MARINE SCIENCES RESEARCH CENTER
STATE UNIVERSITY OF NEW YORK
STONY BROOK, NEW YORK 11794-5000

# NUMERICAL MODEL OF LARVAL DISPERSION

Phase I of the
EAST END ALGAL BLOOM PROGRAM

Scott E. Siddall
Mario E. Vieira
Eugenio Gomez-Reyes
Donald W. Pritchard

This report contains results of work sponsored by
The County of Suffolk, New York and
The New York State Department of Environmental Conservation



Special Report 71
Reference 86-8

Approved for distribution

J. R. Schubel, Director

## PREFACE

This report covers the research activities conducted with the support of the County of Suffolk (Agreement number 14-8225-456-01-0001, dated November 15, 1985) and the New York State Department of Environmental Conservation (Cooperative Agreement 09000-0001276, dated February 20, 1986). These studies were undertaken in response to the so-called "brown tide" algal bloom which significantly affected the marine resources of eastern Long Island in 1985. The proposal on which this research was initiated was entitled "East End algal bloom program - Phase I: model of larval drift and algal identification."

## 1.0 Introduction and need

Throughout the summer of 1985, an exceptionally dense phytoplankton bloom persisted in the major bay systems of Long Island, New York. Environmental conditions (e.g., light, temperature, nutrient availability, lack of grazing by herbivores) which may promote the initial development of phytoplankton blooms typically do not persist, and hence most blooms are short-lived phenomena (< 1 month). This bloom was exceptional not only for its duration, but for its maximum cell concentrations (up to 6 million cells · ml-'), its nearly monospecific composition of an extremely small alga (2-3 µm diameter), and its extensive impact on Long Island's living marine resources.

The phytoplankton bloom was first reported in Great South Bay (GSB) during early May, 1985. Aerial surveys conducted during the bloom's peak in mid-July showed that virtually all of Long Island's bays were affected. While the east end bays are connected to the GSB through the canal into Shinnecock Bay and hence into Moriches Bay, there were discontinuities in the bloom's distribution, suggesting that the bloom developed independently in these water bodies. Marine Sciences Research Center (MSRC) scientists measured bloom concentrations as high as 6 million cells · ml-' in GSB and 2 million cells · ml-' in the Peconic-Gardiners Bays. Chlorophyll measurements in surface waters, which do not normally exceed 7-14 µg/l in the Peconic Bay (Hardy, 1976; Bruno *et al.*, 1980; Turner *et al.*, 1983) were as high as 141 µg/l in Little Peconic Bay during the bloom's peak. Particle size frequency distributions of field samples indicated that this small alga (2.0 - 3.2 µm diameter) clearly dominated the phytoplankton in terms of volume and numbers. Cells larger than 4.0 µm comprised an insignificant volume fraction of the phytoplankton in Peconic-Gardiners Bays field samples until the bloom began to receed in late August. Secchi disk readings (a measure of turbidity, and attenuation of light i water column) were as low as 0.5 m throughout east end waters for most

of the summer. The decline of the bloom was gradual (Figure 1) with major reductions in cell concentration associated with two periods of rainfall (July 26 and August 30).

Several commercially important species of shellfish and finfish were affected by the density and persistence of the phytoplankton bloom particularly larvae and adults of the bay scallop, *Argopecten irradians*. This species supports a local fishery worth $0.8-1.3 million annually (New York State Department of Environmental Conservation). The bay scallop is a rapidly growing, short-lived species which spawns only once in its 18-22 month life span. Each year class consists exclusively of progeny from the preceeding year's spawning. Scallop larvae are planktotrophs for their one to three week larval life, after which they settle usually in association with eelgrass beds. During our investigation of the the bloom, we observed and later confirmed a widespread failure of larval recruitment of the bay scallop in the Peconic-Gardiners Estuary, which typically supplies 15-20% of the nation's landings of bay scallops and over 80% of New York's bay scallop catch (Hardy, 1976). As a result, there is a widespread absence of juvenile scallops to maintain stocks for spawning and harvest in 1986 and subsequent years. Efforts to mitigate these effects through resource management include transplanting cultured adult scallops to protected sites ("spawner sanctuaries" - see Long Island Green Seal Committee Bay Scallop Rehabilitation Program).

Adult bay scallop populations were also affected. Appearance of the bloom led to continued sampling of scallop populations which had been extensively sampled throughout 1984. By early August, the mean dry weight of the adductor muscle (the only part of the scallop which is consumed) was 76% lower than it had been at the same time and sampling stations in 1984 (Bricelj, *et al.*, in review).

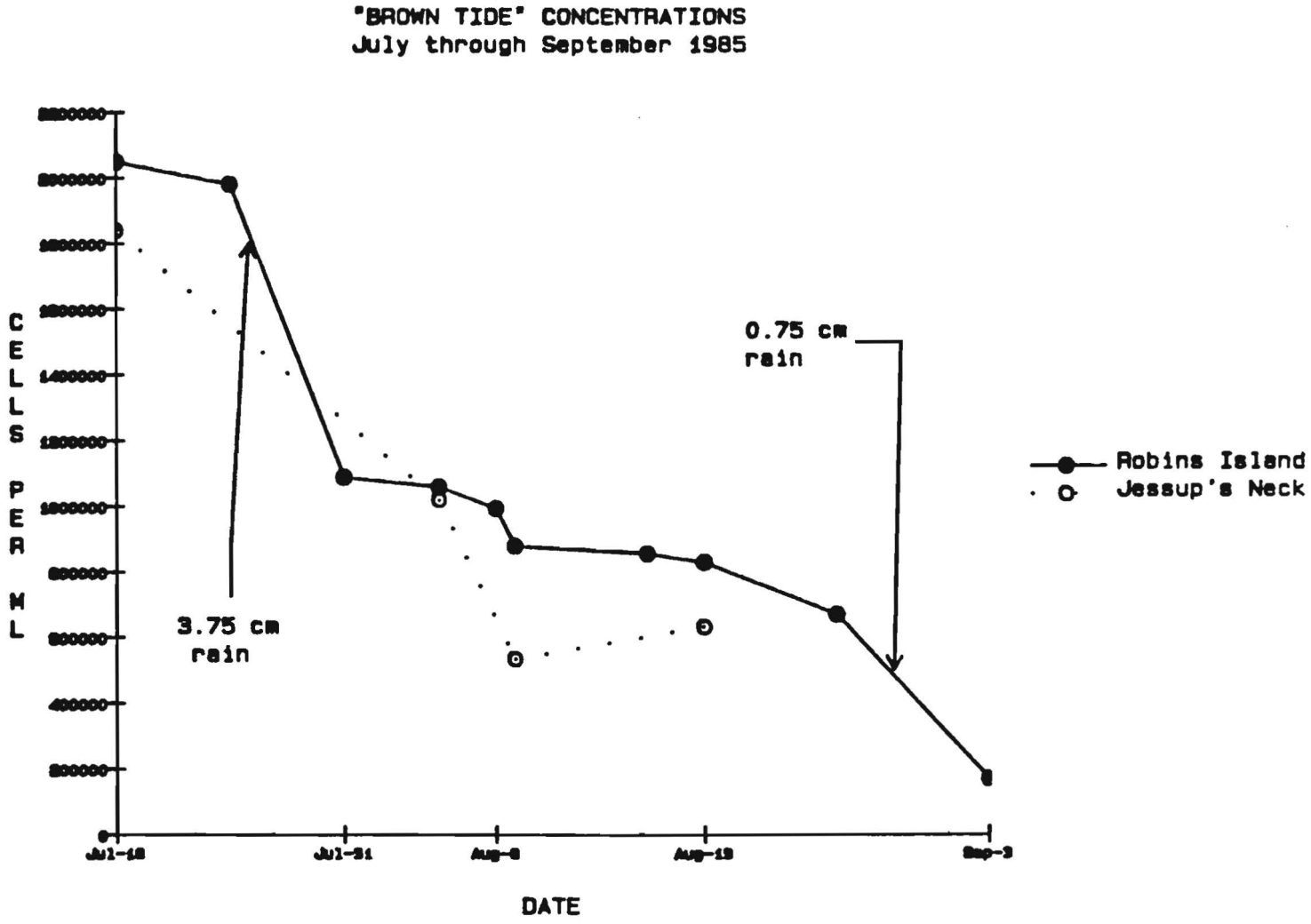


FIGURE 1
Cell concentrations (cells per milliliter) during 1985 bloom.

Commercial fishing strategies changed in response to mortalities in bay scallop populations; the opening of the harvesting season was delayed in many areas to allow the few surviving scallops to build up adductor muscle weights as the diatom bloom receeded and was replaced with a more diverse phytoplankton assemblage. Scallops harvested late in the season had very large adductor muscles and in fact, landings in the scallop fishery for 1985 while low were not significantly different from those of 1983, or several other poor years of the past twenty years (data from NYS Department of Environmental Conservation). The long term economic consequences of the diatom bloom are very likely to be based on the failure of larval recruitment in this opportunistic species whose reproductive strategy is not adapted for maintaining stable population abundances.

Other shellfish and finfish species were affected by the bloom. During the bloom, hard clams (*Mercenaria mercenaria*) landed in the economically important wild fishery (worth $11 million in 1983) and those cultured as 1-8 mm "seed" clams apparently were starving on this unialgal diet in spite of the fact that phytoplankton cell densities in Great South Bay reached 3.5 million cells · ml-' by July. For a two to three week period in July, meat weights of adult hard clams being harvested fell below market standards and could not be sold. Aquaculture production of seed clams had to be relocated to Long Island Sound waters which were not affected by the bloom. Summer flounder (*Paralichthys dentatus*) taken in Long Island's recreational fishery were uniformly smaller and significantly fewer in number during the bloom (NYS Department of Environmental Conservation). Many bay fishermen were forced to fish the

traditional grounds of the offshore trawler fleet, areas outside of GSB and unaffected by the bloom. Additionally, many of the oyster populations being cultivated in the Peconic Estuary died during the last month of the bloom (personal communications, J. Mulhall, Long Island Oyster Farms, Greenport and Chris Smith, Sea Grant Extension).

The transplantation of scallops to spawn in the Peconic-Gardiners Bay Estuary is the sole management effort which has any potential for mitigating the long-term effects of this bloom on the scallop fishery. The Long Island Green Seal Committee Bay Scallop Rehabilitation Program (funded by Suffolk County and the New York State Urban Development Corporation, and conducted with the collaboration of the County, UDC and the New York State Department of Environmental Conservation) focuses on the creation of several protected stocks of hatchery-produced bay scallops in the estuary. The scallops in these spawner sanctuaries could repopulate the scallop beds devastated by the 1985 algal bloom provided the spawner scallops are located in areas where their larvae are not flushed out of the Peconic-Gardiners estuary.

The selection of sites for these spawner sanctuaries is critical. Larvae of the bay scallop spend one to two weeks floating passively in the water during which time they are transported and dispersed throughout the estuary and beyond, often into open ocean waters where they are lost to the fishery. There is no single criterion on which to base the selection of the sites for spawner sanctuaries, and in fact, we know too little about the physical and biological processes which affect recruitment of bivalve larvae to select such sites with known accuracy. Key criteria in the selection of sites include historical productivity of the site, presence or absence of starfish and crab predators, a site's vulnerability to storms and winter damage, and existing commercial activity in the area. This study focuses on yet another criterion for selecting ti sites: an understanding of the detailed circulation patterns witin the

Peconic Bays and Gardiners Bay which lead to the movement of scallop larvae spawned during the peak spawning period of late May and early June.

In 1984, the Marine Sciences Research Center published the results of a study to predict optimum sites for hard clam spawner sanctuaries based on numerical (computer) models of currents and larval dispersion within Great South Bay (Carter, *et al.*, 1984; see Figure 2). This computer model has served as the basis for placement of hard clam broodstock in several town shellfish programs. Furthermore, the Center recently completed a Sea Grant funded project to collect the same types of current and hydrographic information for the Peconic and Gardiners Bays as was used in the Great South Bay model. In fact, part of the justification for this second hydrographic study was the possibility that at some time, the data could be used to estimate larval dispersion in East End waters.

The fundamental objective of this study is to make available the best possible information on the distribution of scallop larvae from proposed spawner sanctuary sites. We have not integrated any of the other important criteria into our conclusions, nor have we prepared any recommendations for specific sites. Data and interpretation of results of this study should be used in conjunction with other biological and socio-political issues in the ultimate selection of sites for spawner sanctuaries.

A secondary objective of this study was to identify the alga which we were able to isolate from field samples taken from Little Peconic Bay waters during the bloom.

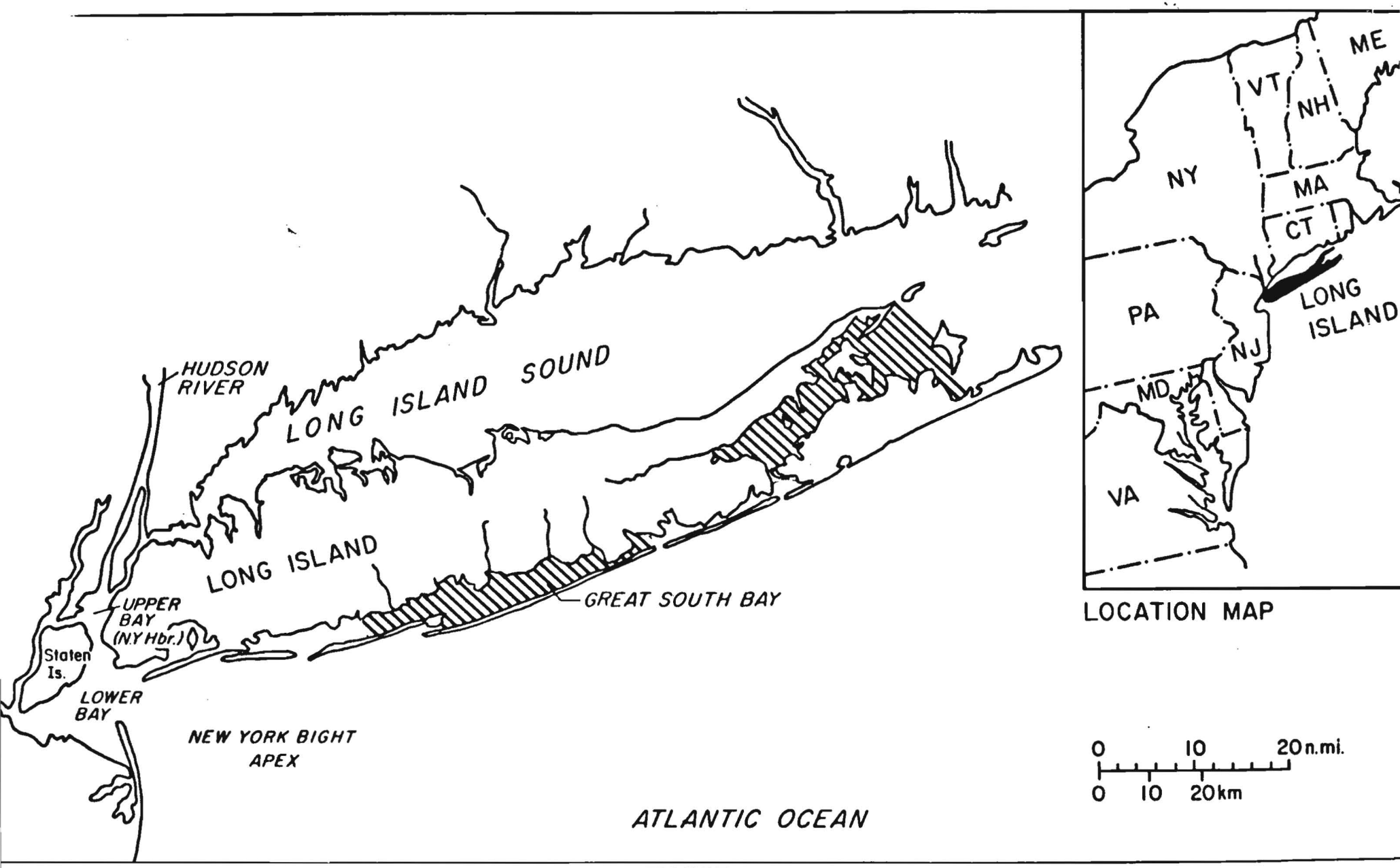


FIGURE 2
LONG ISLAND, NEW YORK
Shading covers study areas of the
Peconic–Gardiners Bays to the east (present study)
and Great South Bay on the Island's south shore (Carter, *et al.*, 1984)

## 1.1 Research objectives

Therefore, the goals of this study were to:

(1) estimate the dispersion of scallop larvae from proposed locations for spawner sanctuaries using a numerical (computer) model calibrated against hydrographic data available for the Peconic-Gardiners Bay Estuary, and

(2) identify the species of alga principally responsible for the bloom.

