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THE POLLUTION SUSCEPTIBILITY OF THE MARINE WATERS OF NASSAU AND SUFFOLK COUNTIES NEW YORK

BY
P. K. WEYL

PREPARED WITH
SUPPORT
FROM THE
NASSAU - SUFFOLK
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Technical Report No. 20

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Prepared with support from the
Nassau-Suffolk Regional Planning Board

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CONVERSION FACTORS

1 metric ton = 10^6 grams
= 2205 pounds
= 1.102 short tons

1 metric ton per day = 92 pounds per hour
= 1.53 pounds per minute

1 cubic meter = 264 gallons
= 35.3 cubic feet

1 day = 24 hours
= 1440 minutes
= 86,400 seconds

1 cubic foot per second = 2447 cubic meters per day

1 kilometer = 0.540 nautical miles
= 0.621 statute miles
= 3281 feet

1 million gallons per day = 3800 cubic meters per day
= 0.0438 cubic meters per second

1 knot = 1 nautical mile per hour
= 51.5 centimeters per second
= 44.5 kilometers per day

ABSTRACT

A new descriptive parameter of the coastline, the pollution susceptibility, is developed. The pollution susceptibility is the average concentration in the water near the coast, that would result from a unit rate of discharge of a conservative pollutant that is miscible with the water. For potential continuous discharges in restricted bays, a second parameter, the steady-state pollution susceptibility, is developed. This is the average concentration that would result from a unit rate of discharge after the bay has come to a steady state with the pollutant. Dilution of pollutants in the Nassau-Suffolk marine waters results primarily from tidal action. The tidal amplitude and phase for the area, interpreted from published data, has been charted (Chart I). This information is used to produce charts of the two pollution susceptibility parameters (Charts II and III). Comparisons of the steady-state pollution susceptibility parameter for Long Island Sound with information on salinity and the concentration of dissolved phosphate indicate that the susceptibility is reliable within a factor of two. Hypothetical illustrations of how the charts can be used in the coastal zone planning process are given. The charts, which measure approximately 2 1/2 x 8 ft each, are not included in this report. They are on file with the Regional Marine Resources Council of the Nassau-Suffolk Regional Planning Board.

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These charts are not furnished with this report. They are on file with the Regional Marine Resources Council of the Nassau-Suffolk Regional Planning Board, Veterans Memorial Highway, Hauppauge, New York 11787.

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INTRODUCTION

The interaction between man's activity and the environment is becoming of increasing concern to decision makers. Man's activity is characterized by fluxes, i.e. rates of transfer of money, matter and energy. These are measured in amounts per unit time, such as dollars per year, tons per day, or British Thermal Units (BTU) per hour. The impact of this activity on the natural environment, however, depends on the resultant concentration, rather than on the fluxes. Thus the intensity of air pollution depends on the concentration of the pollutants in the air, rather than on their rates of discharge. The water quality depends on the concentration of organic matter in the water, rather than on the rates at which organic matter is discharged. The toxicity of the environment depends on the concentration of toxic substances, rather than on the rates at which these substances are released.

Pollution susceptibility describes the relationship between the flux of a pollutant and the resulting concentration. It is the concentration that would result from a unit flux. Pollution susceptibility is a parameter of the environment and depends on the physical processes of mixing and diffusion that tend to disperse the added contaminant. Pollution susceptibility is one of a number of important environmental parameters. Other parameters are the sensitivity of the environment and its present state of pollution. By sensitivity, I mean the extent to which a unit change in concentration of a specified pollutant disturbs the populations of plants and animals. Environments subject to small natural variations or near the tolerance limits of the organisms for that pollutant will be more sensitive than environments that are by nature highly variable. The sensitivity of an environment may also change with the seasons, as a result of natural biological cycles and when the environment is near its climatic extremes.

To estimate the effect of man on the environment requires the following steps. First, the actual or proposed rates of discharge of pollutants must be known. A knowledge of the pollution susceptibility then translates these fluxes into expected average concentrations of the pollutant. A knowledge of the sensitivity of the environment for the pollutant then allows us to estimate the biological impact of the expected concentration level. In addition, the existing state of pollution from other sources must be known in order to evaluate the significance of the proposed change. The pollution susceptibility thus forms only one link in the decision-making process.

The present study is concerned with the pollution susceptibility of the marine waters of Nassau and Suffolk counties. We are concerned with the concentrations of a pollutant that would result in these waters from a unit rate of discharge. The relationship between resultant concentration, C; discharge rate (flux), F; and pollution susceptibility, PS; is:

$$C = PS \times F.$$

If the concentration is given as a mass fraction (mass of pollutant per unit mass of water), it is dimensionless, and therefore the dimension of the pollution susceptibility is the reciprocal of the flux or time per unit mass.

A convenient concentration unit is parts per billion, the weight of the pollutant per billion (10^9) unit weights of water. If the flux is expressed in metric tons per day (2205 lbs/day, 92 lbs/hr), then, because the density of water is approximately 1 ton per cubic meter, the pollution susceptibility is the reciprocal of the volume in cubic kilometers, into which the daily discharge is dispersed (1 km^3 of water weighs 10^9 tons). These units result in convenient values for the pollution susceptibility, spanning a range from about 0.1 to 1 1000. We shall use these units exclusively so that:

$$C \text{ (ppb)} = PS \times F \text{ (metric tons/day)}.$$

The pollution susceptibility is a simple concept that relates the concentration of a pollutant to its rate of discharge. In applying this concept to the real world, however, we face a number of problems, for the discharge of a pollutant does not result in a uniform constant concentration in the environment. Rather the concentration varies from the full concentration discharged at the outflow pipe to zero at great distances from the discharge. Not only does the concentration vary in space, but it will also vary with time in response to the periodic tidal currents and to less predictable variations in the weather.

Our purpose in developing a pollution susceptibility parameter is not to predict the time-space variation that would result from a hypothetical discharge of a pollutant. Rather, we are interested in the relative response of different areas to a unit discharge. To permit such a comparison, we must average the concentration over a fixed area near the outfall, and average out the temporal variations.

The space scale over which we average the concentration is arbitrary. However, a consistent procedure must be used in order that the pollution susceptibility parameter be comparable from place to place. The scale used must be consistent with the purposes for which the parameter will be used by the planner. At the county planning level, one is not concerned with the immediate environment of individual minor outfalls, but rather with the impact of the discharges of major industries and communities. The geography must be considered on a horizontal scale of a mile rather than on a scale of feet. A typical thermal outfall from a major electric generating plant (LILCO's Northport Plant) extends about 1 km seaward from the shoreline. In view of the above, and for convenience, we shall use 1 km as the averaging distance. Conversions to English engineering units will be found at the end of the report. In the case of the open shoreline, we shall therefore use the concentration that would result, if the pollutant were uniformly dispersed through the water column to a distance of 1 km from shore.

Dispersion of pollutants in the bi-county waters results primarily from tidal currents. Averaging over time, we must consider the average tidal flow that passes per day within a distance of 1 km from shore, regardless of direction. The pollution susceptibility then is the reciprocal of the volume of water in cubic kilometers that passes under a line reaching to a distance of 1 km from shore during one day. We neglect the direction of the flow and so must add the average flood and ebb volumes per 24 hours.

For example, assume the average peak tidal velocity is one knot (51.5 cm/sec). Since for a sine wave, the average is $2/\pi = 0.637$ times the peak, the average velocity would be 32.8 cm/sec. Let the average depth of water to a distance of 1 km be 10 m. The total flow per day under the line then is:

$$1 \text{ km} \times .01 \text{ km} \times .328 \text{ m/sec} \times .864 \times 10^5 \text{ sec/day} = 283 \times 10^{-3} \text{km}^3\text{/day}$$

and the pollution susceptibility would be $1000/283 = 3.5$. Thus a discharge of 1 ton per day, if uniformly dispersed through the water out to a distance of 1 km from shore, would result in an average concentration of 3.5 ppb.

