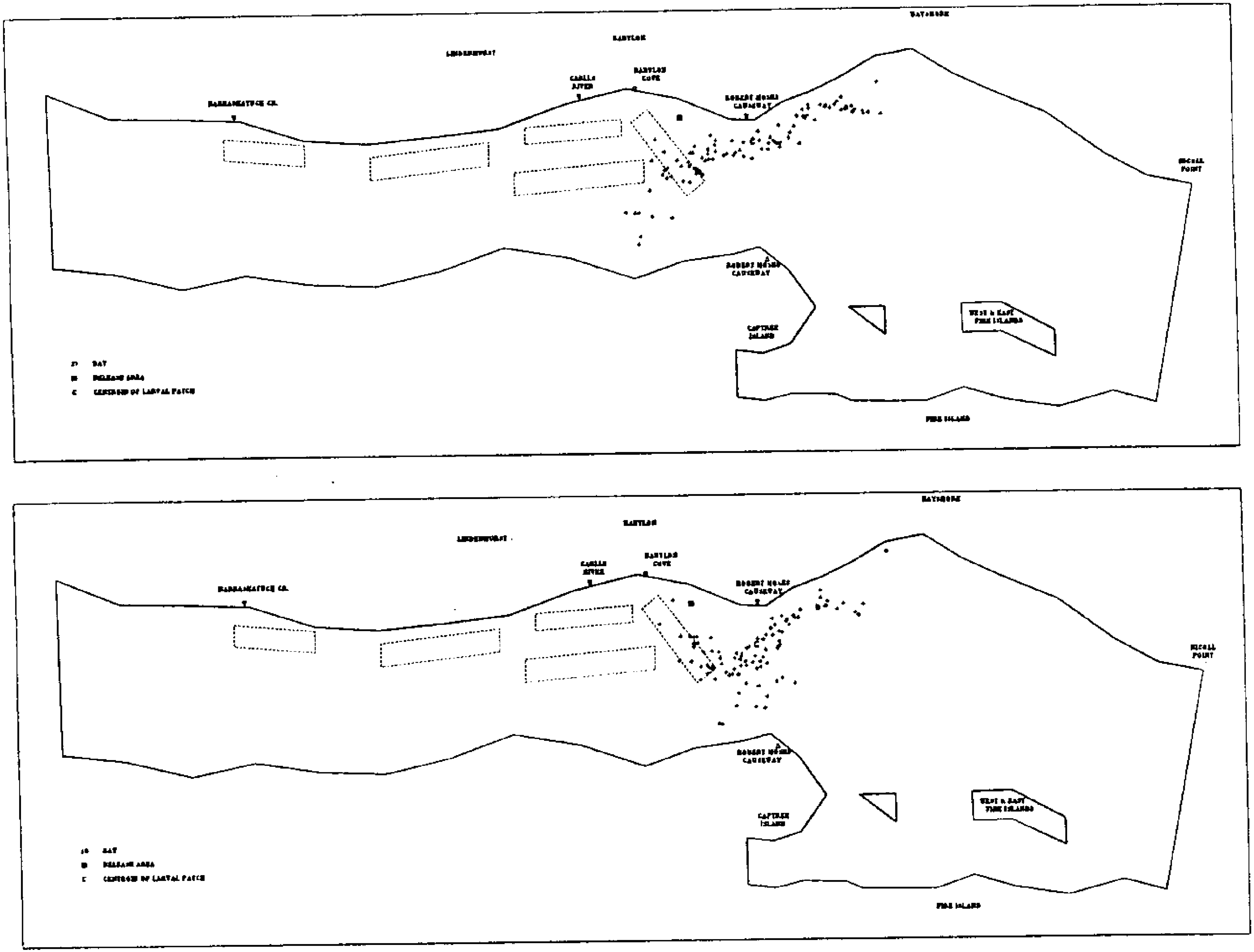


Figure 25. Particle distribution 17 days (upper) and 18 days (lower) after release relative to productive areas (----). t = 0 was 0000, 9 September 1980.

