95-e13

DEPARTMENT OF ECOLOGY

August 7, 1995

TO: Will Kendra
Water Quality Program

FROM: Greg Pelletier Greg
EILS Program

SUBJECT: Mixing zone mass balance calculations including far-field accumulation of effluent and ambient background pollutants

The attached guidance was prepared to provide some consistency for consideration of "reflux" in mixing zone calculations. This guidance has been reviewed by Ecology's *ad hoc* mixing zone work group and comments have been addressed. The need for this guidance came up during internal review of the EILS report for analysis of the Stanwood mixing zone. This guidance has also been used during EILS' review of consultant reports (*e.g.* Everett and Raymond). This guidance will be incorporated in some ongoing studies by NPDES dischargers and may be added to the Permit Writer's Manual.

GP:blt
Attachment

cc: Gary Bailey
Norm Glenn

Mixing Zone Mass Balance Calculations Including Far-Field Accumulation of Effluent and Ambient Background Pollutants

Introduction

Tidal currents may cause effluent to accumulate in the receiving water surrounding an outfall in a tidal river or estuary The receiving water may also contain background concentrations of pollutants from sources other than effluent. This discussion presents mass-balance equations to account for far-field accumulation of effluent and background pollutant concentrations in the receiving water for mixing zones that are tidally-influenced Various methods are available to account for the accumulation of effluent and ambient background sources when determining potential to exceed water quality criteria or estimating waste load allocations

When dye is used as a tracer of effluent in a mixing zone study, the far-field accumulation of effluent may be estimated based on either of two methods:

- the USGS superposition method (Appendix A: a case study by Hubbard and Stamper, 1972) may be used by injecting the tracer during one tidal day and measuring continuously at a fixed monitoring station to determine maximum concentrations during succeeding days until the tracer is undetectable; or
- the Jirka method (Appendix B: section 2 6 of EPA, 1992: EPA Technical Guidance for WLAs, Book III Part 3, EPA/823/R-92/004) may be used by injecting the tracer over several tidal cycles (usually five or more) until a quasi-maximum steady state is reached. Concentrations of the tracer are usually monitored continuously at a fixed monitoring station.

In addition to the alternative methods of tracer injection, two alternative schemes for monitoring stations are considered:

- Alternative 1: tracer concentrations are measured in the near-field at the mixing zone boundary in the approximate centerline of the effluent plume; or
- Alternative 2: tracer concentrations are measured in the far-field at some considerable distance from the effluent plume at a position that is representative of the source of dilution water for the plume.

Either the Jirka or superposition methods may be used to conduct the tracer studies for both Alternatives 1 and 2. A third alternative is also proposed if a tracer study is not conducted:

- Alternative 3: no tracer study is conducted. A default correction for far-field accumulation will be based on recommendations by EPA 1992 and Ecology's Permit Writer's Manual

Definitions

near-field	at the mixing zone boundary in the approximate center-line of the effluent plume
far-field	at some considerable distance from the effluent plume at a position that is representative of the source of dilution water for the plume
V	initial maximum effluent concentration (volume fraction of effluent; *e.g.* 5 percent effluent corresponds to V of 0.05) during first tidal cycle prior to influence of far-field accumulation from previous tidal cycles.
$\overline{V}$	quasi-steady-state maximum effluent concentration (volume fraction of effluent; *e.g.* 5 percent effluent corresponds to $\overline{V}$ of 0.05) after several tidal cycles result in equilibrium with far-field accumulation.
r_d	return rate of dye or effluent mass discharged in the previous tidal cycle as defined in EPA 1992 (Appendix B).
DF	initial effluent dilution factor (reciprocal of volume fraction of effluent; *e.g.* 5 percent effluent corresponds to DF of 20) during first tidal cycle prior to influence of far-field accumulation from previous tidal cycles. DF may be estimated using a model (e.g. PLUMES or CORMIX) or by near-field tracer measurement. DF is usually determined at critical conditions.
$\overline{DF}$	quasi-steady-state effluent dilution factor (reciprocal of volume fraction of effluent; *e.g.* 5 percent effluent corresponds to $\overline{DF}$ of 20) after several tidal cycles (usually 5 or more cycles) result in equilibrium with far-field accumulation. $\overline{DF}$ is usually determined at critical conditions.
C_p	pollutant concentration in the plume at the mixing zone boundary.
C_e	pollutant concentration in effluent before dilution in the mixing zone
C_a	pollutant concentration in upstream ambient receiving water.
WLA	effluent concentration to use for Waste Load Allocation (acute or chronic) for derivation of water quality-based permit limits.
WQC	pollutant concentration for water quality criteria (acute or chronic).

Mass Balance Equations for Alternative 1

If the tracer monitoring station is located in the near-field (at the mixing zone boundary in the approximate centerline of the effluent plume), then the following mass-balance equations are appropriate:

- calculate Jirka's r_d from near-field $\overline{V}$ and V (based on equation 22 in Appendix B):

$$r_d = (\overline{V} - V) / \overline{V} \qquad (1)$$

- calculate the near-field $\overline{DF}$ (acute or chronic boundary), including the effect of far-field accumulation of effluent, from model or tracer estimates of DF and estimated r_d in the previous step (based on equation 22 in Appendix B):

$$\overline{DF} = DF (1 - r_d) \qquad (2)$$

- The following equation is appropriate to calculate pollutant concentrations (C_p) at the mixing zone boundaries for comparisons with water quality criteria. Near-field dilution is corrected for far-field accumulation of effluent in the previous step The following equation incorporates the effect of ambient background (C_a) from sources of pollutants other than effluent. Estimates of C_e may also include a reasonable potential multiplier using methods in chapter VI of Ecology's Permit Writer's Manual. Pollutant concentrations (C_p) are estimated as follows (based on equation 9 in the PLUMES manual; EPA/600/R-93/139):

$$C_p = C_e (1 / \overline{DF}) + C_a (1 - (1 / \overline{DF})) \qquad (3)$$

- calculate acute and chronic WLAs:

$$WLA = WQC\ \overline{DF} - C_a (\overline{DF} - 1) \qquad (4)$$

Example:

Given: near-field V = 02 (2 percent effluent); near-field $\overline{V}$ = .07 (7 percent effluent)

Calculation of near-field $\overline{DF}$ including far-field accumulation of effluent:
r_d=(.07-.02)/.07=.7143; DF=1/.02=50; therefore near-field $\overline{DF}$=50(1-.7143)=14.3.

Mass Balance Equations for Alternative 2

If the tracer monitoring station is located in the far-field at some considerable distance from the effluent plume at a position that is representative of the source of dilution water for the plume, then the following mass-balance equations are applicable:

- calculate near-field DF, excluding the far-field accumulation of effluent, from a model (*e.g.* PLUMES or CORMIX) or from an additional near-field tracer monitoring station (*e.g.* near-field DF = reciprocal of near-field V)

- calculate the near-field $\overline{DF}$ (acute or chronic boundary), including the effect of far-field accumulation of effluent, by mass balance with near-field DF from the previous step and far-field $\overline{V}$ (based on equation 8 from the PLUMES manual, EPA/600/R-93/139):

$$\overline{DF} = DF / (1 + \overline{V} (DF - 1)) \tag{5}$$

- The following equation is appropriate to calculate pollutant concentrations (C_p) at the mixing zone boundaries for comparisons with water quality criteria. Near-field dilution is corrected for far-field accumulation of effluent in the previous step. The following equation incorporates the effect of ambient background (C_a) from sources of pollutants other than effluent. Estimates of C_e may also include a reasonable potential multiplier using methods in chapter VI of Ecology's Permit Writer's Manual. Pollutant concentrations (C_p) are estimated as follows (based on equation 9 in the PLUMES manual; EPA/600/R-93/139):

$$C_p = C_e (1 / \overline{DF}) + C_a (1 - (1 / \overline{DF})) \tag{3}$$

- calculate acute and chronic WLAs:

$$WLA = WQC\ \overline{DF} - C_a (\overline{DF} - 1) \tag{4}$$

Example:

Given: near-field DF=50 from PLUMES model excluding far-field accumulation of effluent; far-field $\overline{V}$=.051 (5.1 percent effluent) from tracer study using super-position method.

Calculation of near-field $\overline{DF}$ including far-field accumulation of effluent: near-field $\overline{DF}$=50/(1+.051(50-1))=14.3.

Mass Balance Equations for Alternative 3

If a tracer study is not conducted to estimate far-field accumulation effects, then the following mass balance equations are appropriate based on recommendations by EPA 1992 and Ecology's Permit Writer's Manual:

- estimate default for Jirka's $r_d = 0.5$ from EPA 1992 and Ecology's Permit Writer's Manual.

- calculate the near-field $\overline{DF}$ (acute or chronic boundary), including the effect of far-field accumulation of effluent, from model or tracer estimates of DF and estimated r_d in the previous step (based on equation 22 in Appendix B):

$$\overline{DF} = DF\ (\ 1 - r_d\ ) \tag{2}$$

- The following equation is appropriate to calculate pollutant concentrations (C_p) at the mixing zone boundaries for comparisons with water quality criteria. Near-field dilution is corrected for far-field accumulation of effluent in the previous step. The following equation incorporates the effect of ambient background (C_a) from sources of pollutants other than effluent. Estimates of C_e may also include a reasonable potential multiplier using methods in chapter VI of Ecology's Permit Writer's Manual. Pollutant concentrations (C_p) are estimated as follows (based on equation 9 in the PLUMES manual; EPA/600/R-93/139):

$$C_p = C_e\ (\ 1\ /\ \overline{DF}\ ) + C_a\ (\ 1 - (\ 1\ /\ \overline{DF}\ )\ ) \tag{3}$$

- calculate acute and chronic WLAs:

$$WLA = WQC\ \overline{DF} - C_a\ (\overline{DF} - 1\ ) \tag{4}$$

Example:

Given: r_d=0.5; DF=50

Calculation of $\overline{DF}$: $\overline{DF}$=50(1-.5)=25

Appendix A

Hubbard and Stamper, 1972.
Movement and Dispersion of Soluble Pollutants
in the Northeast Cape Fear Estuary, North Carolina

Appendix B

Excerpt from draft of Section 2.6 of EPA 1992
EPA Technical Guidance for Manual for Performing Waste Load Allocations
Book III: Estuaries
Part 3: Use of Mixing Zone Models in Estuarine Waste Load Allocations
EPA/823/R-92/004

Appendix A

Hubbard and Stamper, 1972. Movement and Dispersion of Soluble Pollutants in the Northeast Cape Fear Estuary, North Carolina

Movement and Dispersion of Soluble Pollutants in the Northeast Cape Fear Estuary, North Carolina

By E. F. HUBBARD *and* WILLIAM G. STAMPER

ENVIRONMENTAL QUALITY

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1873-E

Prepared in cooperation with the North Carolina Department of Water and Air Resources

The flushing and dispersive characteristics of an essentially well-mixed estuary as defined by a fluorescent-dye study

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ILLUSTRATIONS

GLOSSARY

The following definitions refer to technical terms as specifically used in this report.

Conservative solute. A dissolved substance of low degradability.

Cubic feet per second (cfs). The rate of discharge of a stream whose channel is 1 square foot in cross-sectional area and whose average velocity is 1 foot per second.

Drainage area. The surface area at a certain point on a stream from which runoff is drained by the stream system.

Ebb tide. The outgoing tide, characterized by falling stage and downstream flow.

Flood tide. The incoming tide, characterized by rising stage and upstream flow.

Flushing time. The average time required for a particle of solute to travel from a point of injection to the mouth of the estuary.

Left bank. The streambank that is on the left when facing downstream or seaward.

Low-flow frequency curve. A graph showing the magnitude and frequency of minimum flows for a period of given length. Frequency is usually expressed as the average interval, in years, between recurrences of an annual minimum flow equal to or less than that shown by the magnitude scale.

Micrograms per liter (μg/l). A unit expressing the weight of a dissolved substance with respect to the solution volume. If it can be assumed that a liter of solution weighs 1 kilogram, results in micrograms per liter are equivalent to those in parts per billion.

Mileage figures. The distance along the center of the channel upstream from the mouth in statute miles.

Milligrams per liter (mg/l). A unit expressing the weight of a dissolved substance with respect to the solution volume. If it can be assumed that a liter of solution weighs 1 kilogram, results in milligrams per liter are equivalent to those in parts per million.

Recurrence interval. The average time, in years, within which an extreme event will be equaled or exceeded once. An example of an extreme event would be a drought or period of low streamflow.

Runoff. That part of precipitation that appears in streams.

Semidiurnal. A term which describes an event, or cycle, which occurs during half-day intervals. Since tidal cycles cover approximate intervals of one-half day, they are characterized as semidiurnal.

Solute. A substance which is dissolved in a liquid. Solute may be expressed as a concentration or as the total dry or undiluted weight.

Stationing or station. As used in this report, the distance from the left bank to a sampling point in a cross section.

Tidal excursion. The distance a certain particle of water moves upstream or downstream during a tidal cycle with reference to some stationary point.

MOVEMENT AND DISPERSION OF SOLUBLE POLLUTANTS IN THE NORTHEAST CAPE FEAR ESTUARY, NORTH CAROLINA

By E. F. HUBBARD and WILLIAM G. STAMPER

ABSTRACT

This report presents the results of a fluorescent-dye-tracing study to determine the concentrations of a pollutant that would be present in the Northeast Cape Fear Estuary at various rates of continuous waste injection and fresh-water inflow.

Rhodamine WT dye was introduced into the estuary at a constant rate over a 24.8-hour period (two tidal cycles) at a point 6.4 miles upstream from the mouth in Wilmington, N.C., and concentrations were monitored at several selected sections in the tide-affected part of the river for 17 days. The range between high and low tide in this reach of the estuary averages about 3.5 feet, and there is usually strong flow in both directions.