The spatial averaging must be modified in bays whose width is less than 1 km. In that case, the maximum distance perpendicular to the shore over which the pollutant can be dispersed is to the opposite shoreline.

We have defined a pollution susceptibility parameter by hypothetically dispersing the pollutant to a distance of 1 km from shore, and using the average scalar (irrespective of direction) speed of the tidal flow. Implicit in the treatment is the assumption that the water that passes the location has not previously been polluted by the outfall. This assumption would be correct if the period of discharge is limited to either ebb or flood and does not include a reversal of the tides. For longer periods, or continuous discharges, there is likely to be recirculation; that is, part of the water that has previously passed within 1 km of the shore point and been polluted, will return past the point and receive an additional burden of pollutant.

The extent to which recirculation occurs will depend on the location. On an open coastline with much turbulence, the fraction of water returning will on the average be quite small. In an embayment whose length is much greater than the tidal excursion, recirculation will vary from a small fraction at the mouth of the embayment, to almost 100 percent recirculation at the landward end. The pollution susceptibility parameter discussed previously is still useful if we consider discharges of short duration. It is, however, not realistic, if we wish to plan for more or less continuous outfalls, such as those from sewage plants or thermal outfalls from electric generating stations.

So far, we have only considered averaging over space. Next, we must consider what happens as the discharge extends over time. We have assumed that the hypothetical pollutant mixes readily with the water and that it is conservative. A conservative pollutant is one that is not removed from the water by physical, chemical or biological mechanisms. Now if the pollutant is truly conservative, and if the discharging of that pollutant continues indefinitely, then the concentration of the pollutant in the ocean will gradually increase, until it approaches the concentration of the outfall. This brings us to the ancient question of why the flow of the world's rivers has not reduced the saltiness of the sea. After man recognized the hydrological cycle, which returns the water lost by evaporation from the ocean to fall as precipitation on the land, the question was reversed. Why don't the salts that the rains leach from the land, and the rivers transport to the sea, increase the saltiness of the ocean?

These are questions for geochemists who worry about the stability of the ocean environment over geologic time spans measured in hundreds of millions of years. We are concerned with the pollution of the bays off Long Island Sound over a time scale of, at most, decades. A typical bay may have a volume of 0.1 km^3 (1 km x 10 km x 10 m depth) and an average pollution susceptibility of 100. If we discharge at a rate of 1 ton a day, it would then take only 10 days to deliver an amount of pollutant to produce a uniform concentration of 100 ppb in the bay.

In addition to the 1 km, short-time pollution susceptibility parameter defined above, we will develop a steady-state pollution susceptibility parameter, suitable for estimating the effects of continuous discharges.

METHODOLOGY

A new parameter, the pollution susceptibility, has been developed, and its value has been charted for the marine waters of Nassau and Suffolk Counties, New York. In this section, we shall describe in detail the specific methods used. This is important for the following reasons:

1. The methods used have been newly developed and have not been previously described.
2. The reliability of the results depends on the method used.
3. The charts may have to be improved, as new data become available.
4. Either man-made or natural changes in the water circulation may require a revision of the charts.
5. A detailed discussion of the methods used in the present study will facilitate the charting of the pollution susceptibility in other areas.

In the final section of the report, we shall illustrate how the charts of pollution susceptibility can be used to help answer policy and scientific questions. We shall also apply various tests in order to estimate the reliability of the results.

Tidal Data

The motion of the marine waters in the bi-county area is dominated by the tides. The effect of the tide-producing forces is modified by atmospheric processes, which can produce significant differences over short-time intervals (on the order of a day). Here, however, we are concerned with average behavior, rather than with the prediction of water motions at a specific time or under specific weather conditions. Our analysis will therefore be based exclusively on average tidal motions. In our area, the flux of freshwater discharges is generally negligible compared to the tide-induced motions. The freshwater, however, affects the salinity of the marine waters, and this effect will be considered later, as a means for verifying the estimates of steady-state pollution susceptibility.

Data on the tidal heights and tidal currents are published annually in the Tide Tables and Tidal Current Tables, produced by the National Ocean Survey, NOAA, Department of Commerce. These data were supplemented by tidal data contained on Nautical Chart 120-SC and by data from Special Publication 174 Coast and Geodetic Survey, Tides and Currents in Long Island and Block Island Sounds, by Le Lacheur and Sammons (1932).

Information on the mean tide is summarized in Chart I. The control points, for which information on the mean range and phase of the tide was available, are indicated. Lines of equal range and equal phase are shown. The mean ranges are given in feet. The representation of the phase needs further explanation.

In the analysis that follows, we approximate the level of the tide by a sine wave with the frequency of the dominant semidiurnal lunar tide having a period of 12.42 hrs. The open ocean tide is approximately sinusoidal, with the duration of the falling tide approximately equal to that of the rising tide, 6.21 hrs (Fig. 1). As the tide enters a restricted bay, however, this sinusoidal behavior is modified. Near high tide, the channel is relatively

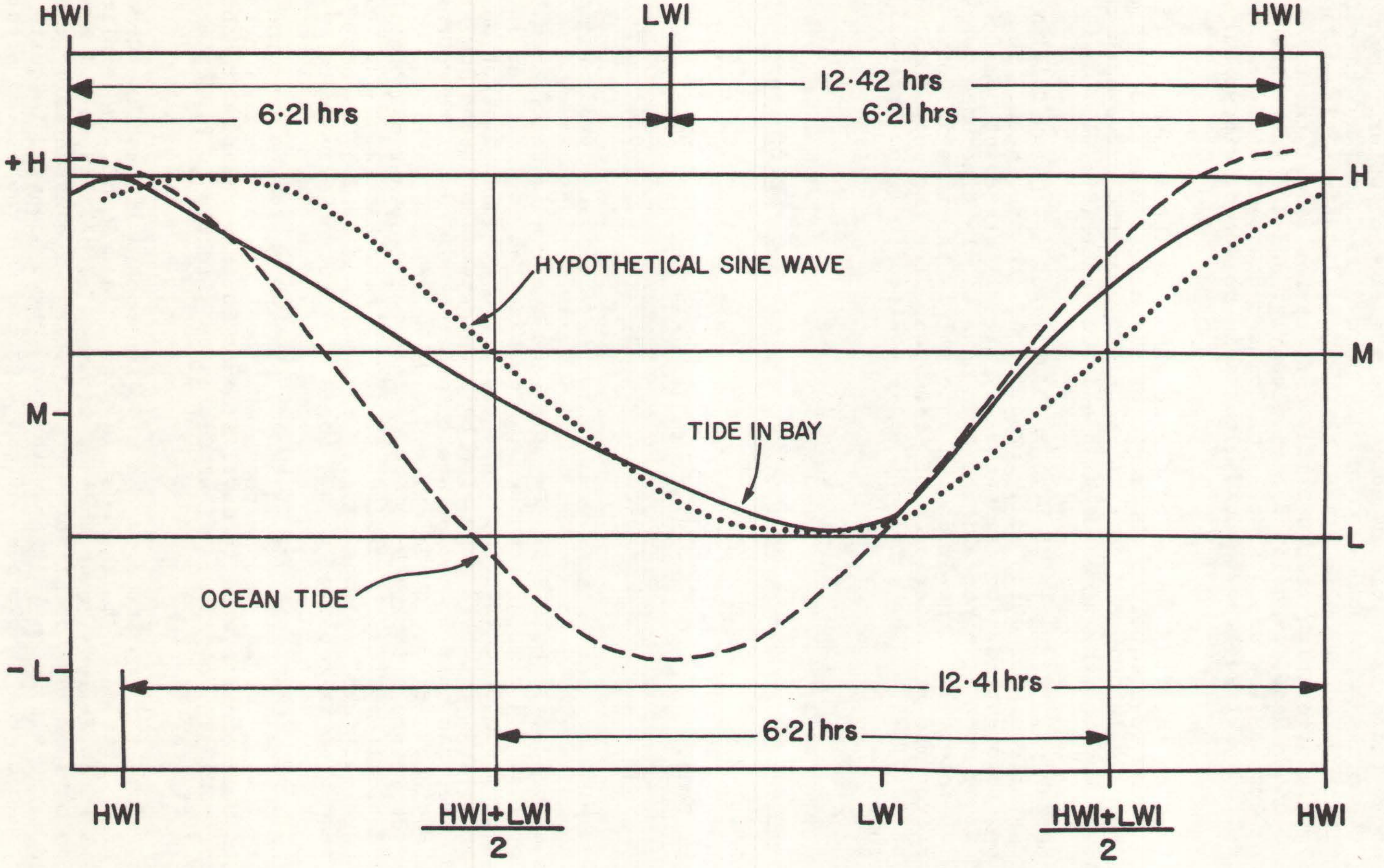

FIG. 1 TIDE LEVEL IN OCEAN AND IN BAY.