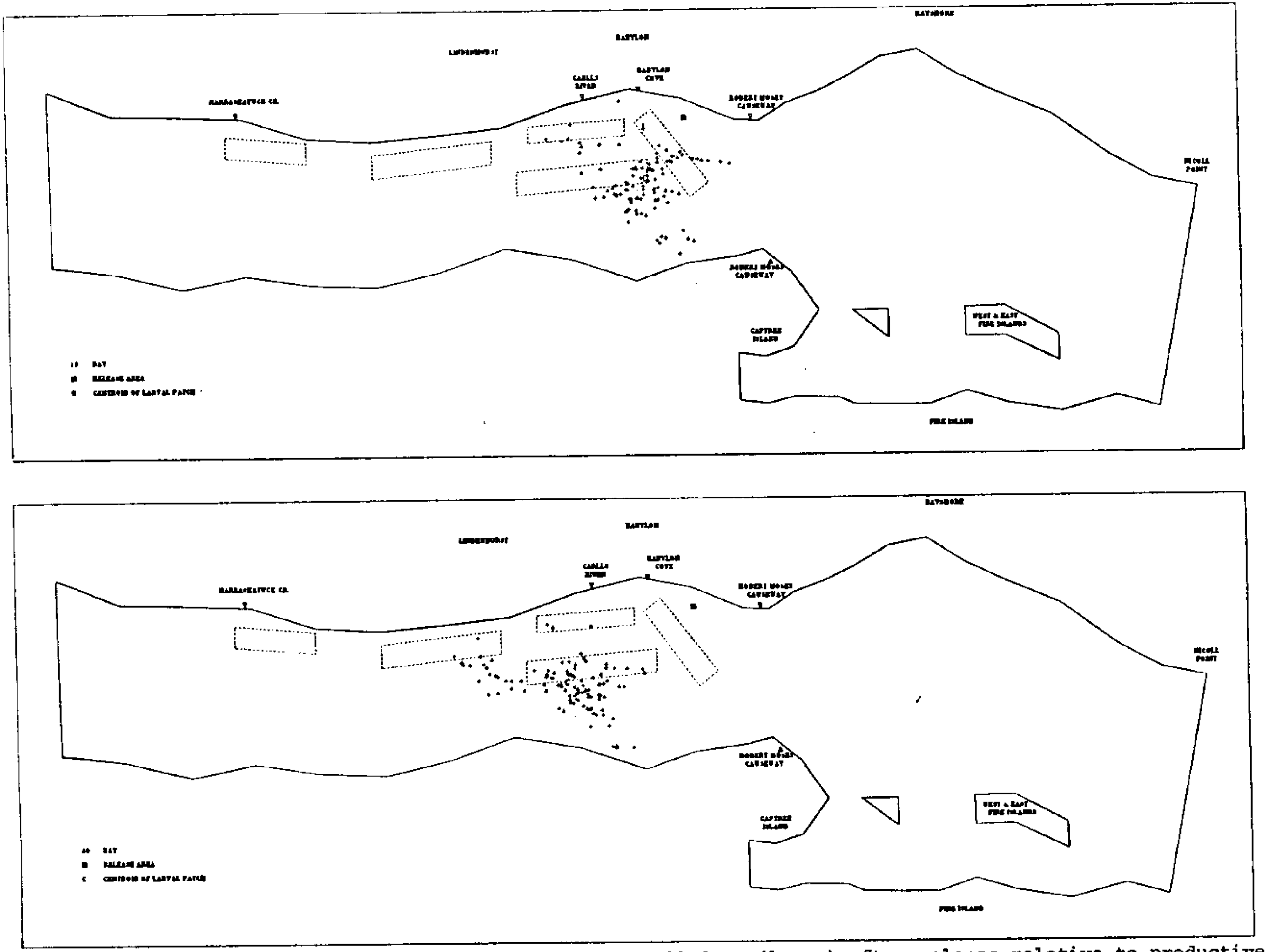


Figure 26. Particle distribution 19 days (upper) and 20 days (lower) after release relative to productive areas (----). t = 0 was 0000, 9 September 1980.

$$N_\ell = N_{\ell,0} \exp(-k_m t) \tag{8}$$

where N_ℓ is the number of hard clam larvae contained in the population at time t and k_m is the fractional rate of change in population per unit time due to death, predation, etc. *but not dilution*. Little is known as to the proper value of k_m. One of us (Carter 1981) estimated its magnitude at 0.758 day^{-1} by reanalyzing data taken in Little Egg Harbor, New Jersey during 1948, 1949, 1950, and 1951 by Carriker (Carriker 1961). This value represents a survival after 18 days of only slightly more than one larvae for every million eggs spawned and fertilized. In the absence of any better information it is the value we will use in the analysis that follows.