Tidal cycle is 12.4 hrs.

river flow = 400 cfs during the study

Results of the dye study indicate that if a pollutant were injected at a rate of 100 pounds per day under the conditions of relatively low inflow existing at the time, concentrations would ultimately build up to 20 micrograms of dye per liter of water 1,000 feet downstream. The flushing time during the study is estimated to be 17 days. These results are extrapolated to include periods of lower or higher inflow. For example, at average intervals of 10 years, it is estimated that inflow is so low that 100 days are required for a pollutant to travel the 6.4 miles from the point of waste release to the mouth of the river. Under these conditions it is expected that 1,000 feet downstream from the point of waste discharge, daily maximum concentrations will average about 130 micrograms per liter for each 100 pounds of pollutant injected per day.

Results of a continuous discharge measurement of flow made by current meter during a complete tidal cycle are presented as a part of this report. Data from this measurement and other evidence indicate that net upstream flow in the estuary is possible over a period of several days.

INTRODUCTION

Increasingly, attention is centered on an important natural resource of North Carolina, the estuaries of its rivers. These tidal reaches have tremendous potential for recreation, waste disposal, navigation, and water supply. In addition to these direct uses by man, biologists stress the dependence of many plants and animals on an estuarine environment during all or a part of their life cycle. For good management of this resource, information is needed on the mechanics of flow in the estuaries.

The lower part of the Northeast Cape Fear River is an example of an estuary that many industries presently use. This use is expected to increase rapidly in the near future, especially for waste disposal. Owing to the varied flow patterns of an estuary, which alternately has upstream and downstream flow, waste disposal can pose complex problems. The concentration of a waste [illegible] estuary may [illegible] (1) natural [illegible] can occur, (2) [illegible] and fresh- [illegible] and (3) [illegible]ation caused by [illegible] inflow and dispersion eventually flush the waste into the [illegible]. Pollution can reach dangerous levels if the buildup in waste concentration exceeds the capacity of the estuary to reduce it. If the estuaries are to be protected from undue pollution and used for the benefit of the public, a thorough knowledge of the system is essential. (For discussions on dispersion models, see Harleman, 1966, and Sayre, 1968.)

The Nuclear Energy Division of the General Electric Co. recently constructed and placed into production a plant located between U.S. Highway 117 and the Northeast Cape Fear River about 6 miles north of Wilmington near Wrightsboro, N.C. Effluent from this plant is being introduced into the river.

Because of the complex flow in the Northeast Cape Fear Estuary, a special investigation was conducted to determine the dispersive and assimilative characteristics of the reach into which the General Electric Co. is discharging wastes. The U.S. Geological Survey, at the request of and in cooperation with the North Carolina Department of Water and Air Resources, made the study. The General Electric Co., in addition to making a financial contribution to the North Carolina Department of Water and Air Resources, furnished a pier and recording instruments for a gaging station to record river stage and velocity and direction of flow on the river near the point at which the wastes are being discharged. (See location map, fig. 1.)

We thank the participants in this project not only for their efforts but also for the willingness with which they performed them. Special thanks are given to James F. Bailey, Nobuhiro Yotsukura, and Frederick A. Kilpatrick, hydraulic engineers of the Geological Survey, who assisted in the initial reconnaissance, the data collection and reduction, the analyses of data, and the review of this report.

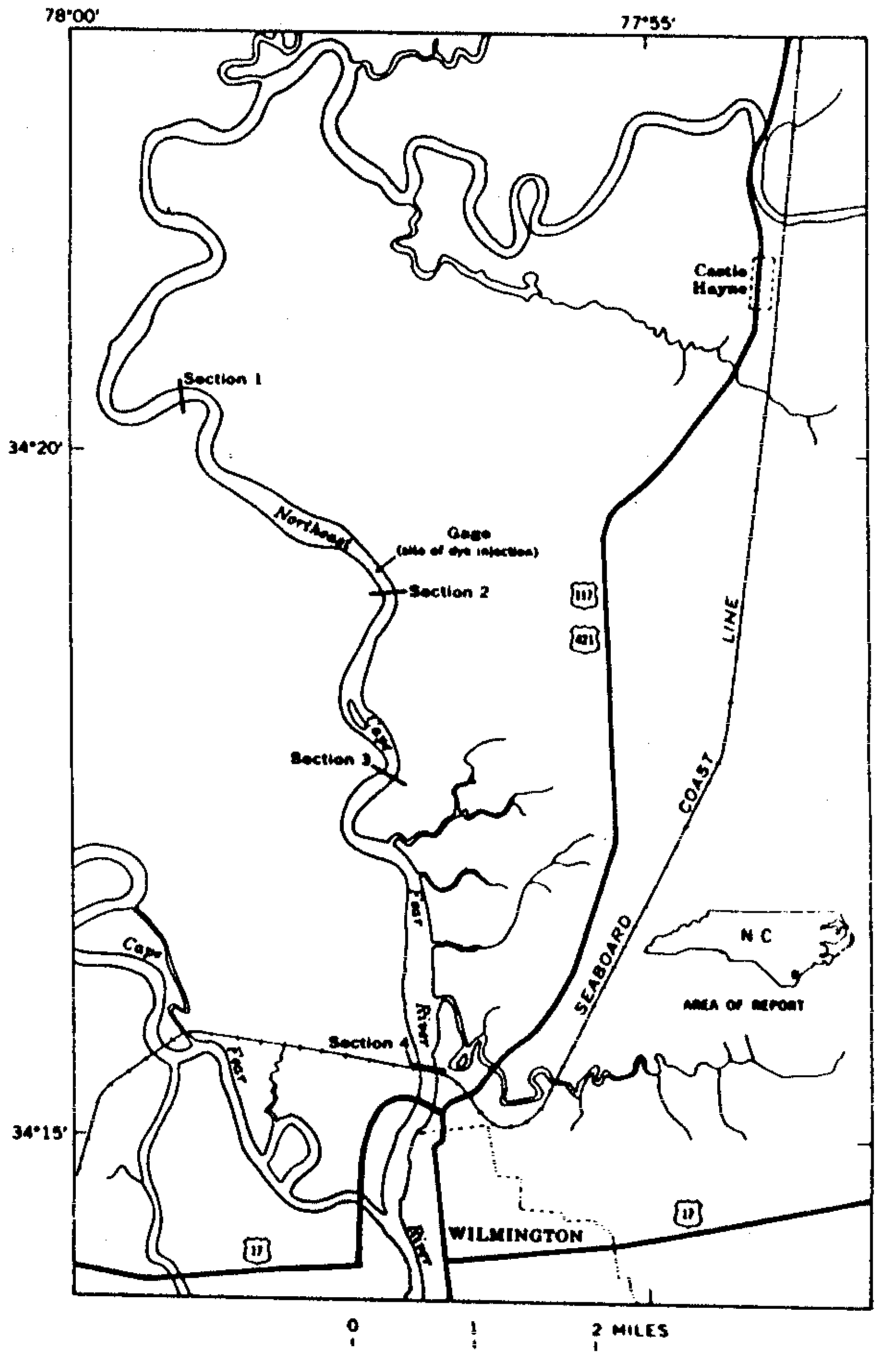

FIGURE 1.—Index map showing cross sections 1-4 and gage site.

OBJECTIVES

The objectives of this study were to:

1. Understand the flow and dispersive characteristics of the Northeast Cape Fear Estuary and determine how they affect the flushing of soluble wastes.
2. Develop methods permitting the prediction of buildup in concentrations to occur at selected points within the estuary when a conservative solute (dissolved substance of low degradability) is discharged to the system.

The authors' objectives were accomplished by injecting a fluorescent dye and tracing its movement and dispersion in the estuary as it was expelled from the system and by measuring tidal velocity, direction, and volume of flow. This experiment, for the most part, took place in October 1969, and the results are included in this report. (For other recent reports on estuarine dye studies, see Williams, 1967, and Beverage and Swecker, 1969.)

It was anticipated at the beginning of the study that waste concentrations might reach undesirably high levels during certain periods of low fresh-water inflow and that it might be necessary to schedule waste releases to make optimum use of the flushing effects of ebb tides and higher inflows and to minimize the upstream migration of the wastes. Scheduling releases requires current data on the direction and velocity of flow in the estuary. The General Electric Co. constructed a pier on which the Geological Survey installed a deflection-vane and a stilling well. The company provided instruments which record direction of flow, vane deflection, and stage. These instruments are arranged so that relative velocity and direction of flow, as well as stage, can be monitored and recorded at the river or in the General Electric plant.

DESCRIPTION OF ESTUARY AND STREAM SYSTEM

The Northeast Cape Fear River heads in Wayne County, N.C., and flows south through Duplin, Pender and New Hanover Counties, and at Wilmington flows into the Cape Fear River which empties into the ocean about 30 miles south of Wilmington. The gage site, also the point of dye injection, is on General Electric Co. property at mile 6.4 above the mouth of the Northeast Cape Fear River. The drainage area at the gage is 1,700 sq mi (square miles) and at the mouth is 1,740 sq mi.

Much of the analysis in this report concerns the reach of the river from the mouth upstream for about 12 miles. This is the area usually affected by the discharge of solutes in the vicinity of the gaging station.

The tidal effect in the Northeast Cape Fear River extends about 20 or 30 miles above the mouth. The tidal range is 3.4 feet at the gaging station, compared to the tidal range of 4.5 feet in the ocean near the mouth of the Cape Fear River. The characteristic diurnal cycle of tides (a high high, a low low, a low high, and a high low tide) is approximately 24 hours and 50 minutes.

The Northeast Cape Fear Estuary is essentially well-mixed; that is, there is practically no vertical stratification of fresh and salt water within the system, except possibly during large floods. This condition usually applies to estuaries in which the volume of water due to tidal flow is several orders of magnitude greater than the volume of fresh-water inflow.

THE DYE STUDY

The dye study, designed to simulate the waste discharge from the industrial facility into the Northeast Cape Fear Estuary, was accomplished by injecting Rhodamine WT dye solution into the estuary at a constant rate from the gaging station pier and monitoring the movement and dispersion of the resulting dye cloud by collecting samples at selected points in the study reach. (For discussions of fluorescent-dye-tracing techniques, see Wilson, 1968, and Pritchard and Carpenter, 1960.) The assumption was made that this dye would be as conservative (see glossary) as the waste material it simulated. In other words, the dye would resist destruction or alteration by chemical, photo-chemical, biological, or other processes to the same degree as waste materials and would not be absorbed or adsorbed by bed materials and substances in the water.

During the study, fresh-water inflow was estimated to be 400 cfs, moderately low for this estuary. Tides were somewhat above normal, probably because of a tropical storm which moved north off the coast during the first few days of the study. These factors, relatively low fresh-water inflow and higher than average tides, provided ideal conditions for the study. Because both factors tend to retard the flushing action of an estuary (Wilder and Hubbard, 1968), the results of the investigation are particularly applicable to times when pollution buildup may reach critical values.

DATA COLLECTION

Before injecting the dye, the authors needed to find the approximate tidal excursion: the distances the dye cloud would move upstream and downstream during one tidal cycle. These distances were determined by the authors observing the movement of floats placed in the estuary when flow conditions were similar to those predicted for the injection period. The estimated upstream and downstream tidal excursions were 2.9 and 5.0 miles from the injection point, respectively.

Four cross sections were established at strategic locations along the estuary. Sampling sections 1 and 4 which, respectively, were the farthest upstream and downstream, were located near the ends of the tidal excursion zone noted above, at river miles 9.3 and 1.4. The locations of the sections and the gage are shown in the following table.

	Distance above mouth (miles)	*Distance from gage and dye-injection point (miles)*
Section 1	9.3	2.9
Gage	6.4	—
Section 2	6.2	0.2
Section 3	4.4	2.0
Section 4	1.4	5.0

One hundred thirty pounds of Rhodamine WT dye in a 6.25 percent solution with water was used in the study. Dye injection began at 2:00 a.m. e.d.t. on October 14, 1969, the time of high-slack tide at the injection point, and continued for two complete tidal cycles, which ended at 3:00 a.m. on October 15.

During the first two tidal cycles after the dye injection began, six to 10 surface samples and two bottom samples at selected stations in each cross section were collected at about 15-minute intervals. These sampling intervals were gradually lengthened as the concentration versus time curves became flatter. (See fig. 2.) The number of sampling stations within each cross section were reduced as lateral mixing became more complete. After the first week of the study, a schedule was developed so that representative samples were collected from each cross section at times of maximum concentration. Sampling was continued through Oct. 30, 1969, when the maximum concentration measured in any cross section was less than 0.25 μg/l, below the level of significance for this analysis; therefore, collection of data was concluded.