deep, and therefore there is little impedance to the flow of water. Near low tide, however, the cross-sectional area of the channel is less, and therefore there is a significant reduction in flow. As a result, high tide in the bay occurs only slightly after high tide outside, and attains almost the same level. Low tide, on the other hand, is delayed significantly, and the water level in the bay does not drop as low as outside. This causes the period of falling tide to exceed the period of rise, and the tidal curve is no longer sinusoidal (Fig. 1).

In approximating the tidal curve by a sine wave, we shall make the range of the hypothetical sine wave equal to the range of the actual mean tide. The phase of the sine wave is adjusted so that the times when the curve goes through zero fall halfway between the times of high and low water (Fig. 1).

In the tide tables, the times of high and low water are given relative to a set of standard stations, for which daily predictions are presented. The standard stations relevant for the present study are Willets Point, Bridgeport, New London and Sandy Hook. To put all the data on a single time base, we shall use the Greenwich intervals. The Greenwich interval is the time in hours after the moon passes over the prime meridian of Greenwich, when the mean local tide is high (HWI) or low (LWI). The pertinent data obtained from the National Ocean Survey are given below:

Greenwich Intervals (hours)

Location	HWI	LWI	Difference
Willets Point, N.Y.	3.95	10.66	6.71
Bridgeport, Conn.	3.81	10.16	6.35
New London, Conn.	2.08	8.52	6.44
Sandy Hook, N.J.	0.38	6.71	6.33

Using the above data, the HWI and LWI for each station is calculated. Care must be taken because the time differences in the tide tables are given in hours and minutes, whereas the Greenwich intervals are given to hundredths of an hour. Finally, we compute (HWI + LWI)/2, the time halfway between high and low water on the falling tide, and this is the parameter plotted on Chart I to represent the phase of the tide. At Montauk Point, the tide has a mean amplitude of 2 ft, and the Greenwich interval is 3.9 hrs. As one proceeds westwards along the ocean shore, the tidal amplitude increases to 4.5 ft near East Rockaway Inlet. The Greenwich interval first becomes earlier to a minimum of 2.5 hrs near Moriches Inlet and then is retarded to 3.4 hours at East Rockaway Inlet.

In Gardiner's Bay, the amplitude of the tide is about 2.5 ft, and the Greenwich interval is retarded, as one goes west, to 6 hrs at the entrances of Peconic Bay. In the Peconics, the interval becomes further retarded to about 7.9 hrs at Riverhead. The amplitude first decreases slightly to 2.3 ft and then increases to 2.7 ft near Riverhead.

At Orient Point, the amplitude of the tide is about 3 ft, and the Greenwich interval is 6 hrs. Proceeding to the west in Long Island Sound, the amplitude increases to 7.3 ft at Willets Point and the interval is delayed to 7.3 hrs. The tides in the bays of the north shore of Long Island are essentially the same as in the Sound. The situation in the south shore bays, however, is quite different. Because of the shallowness of the bays and the restricted nature of the inlets, the tidal amplitudes of the south shore bays is significantly less than in the ocean, and there is a long delay in the Greenwich interval. The changes are less marked in Hempstead Bay than in Great South Bay, where the amplitude drops to under 0.5 ft and the interval is as late as 7.5 hrs.

The tides in the north shore bays are insensitive to changes in the inlets. The tides in the south shore bays, on the other hand, can be expected to change significantly in response to changing conditions of the inlets. Dredging will increase the tidal amplitude in the bay and reduce the delay, whereas continued shoaling will further reduce the amplitude of the tides.

Determination of the Pollution Susceptibility

To illustrate the method used in determining the pollution susceptibility, we shall consider a hypothetical bay (Fig. 2), which incorporates the various features found in the bays of the bi-county area. First the bay is subdivided into a number of segments, 14 in the case of the hypothetical example. For each segment, the following parameters are determined:

1. The surface area at mid-tide in square kilometers, A. This is determined by planimetering the area on the most suitable chart available. Unless more specific data are available, the area used is the average of the areas at mean low and mean high tides.

2. The average range, R, of mean tide for the segment in feet is estimated from the tidal chart (Chart I).

3. The average phase of the tide, P, for the segment in hours is estimated from the tidal chart (Chart I).

Actually, the mean range and phase of the tide were worked out on the most detailed chart available for each bay, and the data were then compiled and redrawn to produce Chart I.

For each segment, the tidal prism is given by:

$$V \text{ tidal prism km}^3 = A \text{ km}^2 \; R \text{ ft} \times 0.3048 \times 10^{-3} \text{ km/ft}$$

Since the semidiurnal lunar tidal period is 12.42 hrs, there are 1.93 tides per day, and therefore the motion of water per day in both directions is 2 x 1.93 or 3.86 times the volume of the tidal prism. Thus the daily water flux, F, irrespective of direction, is given by:

$$F = 1.18 \times 10^{-3} \; A \; R \text{ km}^3\text{/day}$$

A complete tidal period of 12.42 hrs corresponds to a phase angle $\emptyset$ of 360°. To obtain the phase angle in degrees, we must therefore multiply the phase in hours by 360/12.42 = 29.0 degrees/hr.

For each segment of the bay, we then compute the sine and cosine components of the tidal flux F, resulting from the displacement of the tidal prism in the segment, F_1 sine $\emptyset_1$, F_1 cosine $\emptyset_1$, F_2 sine $\emptyset_2$,. . . etc.

We now start at the head of the bay, segment 1. Conservation of water requires that the average flux of water through the boundary between segments 1 and 2 is equal to the tidal flux in segment 1, F_1. The flux through the boundary between segments 2 and 3 is the sum of the fluxes in segments 1 and 2, $F_1 + F_2$. Because of possible changes in the phase of the tide, however, we can not take the simple arithmetic sum but rather must add the sine and cosine