As pointed out earlier, our numerical model (CAFE), which was exercised to simulate the velocity field within the Bay (step 1), produces *vertically integrated* horizontal velocities at the nodal points. This means that the enhancement of horizontal diffusion by the combined effect of vertical shear and vertical diffusion has not been included in our larval dispersion model (step 6). These processes are very important in spreading larvae or dye which, unlike drogues, are not constrained to one level. We can estimate the effect of vertical shear and vertical diffusion on our particle clusters, however, from some results contained in Carter and Okubo (1965) and the following.

Let σ_0^2 be the (radially symmetric) horizontal variance associated with the initial distribution of a dye patch. Then the variance σ^2

of a dye patch dispersing from an initial size may be given by

$$\sigma^2(t) = \sigma_0^2 + \sigma_{rc}^2(t) \tag{9}$$

where $\sigma_{rc}^2(t)$ denotes the variance of dye from an initial *point source*. In our case, σ_0^2 is given by

$$\sigma_0^2 = \frac{1}{3}(a^2 + b^2) \tag{10}$$

where $a = b = 75$ m and $\sigma_0^2 = 3750$ m. According to Carter and Okubo (1965), for values of $t > t_c$ where $t_c \approx 3$ hours,

$$\sigma_{rc}^2(t) = \frac{2}{\sqrt{3}} A_y \Omega_y t^2 \quad \text{for drogues} \tag{11}$$

or particles and

$$\sigma_{rc}^2(t) = \frac{2}{\sqrt{3}} Ay(\Omega y^2 + \Omega_z^2 \frac{A_z}{A_y})^{\frac{1}{2}} t^2 \tag{12}$$

for dye or larvae in well-stirred shallow waters. In Equations (11) and (12), A_y and A_z are the eddy diffusivities in the horizontal (069°/249°T) and vertical directions, and Ω_y and Ω_z the horizontal and vertical shears. From Equations (11) and (12) we have

$$\frac{\sigma_{rc}^2 \text{ (larvae or dye)}}{\sigma_{rc}^2 \text{ (particles)}} = (1 + (\frac{\Omega_z}{\Omega_y})^2 \frac{A_z}{A_y})^{\frac{1}{2}} \tag{13}$$

In Great South Bay,

$\Omega_z = 10/300 = 3.33 \times 10^{-2}\ s^{-1}$ (typically),

$\Omega_y = 10^{-5}\ s^{-1}$ (calculated from CAFE model results),

$A_z = 10\ cm^2\ s^{-1}$ (estimated), and

$A_y = 4 \times 10^4\ cm^2\ s^{-1}$ (Carter 1981).

Thus

$$\frac{\sigma^2_{rc}\ (\text{larvae or dye})}{\sigma^2_{rc}\ (\text{particles})} = 50 \qquad (14)$$

We have calculated $\sigma^2_{rc}(t)$ from four of the 100 particle releases, one on the boundary between Babylon and Islip (Δ), one in the area owned by the Blue Points Company (+), and two in Brookhaven waters (X,$\square$). The locations are shown on Figure 1. On Figure 27 we have plotted these calculated values of $\sigma^2_{rc}(t)$ as a function of time together with $\sigma^2_{rc}(t)$ estimated from dye studies conducted in GSB in 1976 and 1980 (Carter 1981). The ratio of the variances is estimated from Figure 27 as 49-63 which agrees reasonably well with Equation (14). The line of slope $t^{2.5}$ passing through the calculated points was drawn by eye.