DATA ANALYSIS

The dye study was designed to simulate the injection and movement of a conservative soluble substance within the estuary for an indefinite length of time. The experiment could duplicate this situation exactly by the dye's being injected until the flushing process stabilized and daily maximum concentrations measured in the estuary reached a constant value for the prevailing inflow and tidal conditions. It is prohibitively expensive, however, to inject dye for the 15 or more days required to build up concentrations to

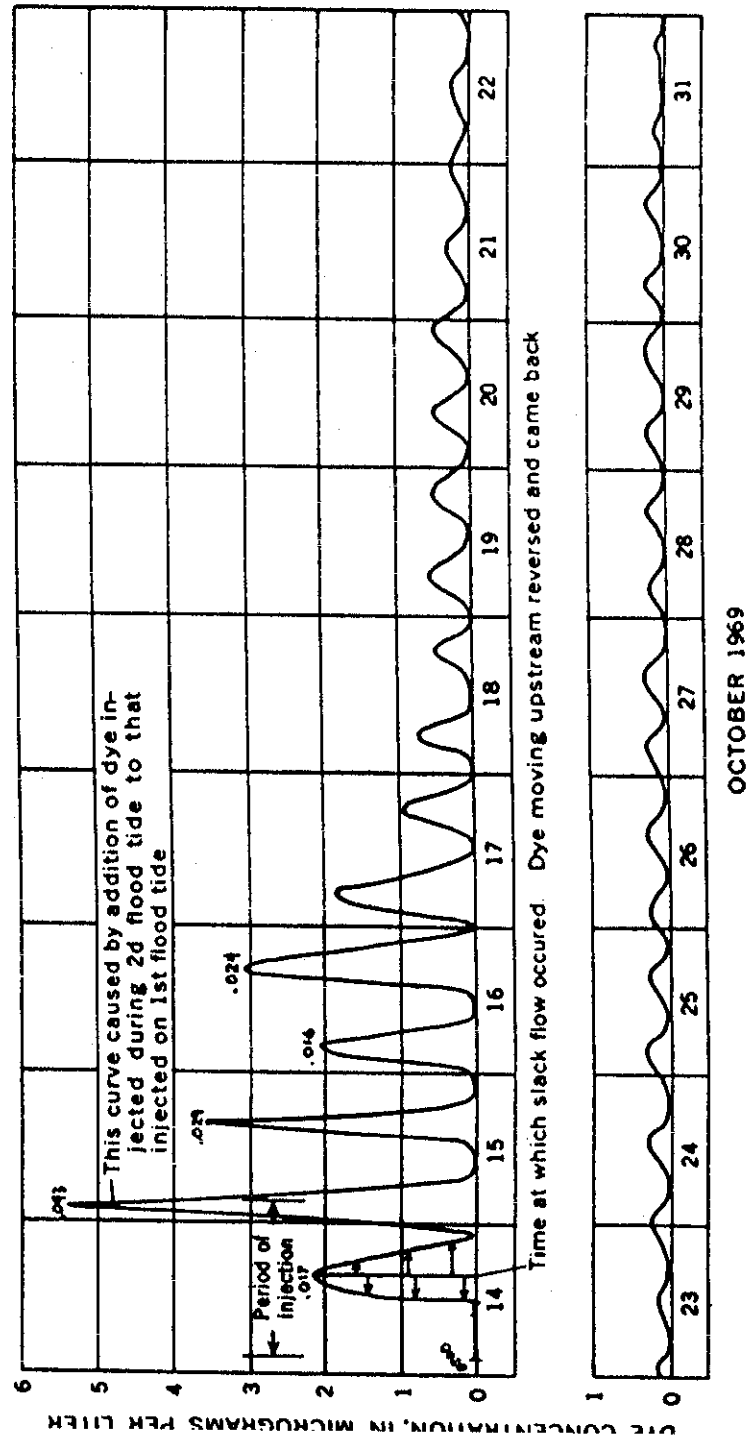

FIGURE 2.—Fluctuation in dye concentration at a sampling point 200 feet from the left bank in cross section 1. The period October 14-15, during which dye was injected into the estuary, is noted.

applied to the observed short-term data to compute the concentration that would result from long-term injection of a solute. Theoretical application of this method, which has been known for some time (Bailey and others, 1966), was recently described by Yotsukura (1968).

Understanding the superposition procedure to estimate the buildup in dye concentrations requires considering the effect of a solute being injected into the river. During the dye study, it was observed that the dye quickly dispersed into a reach of the estuary approximately 6 miles long at low tide. This cloud of dye moved back and forth in the estuary in response to the ebb and flow of the tide. Consequently, if the dye concentration was monitored at a given point, the concentration would rise, reach a peak, and then diminish as the dye cloud moved past. Then during the reverse tide when the cloud recrossed the monitoring point, it would cause another rise, peak, and diminution. The dye-cloud movement produces two peaks of concentration for each tidal cycle unless the dye disperses so uniformly throughout the reach that no peak concentration is discernible. If the concentration is monitored near either end of the reach in which the dye cloud is moving, only one peak is observed during each tidal cycle because the dye cloud arrives at the end of the reach, causing an increase in concentration; remains there during slack tide; and leaves when the tide reverses, causing a decrease in concentration.

The superposition procedure, by which concentration buildup is estimated, used the data from samples collected in the estuary. The dye concentrations of these samples were determined, and graphs of concentration versus time were plotted for selected sampling points. Examples are shown in figures 2 and 3. For simplicity, figures 2 and 3 depict the dye concentrations at sections 1 and 4. Because these sections are near the upstream and downstream ends of the reach affected by the dye cloud, there is only one peak in concentration per tidal cycle of 12.4 hours. Had the concentrations at sections 2 or 3 been shown, there would be two peaks per tidal cycle, as explained above.

These peaks maintain a nearly constant relation with the rise and fall of the tides. For example at section 4, which is near the mouth of the Northeast Cape Fear, the peak in concentration occurs approximately at low slack tide, when the dye cloud is as far downstream as it will travel during that tidal cycle. The concentrations at section 4, the most downstream sampling section, therefore, are at the maximum for that tidal cycle. This relation between the low slack tide and maximum concentration at

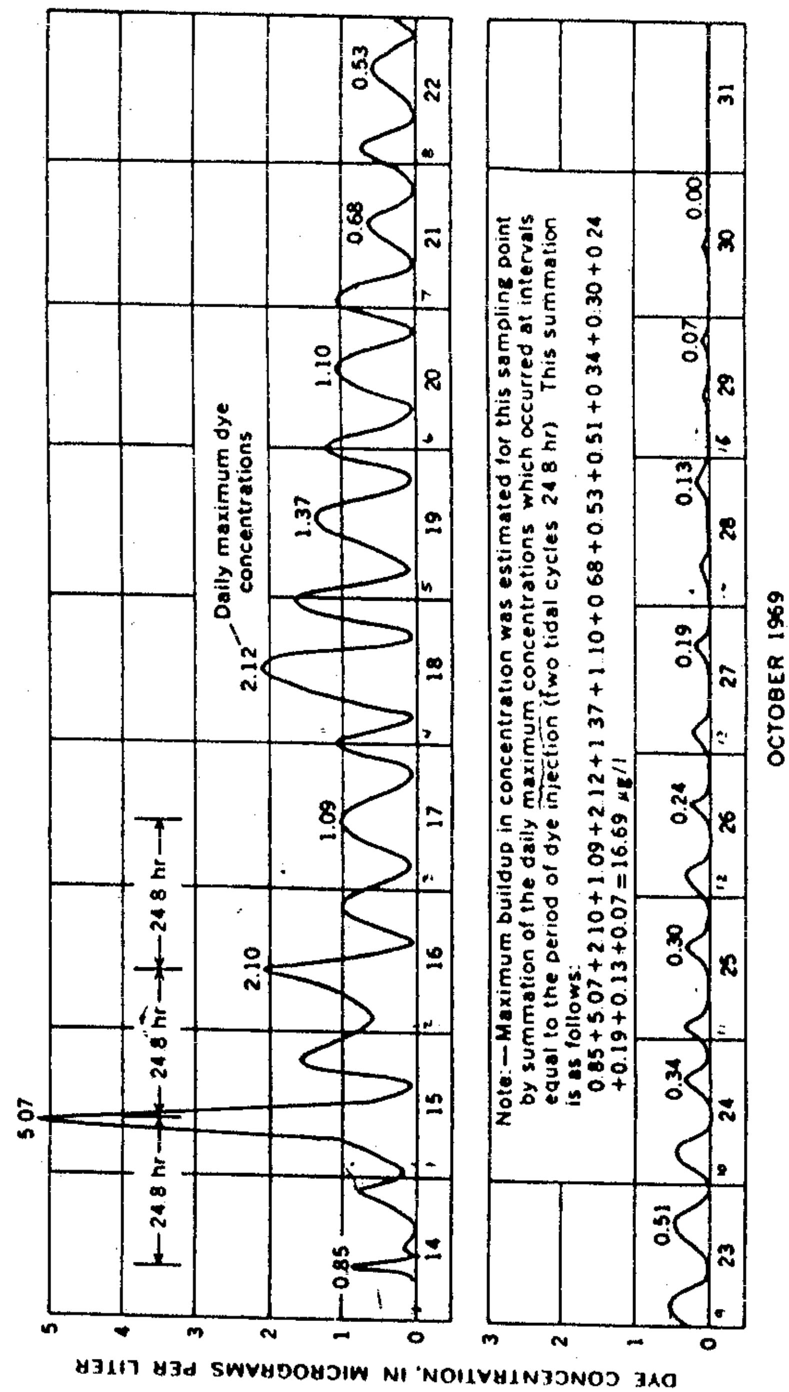

FIGURE 3.—Fluctuation in dye concentration at a sampling point 300 feet from the left bank in cross section 4. The method of computing concentration buildup is illustrated.

section 4 is maintained as long as the solute remains in the estuary. Likewise a fixed relation between the tidal movement and the fluctuation in dye concentration exists at any other point in the reach. The effects of tidal motion on a solute are discussed in greater detail later in this report.

The method of superposition is a technique for adding concentrations observed on succeeding tidal cycles, after a short-term injection of a solute, to approximate the concentration that would result from a long-term injection. Consider the concentration versus time curves illustrated in figures 2 and 3. The amplitude of these curves increased sharply during the dye injection period of two tidal cycles and then gradually decreased as the dye was dispersed and flushed from the system. Had the injection continued for another two tidal cycles, the concentration resulting only from the dye injected during second two cycles would follow the same curve as that for the first injection for two cycles, but the time would be delayed by 24.8 hours. Thus, the concentration observed at a given time after an injection for two tidal cycles plus the concentration observed 24.8 hours earlier would be equal to the concentration that would result at that same given time after (or during) an injection for four tidal cycles. If the injection were continued for the more than 3 days required for another two tidal cycles (six tidal cycles in all), the concentrations on the third day would be equal to the superposition of the concentration curves for the first, second, and third days. If the injection were continued for many days, the concentration of any peak would equal the sum of the peak concentrations resulting from a two-cycle injection taken at the same time in every other tidal cycle. Because the injection was for two tidal cycles, it is necessary to sum only the peak concentration for every other cycle. If the injection were for one tidal cycle, every peak would have to be added to obtain an estimate of concentration buildup.

For this study it was decided to inject dye for two tidal cycles because of the asymmetry of the tides in this region. During a two-tidal cycle period there is a high-high, a low-low, a low-high, and a high-low tide. A determination of the response of the dye cloud to this asymmetry was necessary to estimate the concentration buildup accurately. In other words, it would make some difference in ultimate concentration whether the solute were injected through just the high-high or the low-high cycle. By injecting through both it was possible for the authors to choose the combination of peaks that would add up to the largest dye concentration. This summation was done, as is illustrated in

figure 3, and the value obtained is referred to hereafter as the daily maximum concentration.

One way to understand this computational procedure is to consider that, if there were an injection of dye for many days, the first incremental concentration would represent dye injected that day; the second incremental concentration would represent dye injected the day before. The third would represent dye injected 3 days before, and so on until the concentrations build to a steady level. Under flow conditions similar to those during the dye study, this plateau concentration would be reached after about 17 days.

RESULTS OF THE DYE STUDY

Dye concentrations were added for sampling stations in each section. Dye was injected at the rate of 125 pounds per day. Dye-concentration data were divided by 125 so that the units were micrograms per liter for each pound of solute injected per day. Figures 4-7 illustrate the sum of incremental concentrations in

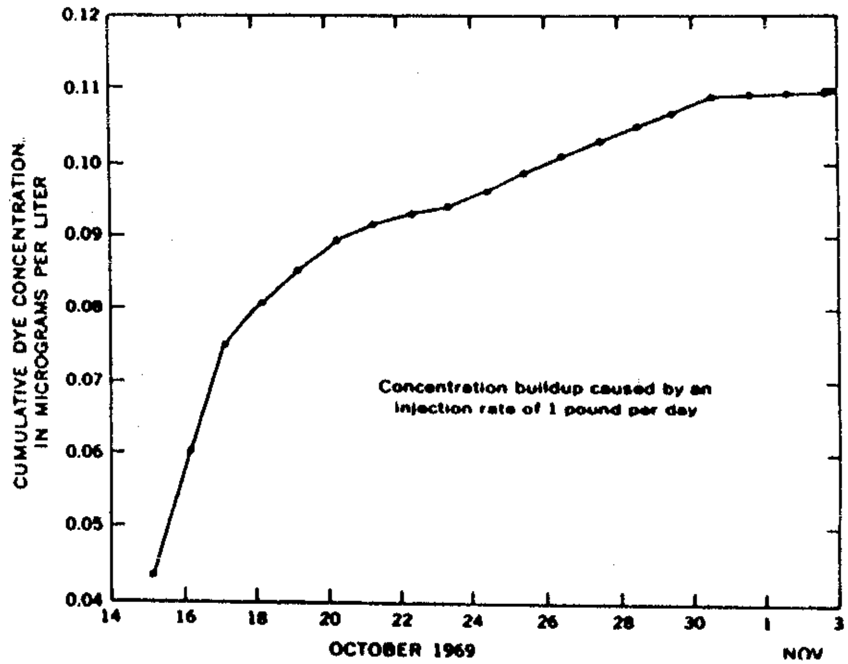

FIGURE 4.—Cumulative dye concentration versus time, in days, at a sampling point 200 feet from the left bank in cross section 1.