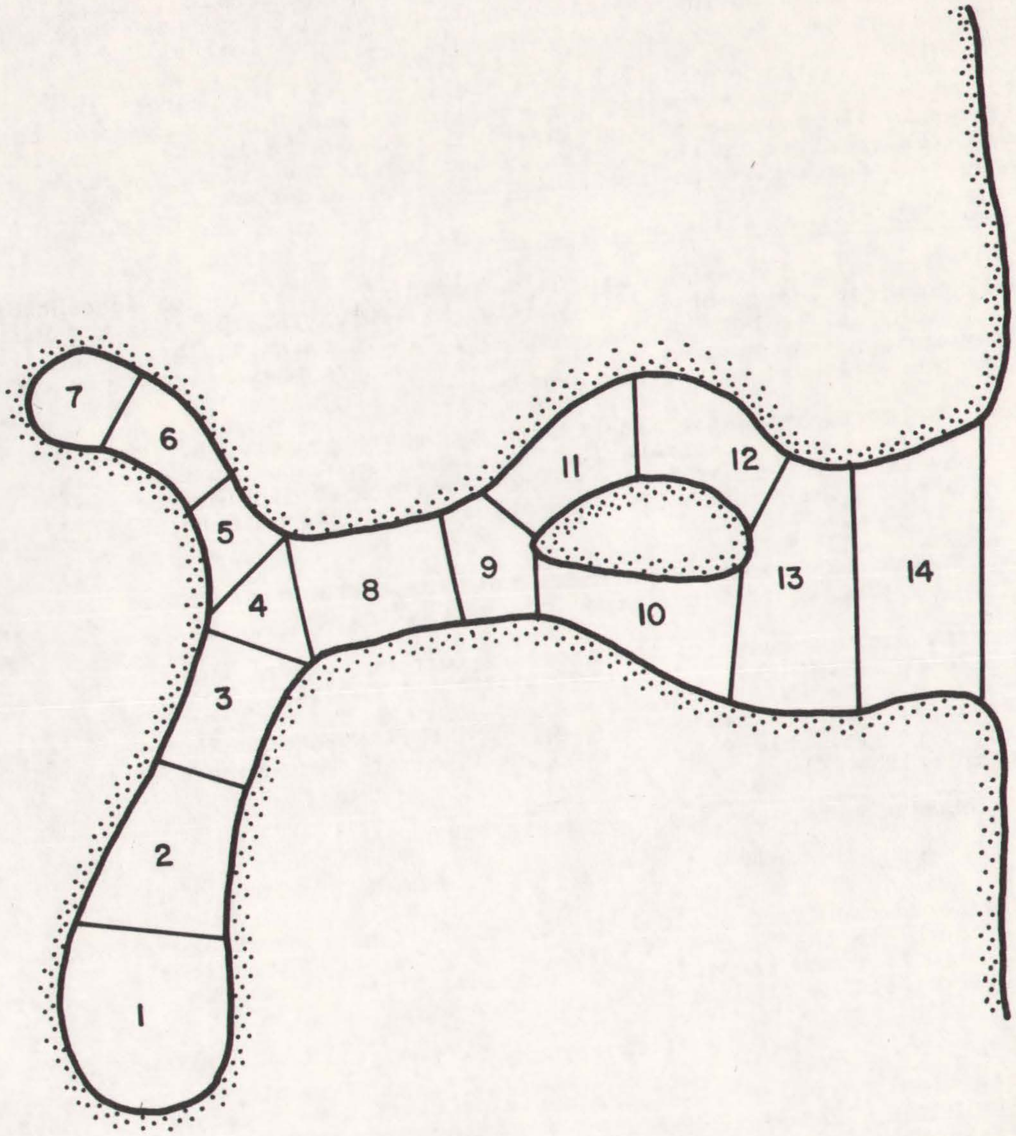

FIG. 2 A HYPOTHETICAL BAY

components separately. The total flux is the square root of the sums of the squares of the components:

$$\text{Flux 2-3} = \sqrt{(F_1 \sin \varnothing_1 + F_1 \sin \varnothing_1)^2 + (F_1 \cos \varnothing_1 + F_2 \cos \varnothing_2)^2}$$

We proceed adding the components to obtain the flux between segments 3 and 4. Next we start at the other end of the bay, segment 7, and proceed seaward in a like manner to segment 5. The two arms of the bay merge at segment 4, and so the flux between 4 and 8 is the sum of the fluxes from 3 to 4, 5 to 4, plus the contribution made by the tidal prism of segment 4. We then proceed adding segments 8 and 9. At this point the presence of the island bifurcates the tidal flux, part of it proceeding to segment 11 and part to segment 12. Using data on the areas of the cross-sections, 9-10 and 9-11, and the tidal current velocities, it is necessary to estimate how the total flux divides itself between the two channels. An example of this is the tidal flushing of the Peconic Bays through the channels on either side of Shelter Island. In that case, we estimate that 58 percent of the flux flows through the northern channel and 42 percent through the southern one. The separate flows are then carried through segments 10, 11, and 12 until they join once more in segment 13. Finally, segment 14 is added to obtain the total average tidal flux of the bay.

By the above procedure, we obtain the mean tidal fluxes through each boundary between segments, F_{1-2}, F_{2-3}, . . . F_{13-14}. To obtain the pollution susceptibility, we must next estimate the fraction of the flux that passes within 1 km of either shore. If the width of the bay is less than 1 km, this is equal to the total flux. The pollution susceptibility at the boundary between segments is equal to the reciprocal of the daily water flux in km^3 per day, that passes within 1 km of the shore line. Using the values found at the segment boundaries, the pollution susceptibility in the bay is then plotted by interpolation. The results are shown in Chart III.

The method used for determining the pollution susceptibility along the open coast of the Atlantic Ocean and Long Island Sound will be discussed later. First, we shall describe the method for obtaining the steady-state pollution susceptibility in a bay.

Consider a hypothetical tidal embayment (Fig. 3). Let the average tidal flow through the seaward margin of the embayment (A-A') be F km^3/day. Thus, on the average, F/2 km^3/day will flow into the embayment and F/2 km^3/day will flow out of the embayment. If the bay contains a continuous discharge point of pollution at the rate of P tons/day and the bay is in steady state with respect to the pollutant, then P tons per day must be discharged through the line A-A'. To accomplish this, the average concentration of the F/2 km^3/day that leaves the bay must exceed the average concentration of the F/2 km^3/day of inflowing water by 2 P/F ppb.

If the hypothetical bay borders on the open ocean, then very little of the discharged pollutant will return to the bay, and the average steady-state concentration of the effluent from the bay will be 2 P/F ppb, and 2/F would be the appropriate steady-state pollution susceptibility for the line A-A'. Since we assume the bay to be in steady state, the pollutant would be dispersed throughout the bay, and therefore we must consider the flux across the entire section A-A', regardless of whether the width at the mouth is more or less than 1 km.

As we proceed landward from the mouth of the embayment, we can no longer assume that the entering water is unpolluted. Consider the next section, B-B', located one tidal displacement in from line A-A'. Let the tidal flow through