It is clear from the forgoing that the variances calculated from the four 100 particle releases are low by a factor of ∿ 50 as a result of the absence of vertical shear and vertical diffusion in our model of larval dispersion. Had these processes been included, the particles would have been much more widely spread (the areas within the envelopes would have enclosed areas ∿ 50 times larger than those shown on Figures 9-26). In the analysis that follows, therefore, where σ^2_{rc} is called for we will use the following relation from Carter (1981) vice our calculated variances from the particle releases

$$\sigma^2_{rc} = 0.084\ t^{2.08} \qquad (15)$$

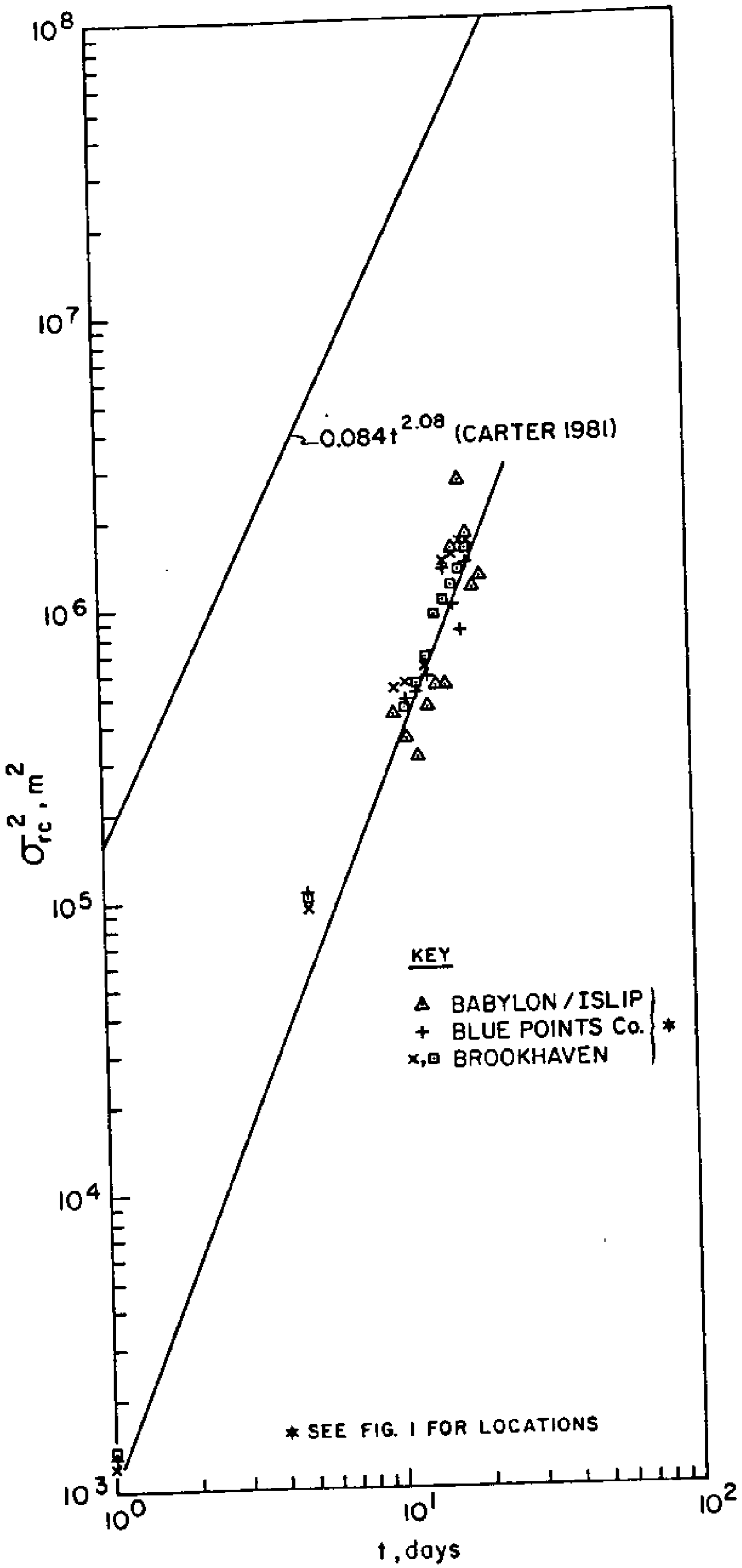


Figure 27. Variance as a function of time or age calculated from four of the 100 particle releases compared to variances estimated from dye studies (Carter 1981). Locations

