A DYE DIFFUSION STUDY OF GREAT SOUTH BAY

H.H. Carter

JONES, C. R.

Special Report 43

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MARINE SCIENCES RESEARCH CENTER

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for the

SUFFOLK COUNTY DEPARTMENT OF PLANNING

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J.R. Schubel, Director

ABSTRACT

A dye tracer study was conducted in Great South Bay (GSB) during September, 1980. The measurement part of the study consisted of releasing a known quantity of a dye tracer and then measuring its subsequent distribution in time and space as it dispersed in GSB. Information from the study was intended to serve two purposes. First, the analysis would provide quantitative information on the coefficients of turbulent diffusion which are required as input to a dispersion model of GSB (DISPER-1) which will be used in another study to simulate the spawning and spreading of hard clam larvae in GSB. Second, the dye concentration data could be interpreted in terms of hard clam setting densities thus providing information to shellfish management personnel regarding their spawner transplant programs.

101 kg of Rhodamine WT solution was released on 15 September 1980 at a position in GSB approximately midway between Green Harbor on the southshore of Long Island and the Pines on Fire Island. The patch was inventoried on 16 (2x), 17, 18, 19, 22, 23, 25, 28 September and finally on 1 October 1980. The dye remained east of a line between Nicoll Point and Sailor's Haven; higher concentrations were usually found closer to Long Island than to Fire Island.

The spatial distribution of the dye was sufficiently well represented by a two-dimensional Gaussian distribution so that the variance of the patch, σ_{rc}^2, the scale of diffusion, ℓ, and the apparent diffusivity, K_a, could be calculated as functions of time. K_a was found to be linearly related to ℓ and approximately the same magnitude as measured by a previous dye study in western GSB in 1976. It was, however, smaller than similar measurements made in oceanic and coastal waters.

Results of scaling the dye concentrations to hard clam setting densities were somewhat inconclusive due to lack of good information regarding mortality of clam larvae between spawning and setting. It was shown, however, that spreading by physical processes is of the same order of magnitude as mortality and, as a result, transplant programs consisting of 1000 bushels or less of spawners are unlikely to achieve any significant augmentation of the natural set.

An experiment which would properly address the question of hard clam larvae mortality during their planktonic existence was described.

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I. BACKGROUND

A. *Great South Bay*

Great South Bay (GSB) is a shallow, coastal bay (Figure 1) 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 which enclosed a series of bays intermittently connected to the ocean by tidal inlets. 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.

The importance of GSB to New York lies in the fact that it produces more hard clams than the rest of the Atlantic coast combined. As pointed out by Professor J.L. McHugh of MSRC in the Summary of the GSB study plan[1],

> "It needs no research to conclude from this that conditions are ideal, and the preservation of this unique environment is essential for continuance of the hard clam industry. At present we have only a very general concept of why the present happy state of affairs exists. Before we can develop plans to preserve it, we must understand how the physical-chemical-geological-biological system works."

In estuaries, an understanding of the forces that cause water to flow in certain ways and waterborne materials such as salt, clam larvae, pollutants, etc., to disperse is fundamental to resource management. In GSB this is particularly true. Local and non-local forces continually compete for dominance. The tidal wave entering GSB from the ocean competes with the local wind. Storms moving west to east offshore south of GSB produce large water level changes at the inlets leading to GSB which either oppose or augment the effect of local winds and astronomical tides. In the wintertime, ice cover effectively removes the stress of the local wind but not the effect of astronomical and storm tides. Changes in freshwater inflow, both surface and submarine, probably are of small importance from the standpoint of circulation but are important biologically as they contribute to the salt balance in the bay.

At the present time we cannot predict with any certainty where such things as spilled oil, sewage discharges, nutrients, or larvae will go -- whether they will be flushed out of the bay or accumulate within the bay; and where. Will changes to Fire Island Inlet raise or lower the salinity within the bay? What should we do if a hurricane breaches Fire Island at a new location? Can we alter the salt flux into GSB to compensate for the loss of fresh water which will result from the Southwest Sewer District project? Where is the best location for placing brood stock so that clam sets will be maximized?

---

[1] A design for a GSB study. Submitted to the NY State Department of Environmental Conservation by the Sea Grant Institute of SUNY and Cornell University, February 10, 1978.

B. *The MSRC GSB Physical Program*

The Great South Bay study is based on the belief that an understanding of why GSB supports such a large hard clam fishery must start with measurements of the spatial and temporal distribution of selected physical parameters. The first year of our physical program, therefore, consisted of measurements over a relatively long period (one month to one year) of water levels, currents, salinities, temperatures, and submarine seepage in sufficient spatial detail so that a reasonably accurate physical analogue of GSB, a numerical model, could be constructed which would reproduce

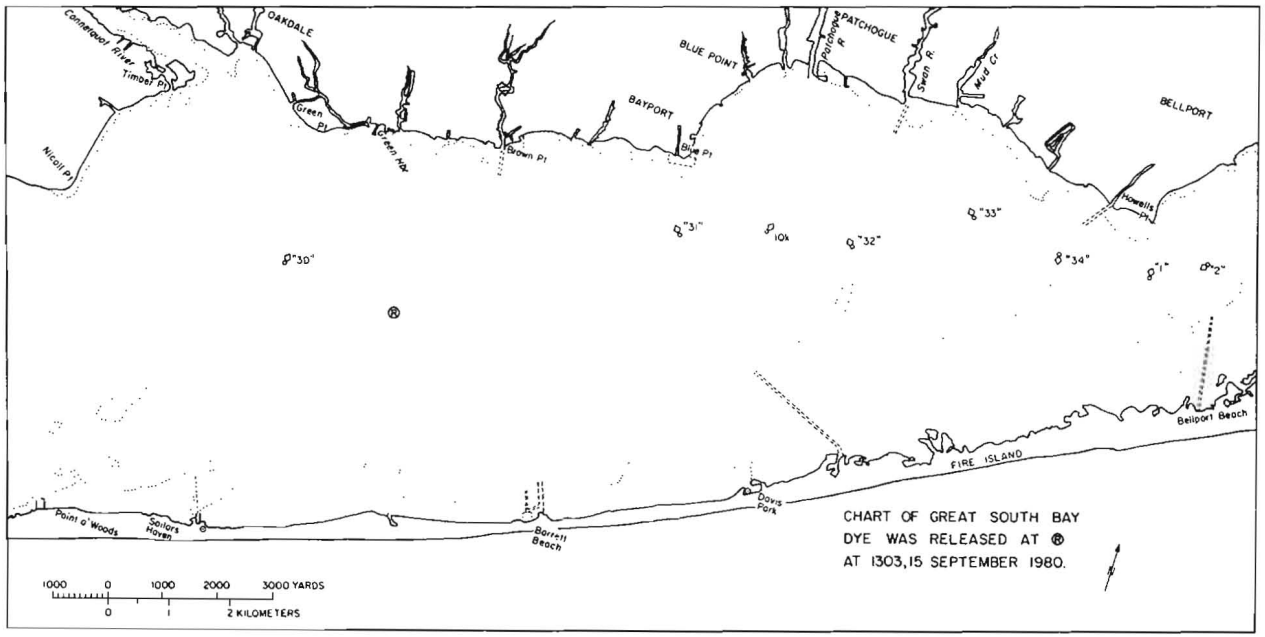

OAKDALE
Connetquot River
Timber Pt
Green Pt
Green Hdy
Brown Pt
BAYPORT
BLUE POINT
Blue Pt
Patchogue R
PATCHOGUE
Swan R
Mud Cr
BELLPORT
Howells Pt
Nicoll Pt
8"30"
8"31"
8"32"
8"33"
8"34"
8"1"
8"2"
10k
FIRE ISLAND
Bellport Beach
Davis Park
Barrett Beach
Point o' Woods
Sailors Haven
CHART OF GREAT SOUTH BAY
DYE WAS RELEASED AT ⊛
AT 1303,15 SEPTEMBER 1980.
1000 0 1000 2000 3000 YARDS
0 1 2 KILOMETERS

Figure 1.

the observed measurements with sufficient precision so that confidence could be had in its exercise in a predictive mode. The key words here are *over a relatively long period* and *in sufficient spatial detail.* Other investigators have looked and are looking at GSB for periods of several weeks -- no one has ever looked long enough, however, to resolve the longer period (2.5, 4, 6, and 18 days in length) fluctuations in volume and salinity which are presumably related to storm cycles.

During the year ending on 30 June 1981 (the second year of our physical program) such a numerical model of GSB was constructed and is currently being exercised to study the relationship between meteorological forcing and the longer period fluctuations in volume referred to above (task 10 of the GSB study plan). This is a modified version of a model known as CAFE.