## 2.0 Identification of alga

The identification of such small nannoplankton is difficult at best, and work to positively identify the species causing the bloom continues. At this time, we are able to draw two conclusions. First, the alga which we isolated on two occasions from two sites in the Peconic-Gardiners Bay Estuary, and now have in culture, was the predominant alga present during the peak of the bloom (late June to early August, 1985). Second, this alga is a diatom, *Minutocellus polymorphus*.

A wide range of research tools were used to come to these conclusions:

(1) Scanning electron microscopy (SEM)

The SEM facilities of the SUNY - Stony Brook Division of Life Sciences, the SUNY - Stony Brook Health Sciences Center and the SEM Laboratory of the

Rosenstiel School of Marine and Atmospheric Sciences (University of Miami, Florida) were used extensively. SEM's provide high magnification views of the exterior surfaces of the alga once the samples have been properly cleaned and prepared for examination. Adequate preparation of the samples was a major obstacle. All algal samples were preserved initially in Lugol's iodine solution and later fixed in gluteraldehyde and osmium tetrozide fixatives. For SEM examination, standard methods of air-drying algal cells, xylene-washing and air-drying the cells or critical point drying the cells (in freon or liquid carbon dioxide) did not produce useful preparations of whole algal cells. The most time-consuming process of freeze-drying droplets of suspended algal cells did produce adequate material for SEM examination of intact, whole cells. Many samples were prepared in this manner and examined; representative examples of the images made of whole algal cells are shown in Figures 3 to 5. The cells of the alga appear to be enveloped in a mucoid sheath which we are continuing to characterize; however the cells do not stand out individually in these preparations. Figure 3 is a freeze-dried preparation of whole cells taken from the field (Jessup's Neck, Little Peconic Bay, July 21). This image should be compared with the representative micrograph of Figure 4 which was prepared from laboratory cultures isolated from Jessup's Neck waters sampled on July 19 (JES-1 isolate). Additionally, Figure 5 illustrates the appearance of the cells isolated and cultured from samples taken offshore of Mattituck in Great Peconic Bay (PECONIC isolate). Figure 6 depicts the increase in phytoplankton diversity in a field sample taken from Northwest Harbor in early September as the bloom receeded.

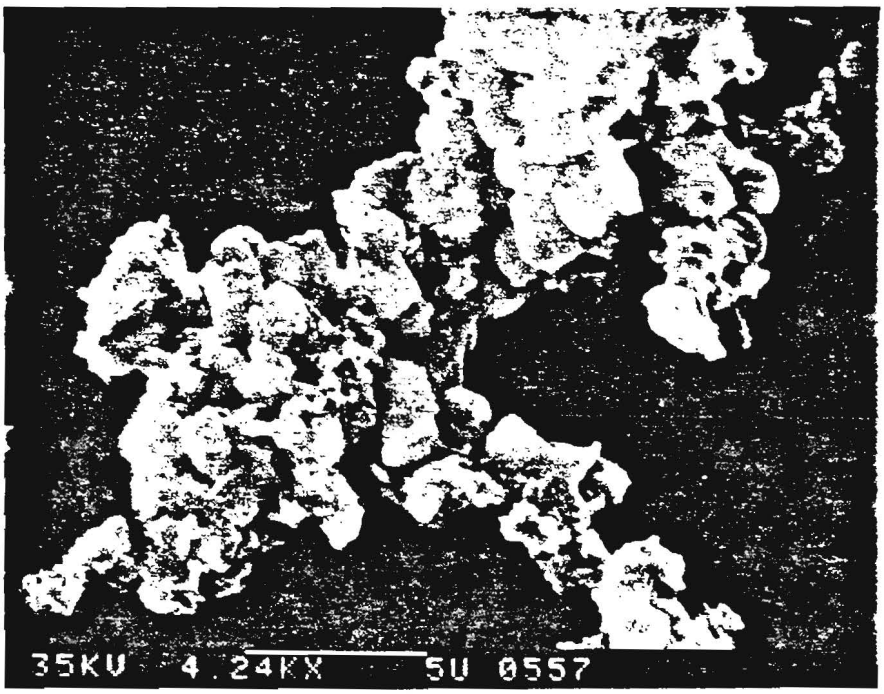


FIGURE 3
SEM (scanning electron micrograph) of field sample
(Jessup's Neck, July 21, 1985)
White bar in lower margin equals 5 microns.

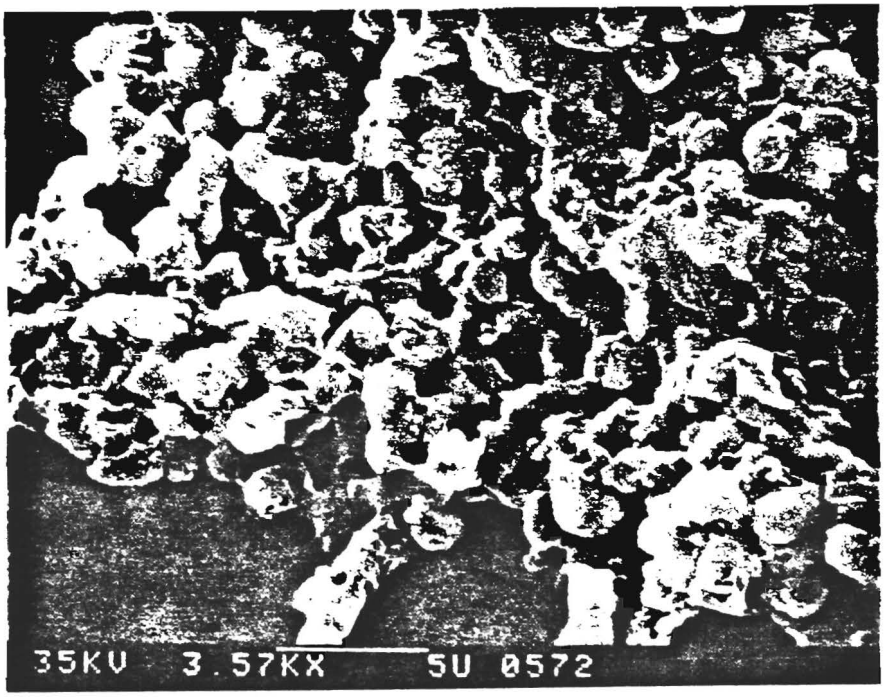


FIGURE 4
SEM of JES–1 isolate (laboratory culture).
White bar in lower margin equals 5 microns.

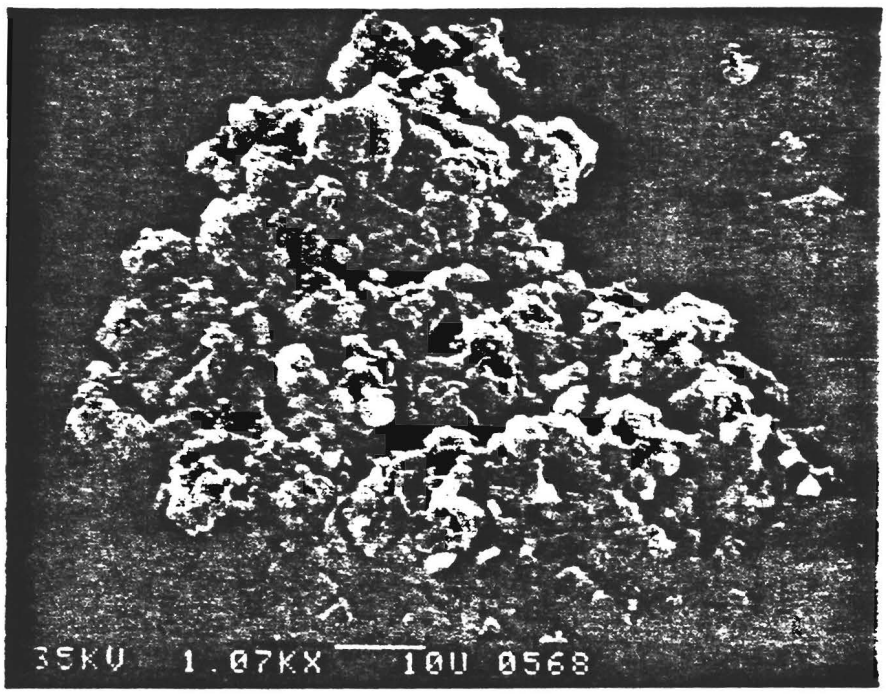


FIGURE 5
SEM of PECONIC isolate (laboratory culture).
White bar in lower margin equals 10 microns.


FIGURE 6
SEM of field sample as bloom declined and phytoplankton diversity increased.
White bar in lower margin equals 50 microns.

(2) Transmission electron microscopy (TEM)

Preserved and fixed algal cells (as above) were imbedded in standard media for thin sectioning (cutting both the imbedding media and cells into slices less than 1 μm thick) and TEM examination. The TEM of the SUNY - Stony Brook Health Sciences Center was used to produce a series of images such as that of Figure 7 which clearly illustrates the pillbox-like silicate test typical of diatoms (the dark, electron-dense band surrounding the cells).

(3) Particle size distributions

The Center's Coulter Counter was used extensively throughout the course of the bloom and later research to estimate the size distribution of algal cells in seawater. Figure 8 presents the results of on such analysis for the seawater samples taken from Jessup's Neck on July 21, 1985. For purposes of comparison, note the scale bars in each SEM micrograph which provide additional indication of the small size of this alga.

(4) Additional algal preparations

It was apparent from the whole cell SEM preparations that the individual structure of these cells could not be observed without removal of the organic (mucoid?) sheath enveloping the cells. Standard methods for diatom preparation (nitric or hydrochloric acid washes) did not remove this organic material. Ultimately, it was found that ethanol effectively removed the sheath without

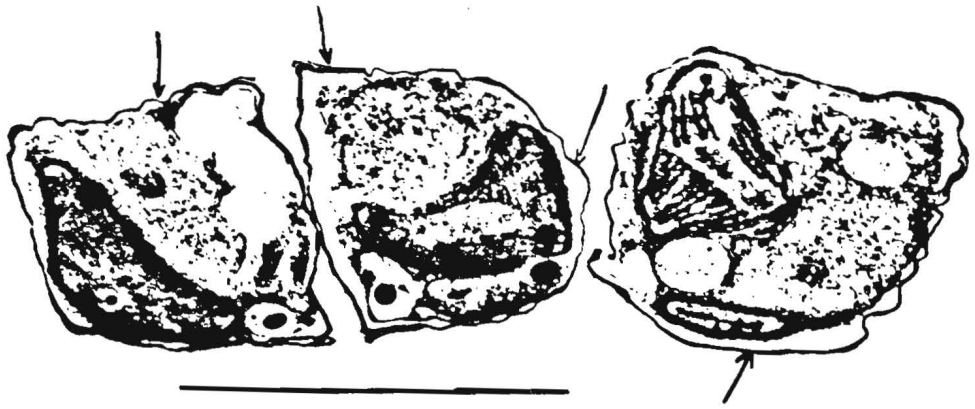

FIGURE 7
TEM (transmission electron micrograph) of thin section of
PECONIC isolate (arrows indiate silcate test surrounding cells.
Solid line equals 5 microns. TEM preparation by J. Mitchell (MSRC)

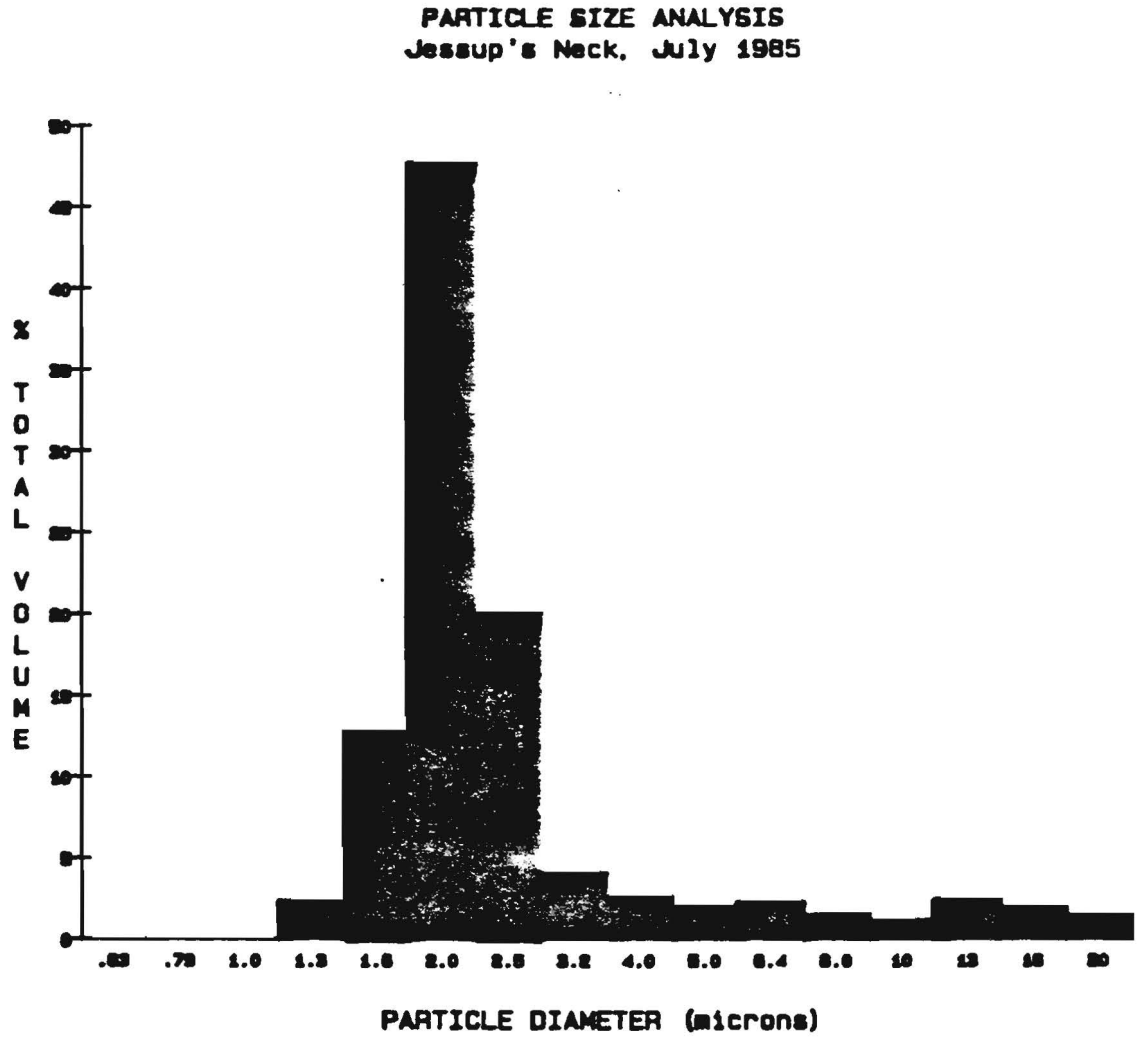


FIGURE 8
Particle size distribution from field sample corresponding to SEM of Figure 3.

apparently damaging the individual cells. An SEM of laboratory-cultured cells freed of the sheath in this manner is shown in Figure 9. Note from the scale bar that the individual cells are approximately 1.5 to 2.5 µm in diameter, in agreement with all earlier observations.