Horizontal diffusion in the sea cannot, in general, be adequately described by a Fickian-type diffusion model, i.e., diffusion characterized by a constant coefficient of eddy diffusion (the turbulent eddy diffusivity). It is also fair to say that today (1983); there is no theory by which eddy fluxes of a diffusing substance can be predicted *a priori*. Frequently, however, by converting the actual concentration distribution to a radially symmetric equivalent one, the spatial distribution of the concentration, C_d, of a diffusing substance such as dye tracer can be well described by a two-dimensional Gaussian distribution, that is

$$C_d(t,r_e) = \frac{M_d/D}{\pi\sigma_{rc}^{2}(t)} \exp\{-\frac{r_e^{2}}{\sigma_{rc}^{2}(t)}\} \tag{16}$$

where M/D denotes the mass of dry dye released per unit depth, D, and $\sigma_{rc}^{2}(t)$ is the variance of the radially symmetric equivalent distribution whose isolines of concentration enclose areas equal to those of the actual irregular concentration distribution. r_e, the radius of these circular isolines of concentration is, therefore, defined by $\sqrt{area/\pi}$.

For larvae, Equation (16) can be rewritten as

$$C_\ell(t,A_\ell)D = \frac{N_{\ell,0}}{\pi\sigma_{rc}^{2}(t)} \exp\{-\frac{A_\ell}{\pi\sigma_{rc}^{2}(t)} - k_m t\} \tag{17}$$

where $N_{\ell,0}$ is the number of hard clam larvae at $t = 0$ (fertilization), A_ℓ is the area contained within a circular isoline of larval concentration, $C_\ell D$, which is the setting density or number of larvae at some later time t in a water column of depth D and 1 m^2 in cross-sectional area. $N_{\ell,0}$ has been multiplied by the factor exp $(-k_m t)$ to take into account larval mortality in accordance with Equation (8). Equation (17) can now be used to calculate the setting density, $C_\ell D$, and total set, N*, for the 3 model runs shown in the *Results* section (pp. 28-45) if we assign appropriate values of $N_{\ell,0}$, σ_{rc}^2, A_ℓ, and k_m. To illustrate the methodology, we shall consider the brood stocks to consist of 1000 bushels each of chowder-size clams.

We shall assume that $k_m = 0.758$ days^{-1} and that $\sigma_{rc}^2(t)$ is given by Equation (15). Our basis for this has been provided in an earlier section. If we further assume that half of our brood stock clams are female and that their fecundity is 6×10^6 eggs/clam (Bricelj 1979), then

$$N_{\ell,0} = (500)(200)(6 \times 10^6) = 6 \times 10^{11} \text{ larvae}$$

since there are ∿ 200 chowder-size clams per bushel.

Upon drawing envelopes of the particle clusters by eye and planimetering the enclosed areas, we found that the ratios of these areas (labeled A_p) to the values of σ_{rc}^2 (calculated from Equation (15)) were approximately constant. See Table 2. This means, according to Equation (17), that these envelopes do not represent isolines of $C_\ell D$ but rather *constant* values of $C_\ell D/(N_{\ell,0}/\pi\sigma_{rc}^2)$. Accordingly, if we substitute A_p for A_ℓ in Equation (17), values of $C_\ell D$ can be assigned to the envelopes knowing $A_p/\pi\sigma_{rc}^2$, $N_{\ell,0}$ and $\sigma_{rc}^2(t)$. $C_\ell D$ can subsequently be adjusted downward to take mortality into account.

Table 2a

N*, the Total Number of Hard Clam Larvae within the Cluster Envelopes For a Site[a] in Brookhaven Waters as a Function of Time of Set

t, days	A_p, m^2	σ^2_{rc}, m^2 [b]	$A_p/\pi\sigma^2_{rc}$	k_m, day^{-1}	$N_{\ell,0}$	$C_\ell D$ [c]	N^* [d]	Required Survival, % [e]
10	2.90×10^6	1.87×10^7	0.049	0.758	6×10^{11}	4.96	1.47×10^7	0.38
11	3.12×10^6	2.28×10^7	0.044	0.758	6×10^{11}	1.92	6.18×10^6	0.90
12	3.27×10^6	2.74×10^7	0.038	0.758	6×10^{11}	0.75	2.51×10^6	2.22
13	3.95×10^6	3.23×10^7	0.039	0.758	6×10^{11}	0.30	1.21×10^6	4.60
14	4.11×10^6	3.77×10^7	0.035	0.758	6×10^{11}	0.12	5.08×10^5	10.94
15	4.37×10^6	4.35×10^7	0.032	0.758	6×10^{11}	0.05	2.18×10^5	25.50
16	4.51×10^6	4.98×10^7	0.029	0.758	6×10^{11}	0.02	9.27×10^4	59.98
17	6.08×10^6	5.64×10^7	0.034	0.758	6×10^{11}	0.01	5.08×10^4	>100.00
18	5.88×10^6	6.36×10^7	0.029	0.758	6×10^{11}	<0.01	2.04×10^4	>100.00