In the third year of our program, we intend to determine the location of the most probable hard clam brood stock areas which produce sets on known productive areas (task 12 of the GSB study plan). Since *Mercenaria mercenaria* larvae are at the mercy of physical processes, i.e., advection and turbulent diffusion, during much of their early existence, our approach to the problem posed by task 12 will be to simulate the spawning and resultant spreading of hard clam larvae during their planktonic existence in a numerical, two-dimensional, finite element, dispersion model of Great South Bay. For this purpose, a dispersion model known as DISPER-1 has been selected. This model will predict and plot or tabulate organism concentration over time at points within a two-dimensional finite element grid representing Great South Bay given the following information:

a) The geometry of GSB in the form of a finite element grid, including the depths,

b) The circulation field, i.e., currents, over time, dispersion or diffusivity values, and larval mortality rates, and

c) The location, duration, and strength of the spawning.

The circulation field (b, above) will be obtained by exercising our modified version of CAFE. This model computes velocities at an array of points known as nodes over time when real time water elevations at all open boundaries and surface wind are inputted. As noted above, we have been exercising this model with actual water elevations and surface wind for several months pursuant to our work on task 10. Larval mortality rates and source strengths (b and c, above) will be estimated and/or parameterized based on the best available archived information. A correct assignment of mortality rates and source strengths (numbers spawned) is not required for a solution to the question of brood stock location; only for predicting setting densities. Direct measurements of dispersion or turbulent diffusion, i.e., dye tracer experiments, have not been made in eastern GSB. Since most of what we have learned concerning turbulent diffusion has come from dye tracer studies (Okubo, 1971, 1976), one was proposed to the County of Suffolk for the summer of 1980 to quantitate the mixing, i.e., spreading rate of waterborne substances such as clam larvae, contaminants, etc. in eastern GSB.

In addition to its primary goal of providing values of the diffusivity for the model, the data obtained was to be analyzed for hard clam management implications, particularly the hard clam spawner transplant programs. The two-part proposal was approved and funded by Suffolk County effective on June 1, 1980.

This report describes and provides results of the 1980 dye study.

II. THE 1980 GSB DYE TRACER STUDY

A. *Experimental*

In simplest terms, the fluorescent dye tracer technique consists of releasing a known quantity of tracer material and

measuring its subsequent distribution as a function of space and time. Thus the required quantities to be measured are concentration of the tracer material and position of the sampling vessel as a function of time. In the manner to be described below, both were measured continuously while underway and correlated through the time of observation.

Position information was obtained from a Motorola Mini-Ranger III System with reference stations located on Fire Island at Sailors Haven and Davis Park (Figure 1). The Mini-Ranger typically exhibits a standard deviation in range of ± 2.5 m or a 1 in 20 chance that the error will exceed 5 m.

The concentrations of the tracer material were determined with a continuous underway sampling and servo-balance recording fluorometer, the Turner Model 111 (G.K. Turner Associates, Palo Alto California). With the installed combination of cuvette, lamp, and filters, the fluorometer read full scale on the most sensitive scale (100 units on 30 scale) for 0.45 ppb of tracer. The instrument is readable and stable to plus or minus one fluorometer unit so that the detection limit might be taken as ± 0.005 ppb during the experiment. However, the background variation for GSB waters was found to be ± 0.02 ppb so that this is considered to be the limiting value of sensitivity or detection for this experiment.

The continuous underway samples were drawn through a one-half inch clear polyethylene hose which terminated on the forward edge at the bottom of an aluminum faired strut. The strut was mounted vertically approximately one foot from the side on the port quarter of the sample boat so that it could swing in a short arc about a vertical axis approximately one foot forward of the strut thus minimizing lateral forces.

The fluorescence of Rhodamine tracer materials decreases with increasing temperatures at a rate of 2.7% per degree C. Accordingly, temperature (T) was measured continuously with a thermistor probe mounted downstream from the fluorometer in the sampling hose. In addition conductivity (C) was measured with an Interoceans Model 550 CTD with a flow cell fitted to its sensor for continuous measurements of C. The C-T-Fl system was plumbed so that water was first drawn through the fluorometer, then the pump, then the temperature flow cell, then the conductivity flow cell, and finally over the side. This way air bubbles were eliminated from the fluorometer cuvette. Fluorescence, temperature, and Mini-Ranger ranges were printed every 2-3 seconds on a Anadex DP650 printer; conductivity was recorded on strip chart. Temperature and fluorescence were also recorded on strip chart for backup.

The sampling program was carried out on the R/V SIOME, a 23 foot Penn Yan with tunnel drive. Background fluorescence was measured throughout central and eastern GSB on 11 and 12 September, 1980.

At 1303, 15 September, 1980, 223 pounds of a 20% solution of Rhodamine WT was released approximately 2150 yards (1966.5 m) east of buoy N"30". The release point is shown on Figure 1 as (R). The release was accomplished by pouring the solution as rapidly as possible (∿ 6 minutes) on the surface from 5 5-gallon Jericans. The patch was sampled on 16(2×), 17, 18, 19, 22, 23, 25, 28 September and on 01 October, 1980.

B. *Results*

Figures 2 through 10 show the horizontal distribution of the dye tracer at various times. Although not shown, vertical casts showed the dye tracer to be well mixed vertically on and after 19 September; on 18 September several casts showed vertical structure with higher concentrations of dye at the bottom. This distribution is considered to be representative of the

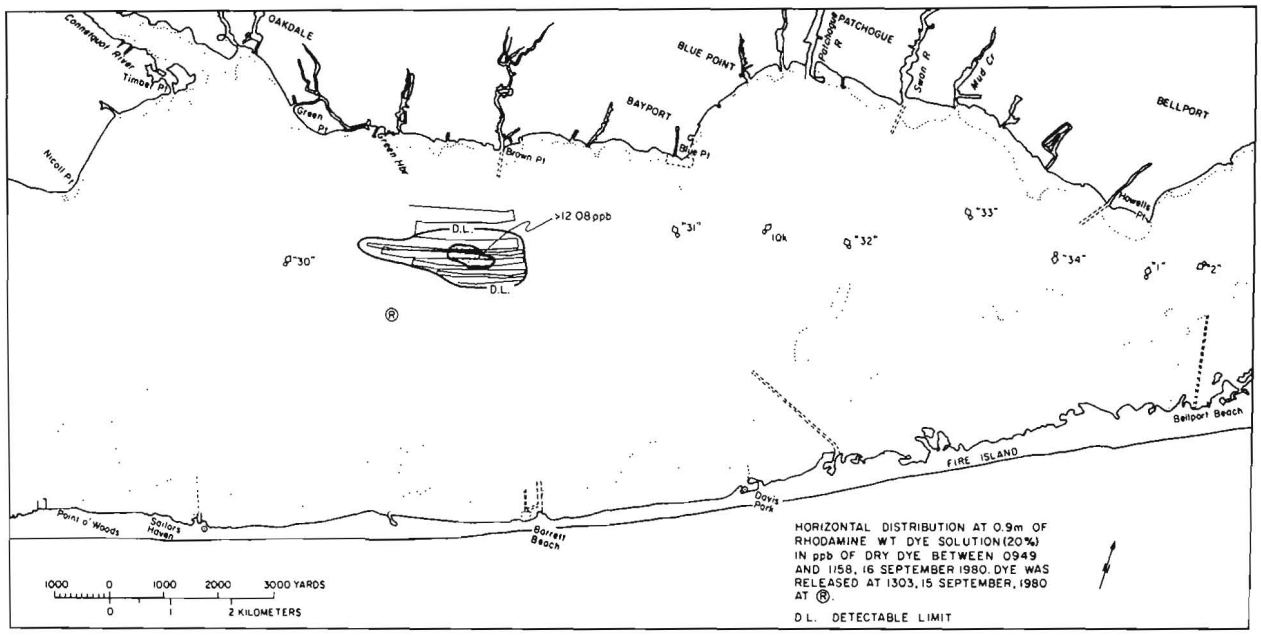
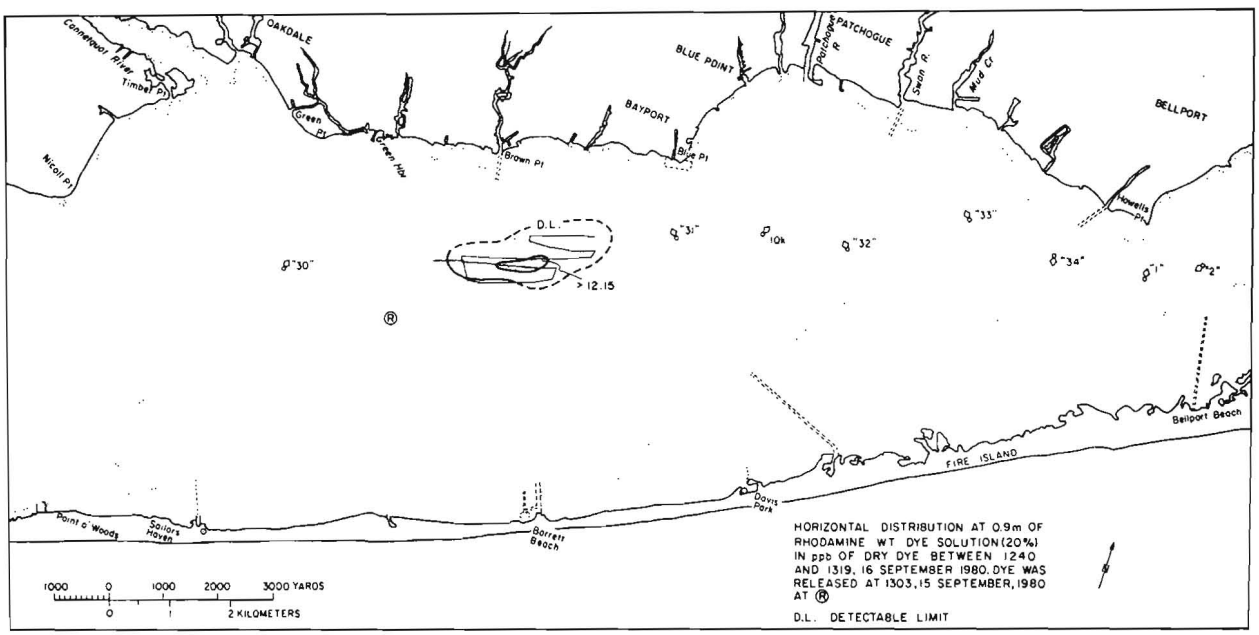