(5) Silicate uptake

Work by a former MSRC graduate student (unpublished work by G. Maillet) demonstrated that the JES-1 isolate removed silicate from seawater samples, and that final cell concentrations in cultures were dependent on initial silicate levels.

Taken together, the scanning and transmission electron microscopy confirms that both the JES-1 and PECONIC isolates are the diatom *Minutocellus polymorphus*. This species had been isolated earlier from the Great South Bay (Hargraves and Guillard, 1974) and the identification of some of our earlier samples had been confirmed by an international authority on the genus, Greta Hasle (University of Oslo, Norway).

The so-called "brown tide" has reappeared in Long Island's coastal bays again in 1986 as this report is being prepared. Preliminary observations of the early phases of the 1986 bloom indicate that a non-diatom, possibly a chrysophyte (tentatively named *Aureococcus anerexiffrens* by J. M. Sieburth, University of Rhode Island), dominates this bloom while *M. polymorphus* is present in increasing numbers. It is possible if not likely that the 1985 and 1986 blooms were very similar in character, and that our isolates of *M. polymorphus* represent the bloom species which succeeded the earlier,


FIGURE 9
SEM of ethanol–cleaned cells of JES–1 isolate.
White bar in lower margin equals 1 micron.
SEM preparation by J. Mitchell (MSRC)

non-diatom species which researchers have been more fortunate to observe in 1986.

## 3.0 Larval dispersion model

The larval dispersion study consists of two separate numerical models. The hydrographic model is based on actual field observations and calculates horizontal currents in the Peconic-Gardiners Estuary. The larval dispersion model tracks particles (larvae) through time as they are transported by the horizontal currents calculated by the first model.

### 3.1 Hydrographic modelling methods

The calculation of the horizontal currents at a suitably dense array of points over the area of the study was executed through a simulation of the Peconics-Gardiners Bay system using a numerical hydrodynamic model, known as HYDRO. This state-of-the-art model is a modified version of a two-dimensional, vertically integrated finite element model originally developed at the University of Rhode Island. HYDRO has been successfully adapted by MSRC to such water bodies as the Moriches Bay-Great South Bay system (Pritchard and DiLorenzo, 1985). One important assumption in the utilization of a vertically averaged model is that the water column is well mixed throughout the study area. This condition has been verified, however, in a separate study of the Peconic-Flanders Bay system now underway (work of M. Vieira, MSRC).

For a given history of sea levels at the ocean entrances to the system, and for a specified waterway geometry, this model numerically simulates both the vertically averaged currents and the sea surface elevations throughout the interior of the waterbody.

Conceptually, this numerical model works by solving the vertically integrated horizontal momentum equations and the equation of continuity at very small time intervals. The model includes pressure forces due to differences in sea level, wind on the water surface, friction on the bottom, Coriolis force and local accelerations. Observed sea surface elevations at each open boundary and the observed temporally varying surface wind stress are used to force the model.

In order to simulate the geometry of the waterway under consideration, the model requires certain geometrical data. The modelled waterway is subdivided into a number of triangular "elements" forming a network or "grid". The corners of the individual triangles are called "nodes". By entering the position and mean low water depth of each node one obtains a reasonable representation of the geometry and bathymetry of the waterbody, provided that a large number of elements is used. However, the greater the number of elements, the smaller the size of the triangles and the greater the computational costs. Thus, a compromise between geometrical detail and operating costs must be achieved. Figure 10 shows the grid utilized for this project.

For this study geometrical and bathymetric data was obtained from the National Ocean Survey (NOS) navigation charts 12358 and 13209.

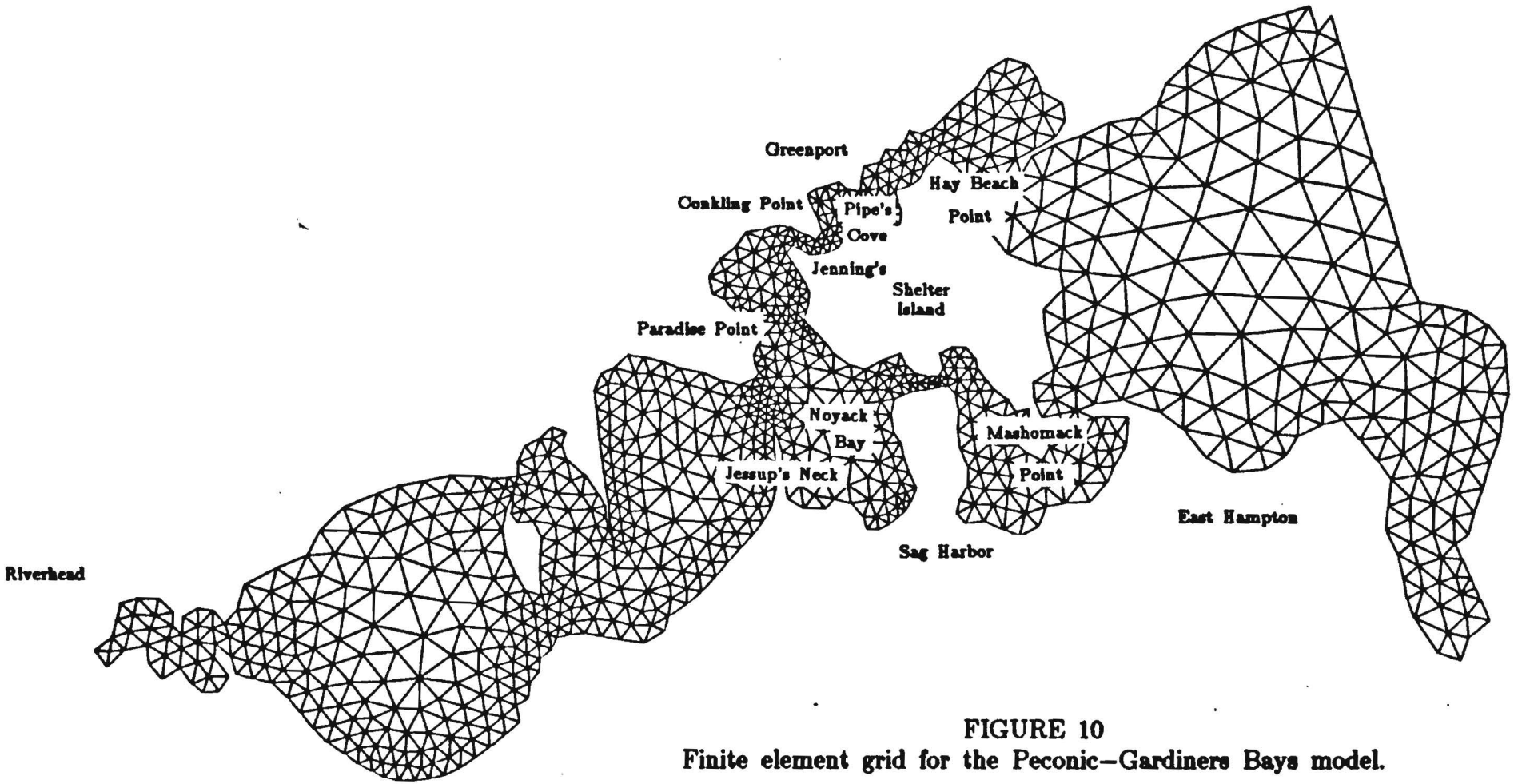


FIGURE 10
Finite element grid for the Peconic–Gardiners Bays model.

Aside from geometrical information, the model requires tidal data at the ocean boundaries of the system. In this study use was made of tidal elevation data collected at Greenport and Sag Harbor with tide gauges installed during 1984 under a study sponsored by the New York Sea Grant Institute. Tidal amplitude and phase information for Plum Gut Harbor and Promised Land were taken from the Tide Tables published by NOS.

Another input parameter was the wind stress over the area; this was extracted from wind speed and direction data provided by the National Weather Service for the Coast Guard meteorological station at Montauk.

Other parameters needed as input to the model are the frictional coefficients, which cannot be determined *a priori*. Consequently, extensive calibration model runs were performed, as described next.

### 3.2 Calibration

It is necessary to verify that the velocities calculated by the model are reasonable; this is done by comparing measured sea levels and currents with model simulations at the exact locations where the measurements were taken. In this calibration process the frictional coefficients are adjusted until an optimal agreement between observed and numerically computed sea levels and currents is obtained.

As mentioned before, observed tidal elevation and current data appropriate for the model calibration were available from a separate study. However, this data was collected only for the Peconic-Flanders Bay waterways, with the exclusion of Gardiners Bay. Furthermore, it became apparent that in order to include the scallop settling areas at Orient Harbor and Northwest Harbor the numerical model study area had to include Gardiners Bay as far out as Gardiners Island, an area for which there is no observed data available either for calibration or to drive the model. This limitation was resolved as follows.

A reduced model, including only the Peconics-Flanders Bays to the west of Shelter Island, was run first. The open boundaries of this model were set at Greenport and at Sag Harbor, for which a whole year of tidal elevation data was available. The model was run for six tidal cycles during the month of March, to coincide with the period for which current meter data was available at different sites within the Peconics-Flanders Bays area. In this manner the reduced model was calibrated and the appropriate frictional coefficients determined. For the calibration runs, the observed, temporally varying wind field on the surface of the Bays was also applied, thus allowing the model to simulate the velocity field within the system generated by the actual combination of tidal motion and subtidal atmospheric forcing; this brings the model to the most realistic conditions for simulation.

The calibration of the reduced model was concluded when a good agreement was obtained between the observed and simulated currents at 14 sites throughout the study area and tidal elevations at two locations inside.

Next the model was extended to its full dimensions, *i.e.*, to Plum Island and Gardiners Island. Tidal elevations were now needed to drive the full model at the three open boundaries. Based upon the information on mean tidal range and phase difference extracted from the Tide Tables for Plum Gut Harbor and Promised Land, the time series of tidal elevation at Greenport and Sag Harbor were extrapolated respectively to the open boundaries at Orient Point - Plum Island, Plum Island - Gardiners Island and Gardiners Island - Promised Land. These having become the driving conditions at the boundaries, the full model was now run and adjusted until the simulated tidal elevations at Greenport and Sag Harbor matched the observed data at those locations, *i.e.*, the very same that had previously driven the reduced model. In this manner the calibration of the full model was assured.

### 3.3 Dispersion Modelling

Larval dispersion in the study area was simulated by assigning advective and diffusive velocities to a large number of particles and then tracking these particles in time. At time $T_o$ the particles are located within each of the three areas designated as being the settling areas. The HYDRO model was run for 14 days, utilizing the tidal data from 21 May to 4 June, 1984, thus obtaining the advective velocity field at the nodes of the grid at every time step (15 seconds) during that period of time. These velocity fields are archived, allowing the velocity at any point within the grid in which each particle may find itself at any time to be computed by simple spatial interpolation.

Since the initial position of each particle is known at time $T_o$, as well as the velocity of the current at that place, by multiplying the time step $\Delta t$ by the velocity, the position of the particle at time $T_o + \Delta t$ is obtained. Once the new position is determined, a new advective velocity is interpolated from the archived velocity field at time $T_o + \Delta t$ and the process repeated to transport the particle from time $T_o + \Delta t$ to $T_o + 2\Delta t$. This procedure is carried on for 14 days, transporting the cluster of particles forward in time, thus simulating the advective larval dispersive processes within the Bay.

In order to realistically simulate the complete larval dispersive mechanism, however, one must also account for the turbulent diffusive processes that affect waterborne particles. This is done by applying to each particle in a cluster an additional small, random velocity numerically generated through the use of the Markov-chain model developed by Awaji (1982), and then tracing the spread of the particle cluster with time. By applying these advective and diffusive velocities at each time step to each and every particle of a cluster, representing a simultaneous release of larvae at a location, the particles are transported forward in time thus simulating the larval dispersion process within the system.

These are the fundamental concepts involved in this part of the study. The computational details and the specifics of the FORTRAN computer programs are quite complex and need not be discussed here. The data and programs of this study have been archived and are available for inspection at the Marine Sciences Research Center.

### 3.4 Sensitivity analysis

An effort was made to assess the possible effect of the phase of the astronomical tide at the time of release. Accordingly, the simulation was done for clusters released at the two most critical stages of the tide, as far as dispersion is concerned: slack water before flood and slack water before ebb.

The sensitivity of dispersion to release time will be implicit in the results from running the complete larval dispersion model and is discussed below.

### 3.5 Biological Assumptions

The principal biological assumptions made for this simulation of larval drift are as follows:

(1) Dispersion of larvae is based on a two-dimensional model of current velocities. There is no vertical component in the model. Bivalve larvae are capable of responding to several environmental stimuli (light, salinity, gravity) by moving up and down in the water column, that dimension which these models do not take into consideration. Buoyancy of bivalve larvae, which may also affect their position in the water column, may also vary as the larvae develop. Taken together, it would appear that this model cannot realistically model the dispersion of larvae if there is any stratification in the waters of

the estuary; however this is a well mixed system which is adequately modeled in two dimensions. In effect, regardless of how or when larvae effect their vertical distribution in the water column, this two-dimensional model is appropriate for the Peconic estuary.