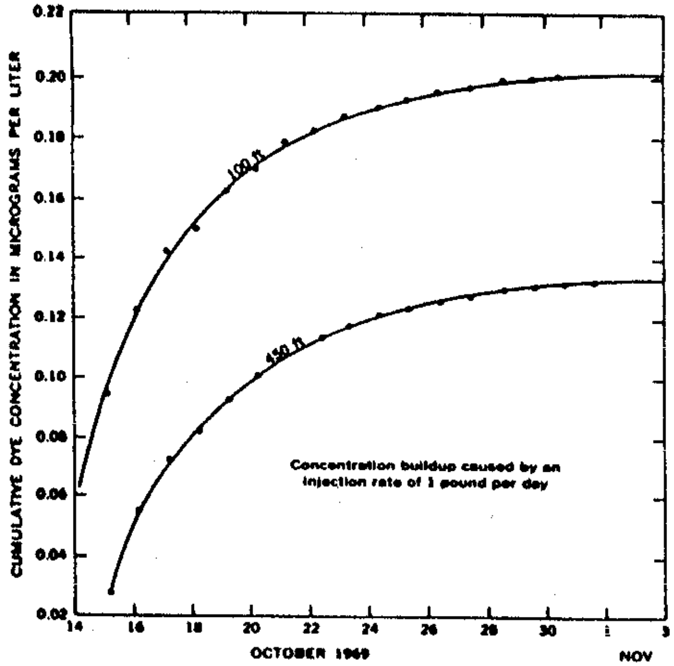

FIGURE 5.—Cumulative dye concentration versus time, in days, at sampling points 100 and 450 feet from the left bank in cross section 2.

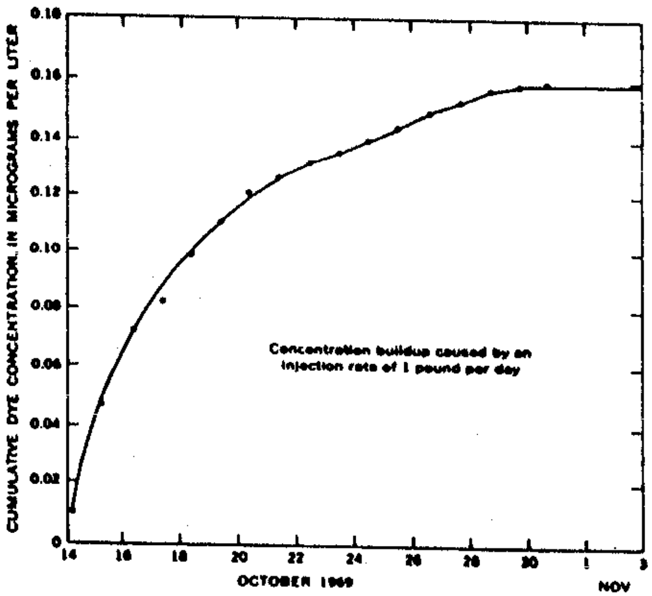

FIGURE 6.—Cumulative dye concentration versus time, in days, at a sampling point 200 feet from the left bank in cross section 3.

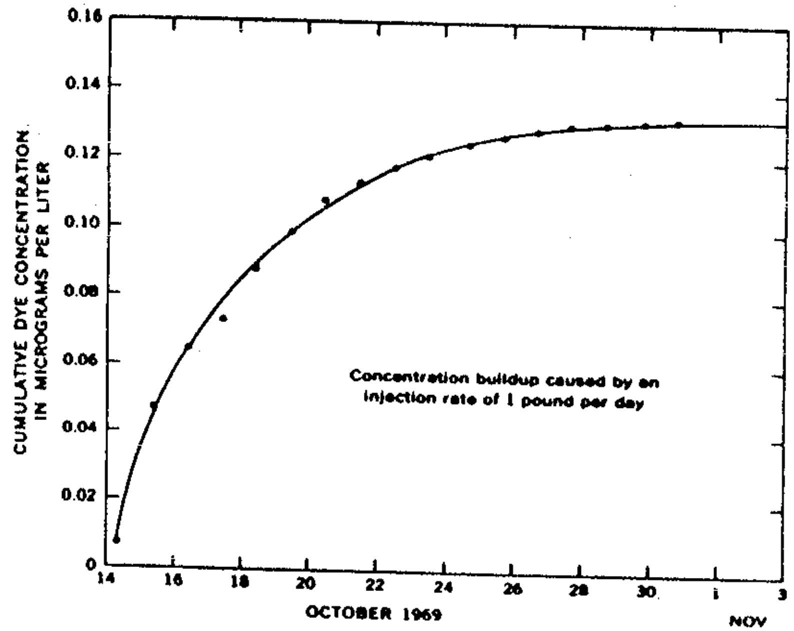

FIGURE 7.—Cumulative dye concentration versus time, in days, at a sampling point 300 feet from the left bank in cross section 4.

these units, as described above. These curves represent the buildup in daily maximum concentrations at the indicated sampling station if there were continuous injection of a solute. The horizontal line which these curves approach asymptotically is the maximum concentration buildup possible for the conditions during the dye study.

Figures 8-11 show the lateral distribution of daily maximum dye concentrations hereafter referred to as unit concentrations, because they represent the maximum daily concentrations that would result from an injection rate of 1 pound per day. The cumulative dye-concentration computations illustrated in figure 3 were done for all sampling stations in each cross section. These unit concentrations can be multiplied by the amount of any solute, in pounds per day injected, to determine the daily maximum buildup of that solute, at any point. For example, suppose it were necessary to determine the daily maximum concentration at a point 500 feet from the left bank in section 3 after long-term injection of phosphate at a rate of 3,000 pounds per day, when a fresh-water inflow of 400 cfs exists. Figure 10 shows that the unit concentration is 0.17 μg/l. Multiplying 0.17 by 3,000, we obtain a maximum daily concentration of 510 μg/l of phosphate. This

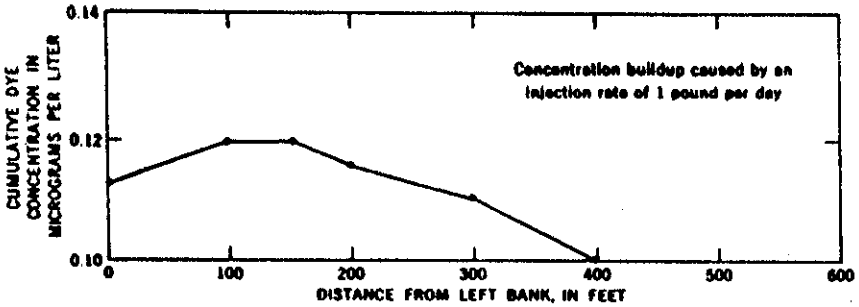

FIGURE 8.—Lateral variation in maximum dye-concentration buildup for sampling stations in section 1, 9.4 miles above mouth.

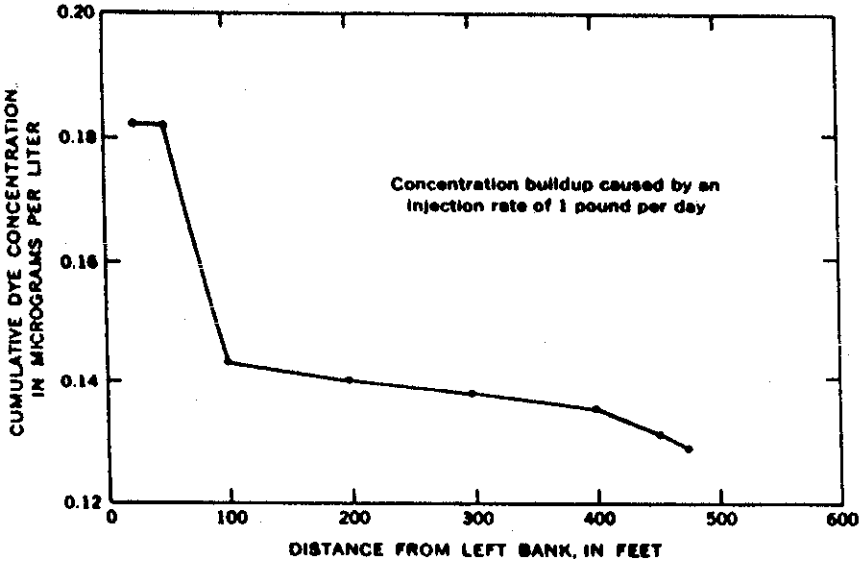

FIGURE 9.—Lateral variation in maximum dye-concentration buildup for sampling stations in section 2, 6.2 miles above mouth.

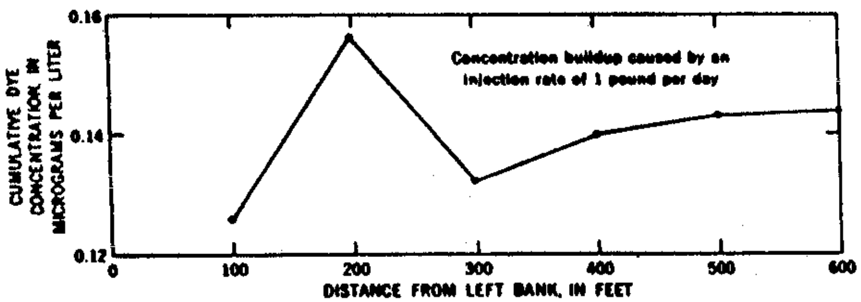

FIGURE 10.—Lateral variation in maximum dye-concentration buildup for sampling stations in section 3, 4.4 miles above mouth.

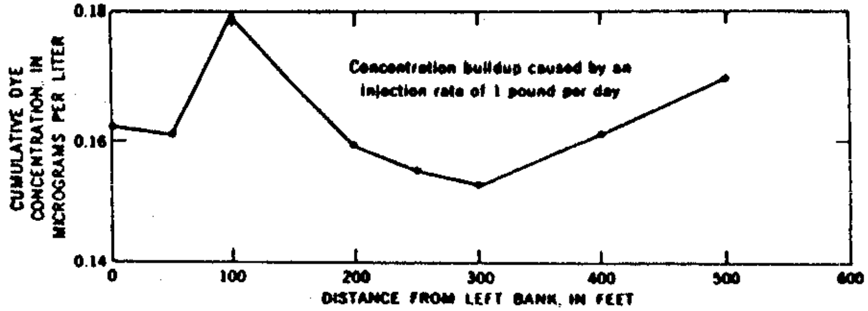

FIGURE 11.—Lateral variation in maximum dye-concentration buildup for sampling stations in section 4, 1.4 miles above mouth.

value applies only for flow conditions similar to those that prevailed during the study.

To eliminate the need for making the computation described above, we calculated pollutant concentrations at each cross section for different rates of injection by using the maximum buildup factors for each section. The resulting curves, the solid lines in figures 12-15, are based on the estimated average fresh-water runoff of the entire basin (to the mouth) which occurred during the dye-injection study. To increase the versatility of these curves, we extrapolated them to cover various rates of fresh-water inflow which are shown as the dashed lines in figures 12-15. This resulting family of curves was extrapolated from this single dye study by the authors assuming that concentration buildup is inversely proportional to fresh-water inflow to the estuary. While this simplifies the complexities involved, and other dye studies at different rates of fresh-water inflow are necessary to test the assumption, we consider the extrapolated curves useful approximations. (For a discussion on the linearity of the response of flushing time to inflow, see Carpenter, 1960.)

To illustrate the use of figures 12-15, we can estimate the daily maximum concentration at section 2 if a solute were introduced into the estuary near the gage at a rate of 1,000 pounds per day when the fresh-water inflow was 200 cfs. Enter figure 13 on the bottom scale and locate the intersection with the 200-cfs curve. The maximum concentration is then read on the left-hand scale opposite this point, which is 400 μg/l for this example. This procedure may be used with any curves in figures 12-15. The resulting estimate represents the highest possible concentration at the section during the daily maximum.

Figures 12-15 may be represented by a simple equation. The equation, like the curves it represents, is more precise for fresh-

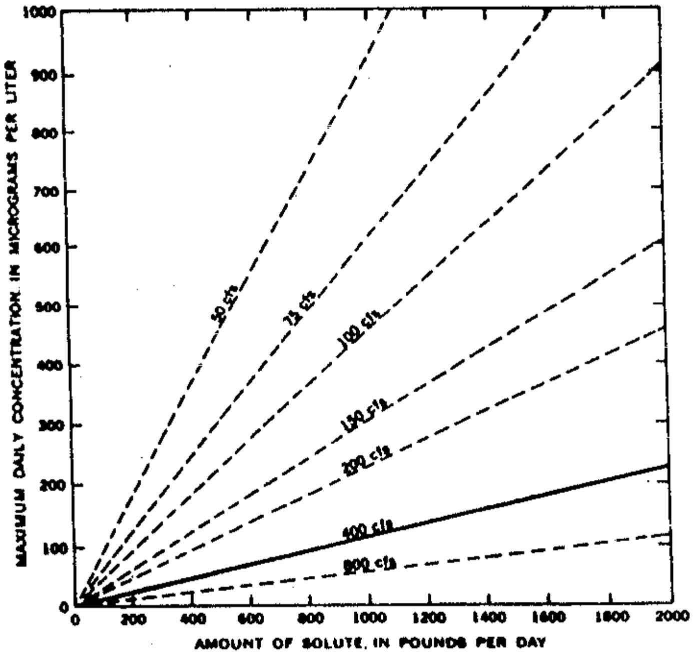

Figure 12.—Maximum concentration buildup versus rate of solute injection for selected fresh-water inflows at section 1.