Figure 2.



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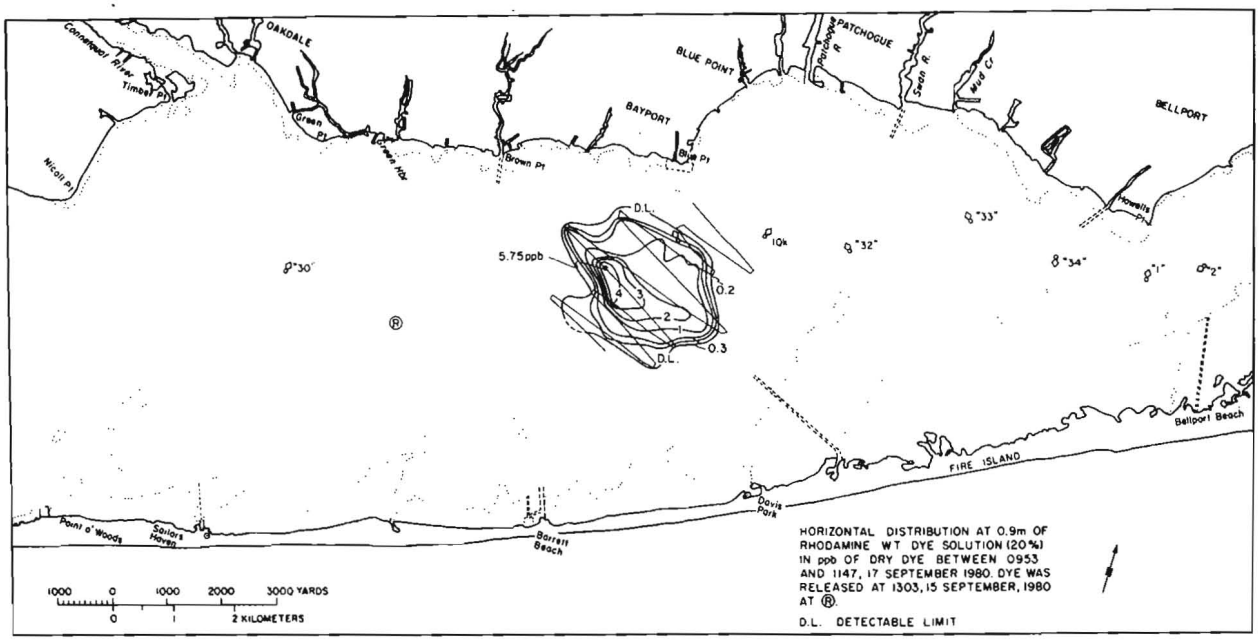

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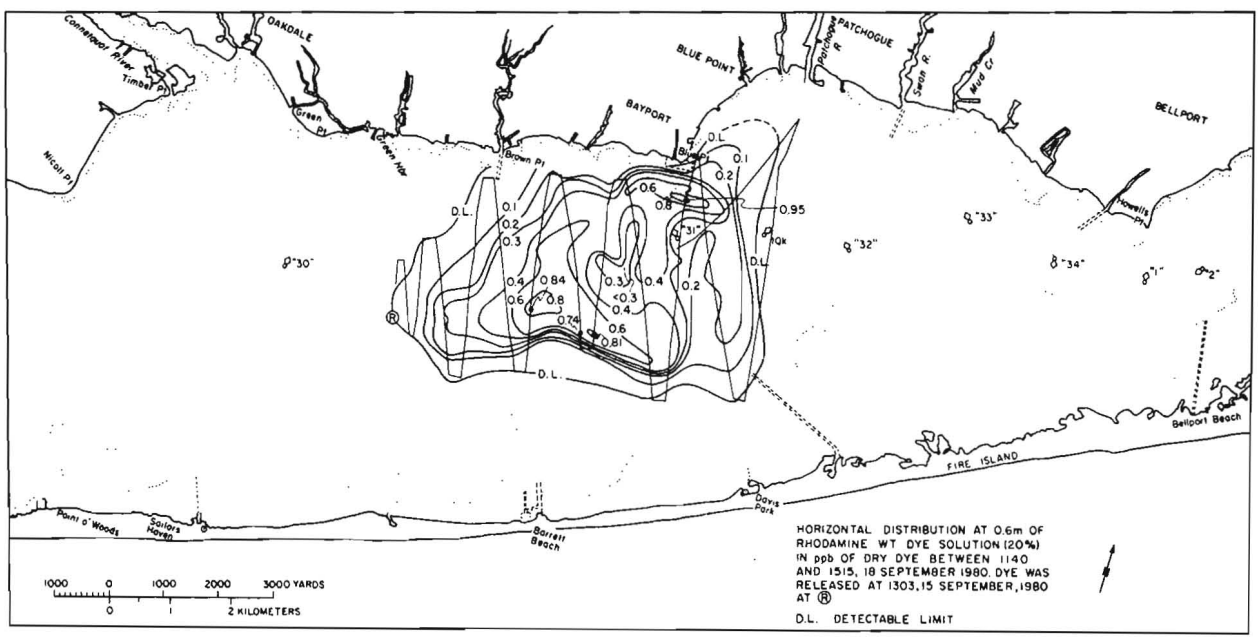

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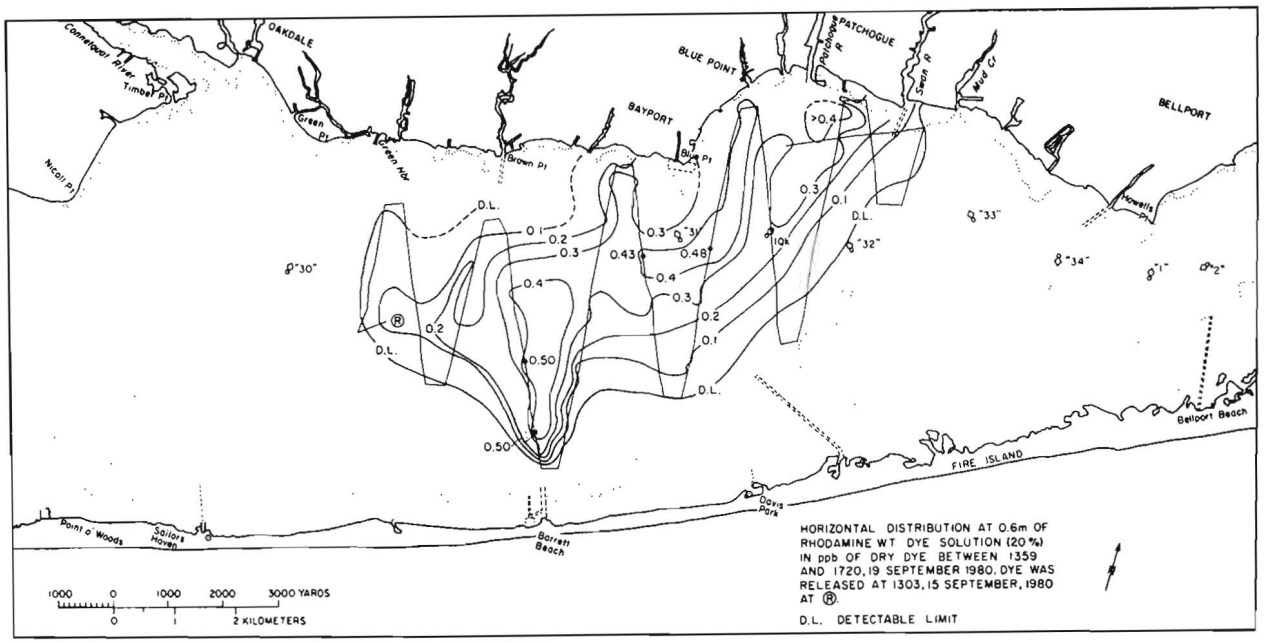