(2) Adult scallops are assumed to spawn as ambient seawater temperatures rise (late May to late June). Because the model of larval dispersion tracks batches of particles (larvae), it is necessary to assume that the larvae being tracked are "released" at specific times. In reality, gametes are shed continuously over a period of many hours; however the computational costs of following such a "plume" of larvae would have been excessive. Also, for purposes of this model, little new information would have been gained over a modelling approach where batches of larvae were "released" at specific times. Therefore, we chose to follow particles (larvae) released at two points during the course of a tidal cycle (12.4 hrs): at slack water before flood and at slack water before ebb. For purposes of these calculations, it is assumed that spawning began on May 21, mid-way through the second half of May, when ambient seawater temperatures may have been sufficiently warm to stimulate spawning. The outcome of the model would not have been materially affected by basing the circulation patterns on tides characteristics cf June rather than late May.

(3) Hatchery-produced scallop seed will be planted in October, 1986, for spawning in the Spring of 1987. To more realistically model the dispersion of larvae in 1987, it would be necessary to calculate features of the tidal cycle for May 21, 1987 which will differ from those of May 21, 1986, or any other day in late May or early June. These are extremely expensive and time-consuming

calculations and in view of the fact that the differences in tidal characteristics are small, the model is based on "typical" May-June tidal cycles rather than tidal cycles computed for specific dates.

(4) The model of current velocities is based on tidal forcing and does not include the far less predictable effects of meteorological events. Storms of varying magnitude could approach at different times in the larval dispersal period and from different directions, all having very different effects on the outcome of the model. In any event, the purpose of the study is to estimate larval dispersion during a "typical" two week period in late May, and there is no rationale for including specific storm effects in this estimate.

(5) Larvae are assumed to be competent to settle and metamorphose after 8-14 days in the plankton. This estimate is based on time to reach competency in a hatchery situation, and does not account for the possible (and unknown) effects of low or patchy phytoplankton (food) distribution which may accelerate or slow growth and development to this stage.

(6) In this application of the dispersion model, we are principally concerned with locations of broodstock and sites of recruitment, not relative or absolute numbers of larvae surviving to metamorphosis. Therefore, no estimates of daily mortality rates are incorporated into the discussion of numbers of competent larvae arriving at a site.

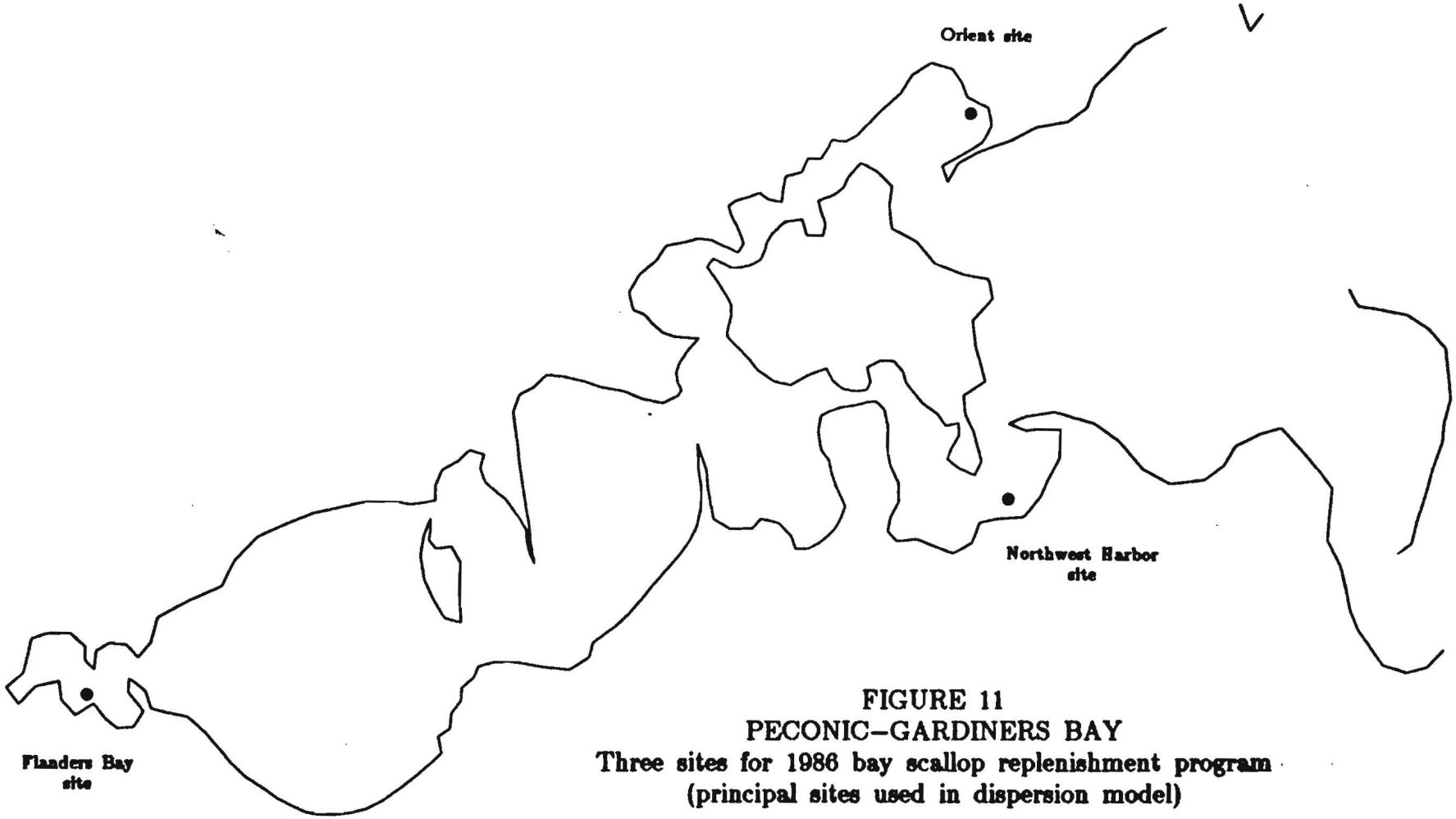


FIGURE 11
PECONIC–GARDINERS BAY
Three sites for 1986 bay scallop replenishment program
(principal sites used in dispersion model)

## 3.6 Results

### 3.6.1 Forecasting settlement from adults at three principal sites

The three principal release points which we considered in this study had been identified by the Long Island Green Seal Committee Bay Scallop Rehabilitation Program (oral and written presentations at the December 9, 1985, meeting at DEC offices, Stony Brook). For purposes of this report, we will refer to these sites as Flanders Bay, Orient Harbor and Northwest Harbor (see Figure 11). At each location, a five acre circle was considered to be the release area (corresponding to the 1.25 acre sanctuary site plus surrounding 3.75 acre buffer zone as specified by the Green Seal Program) from which 100 particles (larvae) were moved forward in time for 14 days with both advective and diffusive velocities.

The releases were assumed to take place on May 21, and as noted earlier, at leach location two separate releases were simulated: one at slack water before ebb (SBE) and another at slack water before flood (SBF). The position of each individual particle was calculated every 80 seconds for 14 days until June 4, using the velocity field obtained from the hydrodynamic model.

The results from exercising the complete larval dispersion model are presented as a series of charts (Figures 12 through 20) which show the position of each particle for each release at the end of 4, 8, 10, 12 and 14 days.

The distribution of the particles at day 4 is shown at SBF for the release at slack water before ebb (thus depicting maximum displacement seaward). The distribution of particles at days 8, 10 and 12 are shown at SBF for the release at SBE (maximum displacement seaward).

Figure 12 shows that 4 days after release, the clusters of particles have dispersed a good amount; at the end of flood, particles have been advected as far as Greenport in the north channel and close to Sag Harbor in the south channel. At the end of ebb (Figure 13), a significant percentage of the particles has been lost to Gardiners Bay from the Orient Harbor site, while in the south they are still retained in Northwest Harbor. At Flanders Bay, dispersion has begun to spread the cluster, but even at the end of ebb (Figure 13), no appreciable number of particles have been lost to Great Peconic Bay.

Figure 14 shows the distributions at SBF after 8 days. The progression of the particles into and out of the north and south channels is clear, as is the increased spread of the clusters. The loss of particles from the Orient Harbor release to Gardiners Bay is still substantial, as is now the loss from Flanders to Great Peconic Bay.

Figure 15 illustrates the situation at 10 days. Particles have now dispersed throughout both channels and Flanders Bay, and there is still advection into Gardiners and Great Peconic Bays. At 12 days (Figure 16), the dispersive trend although decreased, is still apparent at the three sites: particles are being advected toward Shelter Island Sound, Gardiners Bay and Great Peconic Bay.

The results for day 14 are shown in more detail (Figures 17, 18, 19 and 20). First we compare the situation at slack water before ebb for the two different

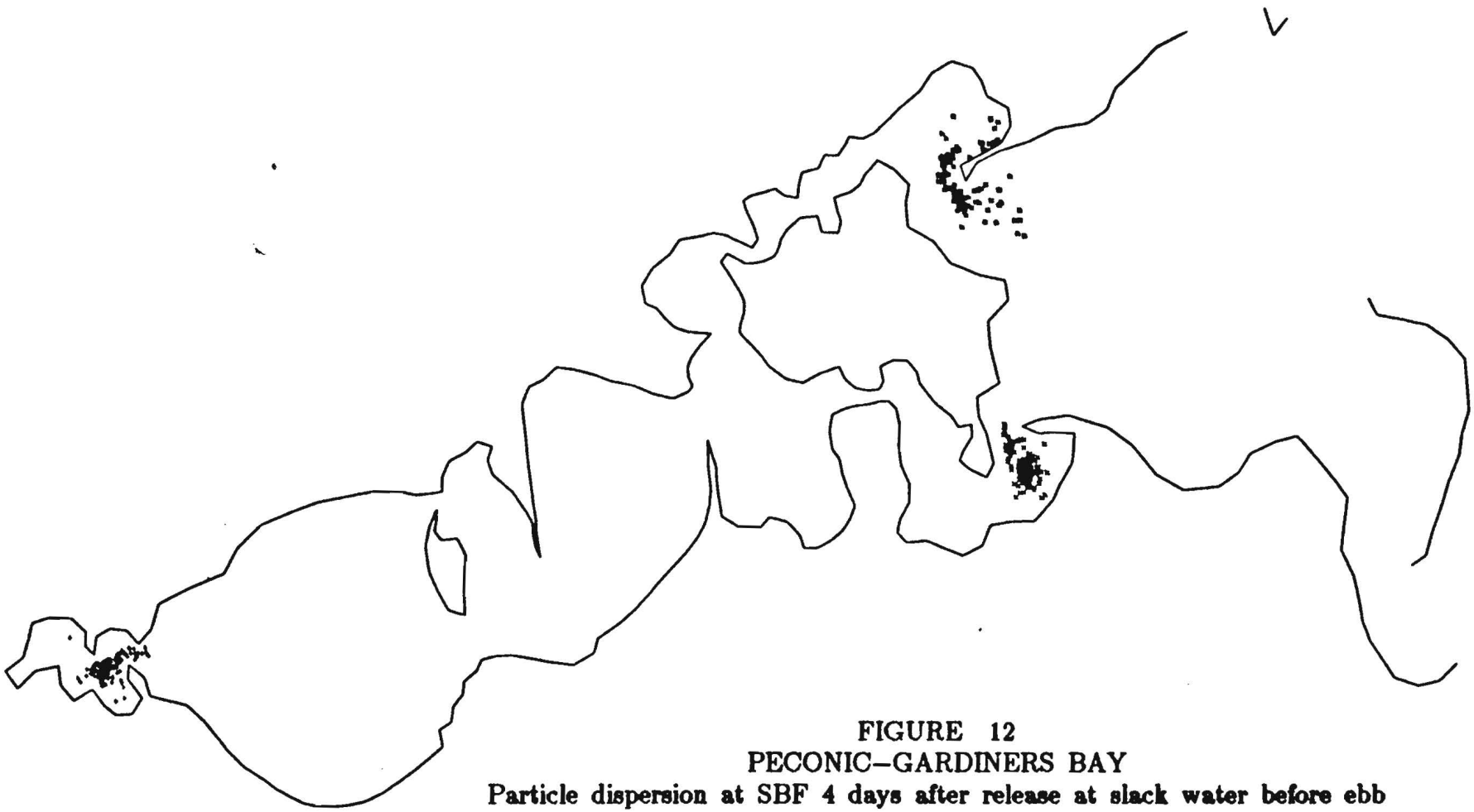

FIGURE 12
PECONIC–GARDINERS BAY
**Particle dispersion at SBF 4 days after release at slack water before ebb**

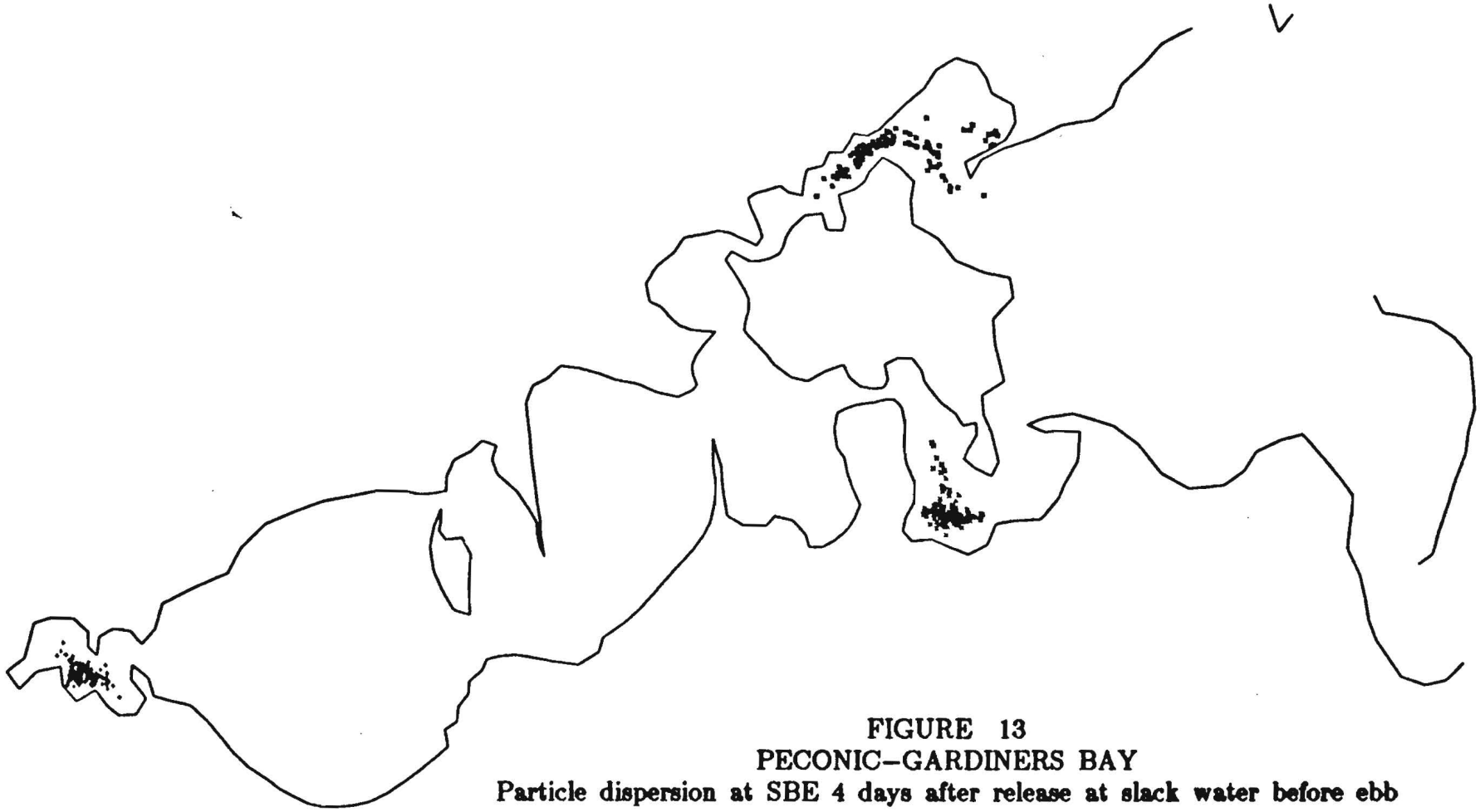

FIGURE 13
PECONIC–GARDINERS BAY
**Particle dispersion at SBE 4 days after release at slack water before ebb**

