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Techniques of Water-Resources Investigations of the United States Geological Survey

Chapter A20

SIMULATION OF SOLUBLE WASTE TRANSPORT AND BUILDUP IN SURFACE WATERS USING TRACERS

By F.A. Kilpatrick

Book 3

APPLICATION OF HYDRAULICS

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, ***Secretary***

U.S. GEOLOGICAL SURVEY
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PREFACE

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The unit of publication, the chapter, is limited to a narrow field of subject matter. This format permits flexibility in revision and publication as the need arises. Chapter A20 of Book 3 (TWRI–3A20) deals with the simulation of soluble waste transport and buildup in surface waters using tracers.

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[1]This manual is a revision of "Measurement of Time of Travel and Dispersion in Streams by Dye Tracing," by E.F. Hubbard, F.A. Kilpatrick, L.A. Martens, and J.F. Wilson, Jr., Book 3, Chapter A9, published in 1982.

[2]Spanish translation also available.

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TWRI 3–B4. Regression modeling of ground-water flow, by Richard L. Cooley and Richard L. Naff. 1990. 232 pages.
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TWRI 3–C1. Fluvial sediment concepts, by H.P. Guy. 1970. 55 pages.
TWRI 3–C2. Field methods of measurement of fluvial sediment, by H.P. Guy and V.W. Norman. 1970. 59 pages.
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[1]This manual is a revision of TWRI 5–A3, "Methods of Analysis of Organic Substances in Water," by Donald F. Goerlitz and Eugene Brown, published in 1972.

[2]This manual supersedes TWRI 5–A4, "Methods for collection and analysis of aquatic biological and microbiological samples," edited by P.E. Greeson and others, published in 1977.

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS

Multiply inch-pound unit	*By*	*To obtain metric unit*
mile (mi)	1.609	kilometer (km)
pound (lb)	453.6	gram (g)
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.0283	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

SYMBOLS AND UNITS

Symbol	*Explanation*	*Unit*
$a, b, \ldots, g$	Designation of streamlines and response curves laterally in channel	—
A_c	Area of observed response curve	(μg/L)(min) or (μg/L)(h)
A_u	Area of unit-response curve	[(μg/L)/lb] (ft^3/L)
C_{cp}	Conservative peak concentrations	μg/L
C_d	Observed dye concentration	μg/L
C_p	Observed peak concentration	μg/L
C_s	Concentration of stock dye solution, generally as obtained from the manufacturer	μg/L or percent
C_t	Observed tracer concentration	μg/L
C_u	Unit concentration	[(μg/L)/lb] (ft^3/s)
C_{up}	Unit-peak concentration	[(μg/L)/lb] (ft^3/s)
c_w	Diluted waste concentration in stream	μg/L
C_w	Waste concentration injected	μg/L
e	A constant, equal to 2.72	—
HHSW	High high slack water; the time near high high tide when zero or minimum current exists	
HHT	High high tide; highest of the two high tidal stages occurring in a tidal day	
HLSW	High low slack water; the time near high low tide when zero or minimum current exists	
HLT	High low tide; highest of the two low tidal stages occurring in a tidal day	
k	Decay rate constant to the base 10	
K	Decay rate constant to the base e	
LHSW	Low high slack water; the time near low high tide when zero or minimum current exists	
LHT	Low high tide; lowest of the two high tidal stages occurring in a tidal day	
LLSW	Low low slack water; the time near low low tide when zero or minimum current exists	