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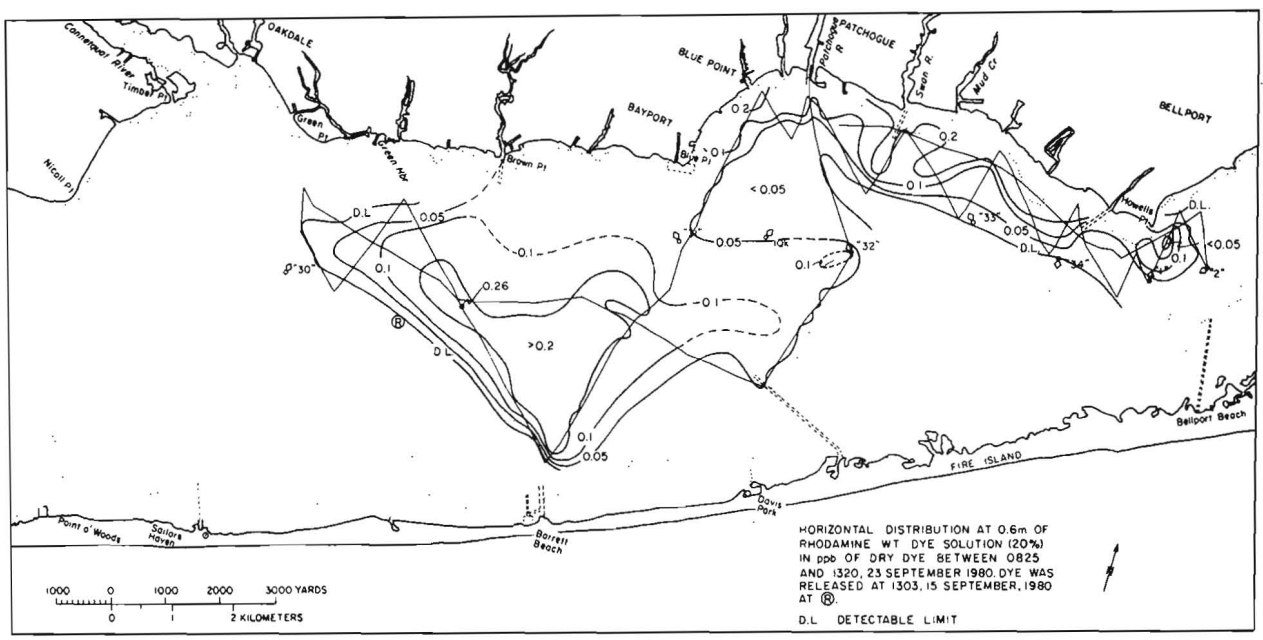

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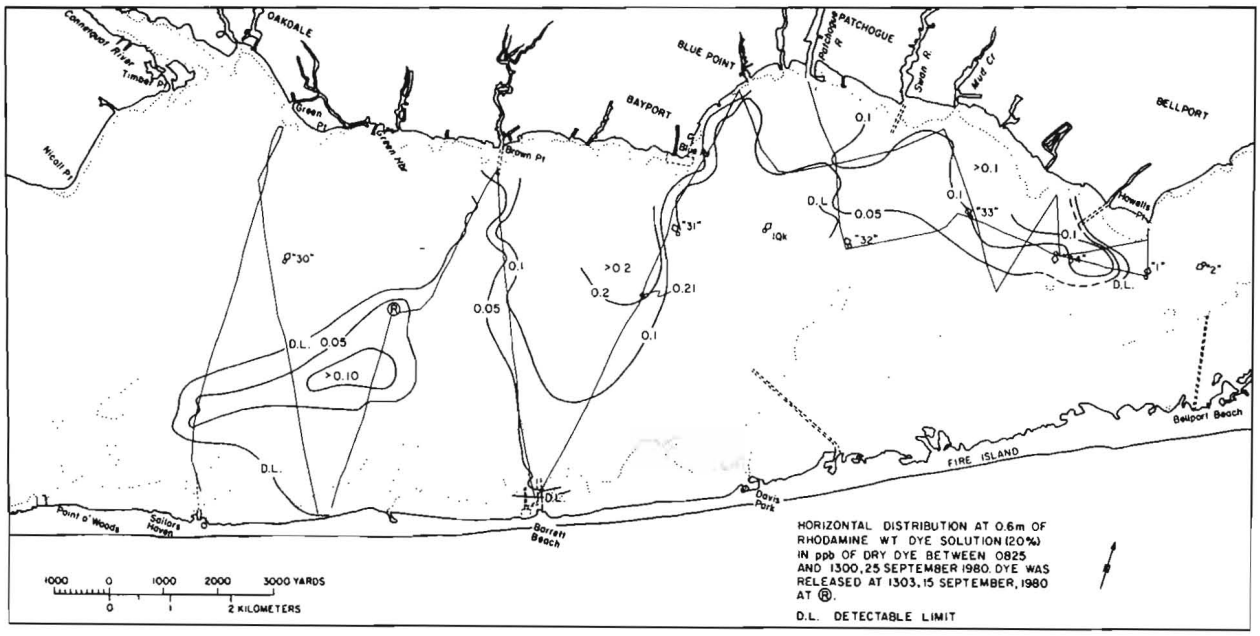

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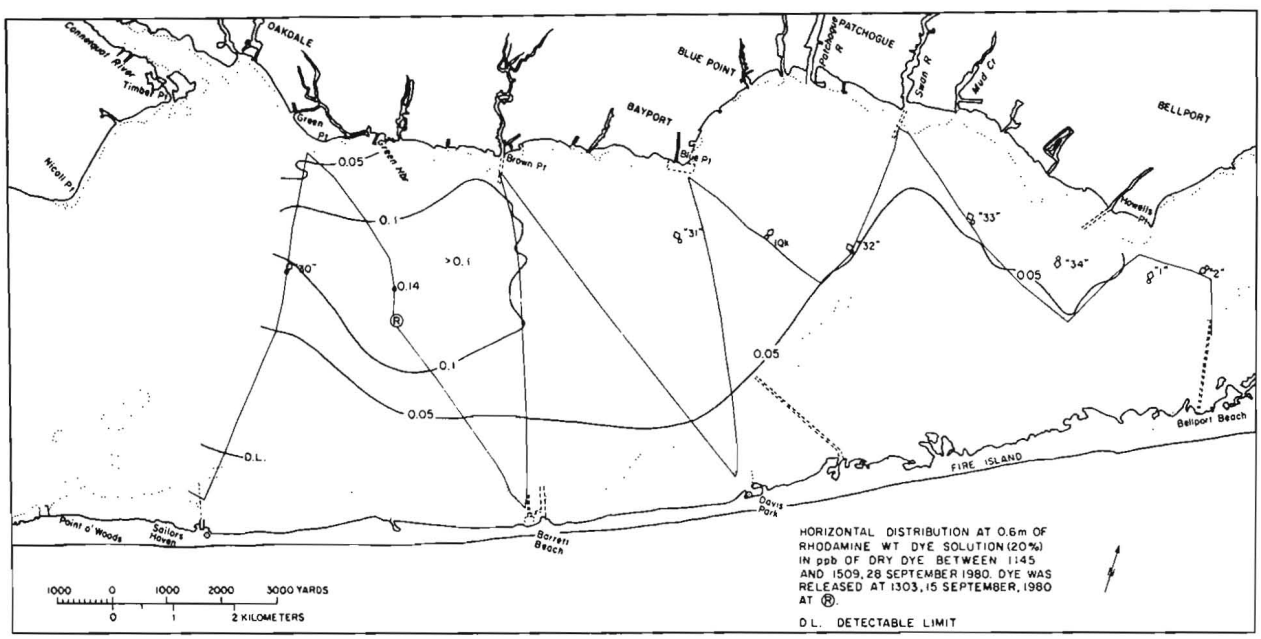