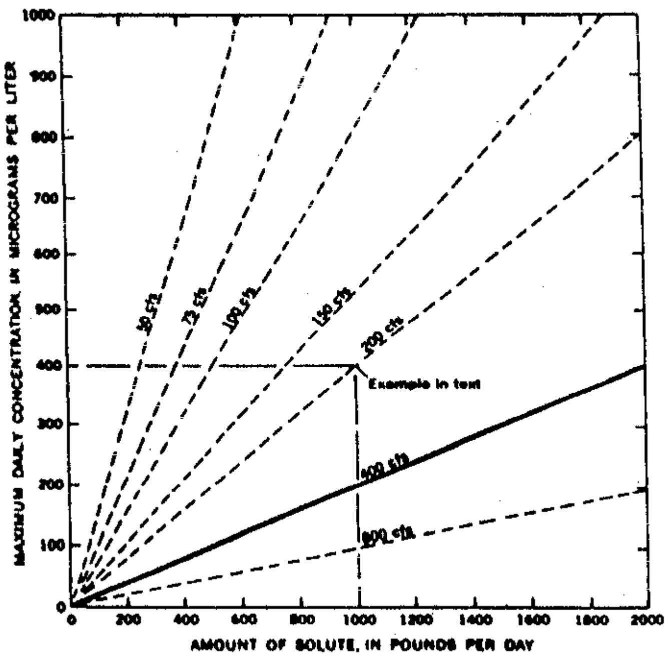

Figure 13.—Maximum concentration buildup versus rate of solute injec-

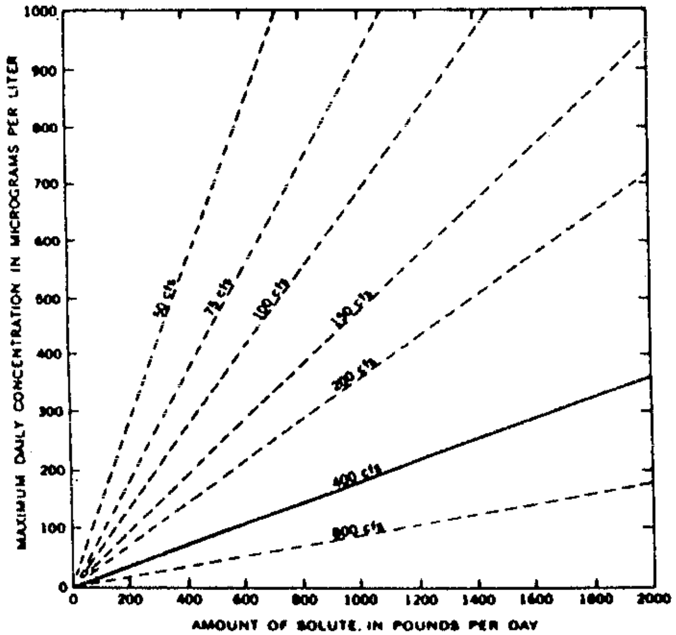

Figure 14.—Maximum concentration buildup versus rate of solute injection for selected fresh-water inflows at section 3.

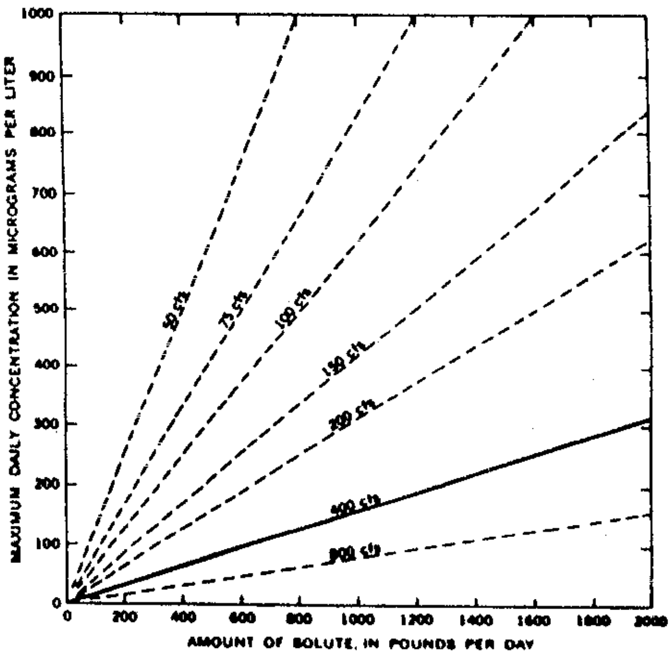

Figure 15.—Maximum concentration buildup versus rate of solute injection for selected fresh-water inflows at section 4.

water inflows near the 400 cfs experienced during the study than for other inflow rates. The general equation is:

$$C_i = K_i \times L/Q \qquad (1)$$

where

- C_i is the estimated maximum daily concentration, in micrograms per liter of a solute at sections 1-4, and i designates the section number;
- K_i is a constant of proportionality for each cross section ($K_1=46$, $K_2=80$, $K_3=72$, and $K_4=63$);
- L is the average daily load of the solute being injected into the estuary, in pounds; and
- Q is the average fresh-water inflow, in cubic feet per second, to the estuary during the designated period.

For example, if one wished to calculate the maximum daily concentration at section 1 if 10,000 pounds of fluoride were injected daily during a period in which fresh-water inflow averaged about 1,000 cfs, these figures could be used in the equation as follows:

$$C_1 = 46 \times 10{,}000/1{,}000 = 460\ \mu g/l$$

This value would represent the concentration of fluoride in the water at section 1 resulting from the injection of 10,000 pounds of fluoride per day in the vicinity of the gaging station. To obtain the total concentration at this point, one would have to add any background concentration already in the water from either natural or man-made sources.

Another application of the superposition method to the present data is the estimation of transient concentrations because of a varied daily load. This capability might be needed if the daily load of injected solute varied so greatly that an average value used in equation 1 would not give a representative answer. Here the computation is performed by summing up daily maximum concentrations which are linearly related to daily loads, or, in equation form:

$$\begin{aligned} C_1 = [&0.047\,(L_{t-0}) + 0.023\,(L_{t-1}) + 0.011\,(L_{t-2}) + 0.007\,(L_{t-3}) \\ &+ 0.005\,(L_{t-4}) + 0.003\,(L_{t-5}) + 0.003\,(L_{t-6}) + 0.002\,(L_{t-7}) \\ &+ 0.002\,(L_{t-8}) + 0.002\,(L_{t-9}) + 0.002\,(L_{t-10}) + 0.002\,(L_{t-11}) \\ &+ 0.001\,(L_{t-12}) + 0.001\,(L_{t-13}) + 0.001\,(L_{t-14}) + 0.001\,(L_{t-15}) \\ &+ 0.001\,(L_{t-16}) + 0.001\,(L_{t-17})]\ \frac{400}{Q} \end{aligned} \qquad (2)$$

$$\begin{aligned} C_2 = [&0.060\,(L_{t-0}) + 0.038\,(L_{t-1}) + 0.026\,(L_{t-2}) + 0.018\,(L_{t-3}) \\ &+ 0.013\,(L_{t-4}) + 0.010\,(L_{t-5}) + 0.008\,(L_{t-6}) + 0.006\,(L_{t-7}) \\ &+ 0.005\,(L_{t-8}) + 0.004\,(L_{t-9}) + 0.003\,(L_{t-10}) + 0.003\,(L_{t-11}) \\ &+ 0.002\,(L_{t-12}) + 0.001\,(L_{t-13}) + 0.001\,(L_{t-14}) + 0.001\,(L_{t-15}) \\ &+ 0.001\,(L_{t-16})]\ \frac{400}{Q} \end{aligned} \qquad (3)$$

$$\begin{aligned} C_3 = [&0.027\,(L_{t-0}) + 0.042\,(L_{t-1}) + 0.025\,(L_{t-2}) + 0.018\,(L_{t-3}) \\ &+ 0.012\,(L_{t-4}) + 0.010\,(L_{t-5}) + 0.009\,(L_{t-6}) + 0.008\,(L_{t-7}) \\ &+ 0.007\,(L_{t-8}) + 0.006\,(L_{t-9}) + 0.005\,(L_{t-10}) + 0.004\,(L_{t-11}) \\ &+ 0.003\,(L_{t-12}) + 0.002\,(L_{t-13}) + 0.001\,(L_{t-14}) + 0.001\,(L_{t-15})] \\ &\frac{400}{Q} \end{aligned} \qquad (4)$$

$$\begin{aligned} C_4 = [&0.004\,(L_{t-0}) + 0.006\,(L_{t-1}) + 0.027\,(L_{t-2}) + 0.015\,(L_{t-3}) \\ &+ 0.010\,(L_{t-4}) + 0.008\,(L_{t-5}) + 0.006\,(L_{t-6}) + 0.005\,(L_{t-7}) \\ &+ 0.004\,(L_{t-8}) + 0.003\,(L_{t-9}) + 0.003\,(L_{t-10}) + 0.002\,(L_{t-11}) \\ &+ 0.002\,(L_{t-12}) + 0.001\,(L_{t-13}) + 0.001\,(L_{t-14}) + 0.001\,(L_{t-15})] \\ &\frac{400}{Q} \end{aligned} \qquad (5)$$

where

- C_1, C_2, C_3, C_4 are the estimated daily maximum concentrations at t days after the start of loading, in micrograms per liter, at cross sections 1, 2, 3, and 4, respectively.
- L_{t-0} is the load of solute, in pounds, being injected on the day for which C_{t-i} is estimated, L_{t-1} is the load injected on the preceding day, L_{t-2} is that injected 2 days before, and so on.
- Q is the average fresh-water inflow, in cubic feet per second, for the period being considered.

These equations were developed from the data collected during the dye study and give the same concentration as does equation 1 when all values are summed. The unit concentrations shown for each day, however, are values taken from a smoothed curve and do not precisely agree with the concentration observed during the study. The curves were smoothed so that the equations would represent the response of the estuary to the injection of a solute and not include the short-term effects of any anomalous tidal movements that occurred during the study.

Equations 2-5 would have application for a process where wastes for perhaps a week would be released in 1 or 2 days. These four equations, like equation 1, are more precise for fresh-inflow around 400 cfs than for other rates of inflow and must be added to the background concentration to obtain the total concentration.

FLOW CHARACTERISTICS

The amount of fresh-water inflow primarily determines the rate at which a solute is flushed from the estuary. Tides cause tremendous volumes of water to flow back and forth past any given point in the estuary. If there is no fresh-water inflow, however, net flow is zero when averaged over many days. The net downstream movement of a particle of water primarily depends, in the long run, on fresh-water inflow.

The dye injected during this study was quickly dispersed by turbulent diffusion resulting from tidal movements. A reach extending approximately 12 miles above the mouth of the estuary contained the dye cloud. A solute discharged into the estuary near the gaging station would also be dispersed into this reach during equivalent inflow and tidal conditions. During periods of higher tides and lower inflow, the affected reach would probably extend a few miles farther upstream. Conversely, during periods of lower tides and higher inflows the affected reach would not extend as far as 12 miles upstream. Effective use of the curves developed in the preceding section, particularly those in figures 12-15, requires some data on fresh-water flow into the estuary.

ESTIMATING FRESH-WATER INFLOW

Figure 16 illustrates a method of estimating the fresh-water inflow to the estuary, upstream from the mouth, by using the flow measured at the gaging station on the Northeast Cape Fear River at Chinquapin, about 78 river miles upstream. This graph is based on flow records collected at Chinquapin and at stations on three downstream tributaries. This curve provides a reliable approximation of the total fresh-water inflow only during stable low-flow recessions. Since such conditions usually occur only when inflow is less than approximately 1,000 cfs, the curve is not extended to higher flows. Under these conditions of low flow, pollution problems are most critical. It is preferable to apply the curve on an average-flow basis, that is, flow at the Chinquapin station averaged over a period of several days and the derived fresh-water inflow taken as the average during the corresponding time period.

The low-flow frequency curves in figure 17 give the expected inflow regime in the estuary at both continuous and partial-record gaging stations in the Northeast Cape Fear River basin. These curves may be used to estimate the recurrence intervals of annual minimum flows less than the indicated values. At average

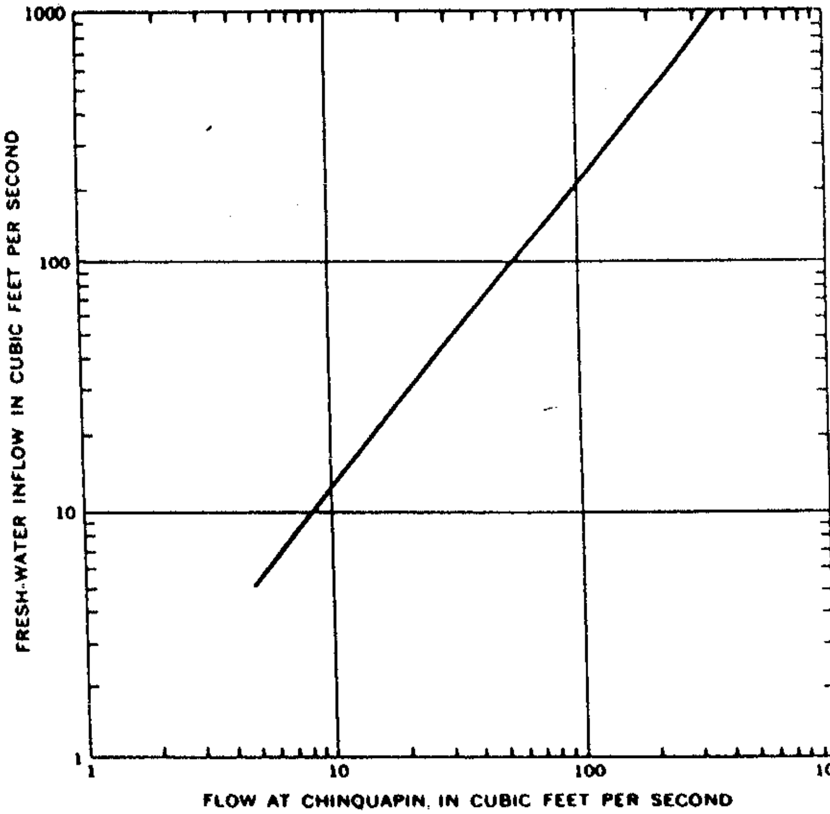

FIGURE 16.—Relation between flow measured at the gaging station, Northeast Cape Fear River at Chinquapin, and the fresh-water inflow to the Northeast Cape Fear Estuary.

intervals of 10 years, for example, the annual minimum flow, averaged over 7 days, is less than about 15 cfs, as the dashed line in figure 17 indicates.