[a] Site shown in Figs. 9-17

[b] From Eq. (15)

[c] From Eq. (17)

[d] From Eq. (18)

[e] Assuming they grow to littleneck size

Table 2b

N*, the Total Number of Hard Clam Larvae within the Cluster Envelopes For a Site[a] in Babylon Waters as a Function of Time of Set

t, days	A_p, m^2	σ^2_{rc}, m^2 [b]	$A_p/\pi\sigma^2_{rc}$	k_m, day^{-1}	$N_{\ell,0}$	$C_\ell D$ [c]	N^* [d]	Required Survival, % [e]
10	1.50×10^6	1.87×10^7	0.026	0.758	6×10^{11}	5.08	7.72×10^6	0.72
11	1.68×10^6	2.28×10^7	0.023	0.758	6×10^{11}	1.96	3.32×10^6	1.67
12	1.35×10^6	2.74×10^7	0.016	0.758	6×10^{11}	0.77	1.05×10^6	5.30
13	-	-	-	0.758	6×10^{11}	-	-	-
14	2.89×10^6	3.77×10^7	0.024	0.758	6×10^{11}	0.12	3.56×10^5	15.62
15	2.62×10^6	4.35×10^7	0.019	0.758	6×10^{11}	0.05	1.32×10^5	42.12
16	3.07×10^6	4.98×10^7	0.020	0.758	6×10^{11}	0.06	6.30×10^4	88.25
17	3.67×10^6	5.64×10^7	0.021	0.758	6×10^{11}	0.01	3.11×10^4	>100.00
18	-	-	-	0.758	6×10^{11}	-	-	>100.00
19	4.94×10^6	7.11×10^7	0.022	0.758	6×10^{11}	<0.01	7.30×10^3	-
20	3.87×10^6	7.91×10^7	0.016	0.758	6×10^{11}	<0.01	2.42×10^3	-

[a] Site in Figs. 22-26

[b] From Eq. (15)

[c] From Eq. (17)

[d] From Eq. (18)

[e] Assuming they grow to littleneck size

Table 2c

N*, the Total Number of Hard Clam Larvae within the Cluster Envelopes For a Site[a] in Islip Waters as a Function of Time of Set

t, days	A_p, m^2	σ^2_{rc}, m^2 [b]	$A_p/\pi\sigma^2_{rc}$	k_m, day^{-1}	$N_{\ell,0}$	$C_\ell D$ [c]	N^* [d]	Required Survival, % [e]
10	2.94×10^6	1.87×10^7	0.050	0.758	6×10^{11}	4.96	1.53×10^7	0.36
11	3.33×10^6	2.28×10^7	0.046	0.758	6×10^{11}	1.91	6.51×10^6	0.85
12	3.56×10^6	2.74×10^7	0.041	0.758	6×10^{11}	0.75	2.73×10^6	2.04
13	4.35×10^6	3.23×10^7	0.043	0.758	6×10^{11}	0.30	1.32×10^6	4.21
14	4.24×10^6	3.77×10^7	0.036	0.758	6×10^{11}	0.12	5.20×10^5	10.69
15	4.16×10^6	4.35×10^7	0.030	0.758	6×10^{11}	0.05	2.08×10^5	26.73
16	-	-	-	0.758	6×10^{11}	-	-	-
17	-	-	-	0.758	6×10^{11}	-	-	-
18	5.15×10^6	6.36×10^7	0.026	0.758	6×10^{11}	<0.01	1.81×10^4	>100.00

[a] Site shown in Figs. 18-21

[b] From Eq. (15)

[c] From Eq. (17)

[d] From Eq. (18)

[e] Assuming they grow to littleneck size

The total number of larvae, N*, within the envelopes at any setting time t can be estimated from

$$N^* = \int_0^{\sqrt{A_p/\pi}} C_\ell D \; 2\pi r_e dr_e \qquad \text{or} \tag{18}$$

$$N^* = N_{\ell,o} \exp(-k_m t)[1 - \exp(-A_p/\pi\sigma_{rc}^2)] \tag{19}$$

Values of N* are also listed in Table 2.