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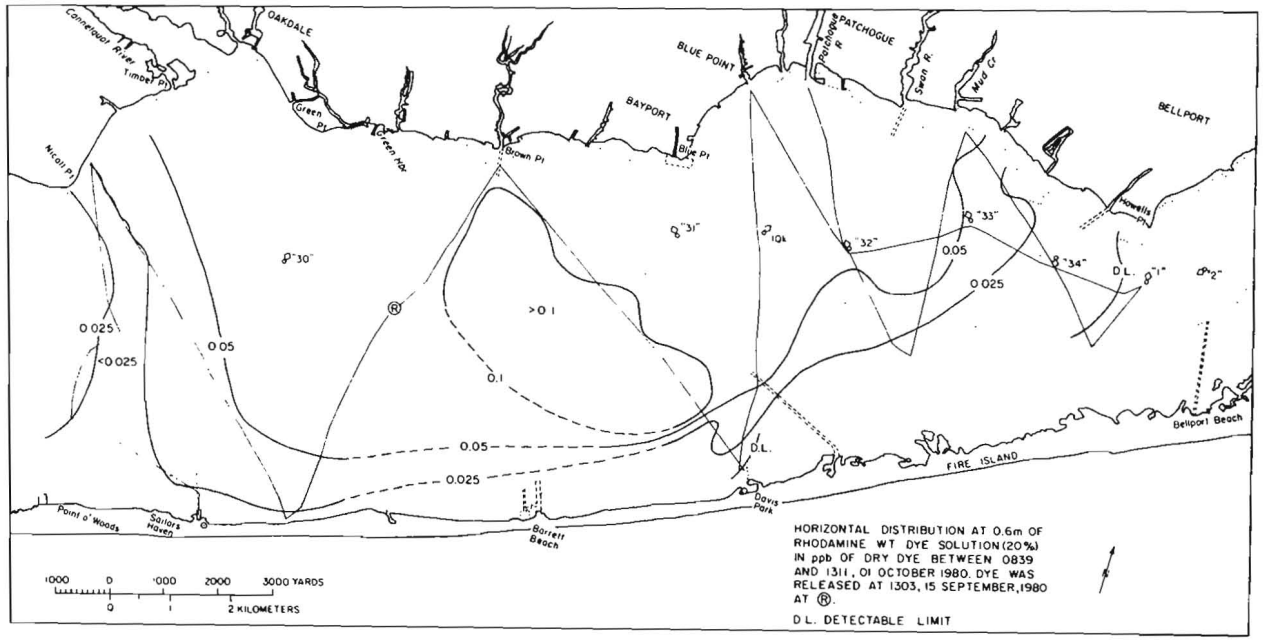
OAKDALE
Connetquot River
Timber Pt
Nicoll Pt
Green Pt
Green Hbr
Brown Pt
BAYPORT
Blue Pt
BLUE POINT
Patchogue R
PATCHOGUE
Swan R
Mud Cr
BELLPORT
Howells Pt
"30"
"31"
"32"
"33"
"34"
"1"
"2"
0.025
<0.025
0.05
>0.1
0.1
0.05
0.025
D.L.
Point o' Woods
Sailors Haven
Barrett Beach
Davis Park
FIRE ISLAND
Bellport Beach
1000 0 1000 2000 3000 YARDS
0 1 2 KILOMETERS
HORIZONTAL DISTRIBUTION AT 0.6m OF RHODAMINE WT DYE SOLUTION (20%) IN ppb OF DRY DYE BETWEEN 0839 AND 1311, 01 OCTOBER 1980. DYE WAS RELEASED AT 1303, 15 SEPTEMBER, 1980 AT Ⓡ.
D.L. DETECTABLE LIMIT

Figure 10.

vertical distribution of dye during the first 3 days after release and was probably due to overturning on the evening of the 15th and early morning of the 16th that was not erased until 19 September. This speculation is borne out by the fact that air temperatures on the evening of the 15th and the morning of the 16th were approximately 4°C colder than the minimum for the previous two days. There is similar evidence that overturning may have also occurred again on the morning of the 19th but by that time the tracer was well mixed vertically and no vertical structure resulted.

III. ANALYSIS & INTERPRETATION OF RESULTS

A. *Turbulent Diffusion Parameters*

Horizontal diffusion in the sea cannot be adequately described by a Fickian-type diffusion model, i.e., diffusion characterized by a constant coefficient of eddy diffusion (the turbulent eddy diffusivity). This fact has been well documented by Richardson, 1926; Burke, 1946; Richardson and Stommel, 1948; Stommel, 1949; Okubo, 1962. It is also fair to say that today (1981), 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

$$C_d(t,r_e) = \frac{M_d/D}{\pi\sigma_{rc}^2(t)} \exp\{-\frac{r_e^2}{\sigma_{rc}^2(t)}\} \qquad (1)$$

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 $\sqrt{\text{area}/\pi}$.

At $r_e = 0$, $C_d = C_{d,p}$, the peak concentration, or from (1) we have

$$C_d(t,r_e) = C_{d,p}(t,o) \exp\{-\frac{r_e^2}{\sigma_{rc}^2(t)}\} \qquad (2)$$

A plot of log $(C_d/C_{d,p})$ versus r_e^2 at various times allows one to determine σ_{rc}^2 as a function of time. We show in Figure 11 to illustrate the methodlogy, $\ell n C_{d,p}$ plotted versus r_e^2 for t = 44.78-46.68 h on 17 September, 1980. According to equation (2), $1/\sigma_{rc}^2 = 2.6738$ or $\sigma_{rc} = 0.6116$ km.

The result of carrying out this procedure at all times for which sufficient closed horizontal concentration distributions were available is a list of σ_{rc}^2 as a function of time. In Figure 12 are plotted $\ell n(C_d/C_{d,p})$ versus $(r_e/\sigma_{rc})^2$ for the 17, 18, 19, and 23 September runs. Figure 12 suggests that until 19 September the distribution was more peaked than a Gaussian distribution. In Table 1 are shown pertinent statistics for the first eight days of the experiment. After eight days, it was either not possible to close sufficient isolines of concentration or the patch was boundary affected. In Table 1 the following definitions were used in the computations:

$\omega \equiv \sigma_{rc}/t$, the diffusion velocity,

$\ell \equiv 3\sigma_{rc}$, the scale of diffusion, and

$K_a \equiv \sigma_{rc}^2/4t$, the apparent diffusivity.

The column labelled M_d is the actual amount of dry dye released, i.e., 20% of 223 pounds and the column labelled D is the depth in meters calculated from

$$D = \frac{M_d}{C_{d,p}\pi\sigma_{rc}^2} \qquad (3)$$

It can be seen that these calculated depths

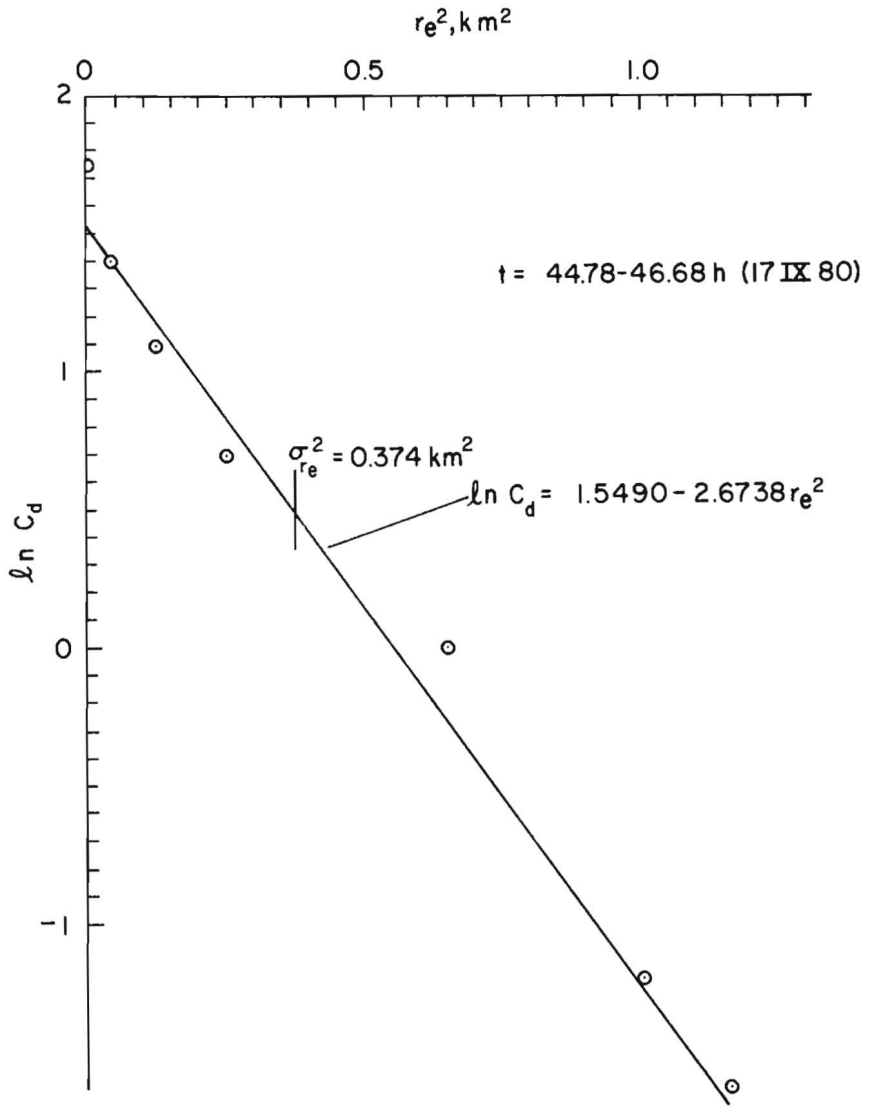

Figure 11. Normalized dye concentrations, $C_d/C_{d,p}$, plotted as a function of r_e^2 for t = 44.8-46.7 h (17 IX 80).