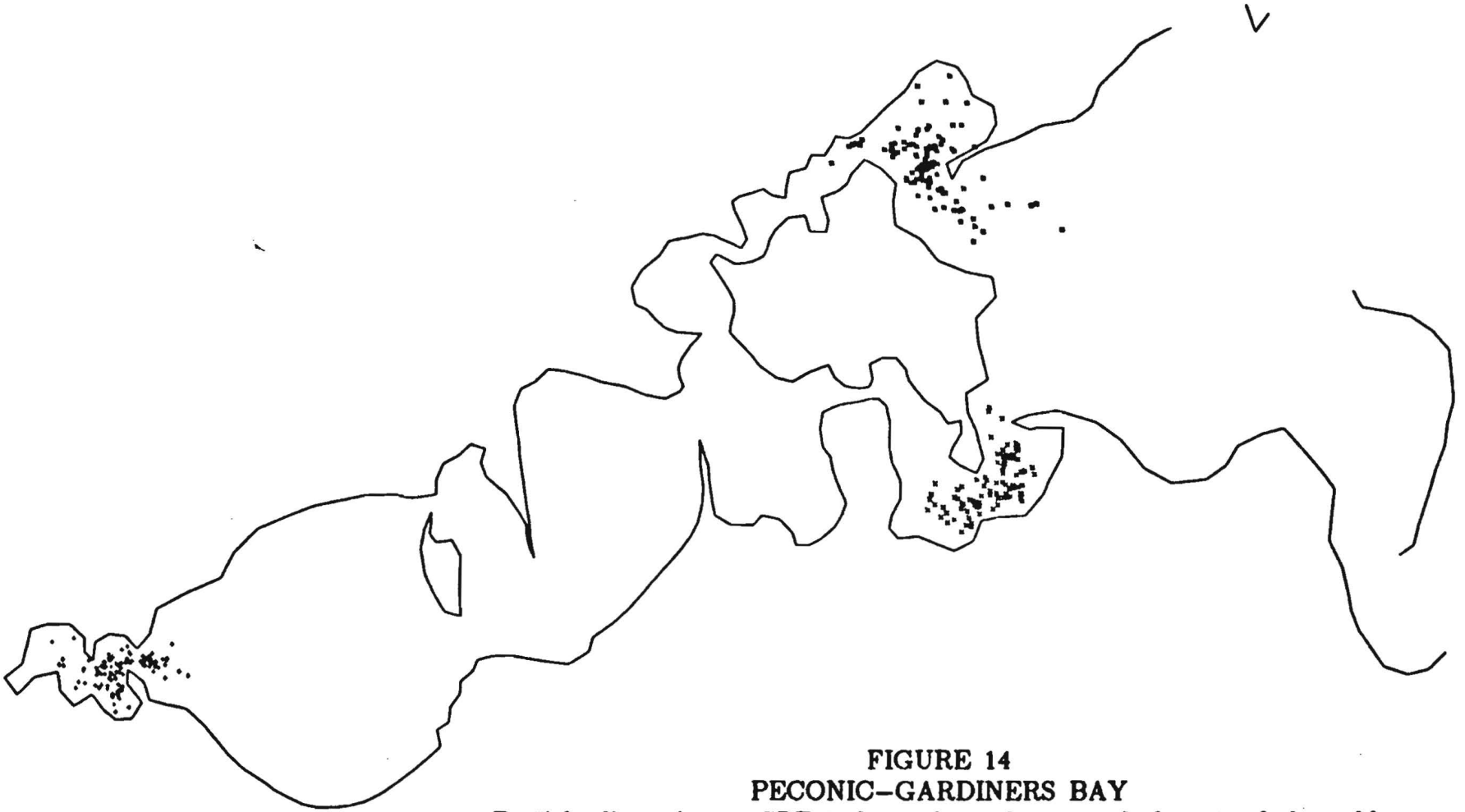

FIGURE 14
PECONIC–GARDINERS BAY
**Particle dispersion at SBF 8 days after release at slack water before ebb**

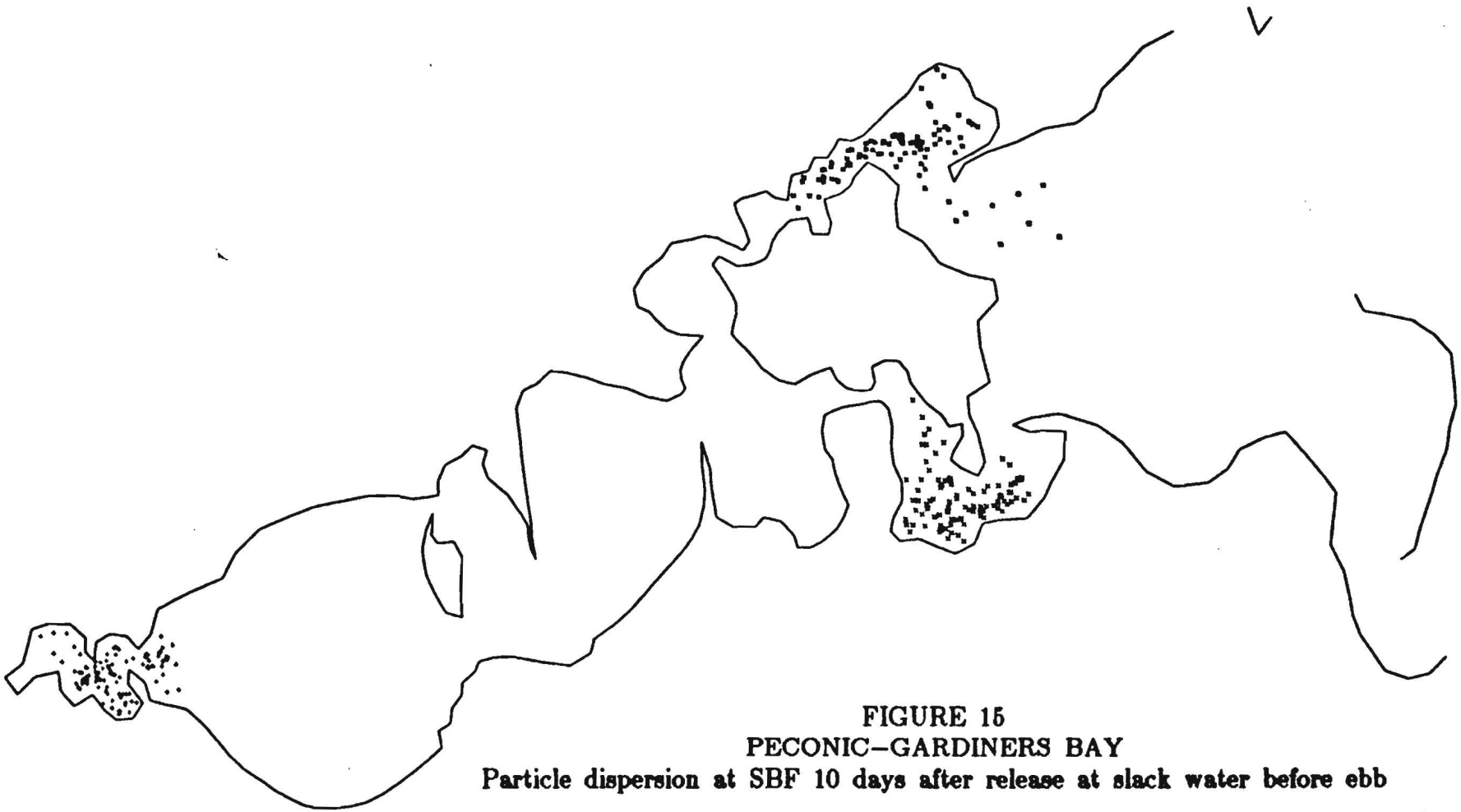

FIGURE 15
PECONIC–GARDINERS BAY
**Particle dispersion at SBF 10 days after release at slack water before ebb**

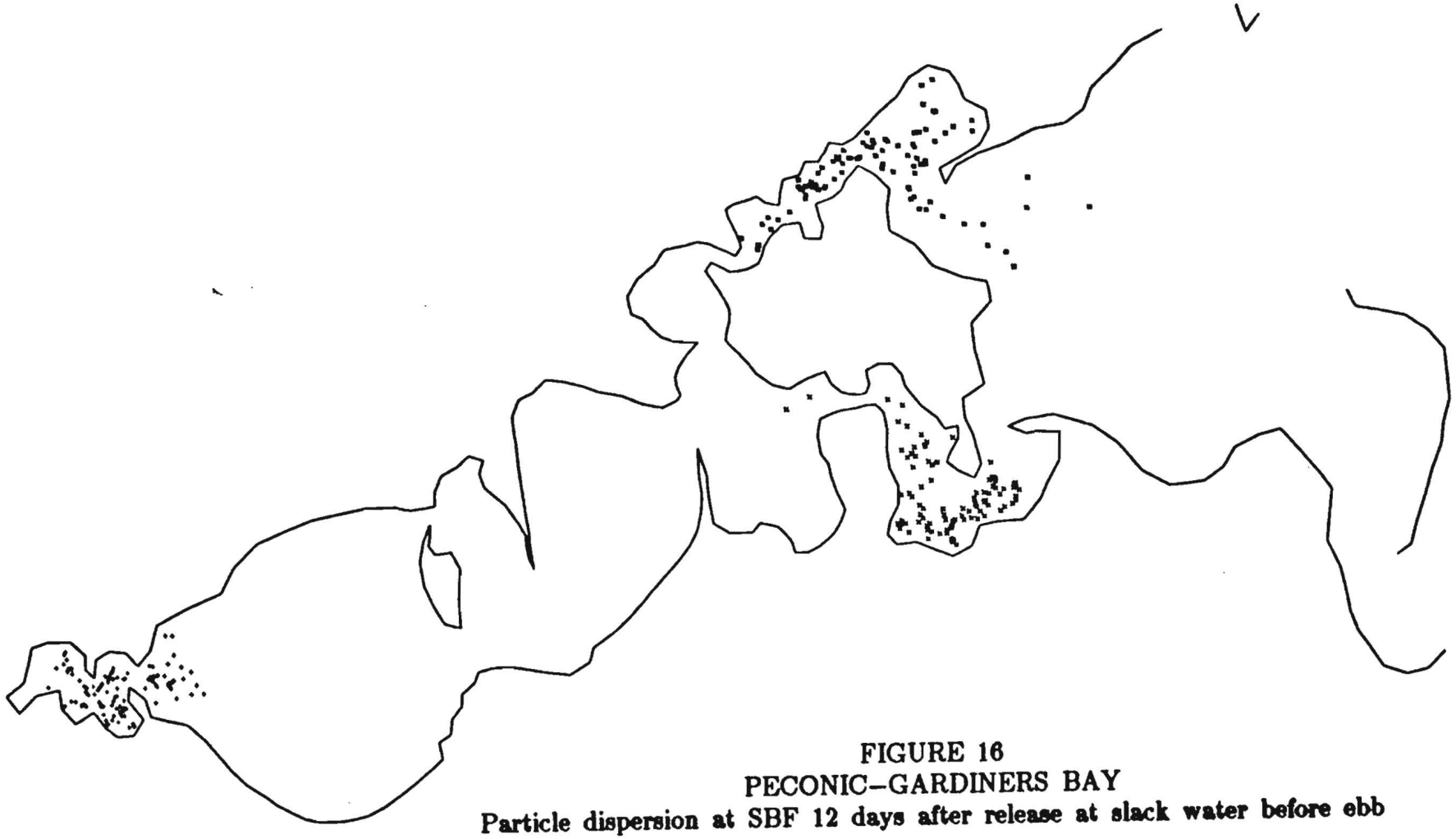

FIGURE 16
PECONIC–GARDINERS BAY
**Particle dispersion at SBF 12 days after release at slack water before ebb**

releases, *i.e.*, at the time of maximum displacement landward (Figures 17 and 18). It can be seen that for the release at SBF the penetration of the particles through the northern channel fills Southold Bay as far as Paradise Point, while for the release at SBE, only four particles go beyond Jennings Point. As far as the southern channel is concerned, the advance of the particles into Shelter island Sound is similar although the SBE release seems to penetrate deeper into Noyack Bay. For both releases, the concentration of particles in the original release sites is equally very low, while most of the concentration is located in Pipes Cove in the north channel and off Sag Harbor in the south channel. For the Flanders Bay releases, the differences are minor, except for a slightly larger number of particles lost to Great Peconic Bay in the SBE release.

The next comparison is for the results at slack water before flood, *i.e.*, at the time of maximum displacement seaward (Figures 19 and 20). In this case the particles dispersed in the northern channel as far as Jennings Point for the SBF release and Conkling Point for the SBE release; in both releases a fair number of particles was lost and dispersed through Gardiners Bay (and eventually out of the system). In the southern channel, for the SBF release very few particles go beyond Mashomack Point, while for the SBE release particles fill Northwest Harbor completely. The penetration of the particles into Shelter Island is very weak for both releases. The concentration of particles appears to be somewhat larger in the original release sites in Northwest Harbor and Orient Harbors for the SBE release. The highest concentrations are located around Hay Beach Point in the north channel and off Sag Harbor in the south channel. In Flanders Bay the differences between release times are again minor and once more the losses to Great Peconic Bay were higher for the SBE release.