Based on current market values (November 1983) of $0.05/clam for chowders and $0.18/clam for littlenecks, it is necessary to harvest at least 3.6 littlenecks for every chowder purchased for brood stock for a spawner sanctuary of 1000 bushels to be cost effective. To put it another way, we must harvest, over the life of the brood stock, 5.56×10^4 littlenecks to break even. In the last column of Table 2 we have converted this requirement into percent survival between setting and littleneck size. It should be noted that each year's set does not have to result in 5.56×10^4 littlenecks--only the total over the life of the brood stock.

Unfortunately, the data in Table 2 cannot be directly interpreted in terms of harvest. There are other factors not previously considered which must be taken into account. Most importantly, our analysis has not included post-set predation. It is fair to say that almost all benthic organisms such as blue, spider, mud, hermit, and horseshoe crabs, snails, oyster drills, etc. are post-set predators. The principal predators in GSB on clams between 4.5 and 20 mm are oyster drills and mud crabs according to MacKenzie (1977) whereas adult clams are preyed upon primarily by whelks and moon snails (Green 1978). Moon snails are less abundant in GSB than whelks which are found in greater numbers in the higher salinity waters near Fire Island Inlet. In a declining resource, man must also be considered a serious predator of young adult clams.

The information available suggests that the smallest clams suffer the greatest mortalities; eventually clams become impervious to attack except from whelks. Therefore the densest clam populations should exist where predators are non-existent or scarce. MacKenzie characterized the one site he sampled in north-central GSB as one where the predator to live clam ratio was low (1/3.9). On the other hand, Greene stated that areas of high predator density do exist in GSB. The magnitude of predation can also be inferred from MacKenzie (1977) wherein he reports an 8-fold increase in clam density on a bed in GSB four years after predator reduction by means of a single application of poison. It is clear from our calculation of $C_\ell D$, the setting density in clams m^{-2} ($\leq 5\ m^{-2}$), that areas where the densities of oyster drills and mud crabs are greater than 1 per m^2 are apt to be areas where losses of juvenile clams will be substantial. Little is known, however, of the baywide distribution of these predators. We wonder whether the areas designated as productive by the various towns are coincidentally areas of low predator density.

On a more positive note, we should point out that the particle envelopes contain only 2-5% ($N^*/N_{\ell,o}$ exp(-0.758 t)) of the potential set; the other 95-98% either set outside the envelopes at quite low densities where presumably, some survive to market size or are discharged to the ocean through Fire Island Inlet. For most of GSB, the residence time is greater than the time to set and this latter fate is unimportant; however, portions of Babylon south of the east-west navigation channel exchange with the ocean through the Fire Island Inlet on a time scale of ∿7 days because of the long period ($T = 7$ days), wind-driven , circulation mode described earlier consisting of flow in from South Oyster Bay (directly driven) and out through Fire Island Inlet (Ekman forced) under the influence of westerly winds, the predominant summertime condition (Fig. 3).

It should also be emphasized that the numbers in Table 2 will increase in direct proportion to the number of spawnings. For that reason, spawner sanctuaries should be viewed as long term solutions and not abandoned, if after 1-2 years, no measurable results have emerged.

Several strategies can be employed to improve the dark picture painted thus far. First of all, setting densities can be increased by adding additional spawner stock; the setting density, $C_\ell D$, will increase in direct proportion to the increase in brood stock. 1000 bushels of brood stock should be viewed only as a point of reference for our calculations. Finally, more attention should be paid to predators, their species, their distributions, their densities (both juvenile and adult), *and the potential for reduction through mechanical or other methods*. Suggested devices for predator reduction together with sketches are described in MacKenzie (1979). Since by means of the rationale described herein, the probability of setting on prescribed areas will be maximized, it seems to us that predator reduction has considerable merit as a next step in hard clam management.

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