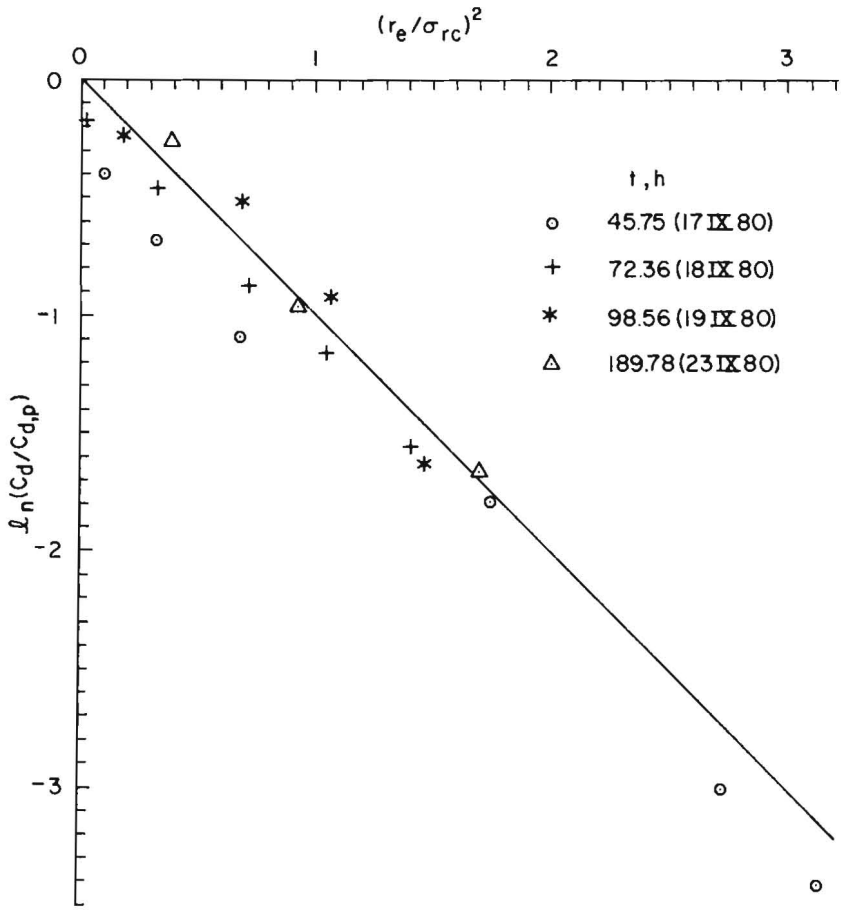

Figure 12. Normalized dye concentrations, $C_d/C_{d,p}$, plotted as a function of r_e^2 normalized by σ_{rc}^2 for t = 45.75 h, 72.36 h, 98.56 h, and 189.78 h.

Table 1

Computed Diffusion Statistics for the IX 80 GSB Dye Study

Date	$\bar{t}$,s	σ_{rc}^2,cm^2	σ_{rc},cm	K_a,cm^{2}s^{-1}	ℓ,cm	$C_{d,p}$,ppb	M_d,k_g	D,m*
17 IX 80	1.612×10^5	3.74×10^9	6.12×10^4	5.80×10^3	1.84×10^5	5.75	20.23	2.99
18 IX 80	2.605×10^5	2.70×10^{10}	1.64×10^5	2.59×10^4	4.93×10^5	0.95	20.23	2.51
19 IX 80	3.548×10^5	4.88×10^{10}	2.21×10^5	3.44×10^4	6.63×10^5	0.50	20.23	2.64
23 IX 80	6.832×10^5	6.05×10^{10}	2.46×10^5	2.21×10^4	7.38×10^5	0.26	20.23	4.09

*Calculated from equation (3).

agree reasonably well with the actual depths in central GSB, $\sim$ 3 m suggesting that little dye has been lost. By the 23rd of September, however, only 65 to 75% of the dry dye released was contained within our contours.

In order to compare our results with those of Okubo's (Okubo, 1971) and the well-known 4/3 power law relating diffusivity to scale, we have plotted our values of σ_{rc}^2 and K_a as functions of time t and scale, ℓ, respectively, on Figures 13 and 14 together with the data from Becker's 1976 dye study in western GSB. Also shown on Figures 13 and 14 are Okubo's equations (3) and (4) which are

$$\sigma_{rc}^2(t) = 0.0108\ t^{2.34}, \text{ and}$$

$$K_a(\ell) = 0.0103\ \ell^{1.15}$$

and a line of slope 4/3 for purposes of comparing the theoretical 4/3 slope with GSB data and Okubo's relations.

It is obvious from our results and Okubo's (Okubo, 1971) that the variance grows much faster than linearly with time; Fickian diffusion characterized by a constant diffusivity would result in the variance increasing linearly with time. On the other hand, the theoretical relations for diffusivity ($\ell^{4/3}$) and variance (t^3) are apparently only followed locally, if at all. In addition, our dye patches spread or diffused less rapidly than what would have been predicted by Okubo's diffusion relationships which are based on a large number of similar dye releases in *oceanic* and *coastal* waters. Okubo notes, however, that scatter in his data is considerable, almost an order of magnitude for the same time of diffusion, due probably to the fact that the data were collected under a wide range of environmental conditions. Accordingly, we consider the following equations to be satisfactory for estimating values of variance or eddy diffusivity appropriate for summertime conditions in Great South Bay.