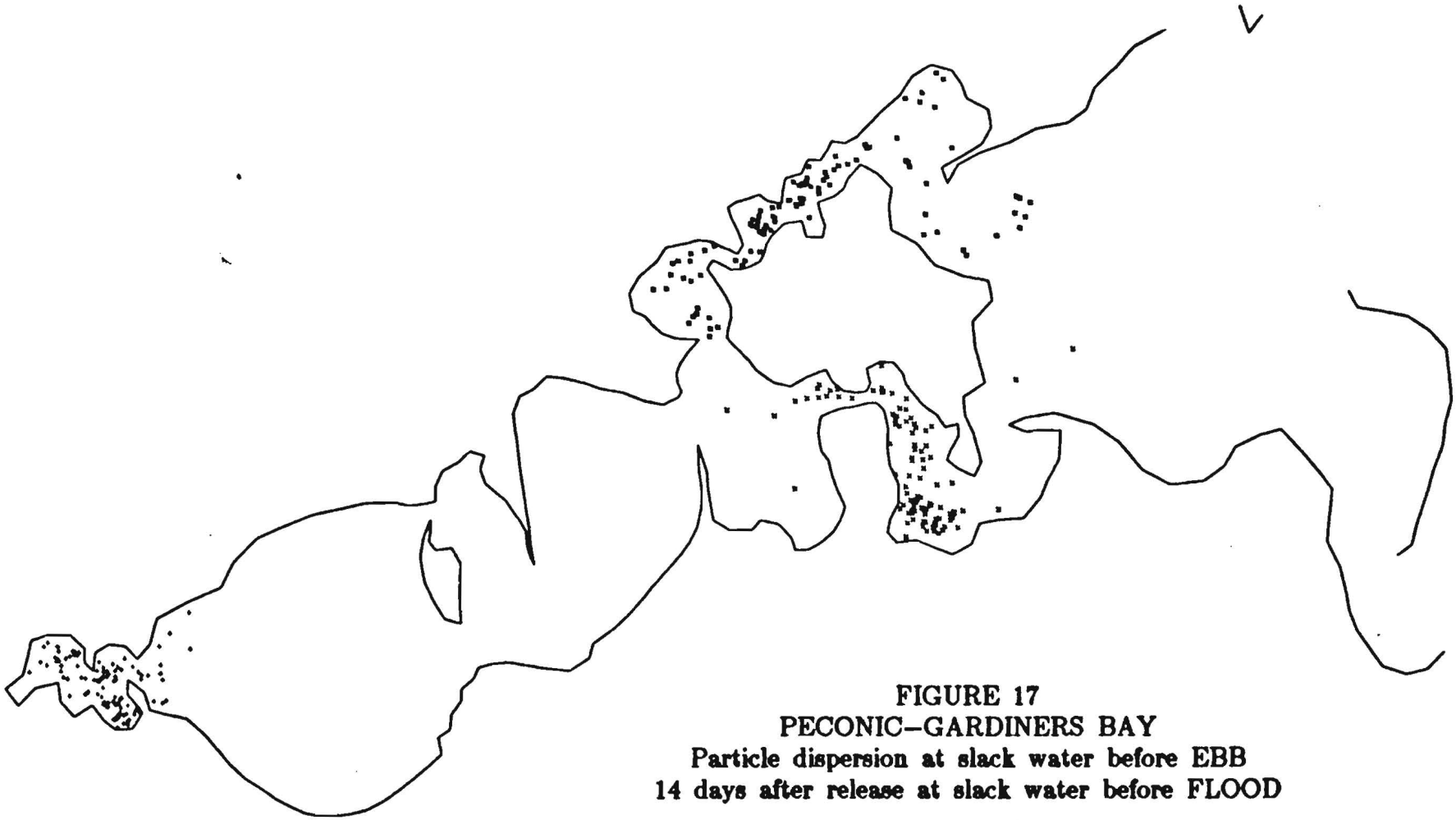

FIGURE 17
PECONIC–GARDINERS BAY
**Particle dispersion at slack water before EBB**
**14 days after release at slack water before FLOOD**

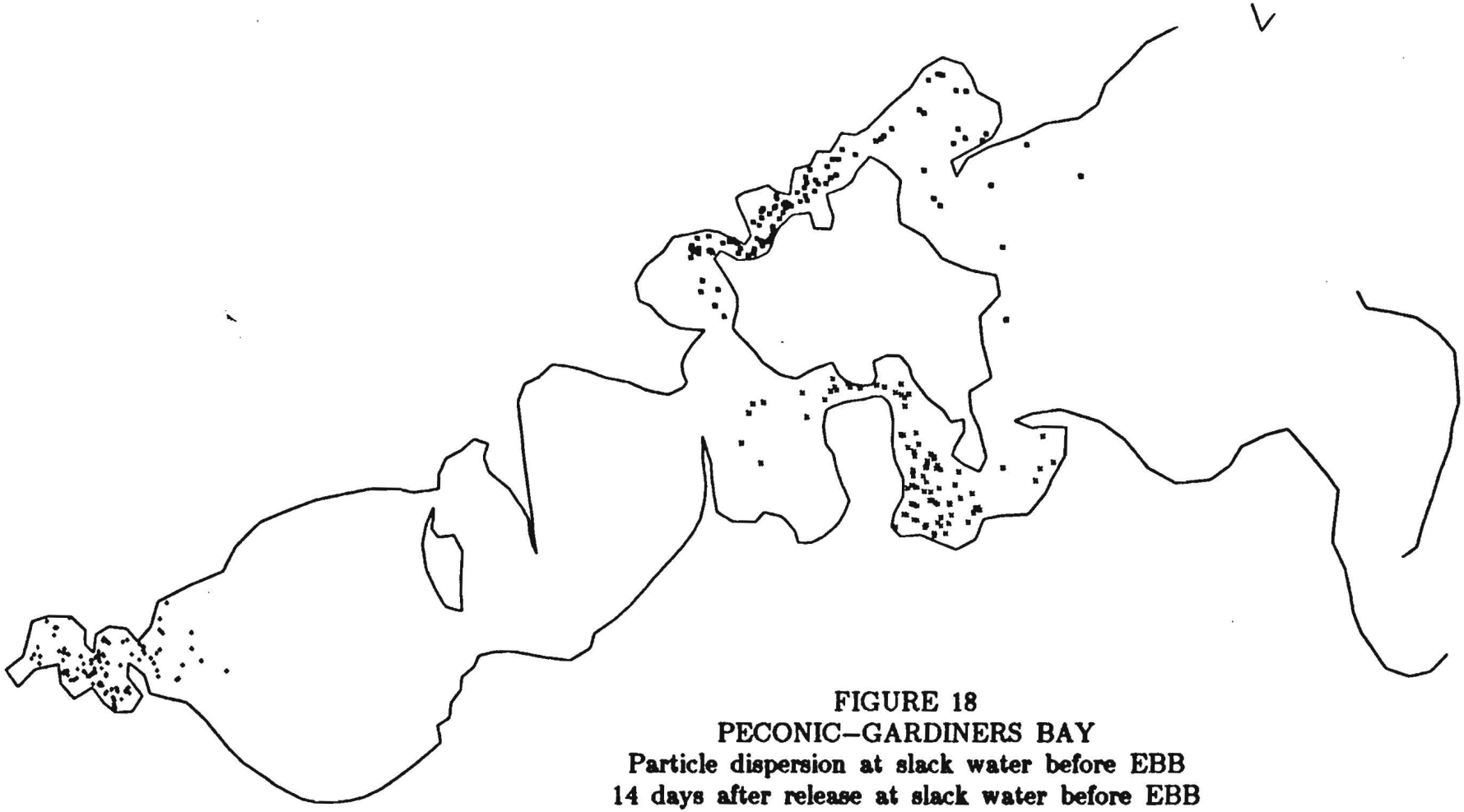

FIGURE 18
PECONIC–GARDINERS BAY
**Particle dispersion at slack water before EBB**
**14 days after release at slack water before EBB**

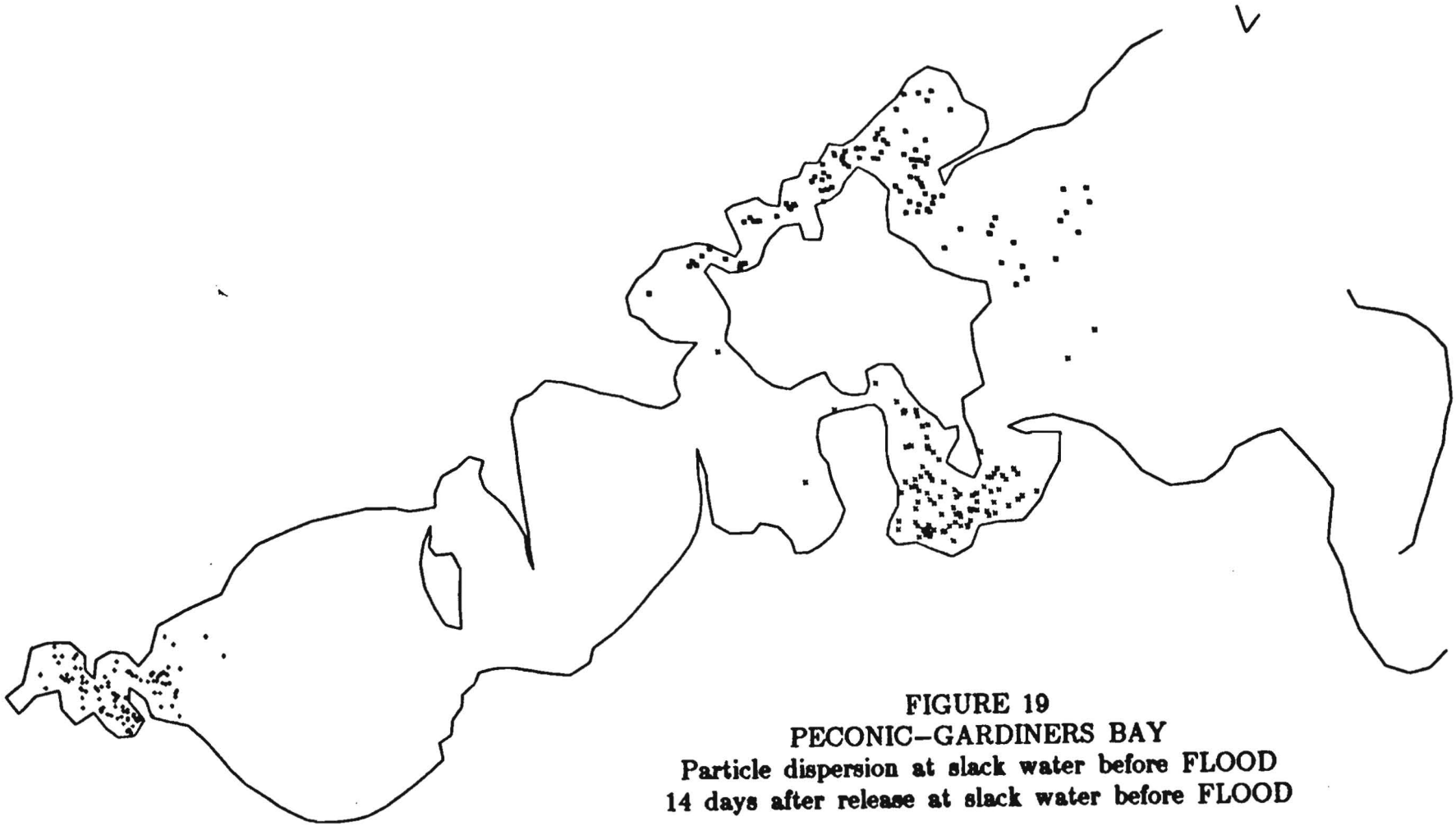

FIGURE 19
PECONIC–GARDINERS BAY
**Particle dispersion at slack water before FLOOD**
**14 days after release at slack water before FLOOD**

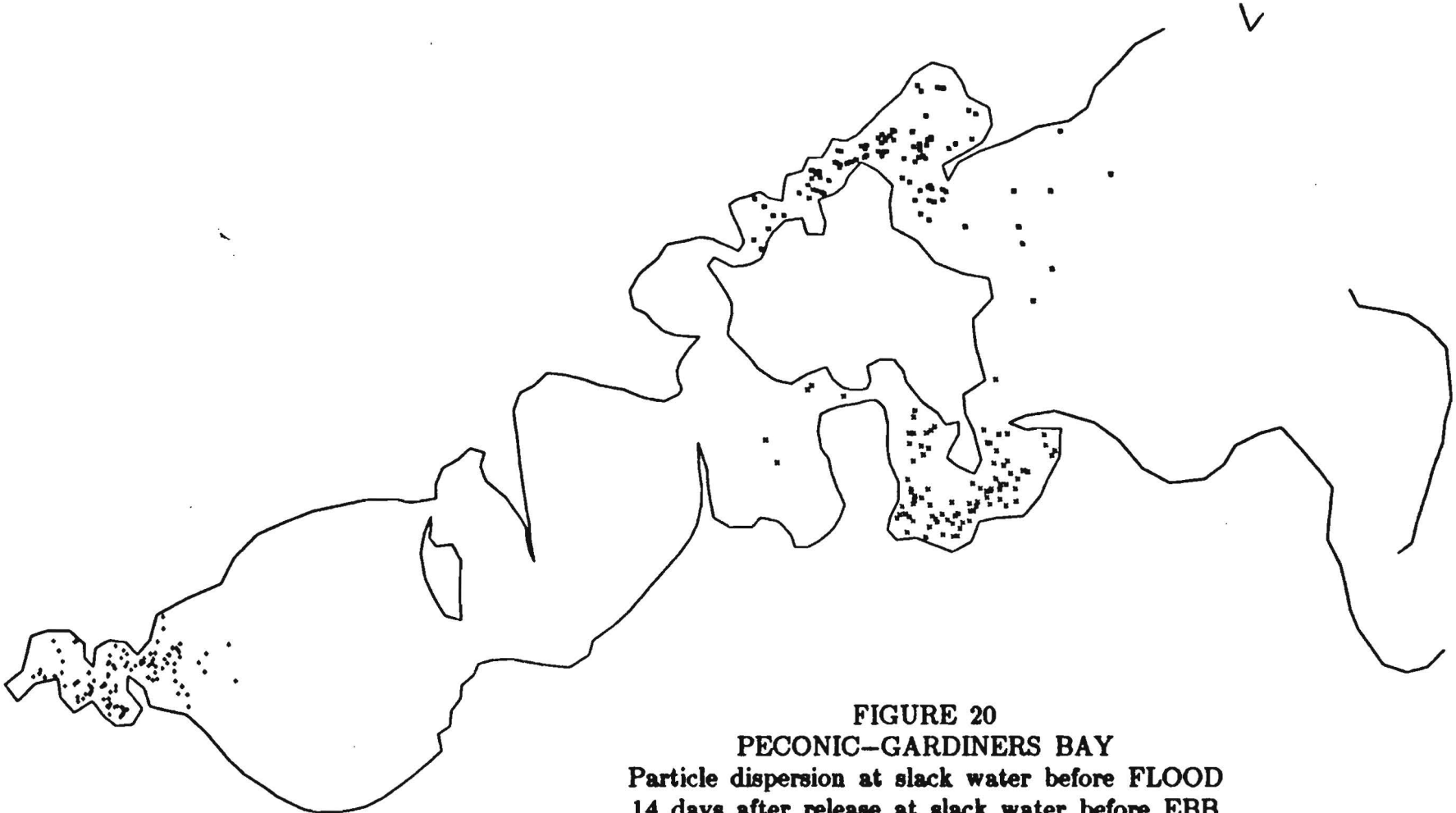

FIGURE 20
PECONIC–GARDINERS BAY
**Particle dispersion at slack water before FLOOD**
**14 days after release at slack water before EBB**

### 3.6.2 Forecasting settlement from adults at 46 additional sites

In collaboration with representatives of the Long Island Green Seal Committee, three East End baymen's associations, the Town Trustees of East Hampton, and staff of NY State Department of Environmental Conservation, 46 additional sites were identified for further evaluation using the model. The selection of these sites was based on production of scallops over the past two decades, and not necessarily the presence of harvestable stocks of bay scallops today. The sites are mapped in Figure 21.