Symbols	*Explanation*	*Unit*
LLT	Low low tide; lowest of the two low tidal stages occurring in a tidal day	
n	Slope of the unit-peak-attenuation curve	
q	Rate of constant injection of dye tracer	mL/min
q_w	Waste injection rate	lbs/day
Q	Total stream discharge	ft^3/s
R_r	Dye recovery ratio	—
ΔT	Quasi-steady-state period in an estuary during which tracer is injected at a constant rate; also the numerical integration interval in applying the superposition principle	hours
t	Elapsed time from start of injection	hours, days
t_b	Period when concentrations are building up to the peak	hours
t_r	Period when concentrations are receding from peak to when $C_t = 0.1C_p$	hours
T	Time in tidal day; normally 24.8 hours	
$T_{c,L,t,p}$	Elapsed time to centroid, leading edge, trailing edge, and to peak, respectively, of dye-response curve	hours or min
T_d	Duration in time for dye cloud to pass any one point in a section	hours or min
$T_{d_{10}}$	Duration of abbreviated response curve to point where $C_t = 0.1C_p$	hours
T_D	Duration of longest response curve in a section	hours or min
UPA	Unit-peak attenuation	
UR	Unit-concentration response	
V_s	Volume of stock dye solution	L or mL
W	Weight of soluble waste	lbs
W_d	Weight of dye injected	g or lbs
W_r	Weight of dye recovered	g or lbs
W_{rt}	Weight of waste remaining	lbs
W_t	Weight of tracer injected	lbs

SIMULATION OF SOLUBLE WASTE TRANSPORT AND BUILDUP IN SURFACE WATERS USING TRACERS

By F.A. Kilpatrick

Abstract

Soluble tracers can be used to simulate the transport and dispersion of soluble wastes that might have been introduced or are planned for introduction into surface waters. Measured tracer-response curves produced from the injection of a known quantity of soluble tracer can be used in conjunction with the superposition principle to simulate potential waste buildup in streams, lakes, and estuaries. Such information is particularly valuable to environmental and water-resource planners in determining the effects of proposed waste discharges.

The theory, techniques, analysis, and presentation of results of tracer-waste simulation tests in rivers, lakes, and estuaries are described. This manual builds on other manuals dealing with dye tracing by emphasizing the expanded use of data from time-of-travel studies.

Introduction

The extensive use of fluorescent dyes as water tracers began in the early to mid-1960's. Prior to that time, floats, chemical salts, and actual contaminants had been used as tracers. After World War II, radioisotopes such as tritium (heavy hydrogen) gained favor as tracers, but their use was severely limited by problems in handling, the special training required, and a general lack of understanding by the public. A search for a suitable substitute for radioisotopes led to the rediscovery of fluorescent dyes for tracing.

Within the U.S. Geological Survey, feasibility tests of dyes and fluorometers were made in 1961–62 and were reported by Wright and Collings (1964). The initial application of fluorometry, and by far the application most used to date, was for the measurement of time of travel of solutes in streams (Buchanan, 1964; Kilpatrick and others, 1989). The procedures also were adapted to the measurement of stream discharge by dye-dilution methods (Kilpatrick and Cobb, 1985). Fluorometry has also been applied to studies to determine reaeration rates of streams (Rathbun and others, 1977; Kilpatrick and others, 1989).

In addition to time-of-travel, dispersion, reaeration, and discharge measurements, hydrologic applications have included studies to simulate waste buildup and flushing in estuaries and streams (Bailey and others, 1966; Kilpatrick and Cummings, 1972; Yotsukura and Kilpatrick, 1973; Kilpatrick and Taylor, 1986). The subject of this manual is the application of tracers to simulate the movement, transport, and buildup of wastes in streams, lakes, and estuaries. Emphasis is on the use of dye tracers, but the principles can be applied to any water tracer.

A soluble tracer can be used to simulate a soluble waste by duplicating its movement in *any* hydrologic system, be it a steady flowing river or the unsteady oscillatory stage and flow of a tidal estuary. In the first case, a typical time-of-travel study will be expanded to provide more than just the predicted speed of a slug of soluble waste; the same tracer that simulated the speed of a river can be used to simulate and, hence, predict waste concentrations for different conditions of flow, time, and location. Similarly, a soluble tracer will replicate the movement characteristics of a soluble waste when injected in an estuary in a like manner and location, a tremendous advantage being that few if any of the complex geometries or flows of the estuary waterway need be measured.