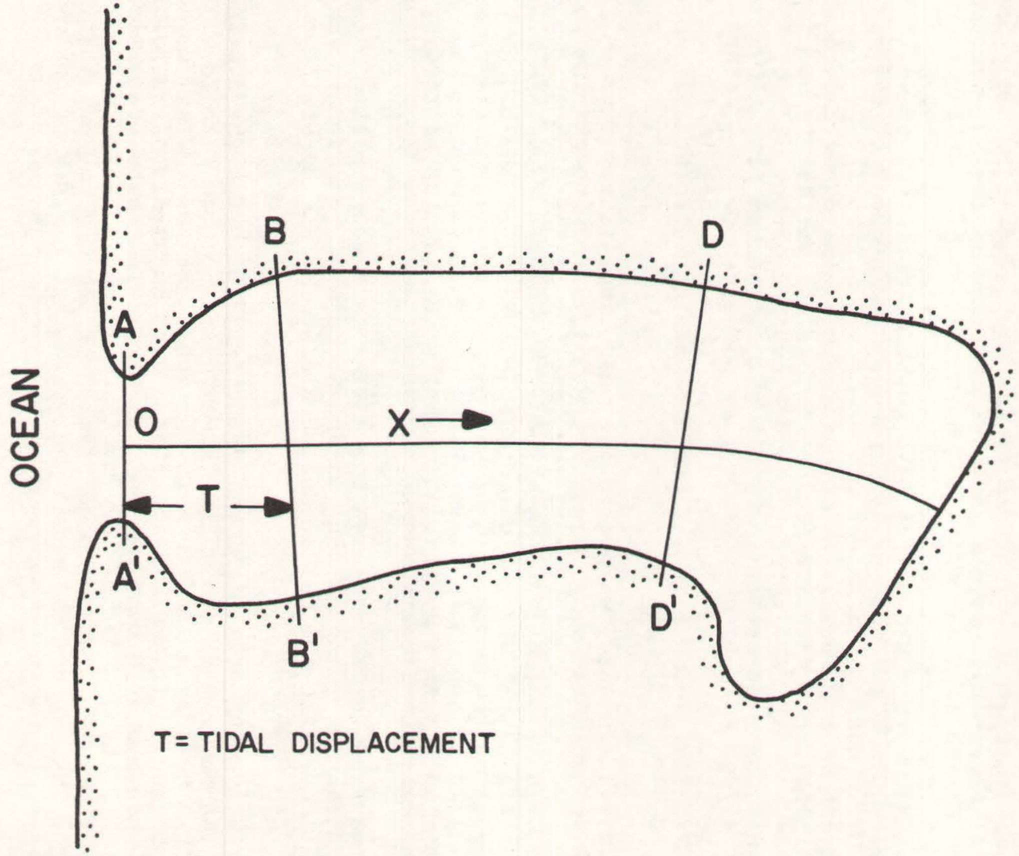

FIG. 3 A HYPOTHETICAL TIDAL EMBAYMENT

this line be $F_b$km^3/day. If the source of pollution is landward of this line, then the difference in concentration between the water leaving and entering across this line is again on the average 2 P/$F_b$ppm. Since the entering water during one tidal displacement came from line A-A', we shall assume that it entered with a concentration 2 P/F, so that the concentration of the water leaving across line B-B' will have an average concentration of 2 P/F + 2 P/F_b and the pollution susceptibility at line B-B' is 2/F + 2/F_b. We thus proceed up the bay in steps corresponding to the tidal displacement, each time adding the new concentration difference, per unit discharge, to the previous value of the pollution susceptibility.

The significance of the steady-state pollution susceptibility is as follows: Assume the pollutant is dispersed into the bay along line D-D' (Fig. 3). In steady state, there will be no net transport of pollutant landward of line D-D', and therefore the concentration in that direction will be constant and have an average value equal to the discharge rate times the steady-state pollution susceptibility along line D-D'. The tidal diffusion mechanism must transport the pollutant seaward at a rate equal to the rate at which it is being added, P, and therefore the concentration must decrease towards the mouth of the bay. The concentration seaward of line D-D' will therefore be equal to P times the steady-state pollution susceptibility.

If there is more than one source, then the concentration will be the sum of the concentrations that result from the separate sources. If the outfall is concentrated near one shore, rather than being distributed across the bay, then the concentrations within 1 km of the outfall, in the case of a wide bay, will be considerably larger than the value suggested by the steady-state pollution susceptibility. The sum of the short-time susceptibility and the steady-state value will give a more reliable index of the pollution levels to be expected locally.

More formally, consider a bay and let x designate the location along its long axis extending from x = 0 at the mouth. The concentration of a pollutant C in ppb will change with x according to:

$$\frac{dC}{dx} = \frac{2P}{F(x)T}$$

where x is measured in km, T is the tidal excursion in km, P is the rate of discharge of the pollutant in tons/day and F is the average scalar tidal flow in km^3/day. The steady-state pollution susceptibility, PS_{ss}, is:

$$PS_{ss}(x) = \int_{x=0}^{x} (2/F(x)T)\,dx$$

The derivation of the steady-state pollution susceptibility is based only on tidal data and is not based on explicit observations of mixing processes. Rather, mixing enters implicitly through use of the tidal displacement. To take variations in mixing into account, the actual tidal displacement should be replaced by an effective tidal displacement. In the absence of data, however, we shall proceed by simply using the tidal displacement. The results so obtained will be compared with available data. Significant relative errors may occur in areas of non-uniform mixing, caused by a complex geometry. More detailed information may indicate that the effective tidal displacement can be approximated by the tidal displacement multiplied by a constant. This will affect the gradient of the pollution susceptibility in a bay, but will not affect relative comparisons between bays.

The Steady-State Pollution Susceptibility of Long Island Sound

In a previous study, I have worked out the mean tidal transport of Long Island Sound in detail (In: Long Island Sound--The Urban Sea; Davies, Gross, Koppelman and Weyl; in press. The data are given in Table A-1, Appendix A of Chapter 4).

Specifically, the amplitude of the mean tidal transport in m^3/sec is listed for a number of north-south cross-sections. To obtain the mean daily flux F, the amplitudes tabulated must be multiplied by $(2/\pi) \times 8.64 \times 10^4$ sec/day. Next we plot 2/F in day/km^3, the reciprocal of the average daily flow in one direction in km^3/day. The logarithm of 2/F is plotted against location in Figure 4a. At the Race, the eastern main outlet of the Sound, this represents the steady-state pollution susceptibility with a value of 0.1. Per day, on the average, 10 km^3 of water leaves the Sound on the ebb. To remove a unit input of 1 ton/day of a pollutant, the average concentration of the outflow would have to be 0.1 ppb, assuming that none of the pollutant is returned on the flood. Next, we estimate the tidal displacement in the Sound. This was done by multiplying the mean tidal surface currents by the duration of the flood. The tidal displacement is plotted on Figure 4a to the same scale as the distance along the axis of the Sound.

At the Race, the steady-state pollution susceptibility is equal to 2/F = 0.1. Next we proceed one tidal displacement to the west. There, 2/F is approximately 0.11. Adding this to the value at the Race, we obtain 0.21 for the steady-state pollution susceptibility. We proceed in like manner, each time stepping one tidal displacement to the west and adding the local value of 2/F to the previous value of the steady-state pollution susceptibility. By the time we reach Throgs Neck, the steady-state pollution susceptibility has increased to 27.

At Throgs Neck, the value of 2/F is 5.8. However, because of recirculation of the water, the steady-state pollution susceptibility is about five times as large, and so a daily discharge of 1 ton of pollutant will result in a concentration of about 27 ppb. The distribution of the steady-state pollution susceptibility for Long Island Sound is shown in Figure 4b and is also indicated on Chart II. In the final section of this report, we use the steady-state pollution susceptibility to construct a salinity model for the Sound in order to verify the method and to illustrate the use of the steady-state pollution susceptibility parameter. The results of that model are included in Figure 4a.

The steady-state pollution susceptibility for the various bays in the Nassau-Suffolk area is determined in a similar way. We always assume that the water entering the bay at its mouth is unpolluted, so that the value of the pollution susceptibility at the entrance is equal to 2/F. In the case of the north shore bays, this represents the situation when the bay has come to a steady state, but before the pollutant has had a significant effect on Long Island Sound. For example, the value for the entrance to Manhasset Bay is 28. Here, the steady-state pollution susceptibility of Long Island Sound is about 22. Thus, if the unit discharge in Manhasset Bay continues sufficiently long for the Sound to come to steady state, the pollution susceptibility would increase to 28 + 22 = 50.

Further to the east, the effect of recirculation of pollution from the Sound is reduced. For example, at the entrance to Port Jefferson Harbor, the steady-state pollution susceptibility is about 50, and this would be increased by only 2 units to 52. This estimate assumes that the outflow from Port Jefferson is uniformly distributed across the Sound. Actually, the concentration will be significantly greater near the entrance. A better estimate can be