FLUSHING TIME

As noted earlier, the maximum concentration buildup is assumed to be inversely proportional to fresh-water inflow. Fresh-water inflow is important because it controls the rate at which wastes are flushed from the estuary. The rate of flushing is expressed in traveltime of a solute (the center of the mass) from its point of injection to the mouth of the estuary.

For this analysis, average traveltimes are computed from the gage to the mouth for various rates of fresh-water inflow. Cross-sectional areas were computed at many points through the reach. Figure 18 shows both the variation and the trend of these cross-sectional areas. Volumes for each 1-mile part of the reach were

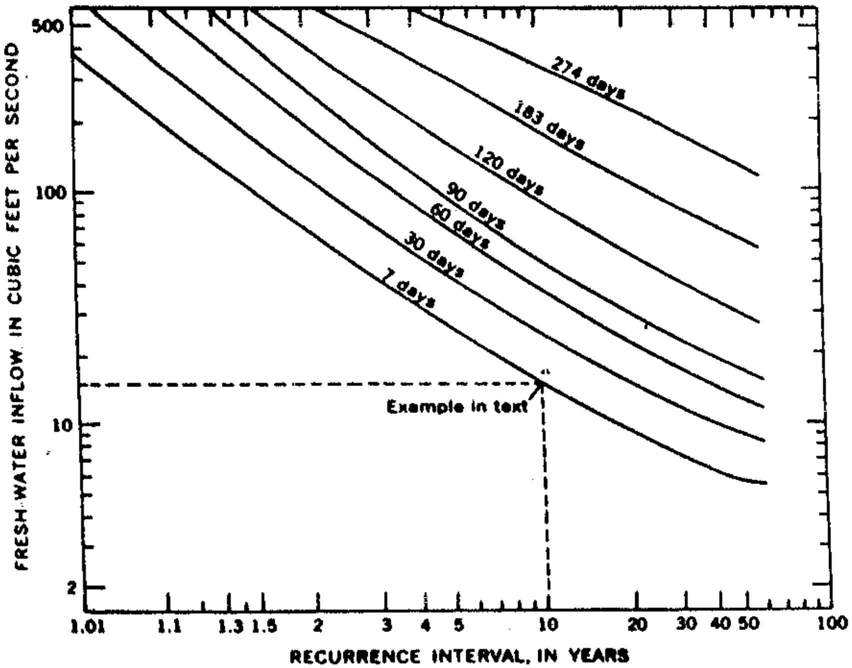

FIGURE 17.—Low-flow frequency curves for the Northeast Cape Fear Estuary.

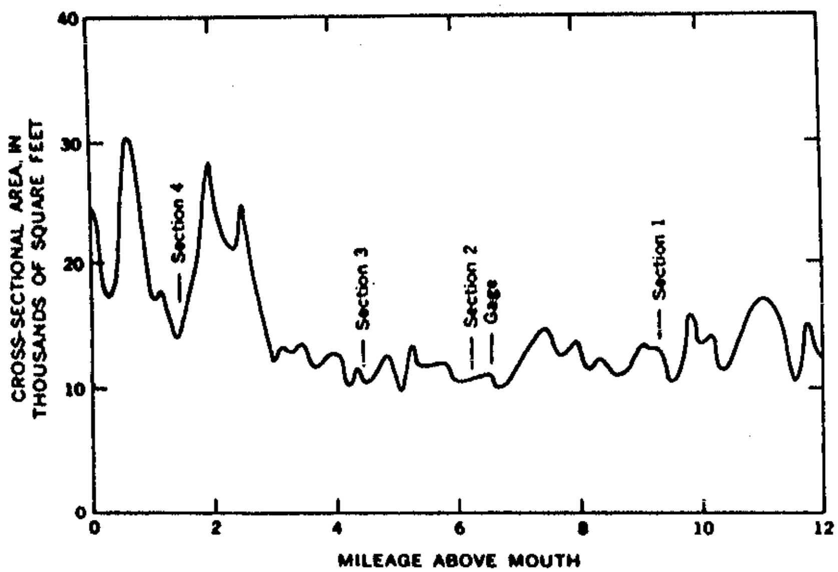

FIGURE 18.—Cross-sectional area in the 12-mile reach above the mouth of

determined from these areas. Mean velocities for each of these subreaches were then computed for various values of fresh-water inflow using the simple flow equation:

$$V = Q/A \qquad (6)$$

where

V = mean velocity, in feet per second through the subreach
Q = inflow, in cubic feet per second
A = area, in square feet.

Dividing the length of each subreach by the mean velocities gave net traveltimes, which are based on fresh-water inflow, disregarding tidal effects. Figure 19 shows the average flushing time versus inflow for the 6½-mile reach from the gage to the mouth. This curve can be used to estimate the average time necessary for a solute to travel through this reach of the estuary under various conditions of inflow. Because the flushing times obtained from

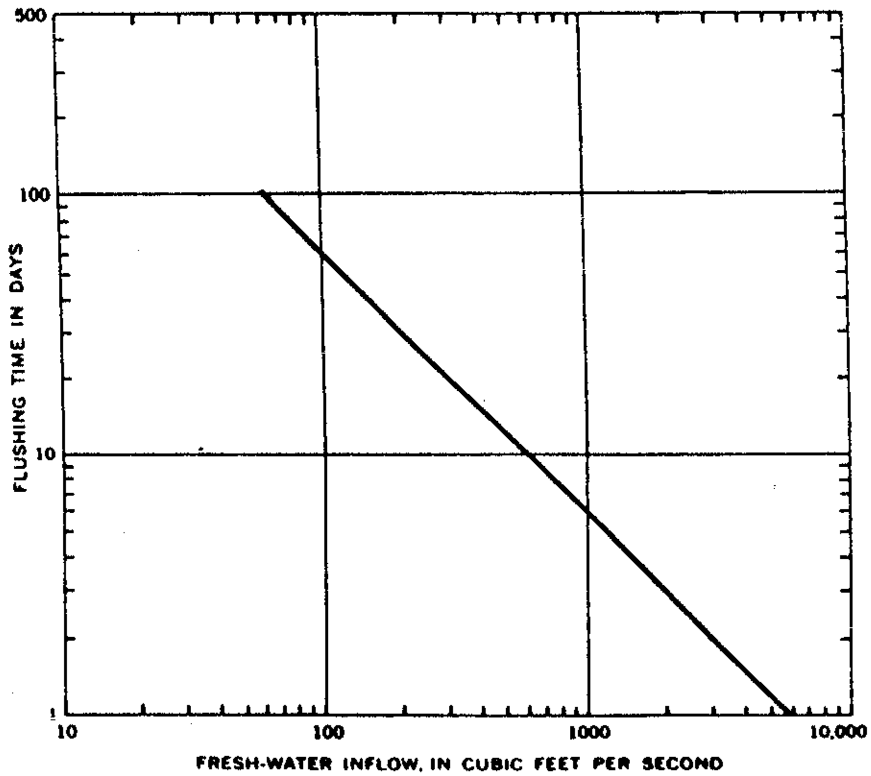

FIGURE 19.—Average flushing time for a solute injected into the Northeast

the graph are average values, only one-half of the dispersed solute would move past the mouth of the Northeast Cape Fear in the indicated time.

Figure 17, the frequency of occurrence of low inflows, and figure 19, the average flushing time as a function of inflow, may be combined for one to estimate the time period required for the estuary to flush for any given recurrence interval. This relation between flushing time and recurrence interval was developed by the authors first selecting flushing times of 30, 60, 90, and 120 days and then determining the corresponding fresh-water inflows, using figure 19. The recurrence interval was then determined for each particular inflow for the designated period, in days, by using the appropriate curve in figure 17. Figure 20 gives the resulting relation of flushing time versus recurrence interval. One can estimate the probability of an average flushing time for any magnitude occurring as the annual maximum.

For example, assume that it is necessary to determine how often a solute being discharged into the estuary near the gage will be retained in the river for longer than 75 days. The frequency of occurrence may be estimated by entering figure 20 on the left-hand scale at 75 days, proceeding horizontally to the curve, and then vertically to the bottom scale, as the dashed line illustrates. This procedure gives a result of about 5 years. Thus, the maximum flushing time would exceed 75 days at average intervals of 5 years.

EFFECT OF TIDES

Fresh-water inflow is the prime force in the long-term net movement of solutes within the Northeast Cape Fear Estuary. In the short run, however, the effects of fresh-water inflow, except during major floods, are insignificant when compared with tidal flows. In the estuary there are strong tides, flood and ebb, which result in large volumes of water moving upstream and downstream past the gage during each tidal cycle.

On October 22-23, 1969, a continuous measurement of discharge was made at the gaging station for one complete tidal cycle. The results of this measurement illustrate the effects of tide. During the first ebb tide of the day, a total of 220 million cubic feet of water passed the gaging station. On the following flood tide 310 million cubic feet was measured at the gage. During these periods, the volume of fresh-water inflow to the estuary is estimated to be only 11 and 10 million cubic feet, respectively. In this case, the component of flow due to fresh-water inflow was

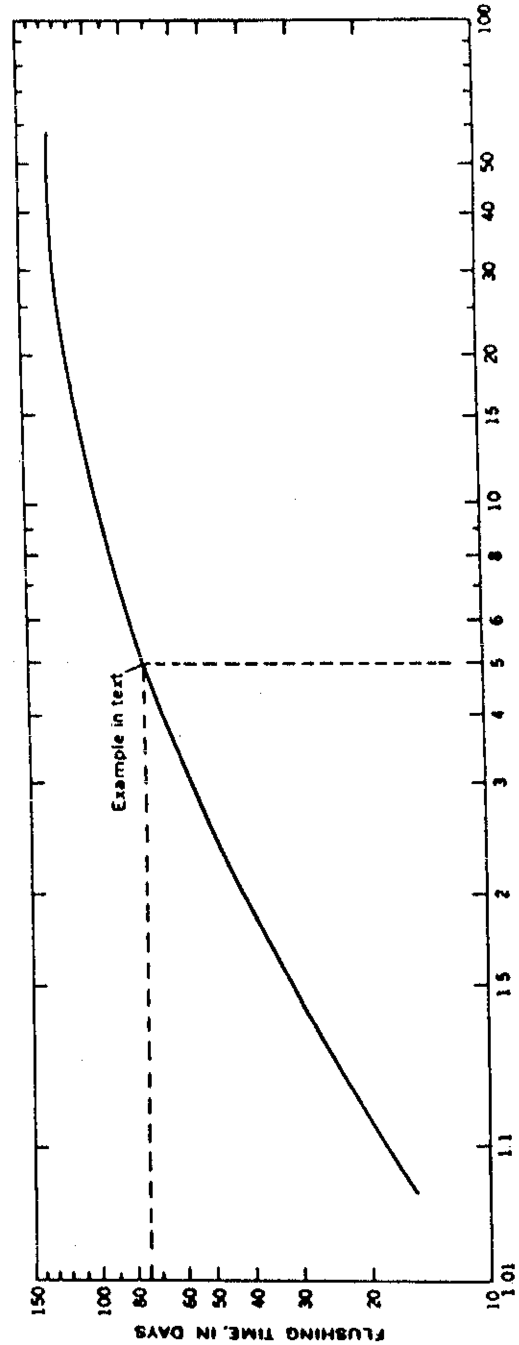

FIGURE 20.—Frequency curve of the maximum flushing time for the reach extending upstream on the Northeast Cape Fear River from the mouth to mile 6.5.

only 5 percent during the ebb tide and 3 percent on the flood tide.

The discharge measurement was made while tides, which were higher than average, effectively raised the water surface and caused water to be backed up or stored in the estuary. For this reason the volume of the flood tide was larger than that of the ebb tide. The difference in these volumes represents the water stored in the estuary upstream from the gaging station during this particular tidal cycle. Such net upstream flow may occur for a few tidal cycles as a result of high tidal levels. Averaged over a longer period of time, however, net flow will be downstream and will equal the fresh-water inflow.

Because the peak concentration of a solute injected into the Northeast Cape Fear Estuary moves back and forth past a given point in the estuary in fixed relation to the tidal cycle, it may be desirable to schedule any program of sampling to obtain data on the maximum concentration rather than on some lower value. The following table shows the relation between the events that occur on the Northeast Cape Fear tidal cycle. This table can be used to schedule sampling so that the maximum concentration of a substance is monitored.

Elapsed time (hours)	*Event and location*	*Time range (hours)*
0	High tide at gage	—
.3	Peak concentration at section 1	±1.0
1.9	High slack tide at gage	± .5
2.9	Peak concentration at section 2	±1.0
4.1	Peak concentration at section 3	±1.0
6.4	Peak concentration at section 4	±2.0
6.8	Low tide at gage	± .5
7.8	Low slack tide at gage	± .5
8.8	Peak concentration at section 3	±1.0
10.7	Peak concentration at section 2	±1.0
11.4	High tide at Wilmington	±1.0
12.4	High tide at gage	±1.0

Although the table is based on the time of high tide at the gaging station, it can be placed in terms of some other tidal event by transposing the figures. In using the table one should allow for the time range shown in the right-hand column, all or part of which may result from variations in the typical tidal pattern due to high fresh-water inflow, wind effects, or other factors.