It will be assumed that the reader is familiar with the several manuals on fluorometry (Wilson and others, 1986), time of travel (Kilpatrick and Wilson, 1989), measurement of discharge (Kilpatrick and Cobb, 1985), and measurement of reaeration (Kilpatrick and others, 1989). For simplicity, these reports will be referred to as the fluorometry, time-of-travel, dilution discharge, and reaeration manuals, respectively.

Particular attention should be given to the last two manuals because an understanding of the superposition principle and of the various means of performing slug and constant rate tracer injections is vital to understanding and performing waste-simulation studies. For continuity and convenience, some of the information available in these manuals will be pre-

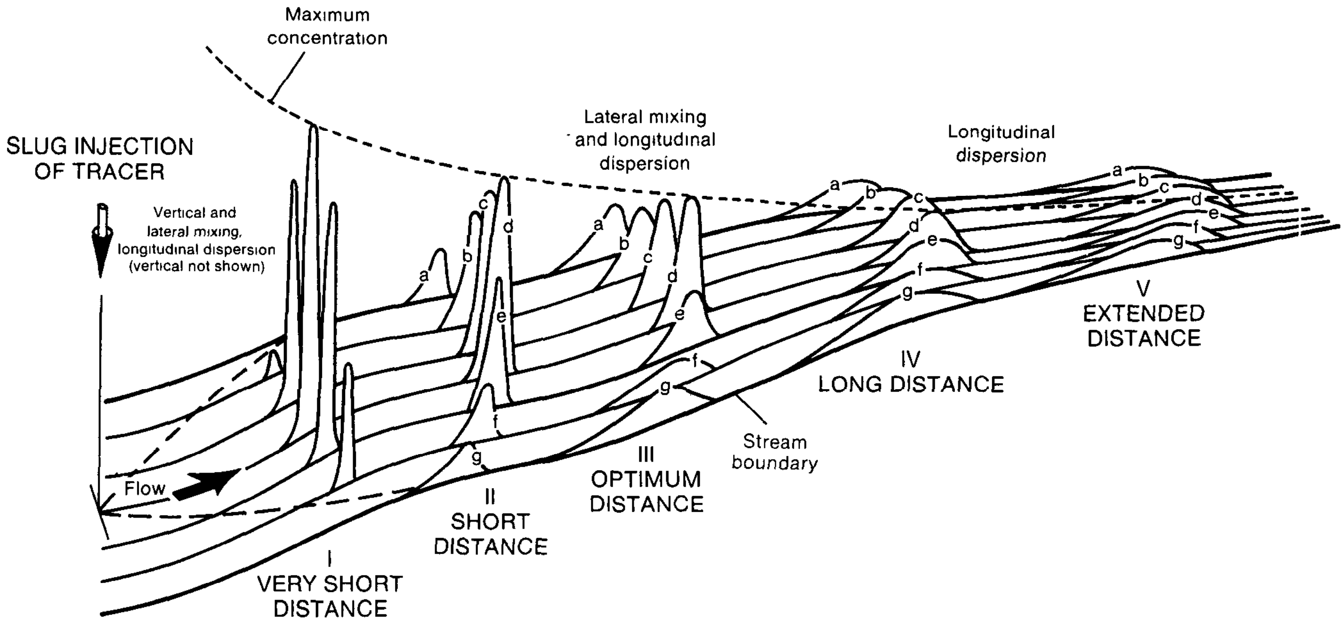


Figure 1.—Lateral mixing and longitudinal dispersion patterns and changes in distribution of concentration downstream from a single, center slug injection of tracer.

sented again. For consistency, when feasible, symbols and definitions will be the same as those presented in these manuals.

Theory

Characteristics of tracer movement in streams

Dispersion and mixing

Tracers used successfully in hydrologic studies are water soluble and have virtually the same physical characteristics as water (Feuerstein and Selleck, 1963; Smart and Laidlaw, 1977). Thus, when introduced into a flowing stream, they undergo the same movement, dispersion, and dilution as does the element of water tagged or the soluble waste introduced. An understanding of how tracers mix and disperse in a stream is essential to an understanding of their application in simulating a soluble waste.