The objective of this part of the study was to evaluate the potential recruitment of scallops from areas other than the three principal sites. It must be emphasized that as long as we assume larvae behave as passive particles in this well-mixed system, they cannot be reconcentrated once they are dispersed. The concentration of passive particles in a mass of seawater cannot be increased simply by moving the seawater around the bays. Furthermore, there are no processes in the model (or in the bays) which "trap" and thus concentrate pelagic larvae. It is possible, however, that larvae from untested source areas are distributed into favorable habitats with minimal dispersion. Therefore, in this evaluation of the 46 additional sites, we seek to identify areas where particle distributions are relatively high as a result of reduced dispersion of larvae from their spawning grounds.

Thirty particles (larvae) were released simultaneously from each of the 46 additional sites and their movement during the course of the next 14 days was followed. The operation of the model was precisely the same as in the evaluation of the three principal sites. The results of this evaluation of

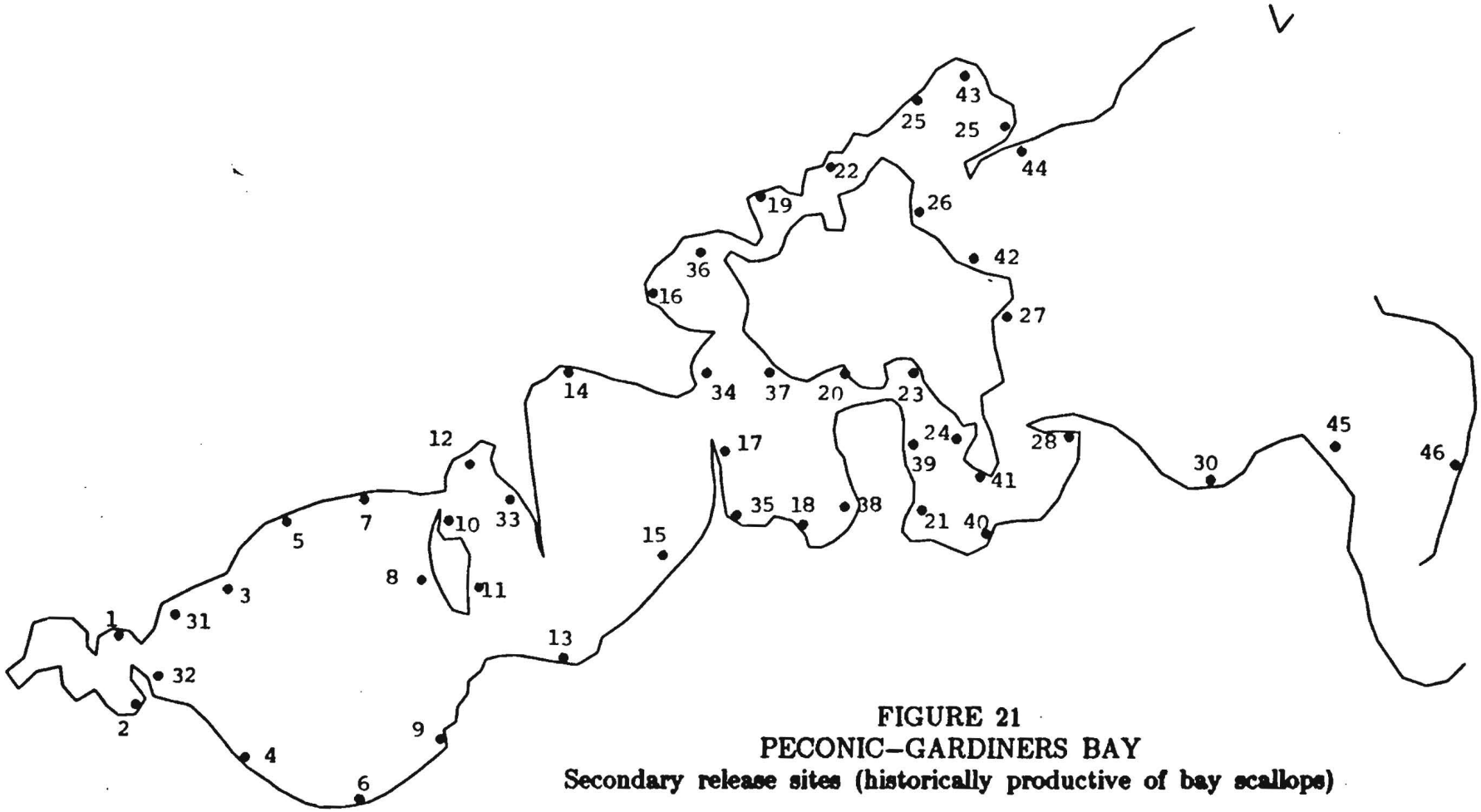


**FIGURE 21**
**PECONIC–GARDINERS BAY**
**Secondary release sites (historically productive of bay scallops)**

larval dispersion from the 46 additional sites are presented in Figures 22 and 23. There were insignificant differences in the final distribution of particles between those released at slack water before flood and those released at slack water before ebb and so both sets of release results are not presented here. Also because of the large number of particles tracked in this run of the model, we have chosen to present only the distributions predicted 14 days after release.

Two important conclusions may be drawn from the analysis of these additional sites. First, as with the three principal sites, the final distribution of particles is influenced by the state of the tide at the time of observation. Figure 22 presents the distribution of particles at slack water before flood when the particles are at their maximum excursion out of the estuary. Figure 23 presents the distribution at slack water before ebb when the particles are at their maximum incursion.

Second, there are six areas where particles are distributed in relatively higher concentrations than throughout most of the estuary. These areas are labeled I through VI in Figure 24. Again, these "concentrations" of larvae are a result of less dispersion from the spawning grounds, not actual concentration or accumulation of particles. However, these areas are of interest for purposes of establishing spawner sanctuaries since the particles are predicted to be distributed to more restricted areas than those from most other sites, potentially increasing their effectiveness in rebuilding scallop stocks in particular areas.

The points of origin for each of the particles in the blackened areas of Figure 24 were determined from the computer model; the results of this descriptive

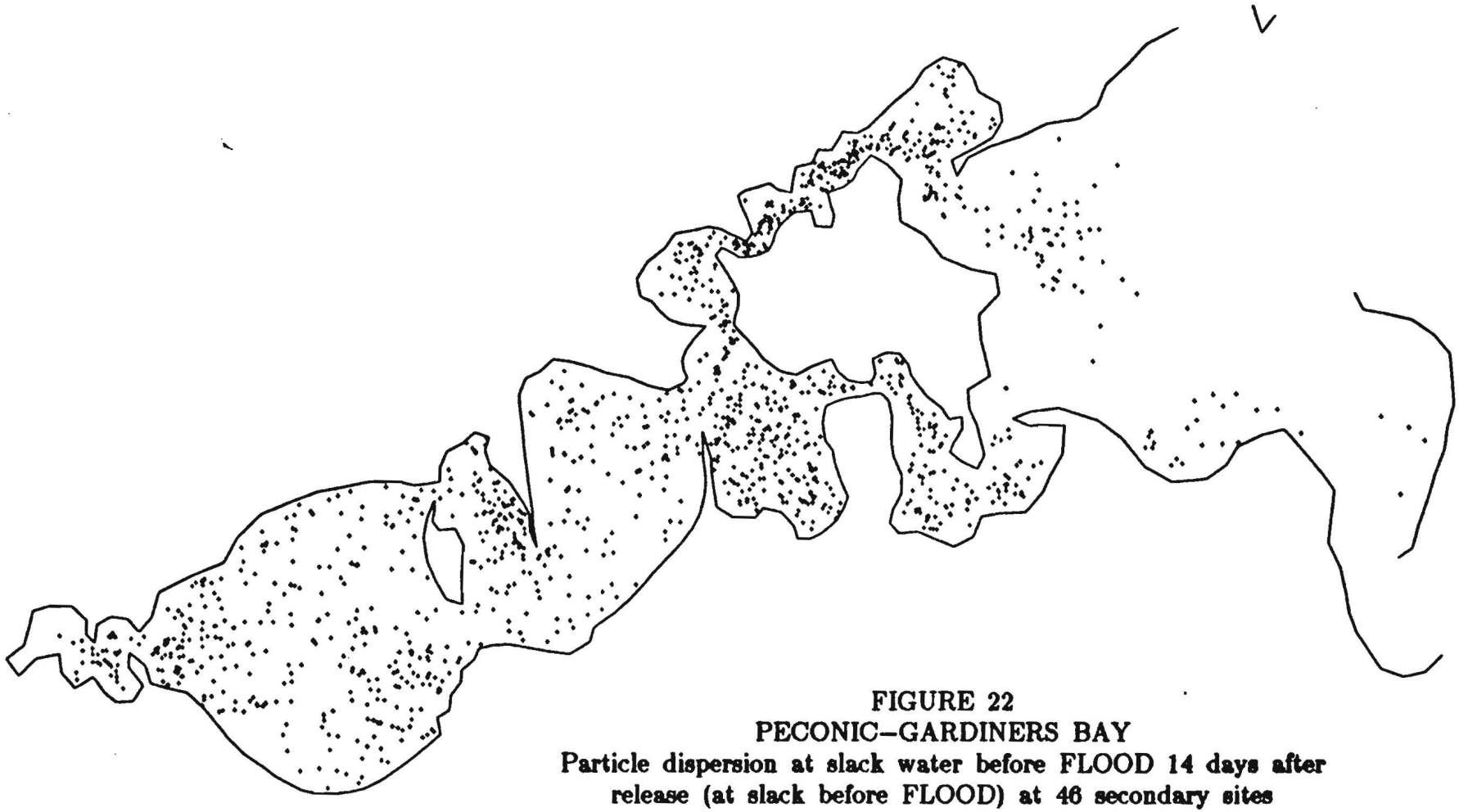

FIGURE 22
PECONIC–GARDINERS BAY
**Particle dispersion at slack water before FLOOD 14 days after release (at slack before FLOOD) at 46 secondary sites**

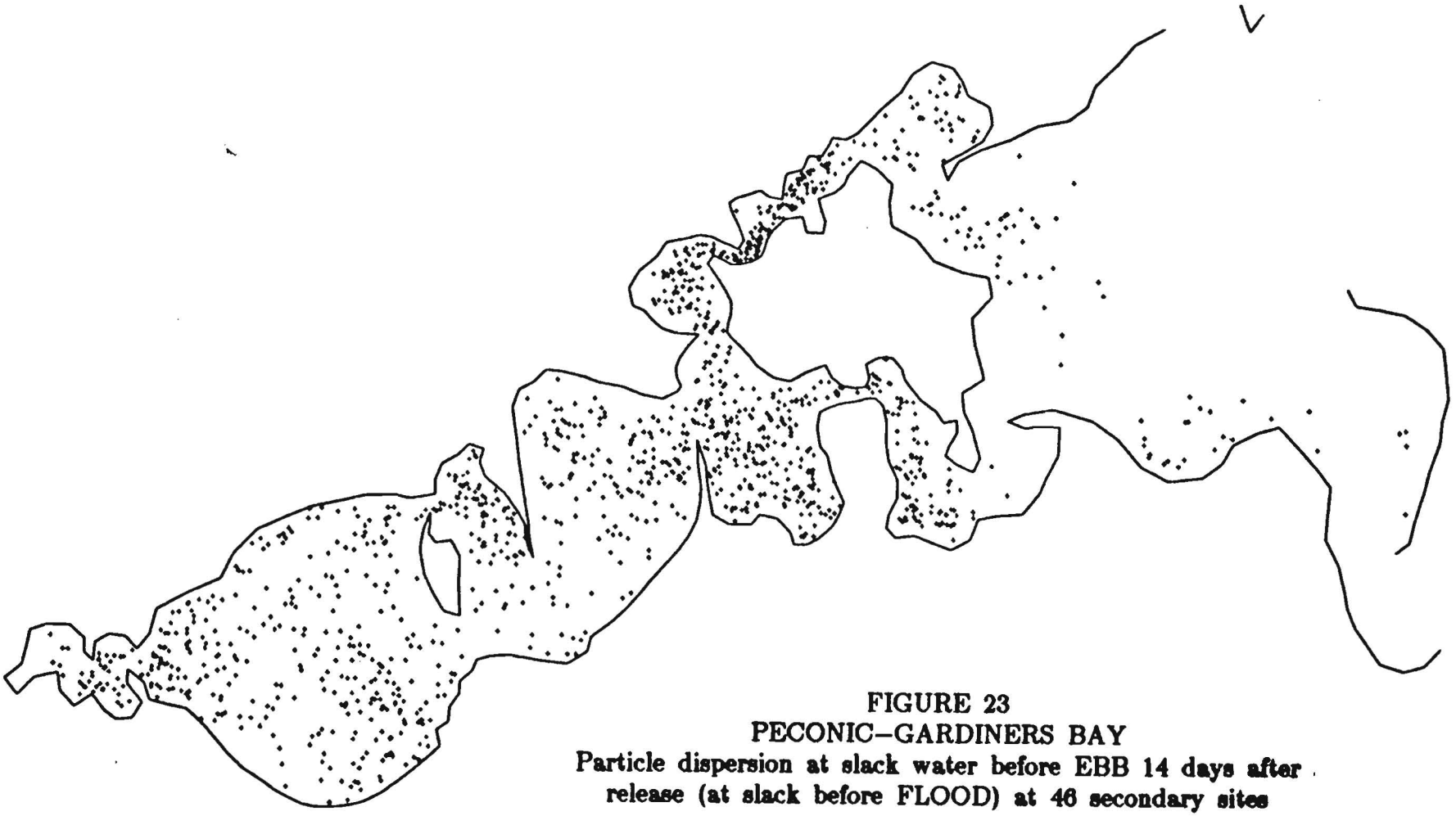

FIGURE 23
PECONIC–GARDINERS BAY
**Particle dispersion at slack water before EBB 14 days after release (at slack before FLOOD) at 46 secondary sites**