THE SCHEDULING OF EFFLUENT RELEASES

An interesting question raised during this project was whether or not the scheduling of waste releases would help reduce the concentration of wastes or their persistence in the estuary. If wastes were released in the vicinity of the gaging station at high slack tide, would they be carried out of the Northeast Cape Fear

on the following ebb tide and not return to cause a buildup of waste concentration in the estuary? The answer to this question is a qualified no. The following three factors, observed during the dye study or inferred from the data, show that the scheduling of waste releases would not preclude the buildup of waste concentrations within the estuary:

1. Ordinarily, a solute released on high slack tide will not reach the mouth of the Northeast Cape Fear and will be returned on the following flood tide. The point to which the center of mass of the solute will be returned, under moderate and low inflow conditions, will be only a short distance below the point of release. Short-term tidal conditions may cause this distance to vary considerably and will, on occasion, cause the center of mass to return to a point upstream from the point of release. Figure 3 indicates that the higher concentrations near the center of mass of the dye cloud would not reach section 4, located 1.4 miles upstream from the mouth of the Northeast Cape Fear River, before two tidal cycles (more than 24 hours) had elapsed.
2. The flow in the estuary becomes swift and turbulent during each tidal phase and causes rather rapid dispersion, as indicated by the reduction of dye concentration with time, as shown in figures 2 and 3. Instead of moving from the estuary as a discrete slug, a solute mixes rather quickly into a part of the system and is gradually removed by the combined flushing action of fresh-water inflow and dispersion.
3. Although a solute that has been moved beyond the mouth of the Northeast Cape Fear by ebb tide is subject to further dispersion in the Cape Fear River, part of the solute may return to the Northeast Cape Fear on the following flood tide. The fraction of the solute which will reenter the Northeast Cape Fear River depends on the flow in the Cape Fear. The lower the Cape Fear flow, the more solute will reenter the Northeast Cape Fear.

In spite of these factors, scheduling of releases may be profitable to limit the upstream buildup of solute. If minimizing the upstream concentrations of solute in the estuary becomes desirable, the gaging station may be used to schedule releases. If a solute were released on high slack tide, the upstream migration of this solute would not be completely eliminated, but it would be significantly reduced. Releasing the solute all at once, however, would cause the maximum concentrations in the downstream part of the estuary to be higher than they would be in continuous release.

Conversely, if solute is released at low slack tide, the mass center of the contaminant will be moved first upstream, increasing the effective distance that the solute must move to be flushed from the estuary. Average retention time in the estuary therefore is longer. The time of low-slack tide is least desirable to release a solute. Periods of high inflow might not last long enough to flush the estuary before periods of low inflow returned.

A solute released in a tributary to the estuary would primarily be introduced into the estuary during the lower part of the tidal cycle because water from the estuary would be backed up into the tributary at high tide so that the solute would be stored in the tributary or in the surrounding marsh. As noted previously, a solute released into the estuary during the lower phase of the tidal cycle would tend to cause a greater upstream migration of the solute and a longer retention time, which might possibly lead to a higher buildup in concentrations.

As previously indicated, the peak concentration of a solute will pass a point in the reach in a fixed relation to the tidal cycle. For example, the peak concentration of a solute released at the gage on high slack tide will pass cross section 3 on the outgoing ebb tide and again on the incoming flood tide. This process will continue on subsequent tides until the solute is flushed from the estuary.

During the flushing of the dye cloud from the estuary, samples were taken at about 1-mile intervals along the center of the channel during low-slack tide. This sampling was begun in the Cape Fear Estuary several miles downstream from Wilmington and ended several miles upstream from section 1 in the Northeast Cape Fear River. These data show that the peak dye concentration at low-slack tide occurs near cross section 4, which is near the mouth at mile 1.4.

Both the center of mass and the peak concentration of the solute will oscillate in response to the tidal flows within the estuary. As fresh-water inflow and dispersion act on the solute, the center of mass will translate seaward. This net movement is the flushing process. The peak concentration does not make any net seaward progress, however, but remains within the Northeast Cape Fear because that part of the solute cloud that moves into the Cape Fear during the ebb tide becomes more diluted than that which remains in the Northeast Cape Fear. When the tide changes and the cloud is starting to move back upstream again, the maximum concentration is in the Northeast Cape Fear just

above the mouth. Since this condition occurs on every tidal cycle, the geometry and dynamics of the system position the peak concentration to keep it in phase with tidal movement. This process is illustrated in figure 21.

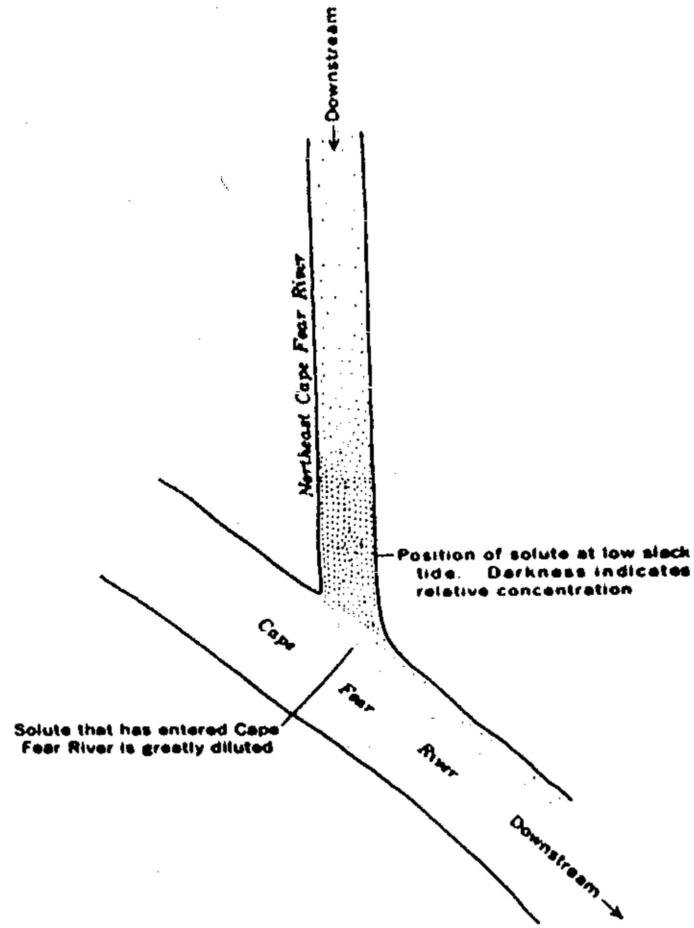

FIGURE 21.—Schematic diagram showing that the peak concentration of a solute released in the Northeast Cape Fear Estuary is located immediately above the mouth at each low-slack tide.

SUMMARY

Data from the dye experiment were used to predict the maximum buildup in concentration of a soluble contaminant introduced into the Northeast Cape Fear Estuary at any given rate. The values of buildup represent the highest concentration that would occur during a day. Also curves were developed for the point of maximum concentration in each cross section. The study was conducted under conditions of below-average fresh-water inflow and above-normal high tides. The concentrations measured would be lower during normal conditions. On the other hand, since much lower inflow rates do occur, correspondingly higher concentrations of contaminants can be expected. Since inflow rates to the estuary vary widely, the results are expanded to provide a basis for estimating the buildup for different inflow conditions. Other curves are presented to give the reader a concept of the average flushing time of the estuary as related to fresh-water inflow, the probability of occurrence of low flows, and the probability of occurrence of flushing times of various durations.

These relations may be applied, with appropriate safety factors, to any waste release in the estuary near the gaging station. In fact it is probably feasible to infer the consequences of pollution from outfalls at sites other than the injection site of this study by shifting the results of the dye experiment either upstream or downstream. Shifting the outfall downstream probably will reduce buildup because shorter net traveltime is required to move the solutes into the Cape Fear River. On the other hand, shifting the outfall upstream would probably increase the amount of buildup because of a longer net traveltime.

If problems are anticipated from the continuous introduction of a certain quantity of industrial wastes into the estuary, a release shedule could be developed which would lessen upstream migration of the pollutant. Releases only at high slack tide, or for a short period thereafter, would significantly reduce concentrations upstream from the point of injection. The pollutant would be flushed from the estuary more quickly because of the initial downstream displacement of the solute cloud.

Discharge measurements during the tidal cycle measured showed upstream flow exceeded downstream flow. A pollutant released on the high-slack tide preceding the measurements would make no net downstream progress during the cycle. This phenomenon was observed during a period of only moderately low fresh-water inflow. During periods of extremely low fresh-water inflow, furthermore, the net movement of water in the estuary could be upstream for several days, particularly if higher-than-normal tidal levels prevailed.

The Northeast Cape Fear quickly disperses a solute both vertically and horizontally. Little difference was noticed between dye concentrations of samples collected at the surface and those collected near the bottom during the dye study. Figures 8-11 show that no really significant difference in concentration buildup can be detected at any of the sampling cross sections with the exception of section 2 which is only about 1,000 feet from the point of injection. The high velocities and resulting turbulence of water associated with the tidal movement cause this rapid dispersion.

Pollutants released into the Northeast Cape Fear Estuary do not tend to remain in a discrete, highly concentrated mass, but rather quickly disperse into a tremendous volume of water. For this reason during moderate flow conditions, tidal flow will not immediately carry a solute injected in the vicinity of the gaging station out of the Northeast Cape Fear. It will instead be dispersed to form a cloud several miles long which will gradually decrease in concentration as the forces of dispersion and the effects of fresh-water inflow remove it from the estuary.

REFERENCES CITED

Bailey, T. E., McCullough, C. A., Gunnerson, C. G., 1966, Mixing and dispersion studies in San Francisco Bay: Jour. Sanitary Eng. Div., Proceedings of the Am. Soc. of Civil Eng., p. 23-45.

Beverage, J. P., and Swecker, M. N., 1969, Estuarine studies in Upper Grays Harbor Washington: U.S. Geol. Survey Water-Supply Paper 1873-B, p. B1-B90.

Carpenter, J. H., 1960, The Chesapeake Bay Institute study of the Baltimore Harbor: The Maryland-Delaware Water and Sewage Assoc., Proceedings of the 33d Annual Conf., Chesapeake Bay Institute, Johns Hopkins University, p. 62-78.

Harleman, D. R. F., 1966, Pollution in estuaries, *in* Ippen, A. T., ed., Estuary and coastline hydrodynamics: New York, McGraw-Hill, chap. 14, p. 630-647.

Pritchard, D. W., and Carpenter, J. H., 1960, Measurement of turbulent diffusion in estuarine and inshore waters: Internat. Assoc. of Sci. Hydrol. Bull. 20, p. 37-50.

Sayre, W. W., 1968, Dispersion of mass in open-channel flow: Colorado State University Hydraulics Papers.

Wilder, H. B., and Hubbard, E. F., 1968, Interim report on sea-water encroachment in the Cape Fear River estuary, North Carolina: U.S. Geol. Survey open-file report, 35 p.

Williams, J. R., 1967, Movement and dispersion of fluorescent dye in the Duwamish River estuary, Washington: U.S. Geol. Survey Prof. Paper 575-B, p. B245-B249.

Wilson, J. F., Jr., 1968, Fluorometric procedures for dye tracing: Techniques of Water-Resources Investigations of the U.S. Geol. Survey, Book 3, Chap. A12, 31 p.

Yotsukura, Nobuhiro, 1968, (Discussion of "Longitudinal mixing in natural streams," by E. L. Thackston and P. A. Krenkel: Jour. San. Eng., v. 93, no. SA5, Oct. 1967): Jour. San. Eng., v. 94, no. SA3, p. 568-571.

Appendix B

Excerpt from draft of Section 2.6 of EPA 1992.
EPA Technical Guidance for Manual for Performing Waste Load Allocations.
Book III: Estuaries.
Part 3: Use of Mixing Zone Models in Estuarine Waste Load Allocations.
EPA/823/R-92/004

United States Environmental Protection Agency

Office Of Water (WH-585)

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Technical Guidance Manual For Performing Waste Load Allocations

PB93-145704

Book III: Estuaries

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8.6 Mixing Zone Predictions Under Unsteady Reversing Tidal Currents

As has been remarked earlier in Section 8.1, the time scale for initial mixing processes is usually short enough relative to the tidal period, so that it is acceptable to apply initial mixing models under steady-state conditions, e.g. corresponding to certain stages within the tidal cycle. However, this approach is no longer valid if predictions are desired over a larger area encompassing distances that, in fact, provide a transition to the far-field.

In the present state-of-the-art no complete models for pollutant predictions in the water environment are available (see Section 8.2). This restriction stems from the difficulties of representing the variety of transport processes that govern the distribution in unconfined estuarine or coastal water bodies in a single analytical or numerical technique. Therefore, an integration of near-field mixing models and of predictive techniques for the far-field effects must be employed. Far-field processes, that include the transport by the varying tidal flow, turbulent diffusion, and various biochemical transformation phenomena, have been addressed in Parts I and II of this estuarine waste load allocation manual. The following comments provide some guidance on *estimating* the interaction between near-field mixing and far-field accumulation effects. The methodology is adapted from that suggested by Jirka et al. (1976).

8.6.1 Far-Field Accumulation Effects

The two major methods for estimating the unsteady far-field accumulation of discharged material, at variable distances from the outfall and in an unsteady tidal flow, are either *numerical models* or *field dispersion tests*. In the following it is assumed that a dispersion test is being employed, but the comments apply equally well to the results of an unsteady numerical model.

The schematics of a field dispersion test in a reversing tidal current system are shown in Figure 8-19. The tracer release line may represent the location of a submerged multiport diffuser with alternating nozzles. The tidal system is assumed as approximately periodic as indicated by the velocity curve. The figure also shows the hypothetical dye concentration tracer $C(x,y)$ measured at some point (x, y) as a function of time. (Note that in practice, fewer discrete measurements over time would be available). If the field dispersion test consists of a tracer release period, n tidal cycles long, then the continuous monitoring would usually indicate a period of concentration *build-up*, a *quasi-steady* period and a *fall-off* period. If an accurate simulation of the pollutant discharge over a large-scale and for a long-term is required, then consideration (and measurement) for at least two of these periods is necessary.