$$\sigma_{rc}(t)^2 = 0.084\ t^{2.08}\ [\text{cm}^2], \text{ and} \quad (4)$$

$$K_a(\ell) = 0.024\ \ell^{1.04}\ [\text{cm}^2\ \text{s}^{-1}]. \quad (5)$$

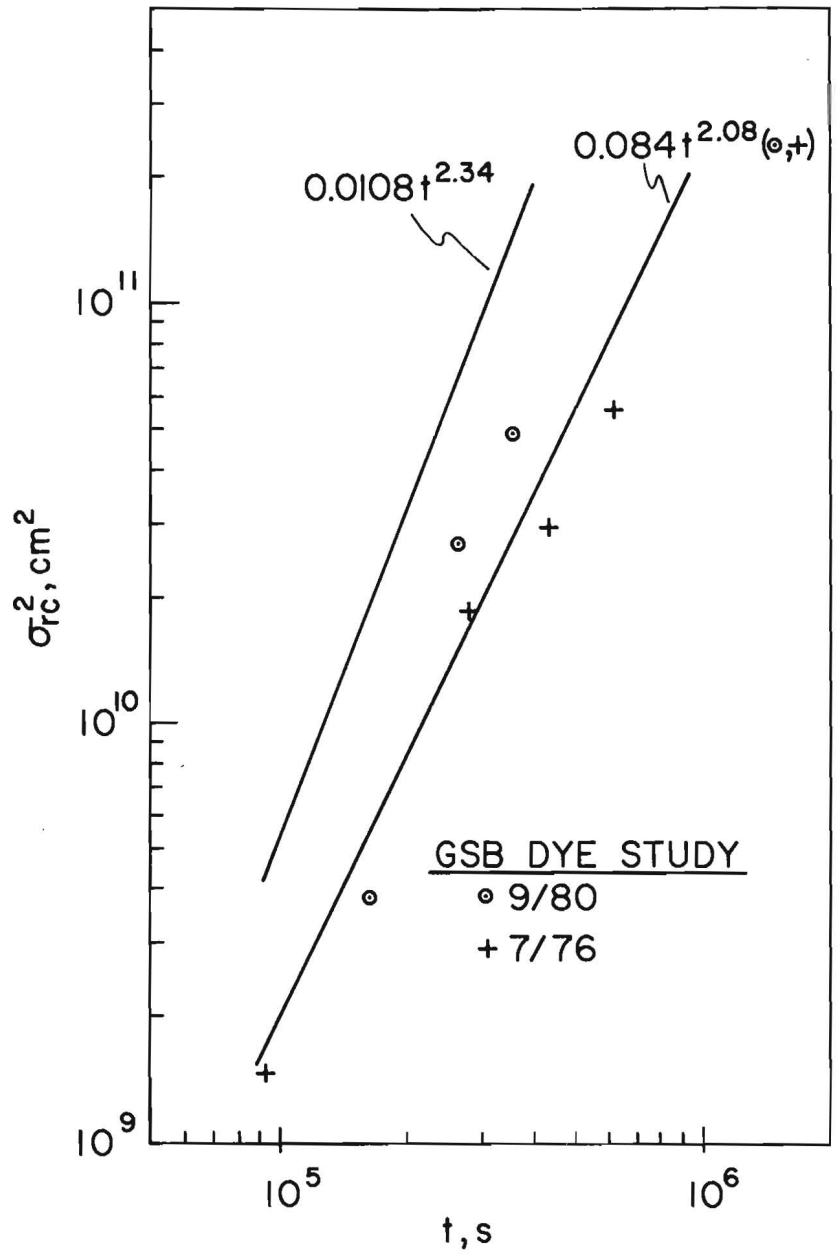

Figure 13. The variance, $\sigma_{rc}^2(t)$, of the dye patch as a function of time t since release.

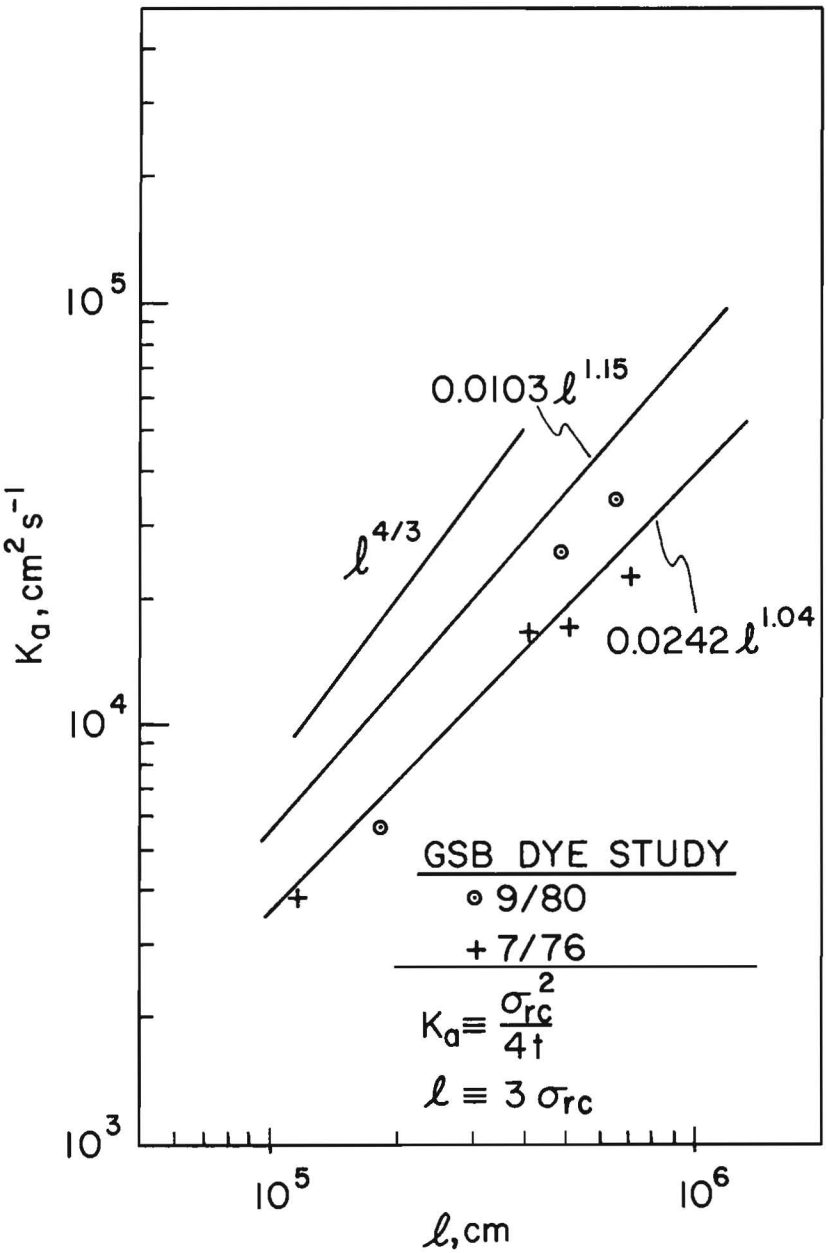

Figure 14. The apparent diffusivity, K_a, as a function of the scale of diffusion, ℓ.

There is a diffusion model known as the Okubo-Pritchard (O-P) diffusion model (Okubo and Pritchard, unpublished note in Pritchard (1960)). This model is one of a class of radially symmetric solutions for horizontal diffusion from an instantaneous vertical line source characterized by a "diffusion velocity." The O-P model is based on the intuitive concept that the rate of change of local variance, i.e., the diffusivity, depends on a characteristic velocity, ω, and the time of diffusion. We recognize that in a turbulent environment the shape of an instantaneous release of material is seldom if ever circular and that by characterizing the velocity field as spatially uniform we cannot account for the highly variable trajectories taken by the various patches. Nevertheless, radially symmetric models have achieved considerable success in predicting the diffusion of introduced substances.

In the O-P model

$$\sigma_{rc}^2(t) \equiv \omega^2 t^2 \qquad (6)$$

which seems to fit our data quite well if we use an overall value of 0.29 cm s^{-1} for ω.

B. *Management Implications*

1. Where We Derive the Relation Between Dye and Larvae

If we assume that the hard clam larvae are advected and diffused during their approximately 8-16 day planktonic existence, then the observed horizontal distribution of dye tracer may be used to determine the probable distribution of larvae if we take into account the differences in dye released or eggs spawned and fertilized (larvae), depths of mixing, and larval mortality. That is, we can write

$$\frac{C_d D_d}{M_d} = \frac{C_\ell D_\ell}{N_\ell} \qquad (7)$$

where C_d; C_ℓ = concentrations of dye tracer and larvae, respectively, at time t after release or spawning,

M_d; N_ℓ = mass of dry dye initially released; the number of larvae contained in the population at time t, and

D_d; D_ℓ = vertical extent of the dye and larvae, respectively, at time t.

If we assume that the rate of change of larval population at any time t because of predation, death, and other unspecified causes (not dilution) is proportional to the population at the same time t, then

$$\frac{dN_\ell}{dt} = -k_m N_\ell \qquad (8)$$

and

$$N_\ell = N_{\ell,0} \exp(-k_m t) \qquad (9)$$

Substituting equation (9) in equation (7) we have that

$$C_\ell = C_d \frac{D_d}{D_\ell} \frac{N_{\ell,o} \exp(-k_m t)}{M_d} \qquad (10)$$

which is the required scaling relation of dye to larval concentration.

2. Where We Estimate the Value of k_m

All the parameters in equation (10) are known or can be assumed with some degree of accuracy except k_m. Little is known of its proper value. Carriker (Carriker, 1961) has estimated the percentage survival of 10 dense swarms of clam veligers in upper Lower Little Egg Harbor, New Jersey during 1948, 1949, 1950 and 1951. In 4 of the 10 swarms, there were no survivors; the mean disappearance rate of the remaining 6 swarms was 68% per day. The data, however, contains unknown effects of dilution by physical processes. Carriker notes that on the 4 occasions when no larvae survived, tidal amplitudes had increased from 1.4 to 2.7 feet. In addition,

he notes that, in general, there was a progressive decrease in larvae between upper Lower Little Egg Harbor and the ocean inlets. *This is consistent with the hypothesis that a substantial fraction of the water leaving Lower Little Egg Harbor does not return but is replaced by ocean water.* From Carriker's measurements, 30.3% of the sea water in Little Egg Harbor at mean high water empties into the Atlantic Ocean on the subsequent ebb tide. A residence time, τ, of 2.11 days for Little Egg Harbor can thus be calculated if we assume that the water in the Harbor is fully mixed on each flood tide. Therefore,

$$C_{\ell,t} = C_{\ell,o} \exp\{-\frac{t}{\tau}\} \qquad (11)$$

where $C_{\ell,o}$ is the initial larval concentration, and $C_{\ell,t}$ is the larval concentration at time t due to exchange between upper Lower Little Egg Harbor and the ocean.