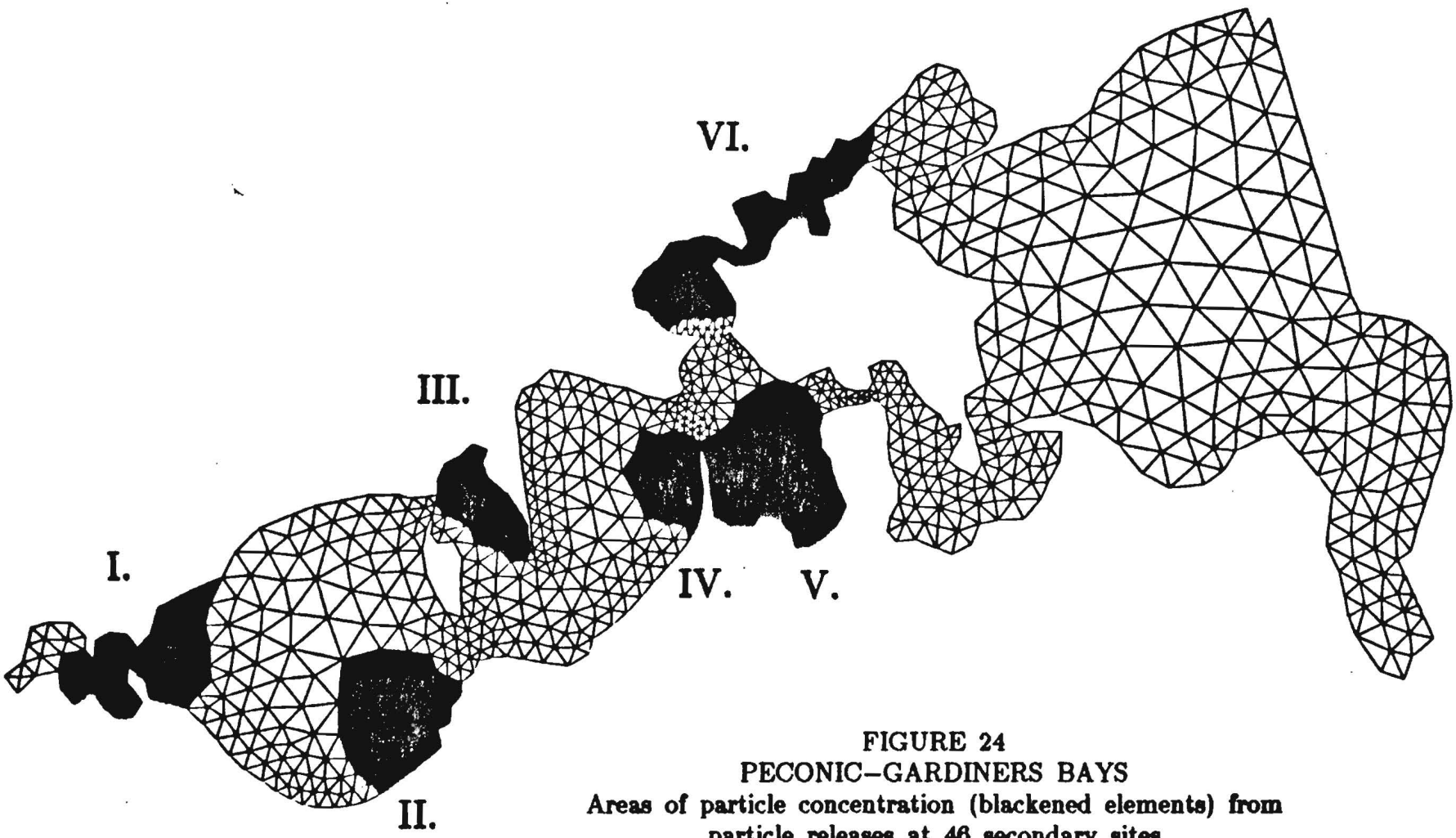


FIGURE 24
PECONIC–GARDINERS BAYS
**Areas of particle concentration (blackened elements) from particle releases at 46 secondary sites**

statistical analysis are presented in Tables 1 and 2. Note that 30 particles were released from each of the 46 additional sites and that no single source site could contribute more than 30/N percent (where N = total number of particles in the concentrated area). For example, larvae at site I came principally from source areas 1 and 2, but in neither case could this percentage have exceeded 30/96 or 31.25%. The fact that nearly all the particles released from source sites 1 and 2 remained in the area is reflected in their high percentage contributions: 23.53 to 29.17% out of a possible 31.25%.

Careful examination of Figures 22 and 23 and Tables 1 and 2 is required to interpret the results of the model's evaluation of the additional sites. The need to develop and run this computer simulation is underscored by some of the patterns of larval dispersion seen in these results; some of the observed distributions of particles could not have been predicted on the basis of experience with the estuary's hydrography. For example, more than 10% of the larvae arriving at site VI (Southold Bay; Table 1) on the 14th day after release came from source site 21 at Sag Harbor. The particles had moved back and forth with the tides in the estuary until many coming from Sag Harbor moved toward the north channel and Southold Bay. An approximately equal number of particles at site VI came from source site 36, directly adjacent to site VI. These are not results one might have predicted from an understanding of the current fields themselves. As another example of the contribution of this computer simulation, the model predicted a notable lack of dispersion of larvae out of site III just west of Little Hog Neck. The larvae predicted to arrive

TABLE 1

Percentage of particles "concentrated" in selected areas
(distribution as of slack water before flood tide)
14 days after release at slack water before flood.

| SOURCE AREAS | TARGET SITES I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|
| 1 | 27.08% | | | | | |
| 2 | 29.17 | | | | | |
| 3 | 4.17 | | | | | |
| 4 | 3.12 | 2.35% | | | | |
| 5 | | 1.18 | 1.47% | | | |
| 6 | | 22.35 | 4.41 | | | |
| 7 | | 5.88 | 20.59 | | | |
| 8 | | 18.82 | | | | |
| 9 | | 17.65 | 7.35 | | | |
| 10 | | 8.24 | 19.12 | | | |
| 11 | | 8.24 | 11.76 | | | |
| 12 | | 5.88 | 11.76 | | | |
| 13 | | 9.41 | 1.47 | | | |
| 14 | | | | 13.33% | | |
| 15 | | | | 20.00 | 1.16% | 6.88 |
| 16 | | | | 16.67 | 3.49 | 7.94 |
| 17 | | | | 3.33 | 9.88 | 0.53 |
| 18 | | | | | 6.40 | 7.41 |
| 19 | | | | 3.33 | 5.23 | 6.88 |
| 20 | | | | | 6.98 | |
| 21 | | | | | 1.16 | 10.05 |
| 22 | | | | | 5.23 | 4.76 |
| 23 | | | | 3.33 | 10.47 | |
| 24 | | | | 3.33 | 2.33 | 4.23 |
| 25 | | | | | | 6.88 |
| 26 | | | | | | 0.53 |
| 27 | | | | | | |
| 28 | | | | | | 6.88 |
| 29 | | | | | | |
| 30 | | | | | | |
| 31 | 16.67 | | | | | |
| 32 | 19.79 | | 1.47 | | | |
| 33 | | | 20.59 | | | |
| 34 | | | | 23.33 | 4.07 | |
| 35 | | | | 3.33 | 7.56 | 2.65 |
| 36 | | | | | 1.16 | 10.58 |
| 37 | | | | 10.00 | 5.81 | 1.06 |
| 38 | | | | | 15.70 | |
| 39 | | | | | 5.81 | 0.53 |
| 40 | | | | | 2.33 | |
| 41 | | | | | 5.23 | 1.59 |
| 42 | | | | | | 7.94 |
| 43 | | | | | | 7.94 |
| 44 | | | | | | 4.76 |
| 45 | | | | | | |
| 46 | | | | | | |
| TOTAL (N) | 96 | 85 | 68 | 30 | 172 | 189 |

TABLE 2

Percentage of particles "concentrated" in selected areas
(distribution as of slack water before ebb tide)
14 days after release at slack water before flood.

| SOURCE AREAS | TARGET SITES I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|
| 1 | 23.53% | | | | | |
| 2 | 26.47 | | | | | |
| 3 | 3.92 | | | | | |
| 4 | 5.88 | 1.14% | | | | |
| 5 | | | 2.86% | | | |
| 6 | | 20.45 | 2.86 | | | |
| 7 | | 3.41 | 17.14 | | | |
| 8 | | 20.45 | | | | |
| 9 | | 20.45 | 7.14 | | | |
| 10 | | 7.95 | 22.86 | | | |
| 11 | | 9.09 | 10.00 | | | |
| 12 | | 6.82 | 14.29 | | | |
| 13 | | 10.23 | 1.43 | | | |
| 14 | | | | 11.11% | 1.18% | |
| 15 | | | 1.43 | 13.33 | | 5.31 |
| 16 | | | | 6.67 | 2.94 | 5.31 |
| 17 | | | | 8.89 | 8.82 | 0.49 |
| 18 | | | | 4.44 | 6.47 | 7.73 |
| 19 | | | | 6.67 | 4.71 | 5.31 |
| 20 | | | | | 7.06 | |
| 21 | | | | | 1.18 | 9.17 |
| 22 | | | | 6.67 | 5.88 | 4.35 |
| 23 | | | | 6.67 | 10.00 | |
| 24 | | | | 2.22 | 2.94 | 4.35 |
| 25 | | | | | | 7.73 |
| 26 | | | | | | 2.42 |
| 27 | | | | | 1.18 | 0.49 |
| 28 | | | | | | 8.21 |
| 29 | | | | | | 0.49 |
| 30 | | | | | | |
| 31 | 17.65 | | | | | |
| 32 | 22.55 | | | | | |
| 33 | | | 20.00 | | | |
| 34 | | | | 15.55 | 2.94 | |
| 35 | | | | 8.87 | 7.65 | 0.97 |
| 36 | | | | | 0.59 | 8.69 |
| 37 | | | | 6.67 | 6.47 | 0.49 |
| 38 | | | | | 15.88 | |
| 39 | | | | 2.22 | 5.88 | 0.49 |
| 40 | | | | | 2.35 | |
| 41 | | | | | 5.29 | 3.38 |
| 42 | | | | | | 8.69 |
| 43 | | | | | | 10.14 |
| 44 | | | | | | 4.83 |
| 45 | | | | | | |
| 46 | | | | | | |
| TOTAL (N) | 102 | 88 | 70 | 45 | 170 | 207 |

in this area by the 14th day after release came principally from source areas 7 (northwest of Robins Island) and 10 (on the northeast side of Robins Island); it was not immediately obvious from known patterns of circulation that particles might be concentrated in these areas.

### 3.7 Overall comments and interpretation

The model predicts that a greater number of larvae will be lost to open ocean areas (Gardiners Bay and beyond) from the Orient Harbor and Northwest Harbor locations than from locations further inside the estuary, such as the Flanders Bay site, however the number of "lost" larvae does not represent the majority of particles released at these eastern sites. In terms of larval dispersion alone, this indicates that the Flanders Bay site is a more conservative choice for a spawner sanctuary; more larvae produced at this site have a greater chance of remaining in the estuary. If we were to rank the three principal sites according to the number of larvae predicted to be retained in the estuary, the Flanders Bay site would be first (most retained) followed by the Northwest Harbor site and the Orient Harbor site (least retained). The results of this model alone should not be used to rank and select sites for spawner sanctuaries; for example, although the Flanders Bay site is most conservative of larvae, this is the region of the estuary in which the so-called "brown tide" algal bloom first appeared during what would have been the months of peak spawning for scallops in 1986.

On the other hand, in terms of absolute numbers of larvae predicted to be lost, neither the Northwest Harbor nor the Orient Harbor sites should be eliminated from consideration. While perhaps as many as 20% of the larvae spawned at

Orient Harbor are predicted to leave the estuary, the larvae that remain in the system from this site are predicted to move in and out of the northern and southern channels around Shelter Island, putting them in the vicinity of historically good areas for larval settlement. Additionally, there are areas east of Shelter Island where scallops have been harvested in commercial quantities in the recent past; the model predicts that larvae dispersed into these areas come from Orient Harbor.

Additional consideration should be given to those source areas in the list of 46 additional sites which contributed more than 15% of the particles arriving in any of the six sites of Figure 24. These include source areas:

1 west of Miamogue Point

2 southwest of Red Cedar Point

6 at inlet to Cold Spring Pond

7 off Marratooka Point

8 southwest of Robins Island

9 off Sebonac Creek

10 northeast of Robins Island

31 east of Miamogue Point

32 northeast of Red Cedar Point

33 west of Little Hog Neck

34 east of Great Hog Neck

38 off Noyack Creek

As mentioned in the Introduction of this report, the objective of this study was to present the best information available on the dispersion of larvae, not to recommend specific sites for spawner sanctuaries. The results of this computer simulation should be combined with consideration of many other criteria in the ultimate determination of sites for bay scallop spawner sanctuaries.

## REFERENCES

Awaji, T., 1982. Water mixing in a tidal current and the effect of turbulence on tidal exchange through a strait. J. Phys. Ocean. 12: 501-514.

Bricelj, V. M., J. Epp and R. E. Malouf, in review. Fecundity and growth and reproductive cycles of bay scallops, *Argopecten irradians* in the Peconic estuary, N. Y.

Bruno, S. F., R. D. Staker and G. M. Sharma, 1980. Dynamics of phytoplankton productivity in the Peconic Bay estuary, Long Island. Est and Coastal Marine Science 10:244-263.

Carter, H. H., K-C. Wong and R. E. Malouf, 1984. Maximizing hard clam sets at specified location sin Great South Bay by means of a larval dispersion model. MSRC Special Report 54, ref. 84-1. 65 pp.

Hardy, C. D., 1976. A preliminary description of the Peconic Bay Estuary. MSRC Special Report 3, 65 pp.

Hargraves, P. E. and R. R. L. Guillard, 1974. Structural and physiological observations on some small marine diatoms. Phycologia 13(2):163-172.

Pritchard, D. W. and J. DiLorenzo, 1985. Assessment of the effects of inlet geometry on currents in Moriches Inlet and on tidal ranges and storm surge elevations in Moriches Bay. Report prepared for the Count of Suffolk, Department of Health Services, by the Marine Sciences Research Ceter, SUNY, NY. 92 pp.

Turner, J. T., S. F. Bruno, R. Y. Larson, R. D. Staker and G. M. Sharma, 1983. Seasonality of plankton assemblages in a temperate estuary. Mar. Ecol. (Pubbl. Stn. Zool. Napoli I) 4(1):81-99.