The downstream characteristic of a tracer injected as a slug in the center of flow is shown in figure 1. Note that in figure 1, the response curves are shown as a function of longitudinal distance and not as a function of time. For clarity, the stream has been arbitrarily divided laterally into six stream tubes.

The dispersion and mixing of a tracer in a receiving stream take place in all three dimensions of the channel (fig. 1). In this manual, vertical and lateral dispersion will be referred to in a general way as "mixing." The elongation of a tracer-response cloud longitudinally will be referred to as "longitudinal dispersion." Vertical mixing is normally completed first and lateral later, depending upon the characteristics of the stream and velocity variations. Longitudinal dispersion, having no boundaries, continues indefinitely. Thus, at section I (fig. 1), vertical mixing could be complete, meaning that at any one streamline and time, the tracer concentration is the same throughout the water column, even though it varies drastically laterally. At a short distance, lateral mixing is still taking place, and the tracer mass in transport along the different streamlines is not equal because the response curves do not have equal areas. Mixing and dispersion in two dimensions, therefore, exist between sections I and III.

An optimum mixing distance (section III) is reached when the tracer-response curves *a*, *b*, *c*,..., *g*, as observed laterally, have about the same areas, even though the individual response curves can vary considerably in shape and dimensions; dispersion is approaching the one-dimensional state. Nevertheless, the peak concentrations in the center of the channel could be considerably greater than peak concentrations along the banks, while the latter response curves are longer both physically and in time of passage. Also, the tracer cloud is skewed, advancing faster in the center of the flow compared with the channel boundaries. Furthermore, as shown in figure 1, the tracer cloud might not be uniformly skewed. Sampling of the tracer cloud at several points laterally is advisable.