Using Carriker's data for the 10 swarms sampled, a disappearance rate, $k_{m,d}$, of 1.232 days^{-1} for both exchange and mortality can be calculated. Since the two processes, exchange and mortality, are exponential

$$\frac{1}{\tau} + k_m = 1.232 \text{ day}^{-1} \text{ or}$$

$$k_m = 1.232 - \frac{1}{\tau} = 1.232 - 0.474$$
$$= 0.758 \text{ day}^{-1}$$

3. Where We Calculate an Estimated Set from 500 Bushels of Brood Stock

We wish now to calculate the additional set in Great South Bay from a hypothetical brood stock of 500 bushels of littlenecks (250,000 clams) planted in the vicinity of our dye release point. If it is assumed that the fecundity of these littleneck clams is 3×10^6 eggs/clam (Bricelj, 1979) then

$$N_\ell(0) = (500)(500)\ 3\times10^6 = 7.5\times10^{11} \text{ larvae}$$

If the temperature is optimum for growth and the food supply is ample, the larvae will set, on the average, in 10 days (personal communication, R.E. Malouf). We will consider 3 possibilities, 8, 10, and 16 days. From equation (10), therefore, for t = 10 days and $D_d = D_\ell = 3$ m we have that the clams m^{-2}, $C_\ell D_\ell$, is given by

$$C_\ell D_\ell = \frac{C_d D_d}{M_d} \cdot N_{\ell,o} \exp\{-0.758\ t\}$$

$$= \frac{C_d \cdot 300}{2.023\times10^4} \times 7.50\times10^{11}$$
$$\exp\{-0.758\times10\}$$

$$= C_d\{5.68\times10^6\} \text{ clams/cm}^2$$

$$= C_d\{5.68\times10^{10}\} \text{ clams/m}^2$$
$$t = 10 \text{ days} \qquad (12)$$

Similarly, for t = 8 and 16 days, we have that

$$C_\ell D_\ell = C_d\{2.59\times10^{11}\} \text{ clams/m}^2$$
$$\text{for } t = 8 \text{ days, and} \qquad (13)$$

$$C_\ell D_\ell = C_d\{6.01\times10^8\} \text{ clams/m}^2$$
$$\text{for } t = 16 \text{ days.} \qquad (14)$$

We can now convert a few of the dye concentrations (ppb or g cm$^{-3}\times10^{-9}$) on Figures 7, 8, and 10 to clams m^{-2}, measure the areas they enclose, calculate the total set, and tabulate. The results are shown in Table 2.

It is clear from Table 2 that as the time since fertilization increases, both larval density, clams m^{-2}, and the area enclosed by a given isoline of C_d or C_ℓ, decrease as a result of the combined effects of mortality and mixing. Larval density decreases, of course, as the result of both mortality and mixing. The reason for the reduction in area is not so obvious. Qualitatively it can be seen by visualizing a puff of smoke released instantaneously by a smoker. The smoke cloud will be seen to grow and then to disappear. It can be shown mathematically that the radius of all isolines of concentration greater than some

Table 2

Clam Sets at 8, 10, and 16 days - Estimated from Dye Results

	t = 8 days			t = 10 days			t = 16 days		
C_d,ppb	Clams/m^2	Area,km^2	# Clams	Clams/m^2	Area,km^2	# Clams	Clams/m^2	Area,km^2	# Clams
0.10	25.9	17.84	4.62×10^{12}	5.68	14.18	8.05×10^{11}	0.06	9.34	5.61×10^{5}
0.20	51.8	7.09	3.67×10^{12}	11.36	4.52	5.13×10^{11}	-	-	-

value[1] will first increase, then peak, and ultimately decrease to undetectable levels. The radius of the 0.1 and 0.2 ppb isolines had obviously peaked prior to t = 8 days (Table 2).

If we have correctly estimated the order of magnitude of k_m, Table 2 suggests that late setters (t = 16 days) will not augment the natural set. 5.61×10^5 clams is only two times the number of spawners planted and, if one takes into account predation between setting and growth to littleneck size, will more than likely be reduced to a number considerably less than the 500 bushels planted.

The early setters on the other hand, although considerably more numerous will be subjected to an additional period of predation by a wide variety of predators in GSB. 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. Thus if the post setting mortality rate is of the same order (or greater) than before, an augmentation of the natural set will not occur for the early setters either, at least for quantities of spawners less than 1000 bushels.

The numbers in Table 2 should be interpreted cautiously however, since our estimate of k_m is crude at best having been derived from a system other than GSB with minimal data. The numerical exercise does serve to illustrate, however, the necessity of defining the parameters which must be measured simultaneously in a natural system if one is to make any meaningful estimate of the supplemental set due to a spawner transplant program. What is required is some method of tagging a swarm of clam larvae with a dye tracer so that it can be followed, organism and dye concentrations monitored, and the dilution extracted from the data. Any remaining decrease in larval concentration would be considered mortality of course.

I have carried out experiments of this type for the purpose of measuring the disappearance rate of coliform bacteria when discharged into receiving waters through a sewage outfall (Carter, 1967). In that case, however, it was possible to discharge a large slug of dyed sewage effluent, high in both dye concentration and coliforms, so that dilution and disappearance due to all causes such as predation, temperature, salinity, etc. could be separated.

More closely related to the hard clam problem was an experiment that was carried out in 1961 by N.A. Chamberlain (Chamberlain, 1962) in Lake Ogleton, MD for the purpose of measuring the mortality rate of the mud crab (*Rhithropanopeus Harrisii*) larvae. Lake Ogleton is a small tidal embayment located near the junction of the Severn River and Chesapeake Bay. It was chosen for the experiment because it had a substantial adult crab population and minimal exchange with the Severn River/Chesapeake Bay. Chamberlain simply dyed the whole lake (low water volume = 1.3×10^6 m^3) with rhodamine dye just prior to the onset of spawning and followed the dye and larvae for approximately 30 days. He calculated that between 4 and 18 June, the observed loss of dye was 1.90% per tidal cycle, i.e., loss due to exchange of Lake Ogleton water with Severn River/Chesapeake Bay water, and the loss of larvae to be 3.84% per tidal cycle. Thus, the larval mortality rate was actually 3.84%-1.90% or 1.94% per tidal cycle. From this and our numerical example, it is clear that reductions in larval concentrations by dilution are of the same order of magnitude as those due to other causes and that an experiment similar to the one performed by Chamberlain in Lake Ogleton is needed in GSB before one can more precisely evaluate GSB spawner transplant programs.

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[1]This value of concentration is given by the amount of smoke released divided by the volume into which it is mixed.

REFERENCES

Bricelj, V.M. 1979. Fecundity and related aspects of hard clam *(Mercenaria mercenaria)* reproduction in Great South Bay, New York. M.S. Thesis, Marine Sciences Research Center, State University of New York at Stony Brook, 98 pp.

Burke, C.J. 1946. Horizontal diffusion of dyes in the ocean. Scripps Institution of Oceanography, Univ. of California, Oceanographic Report No. 2.

Carriker, M.R. 1961. Interrelation of functional morphology, behavior, and autecology in early stages of the bivalve *Mercenaria mercenaria.* Journal of the Elisha Mitchell Scientific Society, Vol. 77, No. 2, 168-241.

Carter, H.H., J.H. Carpenter, and R.C. Whaley. 1967. The bactericidal effect of seawater under natural conditions. J. Water Pollution Control Federation. Vol. 39, 7:1184-1189.

Chamberlain, N.A. 1962. Ecological studies of the larval development of *Rhithropanopeus Harrisii* (Xanthidae, Brachyura). Chesapeake Bay Institute, The Johns Hopkins Univ. Tech. Rept. 28, Ref. 62-18.

Okubo, A. 1962. Horizontal diffusion from an instantaneous point-source due to oceanic turbulence. Chesapeake Bay Institute, The Johns Hopkins Univ. Tech. Rept. 38, Ref. 68-6.

_____. 1971. Oceanic diffusion diagrams. Deep-Sea Research, Vol. 18, 789-802.

_____. 1976. Remarks on the use of 'diffusion diagrams' in modeling scale-dependent diffusion. Deep-Sea Research, Vol. 23, 1213-1214.

Pritchard, D.W. 1960. The application of existing oceanographic knowledge to the problem of radioactive waste disposal into the sea, *In* Disposal of radioactive wastes. Vol. 2, International Atomic Energy Agency, Vienna, pp. 229-248.

Richardson, L.F. 1926. Atmospheric diffusion shown on a distance-neighbour graph. Proc. Roy. Soc. London, *A110:*709-727.

_____ and H. Stommel. 1948. Note on eddy diffusion in the sea. J. Meteorol. *5:*238-240.

Stommel, H. 1949. Horizontal diffusion due to oceanic turbulence. J. Mar. Res. *VIII*(3):199-225.

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