Considering the maximum dye concentration during any tidal cycle at (x, y) the following sequence is generally observable: During the first cycle C_{max} is found, in the second cycle the concentration is C_{max} plus some fraction of dye tracer returning from the previous cycle, thus $C_{max} + r_d C_{max} = C_{max}(1+r_d)$. If these are continuously repeated, then the quasi-steady maximum concentration $\overline{C}_{max}$ is given by the geometric series

$$\overline{C}_{max} = C_{max}(1 + r_d + r_d^2 + r_d^3 + \ldots) \qquad (20)$$

or, in the limit,

$$\overline{C}_{max} = C_{max}\frac{1}{1-r_d} \qquad (21)$$

The quantity r_d is labelled the dye *return rate* of mass discharged in the previous cycle (r_d implicitly includes any dye mass decay during the tidal period). The complement quantity $(1-r_d)$ is frequently referred to as *flushing rate*. The return rate will depend on the characteristics of the tidal flow, notably tidal excursion, mean velocity, diffusion, etc. r_d is also dependent on the position (x, y) with respect to the release area. Quasi-steady conditions are typically encountered after about 5 to 10 tidal cycles. Build-up curves, similar to Equation 20 correspond also to other quantities of interest, such as the minimum or average concentrations during a tidal cycle, thus

$$\bar{C}_i(x,y,t) = C_i(x,y,t)\frac{1}{1-r_d} \tag{22}$$

where $C_i(x,y)$ is a single cycle concentration quantity of interest (C_{max}, C_{min}, C_{avg}, etc.).

For the actual pollutant discharge the quasi-steady condition is usually of primary importance. From Equation 22 it is seen that this depends on two factors: the mixing characteristics C_i within a single tidal cycle, and the return rate from previous cycles. To translate the quasi-steady dye concentration conditions into pollutant concentration, therefore, two adjustments are needed:

(a) Within a tidal cycle, the pollutant concentration c is related to the dye concentration C

$$c_i(x,y,t) = C_i(x,y,t)\frac{Q_{co}}{Q_{do}}e^{-(k_c-k_d)t_i(x,y)} \tag{23}$$

where $t_i(x,y)$ = time interval between occurence of event i (maximum, minimum concentration) at (x,y) and time of release of that tracer patch, i.e., travel time. Q_{co} is the pollutant mass release rate and Q_{do} is the dye mass release rate. k_c and k_d represent the decay constants for pollutant and dye, respectively. (for a conservative dye, $k_d = 0$). Determination of t_i depends on the detailed knowledge of the velocity field; for average concentrations the average tidal velocity is representative. It is noted that for points far from the release area, especially more than several tidal excursions away, the exponential correction term in Equation 23 becomes significant. In the discharge vicinity, however, it is frequently negligible, since t_i is less than one tidal period. This is, in fact, the usual assumption in most mixing zone predictions.

(b) The *return rate for pollutant* r_c is related to the dye return rate r_d

$$r_c = r_d\, e^{-(k_c-k_d)t^*} \tag{24}$$

where t^* = tidal period (12.4 hours). The quasi-steady pollutant concentration $\bar{c}_i(x,y)$ is therefore related to the measured single cycle dye concentration $C_i(x,y)$

$$\bar{c}_i(x,y,t) = C_i(x,y,t)\frac{Q_{co}}{Q_{do}}\left[e^{-(k_c-k_d)t_i}\right]\frac{1-r_d}{1-r_c} \tag{25}$$

Hence, for an accurate prediction of far-field effects over a large area (larger than the tidal excursion length) it is necessary to (i) measure the velocity field in some detail so $t_i(x,y)$ can be found for the points under consideration, and (ii) measure not only the quasi-steady period of tracer distribution, but also the build-up or fall-off period so the dye return rate r_d can be evaluated as shown in Figure 8-19. In actual tracer monitoring it is not always possible to have continuous records. Nevertheless, a few measurements during the build-up or fall-off period usually give some indication of r_d.

If attention is restricted to a smaller area around the discharge and if the tracer used is relatively conservative (small k_d), then both correction factors in Equation 25 are negligible and the measured concentrations can be used directly to evaluate the pollutant accumulation in the far-field.

8.6.2 *Linkage to Initial Mixing Predictions*

All initial mixing models discussed in the preceding are steady-state models and do not consider the far-field return (accumulation). The following procedure provides an approximate linkage:

(a) Carry out a series of initial mixing predictions using a steady-state near-field mixing model for different intervals (e.g. 6 or 12, corresponding to 2 or 1-hour intervals, respectively) within the tidal cycle. The predictions at any point of interest (e.g. at the boundary of a Legal Mixing Zone) provide approximate time-dependent predictions for pollutant concentration $c_i(x,y,t)$ within a tidal cycle.

(b) Use the far-field pollutant return rate r_c, that applies for the region of interest (e.g. the Legal Mixing Zone), to calculate the quasi-steady (i.e. long-term) pollutant concentration

$$\bar{c}_i(x,y,t) = c_i(x,y,t)\frac{1}{1-r_c} \tag{26}$$

The return rate r_c that applies to the area of interest can be estimated using the procedures outlined in the preceding paragraph, i.e. relying on a dye dispersion test or numerical model. It should be noted that r_c in turn, is a function of the distance from the outfall: r_c tends to be very small in the immediate near-field, where the pollutant concentrations are high; r_c becomes larger for increasing distances, where the induced concentrations are falling off, however. This dependence suggests the following practical guidelines in the absence of detailed measurements or predictions for r_c :

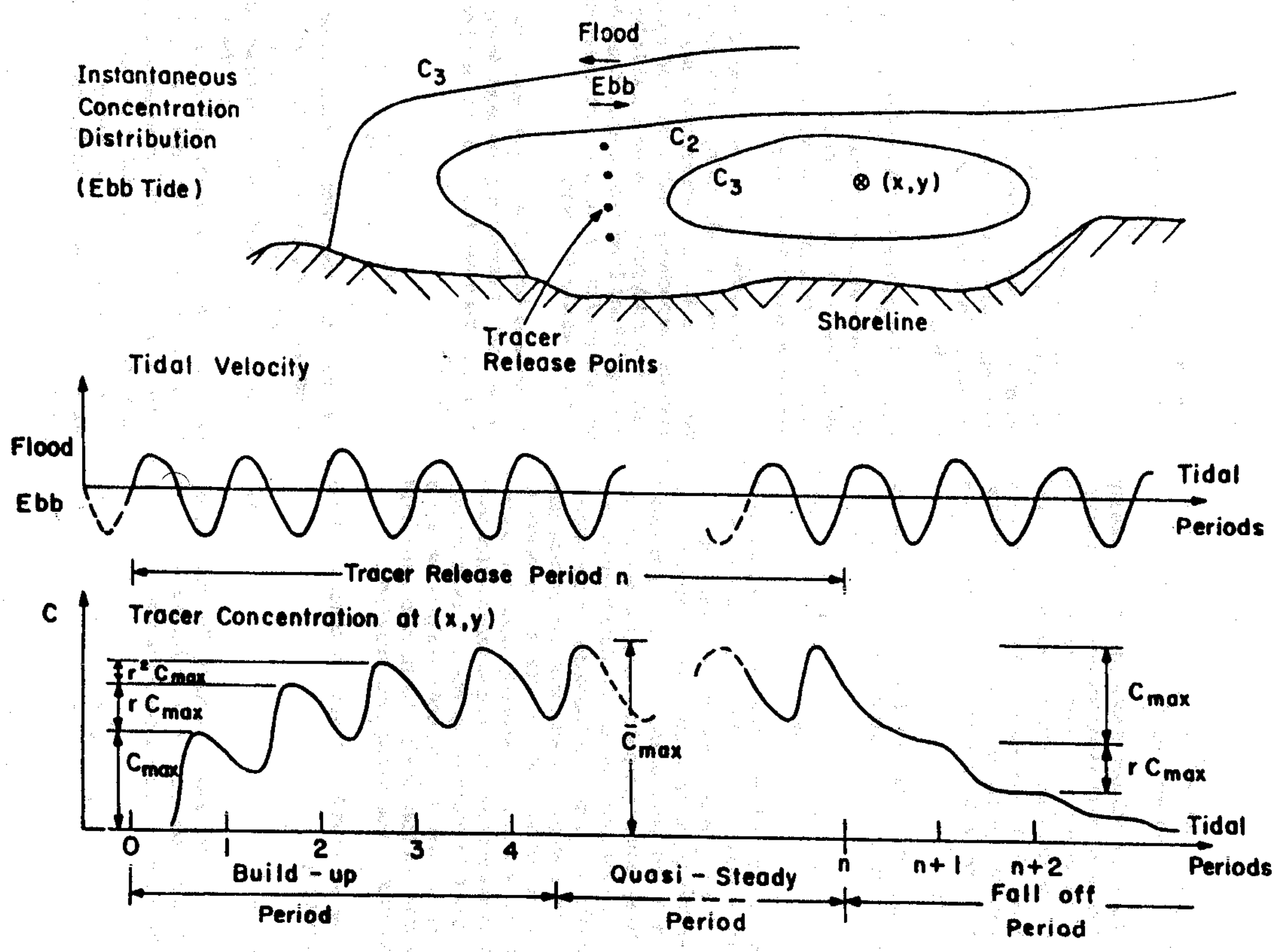

Figure 8-19. Schematics of a field tracer dispersion test in a periodically reversing tidal system.

- For Toxic Dilution Zone (TDZ) predictions, the effect of far-field return is always negligible ($r_c \approx 0$) due to the strong spatial restriction of the TDZ.
- For most Legal Mixing Zone predictions, the r_c factor can be expected to vary in the range of ≤ 0.1 to ≈ 0.5 (highly conservative estimate). It is very small (≤ 0.1) for deep water discharges in the open coastal zone that are often associated with internal trapping or buoyant surface layer formation. In those cases, the initial (buoyant jet) mixing is, in fact, quite independent of far-field effects. It may be reasonably high (up to 0.5) for shallow water, vertically mixed, discharges in strongly restricted estuaries with weak flushing. For additional flushing estimates in such tidal channels, see the methods discussed in Fischer et al. (1979).

8.7 References

Abraham, G. 1963. Jet Diffusion in Stagnant Ambient Fluid. Publ. No. 29, Delft Hydraulics Laboratory, The Netherlands.

Akar, P. J., and G. H. Jirka. 1991. CORMIX2: An Expert System for Hydrodynamic Mixing Zone Analysis of Conventional and Toxic Submerged Multiport Diffuser Discharges. Technical Report, U.S. EPA, Environmental Research Laboratory, Athens, GA, (in preparation).

Doneker, R. L., and G. H. Jirka. 1990. CORMIX1: An Expert System for Hydrodynamic Mixing Zone Analysis of Conventional and Toxic Submerged Single Port Discharges. Technical Report EPA 600/3-90/012, U.S. EPA, Environmental Research Laboratory, Athens, GA.

Fischer, H. B. et al. 1979. Mixing in Inland and Coastal Waters. Academic Press, NY. 483 pp.

Hirst, E.A. 1971. Analysis of Buoyant Jets Discharged to Flowing Stratified Ambients. Rep. ORNL-TM-4685, U.S. Atomic Energy Commission, Oak Ridge National Lab., Oak Ridge, TN.

Holley, E. R. and G. H. Jirka. 1986. Mixing in Rivers, Technical Report E-86-11, U.S. Army Corps of Engineers, Washington, DC.

Jirka, G. H. 1982a. Turbulent Buoyant Jets in Shallow Fluid Layers. In Turbulent Jets and Plumes, W. Rodi (Ed.), Pergamon Press.

Jirka, G. H. 1982b. Multiport Diffusers for Heat Disposal - A Summary. Journal of the Hydraulics Div., ASCE, Vol. 108, December.

Jirka, G. H., G. Abraham, and D.R.F. Harleman. 1976. An Assessment of Techniques for Hydrothermal Prediction. Technical Report NUREG-0044, U.S. Nuclear Regulatory Commission, Washington, DC.

Jirka, G. H. and L.M. Fong. 1981. Vortex Dynamics and Bifurcation of Buoyant Jets in Crossflow. Journal of the Engineering Mechanics Division, American Society of Civil Engineers, Vol. 107, No. EM3, June.

Jones, G.R. and G.H. Jirka. 1991. CORMIX3: An Expert System for the Analysis and Prediction of Buoyant Surface Discharges, Technical Report, DeFrees Hydraulics Laboratory, School of Civil and Environmental Engineering, Cornell University. Also to be published by U.S. Environmental Protection Agency, Technical Report, Environmental Reasearch Lab, Athens, GA.

Kannberg, L. D., and L.R. Davis. 1976. An Experimental/Analytical Investigation of Deep Submerged Multiple Buoyant Jets. EPA-600/3-76-101. U.S. Environmental Protection Agency, Corvallis, OR. 266 pp.

Muellenhoff, W. P., et al. 1985. Initial Mixing Characteristics of Municipal Ocean Discharges (Vol. 1&2). U.S.EPA. Environmental Research Laboratory, Narragansett, R.I.

Roberts, P.J.W. 1977. Dispersion of Buoyant Waste Discharge from Outfall Diffusers of Finite Length. Rep. No. KH-R-35. W. M. Keck Lab. of Hydraulics and Water Resources, California Institute of Technology, Pasadena, CA, 183 pp.

Schatzmann, M. 1978. The Integral Equations for Round Buoyant Jets in Stratified Flows. J. Appl. Math and Physics 29: 608-20.

USEPA. 1982. Revised Section 301 (h) Technical Support Document. EPA 430/9-82-011, Washington, DC.

Winiarski, L. D., and W.E. Frick. 1976. Cooling tower plume model. EPA-600/3-76-100. U.S. Environmental Protection Agency, Corvallis, OR.

Wong, D. R. 1984. Buoyant Jet Entrainment in Stratified Fluids. Ph.D. Thesis, Civil Engineering Dept., The University of Michigan, Ann Arbor, MI.