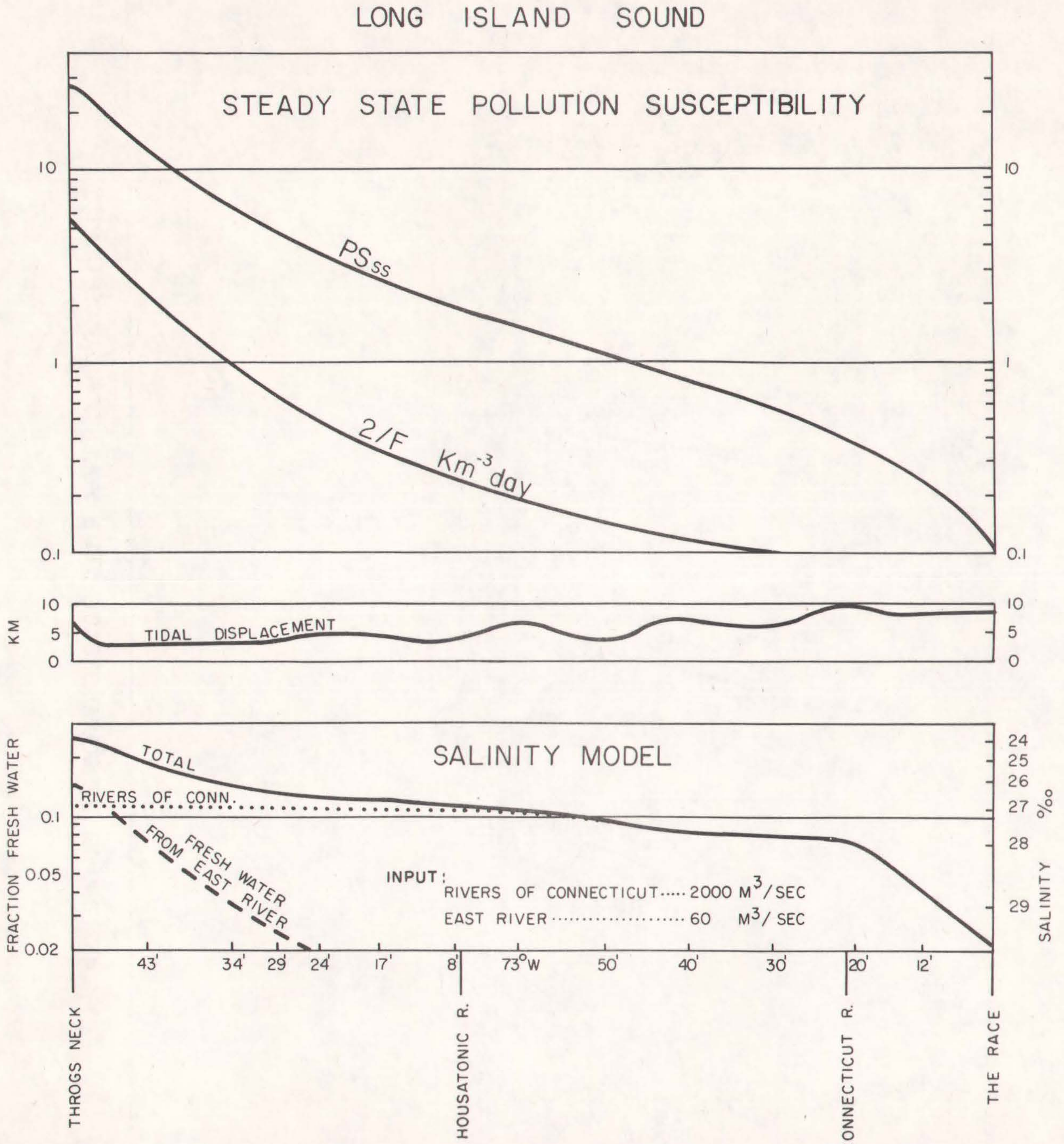

FIGURE 4-a. THE STEADY STATE POLLUTION SUSCEPTIBILITY OF LONG ISLAND SOUND.

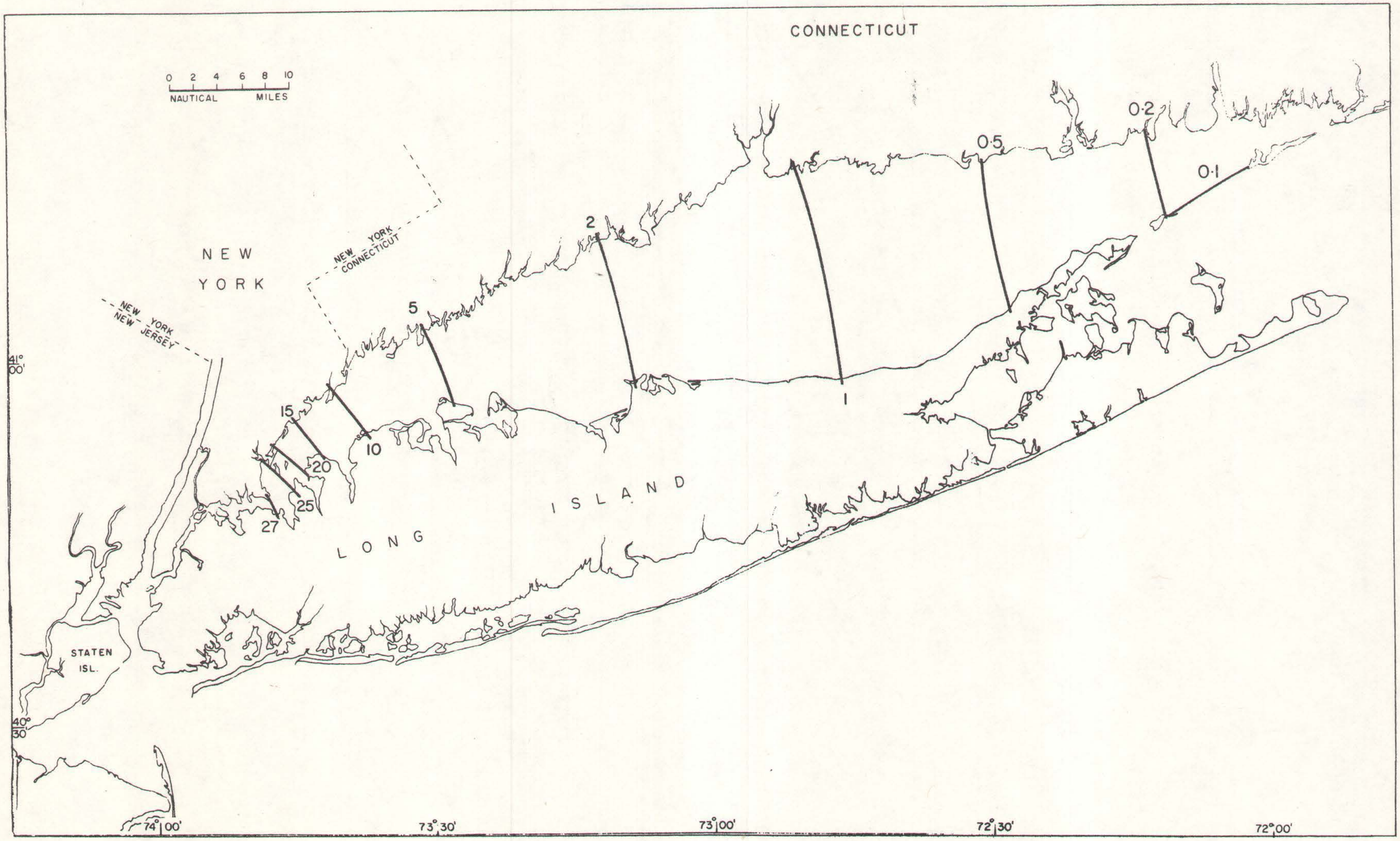

FIG. 4b LONG ISLAND SOUND STEADY STATE POLLUTION SUSCEPTIBILITY

obtained by adding the short-time, 1 km average susceptibility, about 6, to the steady-state value at the entrance.

The Pollution Susceptibility on the Open Coast

So far, we have shown how the short-time and steady-state pollution susceptibilities are determined. The same method was also used for determining the steady-state pollution susceptibility in Long Island Sound. On the ocean shore to the south of Long Island, the steady-state pollution susceptibility is meaningless, for it would involve a steady state of the entire North Atlantic Ocean. The chart of the steady-state pollution susceptibility (Chart II) therefore does not show any data for this coastline.

Finally, we must determine the short-time, 1 km pollution susceptibility for the open shores of Long Island Sound and on the south coast of Long Island. The procedure used is as follows. For key points along the coasts, we first determine the average depth in meters out to a distance of 1 km from the coast. The locations along the shore are marked off on a piece of semilog graph paper, and the average depth to a distance of 1 km is plotted (Fig. 5). Using the tidal current tables, we next look up the average peak speed of the tidal currents near the shore. The available data are then plotted on the graph. We then obtain the product, average depth times speed, by adding the curves of log speed and log depth. A product of 10 knot meters corresponds to an average flow out to a distance of 1 km of 0.283 km^3/day, corresponding to a pollution susceptibility of 1/0.283 = 3.53. As the speed of flow will decrease both with depth and as one approaches the shoreline, we shall assume that the actual flow is reduced to 2/3, and therefore the pollution susceptibility corresponding to 10 knot meters is 5.3. Using an inverted logarithmic scale and setting 53 on the pollution susceptibility scale equal to a product of 1 knot meter, we can then read off the pollution susceptibility along the shoreline. The data so obtained are shown in Chart III. The data on average depth to a distance of 1 km and the tidal current data used are indicated on Chart IV.