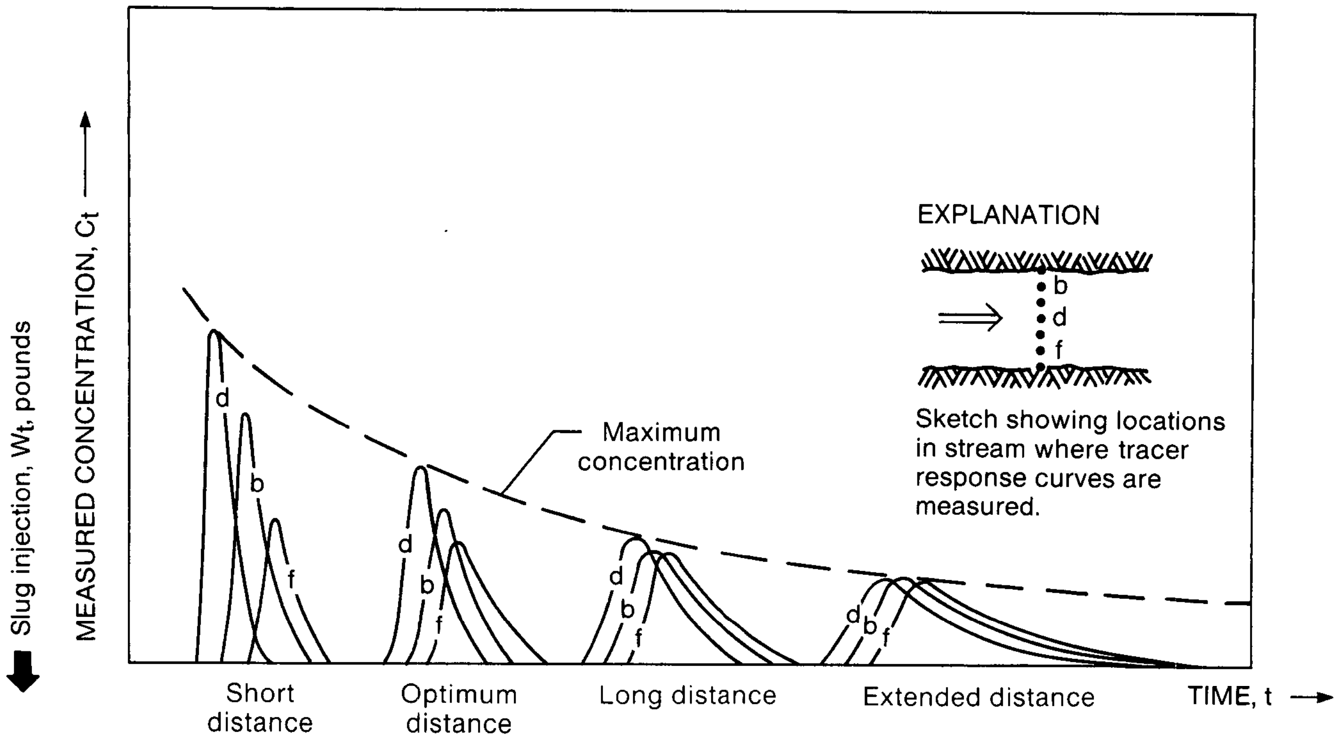


Figure 2.—Time-concentration response curves for slug injection observed at three points laterally across a channel at four different distances downstream from the injection point.

If the tracer-response curves are next examined at a long distance (section IV), the curve areas will be found to be nearly identical and peak concentrations more nearly the same laterally. Thus, a dispersion state that is nearly one-dimensional exists between sections III and IV, where longitudinal dispersion dominates and continues indefinitely downstream. Ultimately, at extended distances, peak concentrations become virtually the same laterally, and longitudinal dispersion affects the shape and dimensions of the response curves exclusively. With time and distance, peak concentrations become attenuated and the cloud lengths get longer and longer (Kilpatrick and Taylor, 1986).

Characteristics of response curve

The conventional manner of illustrating the response in a stream to a slug injection of tracer is to plot concentration variation with elapsed time as observed at one or more points laterally in a stream cross section. This same response is observed in a like manner at other distances downstream to provide information on the time of travel or speed of a slug of solute as well as to measure its dispersion.

To illustrate this, the measured tracer-response curves for a single center-point slug injection (see fig. 1) for streamlines b, d, and f are shown in figure 2 for the short, optimum, long, and extended distances. The travel time to the leading edges, peaks, centroids, and trailing edges can be obtained from these data and related to distance and streamflow duration if tests at more than one discharge are made. The analysis and presentation of time-of-travel data are covered in the report by Kilpatrick and Wilson (1989).

Unitizing of tracer data

The shape and magnitude of the observed tracer-response curves shown in figures 1 and 2 are determined by four factors:

1. The quantity of tracer injected.
2. The degree to which the tracer is conservative.
3. The magnitude of the stream discharge.
4. Longitudinal dispersion.

Any attempt to use tracer-concentration data to predict the concentrations of contaminants that might be injected into a stream must take into consideration these four factors.

The magnitude of the tracer concentrations produced at the four downstream locations is in direct proportion to the quantity of tracer injected, W_t; doubling the amount of tracer injected would yield observed concentration values twice as large while retaining the same shape and duration. Previous investigators thus have normalized their data by dividing all observed tracer concentrations, C_t, by the weight of tracer injected. The resulting concentrations were per pound of tracer (or contaminant) used (Bailey and others, 1966; Martens and others, 1974).

It also has been found that various tracers are lost in transit due to adhesion on sediments (Scott and others, 1969), particularly where fine suspended clays are present. Rhodamine WT dye has been shown both in the field and laboratory to decay photochemically about 2 to 4 percent per day (Hetling and O'Connell, 1966; Tai and Rathbun, 1988). Kilpatrick (U.S. Geological Survey, written commun., 1988) noted decay rates for rhodamine WT dye tended to be higher in rivers, about 5 percent per day, compared with about 3 percent in estuaries. Tracer loss can vary greatly, depending on the characteristics of both the tracer and the water being tagged. In estuaries, the greater depths might reduce photochemical decay in the case of dyes, whereas in streams, larger sediment concentrations could increase dye losses. This is especially true where fine clay is present. Clays have tremendous surface areas for dye to adhere to.