For Long Island Sound and Gardiner's Bay, there are adequate current data to estimate the short-time pollution susceptibility. Along the south shore of Long Island, however, there are almost no data. Some current measurements made in connection with sewer outfall studies suggest that the mean peak tidal current is about 0.5 knots. That value has been used along the entire south shore in conjunction with the local data on the average depth to 1 km. These estimates will have to be revised, if more extensive current data become available.

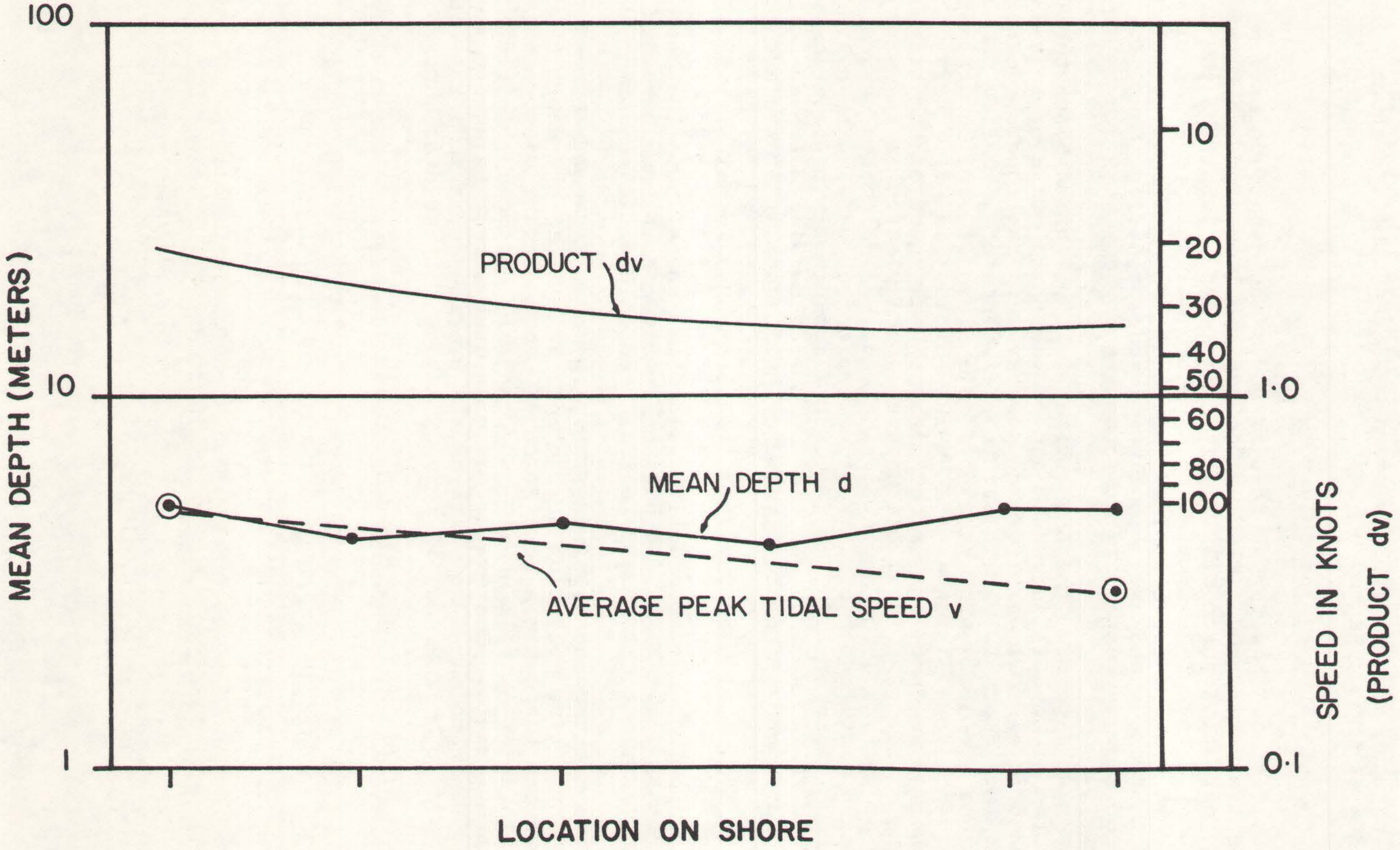

FIG. 5 POLLUTION SUSCEPTIBILITY ALONG SHORE

VERIFICATION AND APPLICATION

Having shown how the two pollution susceptibility parameters were obtained, it is now necessary to verify the results shown in Charts II and III. Further, we will show how the parameters can be used in the planning process by considering some hypothetical situations.

Verification

The only area where sufficient data are available to attempt a verification is Long Island Sound. Specifically, data from the input of phosphate by the East River sewage plants permit us to verify the steady-state pollution susceptibility data for the Sound. We will also use the steady-state pollution susceptibility data to construct a salinity model for the Sound. These calculations help verify the method and indicate how further verifications may be obtained if new data become available.

The concentration of dissolved phosphate in the western end of the Sound was obtained on a cruise by the Marine Sciences Research Center on April 9, 1971. The pertinent data are listed below:

Station #	P ppb	Steady-state pollution susceptibility*	Calculated discharge rate (tons P/day)
16	62	10	6.2
14	112	22	5.1
13	133	27	4.9

*from Figure 4b

The observed phosphate concentrations thus imply an influx of that nutrient from the East River at a rate between 5 and 6 tons per day. The reports of the New York City Department of Water Resources for April, 1971, permit us to estimate the discharge from sewage plants into the East River. Multiplying the phosphate concentration by the discharges of the following sewage plants: Tallman Island, Hunts Point, Bowery Bay, Wards Island and Newtown Creek, we obtain a rate of 11.7 tons total phosphorus and 6.8 tons dissolved phosphorus per day. Something like half this load will discharge through Long Island Sound, and the rest will discharge through New York Harbor. Thus, the expected discharge to the Sound is between 3.5 and 6 tons per day, depending on the extent to which the particulate phosphorus is converted to dissolved phosphorus. Considering the quality of the data, the results are in excellent agreement. Thus, both the rough magnitude of the pollution susceptibility and the rate at which it drops off between stations 13 and 16 are approximately correct. To refine the estimates, average values of the phosphate concentration over a tidal cycle would have to be obtained. Further, the concentration of phosphate in the effluent from the sewage plants was based on one analysis during the month. As this concentration can be expected to vary diurnally and with a weekly cycle, more detailed analytical data are required to obtain a more accurate measure of the actual discharge.

A check on the short-time, 1 km pollution susceptibility can be obtained from dye studies carried out for Long Island Lighting Company. The studies were carried out at the Shoreham and Jamesport power plant sites to predict the behavior of proposed thermal effluent diffusers. Dye was released from 5 boats spaced over a distance of about 1 km perpendicular from the shore at a rate of

0.032 tons/day. At the locations, Chart III gives pollution susceptibilities of 10 and 18 for Jamesport and Shoreham, respectively. Thus, one would expect average dye concentrations of 0.3 and 0.6 ppb for the two sites.

If the dye diffusion experiments had been designed to determine the pollution susceptibility, the dye should have been mixed through the water column from the shore to a distance of 1 km from shore. The purpose of the LILCO studies, however, was to determine the distribution of thermal effluents from a jet diffuser. The dye was mixed only into the surface layer. The line of discharge did not start at the shore, but rather 1.1 km from shore in the case of Jamesport and 1.7 km from shore at Shoreham. These distances are governed by the need to reach a water depth of 10 meters. The higher pollution susceptibility at the Shoreham site is due to the lower average depth to a distance of 1 km from shore. The greater length of the proposed outfall pipe at this location compensates for this factor, and the dye dispersion at the two sites is therefore roughly the same.

The fact that the dye diffusion line did not start at the shore line will result in lower concentrations, since the currents offshore will tend to be stronger and the depth is greater. The difference in the spacing at Jamesport and Shoreham will tend to eliminate the differences in the rates of diffusion at the two sites. The fact that the dye was dispersed only through the surface layer will tend to increase the concentration of dye. The two effects thus tend to counteract each other.

The dye studies, as could be expected, indicate large variations in dye concentration with the state of the tide and away from the release area. The average concentrations measured about 1 km east or west of the release line parallel to the release area peak at average concentrations of about 0.5 ppb, and more typically are about 0.4 ppb, except when the tides move the dye plume out of the area. A cursory examination does not reveal significant differences between the two sites. The observed values thus fall between the expected results of 0.3 ppb for Jamesport and 0.6 ppb for Shoreham. This indicates that the pollution susceptibility charts can be used to obtain rough estimates of the diffusion characteristics of the near shoreline waters of Long Island Sound.

We can consider freshwater to be a pollutant and so use the steady-state pollution susceptibility to relate the inputs of freshwater to the salinity distribution. We shall use the following approach. We shall assume characteristic salinities at the two ends of Long Island Sound and near the middle. From these values we shall derive the required freshwater inputs and compare these with observations. Finally we will derive the detailed salinity distribution along the central axis of the Sound. We start with the following assumptions.

Location	Salinity (^{o}/oo)	Freshwater (^{o}/o)	Steady-State Pollution Susceptibility
The Race	30	0.00	0.1
Mouth of Housatonic River	27	11.1	0.63
Throgs Neck	24	25.0	27

We neglect the Thames River since it discharges into the Sound to the east of The Race. The rest of the discharge is 85 percent from the Connecticut River and 15 percent from the Housatonic. We construct a pollution susceptibility curve for the Housatonic and Connecticut Rivers. This corresponds to the pollutant concentration that would result from a discharge of 0.85 tons/day from the Connecticut River and 0.15 tons/day from the Housatonic. This curve is the same as the steady-state pollution susceptibility between The Race and the mouth of the Connecticut River. Between the Connecticut and the Housatonic Rivers, the curve is obtained by adding 85 percent of the value of the pollution susceptibility at the mouth of the Connecticut River (0.85 x 0.41) to 15 percent of the Long Island Sound steady-state pollution susceptibility. This gives a value of 0.63 for the pollution susceptibility at the mouth of the Housatonic, and it remains at this value to the west of the mouth.

We assume that the salinity in the center of the Sound at the longitude of the Housatonic mouth is 27 $^{o}/oo$, requiring an 11.1 $^{o}/o$ addition of freshwater to the assumed 30 $^{o}/oo$ water that enters the Sound at The Race. This amount of dilution would result from a freshwater addition of $0.11 \times 10^9/0.63 = 1.76 \times 10^8$ tons/day, equal to a flux of 2000 m^3/sec.

We assume that the salinity at Throgs Neck is 24 $^{o}/oo$. This requires a dilution of 25 percent of the incoming water or a dilution of 14 percent from the East River, in addition to the discharge from Connecticut. At Throgs Neck, the steady-state pollution susceptibility of the Sound is 27. To provide 14 percent dilution thus requires a flux of $0.14 \times 10^9/27 = 5.19 \times 10^6$ tons/day of freshwater or a flux of 60 m^3/sec. Adding the freshwater dilution curve from the East River to that from the rivers of Connecticut, we then obtain the total dilution curve for Long Island Sound and hence the salinity distribution along the west-east axis (Fig. 4a). This curve reproduces very well the characteristic salinity trend in the Sound, namely very steep salinity gradients at the two ends with a rather gradual salinity gradient in the Central Basin.

In the previous study of Long Island Sound, I showed that the salinity in the center of the Sound is represented by the equation: $S\ ^{o}/oo = 28.6 - 0.00176\ R$, where R is the discharge of the rivers of Connecticut in m^3/sec. For a salinity at the center of 27 $^{o}/oo$, this leads to a discharge of 900 m^3/sec, or about one-half the discharge derived in the present salinity model. This suggests that the steady-state pollution susceptibility to the center of the Sound is too low by about a factor of two. This may be accounted for by the fact that we used the surface tidal displacement for calculating the pollution susceptibility. This displacement will be larger than the tidal displacement averaged over depth. Using one-half the surface tidal displacement would have given steady-state pollution susceptibility values twice as large, in agreement with the salinity model.

Not enough is known to compare the derived freshwater flux from the East River with actual observations. About all one can say is that the value found, 60 m^3/sec, is about the right order of magnitude. If we cut the tidal displacement in half, this would give a pollution susceptibility of 2 x 27 = 54 at Throgs Neck and hence would halve the input of freshwater there. This would also imply that the input of phosphate into the Sound from the East River is about 3 tons/day rather than the 6 tons estimated at the beginning of this section.

When we determined the tidal displacement in the various bays, we used the total transport and cross-sectional area of the bays, rather than the surface currents. Thus the discrepancy found for the steady-state pollution susceptibility would not apply to these bays. Unfortunately, we do not have enough data at this time to verify the results for the bays. One would expect, however, that the absolute values shown on Charts II and III are reliable within a factor of two. Since the values range from roughly 10 to over 1000, the uncertainty in the results does not negate the value of the charts as a planning tool. The relative values in a particular bay will be much more accurate. Thus comparisons of different locations within a particular bay will be more reliable than comparisons between bays, or between a bay and the open coast. Even in the latter cases, differences of a factor of 10 in the pollution susceptibility will be highly significant.

Hypothetical Applications to Coastal Zone Planning

Finally let us consider some hypothetical applications of the pollution susceptibility charts to coastal zone planning. An industrial installation that will discharge a pollutant could be sited at either Riverhead or at Greenport. The steady-state pollution susceptibilities at these locations are 1000 and 10, respectively. Other things being equal, the plant at Riverhead would have to remove 99 percent of the pollutant from its discharge, in order to produce the same pollution as a plant at Greenport. The short-time pollution susceptibilities at the two sites are about 500 and 3, respectively. Thus an occasional accidental spill at Riverhead would result in roughly 170 times the concentration, at a distance of 1 km from the plant, as a similar spill at Greenport.

A sewage plant is to be constructed in Hempstead Harbor. The steady-state pollution susceptibility ranges from over 1000 at the head of the bay to 20 at its mouth. Locating the outfall near the mouth will thus result in 1/50 the nutrient concentration compared to locating the outfall near the head of the bay.

Where cluster developments are planned, the disposition of open space and housing should take the gradients in pollution susceptibility into account. The areas of high pollution susceptibility should remain undeveloped, and development should be located in the area of lower pollution susceptibility. In general, past practice has concentrated development at the heads of bays and left the area near the mouth of the bays relatively undeveloped. The reason for this was not an attempt to maximize pollution, rather the development was guided by the transportation and distribution network. To avoid such trends in the future, transportation systems should avoid areas of the coastline with a high pollution susceptibility.

CONVERSION FACTORS

1 metric ton = 10^6 grams
= 2205 pounds
= 1.102 short tons

1 metric ton per day = 92 pounds per hour
= 1.53 pounds per minute

1 cubic meter = 264 gallons
= 35.3 cubic feet

1 day = 24 hours
= 1440 minutes
= 86,400 seconds

1 cubic foot per second = 2447 cubic meters per day

1 kilometer = 0.540 nautical miles
= 0.621 statute miles
= 3281 feet

1 million gallons per day = 3800 cubic meters per day
= 0.0438 cubic meters per second

1 knot = 1 nautical mile per hour
= 51.5 centimeters per second
= 44.5 kilometers per day