To compare data and to have them simulate a conservative substance, it is desirable to eliminate the effects of tracer loss. If stream discharge, Q, is independently measured at the same time and location of the tracer-response curve, it is possible to evaluate the weight of tracer recovered, W_r, or accounted for by sampling as

$$W_r = Q\int_{T_L}^{T_t} C_t dt = QA_c\,, \qquad (1)$$

where

C_t is the observed concentration,
A_c is the area of the observed tracer-response curve, and
T_L and T_t are the elapsed times to the leading and trailing edges of the observed tracer-response curve.

Equation 1 is based on the assumption that mixing is complete. If mixing is incomplete, computations can be made along stream tubes and summed. When the weight of tracer injected, W_t, is known, the tracer recovery ratio, R_r, can be expressed as

$$R_r = W_r/W_t = \frac{QA_c}{W_t}\,. \qquad (2)$$

The factor that inversely affects the magnitude of the concentration-response curves is stream discharge. The diluting effect of tributary inflows, as well as that of natural ground-water accretion, differs from stream to stream and with location on a reach of stream. To counter the variable diluting effects of differing discharges on the same stream, as well as between streams, it is possible to adjust concentration data to a "unit" discharge, defined as "what would be observed in 1 cubic foot per second (ft^3/s)."

Unit concentrations

Observed concentrations can be adjusted for (1) the amount of tracer injected, (2) tracer loss, and (3) stream discharge to what will be termed "unit concentration," C_u, as follows:

$$C_u = Q\,\frac{(C_t/W_t)}{R_r}\,. \qquad (3)$$

Substituting equation 2 for the recovery ratio, adding the appropriate proportionality constant, and canceling terms, the unit concentration can be expressed as

$$C_u = 4{,}450\,\frac{C_t}{A_c}\,. \qquad (4)$$

When the area of the observed-response curve is in units of hours times micrograms per liter, and C_t is in units of micrograms per liter, then C_u is in units of micrograms per liter per pound times cubic feet per second [(µg/L)/lb](ft^3/s).

The unit-response curve

Equation 4 can be used to reconstruct any measured tracer-response curve to a unit-concentration-response (UR) curve. A typical measured response curve of time versus concentration is shown in figure 3*A*; if the vertical concentration ordinates are changed to unit values using equation 4, the UR for this location and dispersion time will be obtained as shown in figure 3*B*. Note that only the vertical ordinates are changed, such that the response curve now gives the concentrations that would be at that location for the injection of 1 lb of conservative tracer into 1 ft^3/s of flow. This UR curve can be used as the building block for simulating the concentrations to be expected at that location for various waste loadings.

Unitizing the tracer-response curves, in effect, fits one unit weight of tracer into one unit of flow. As such, when mixing is complete, all UR curves have the same area, 4,450 [(µg/L)/lb](ft^3/s) hours, regardless of the particular stream or the location on a stream.

Peak attenuations

Variations in dispersion on the same stream or different streams become most apparent if the unit concentrations for just the peaks, C_{up}, are plotted as a function of elapsed time to the peaks. Equation 4 can be written to apply to just the unit-peak concentration, C_{up}, as

EXPLANATION OF TERMS

A_c = Area of observed response curve
A_u = Area of unit-response curve
C_p = Observed peak concentration
C_t = Observed tracer concentration
C_{up} = Unit-peak concentration
C_u = Unit concentration
T_d = Duration of entire response curve
$T_{d_{10}}$ = Duration of abbreviated response curve to point where $C_t = 0.1C_p$

T_p = Elapsed time to peak concentration
T_L = Elapsed time to leading edge
T_t = Elapsed time to trailing edge of entire response curve
t_b = Period when concentrations are building up to the peak
t_r = Period when concentrations are receding from peak to when $C_t = 0.1C_p$

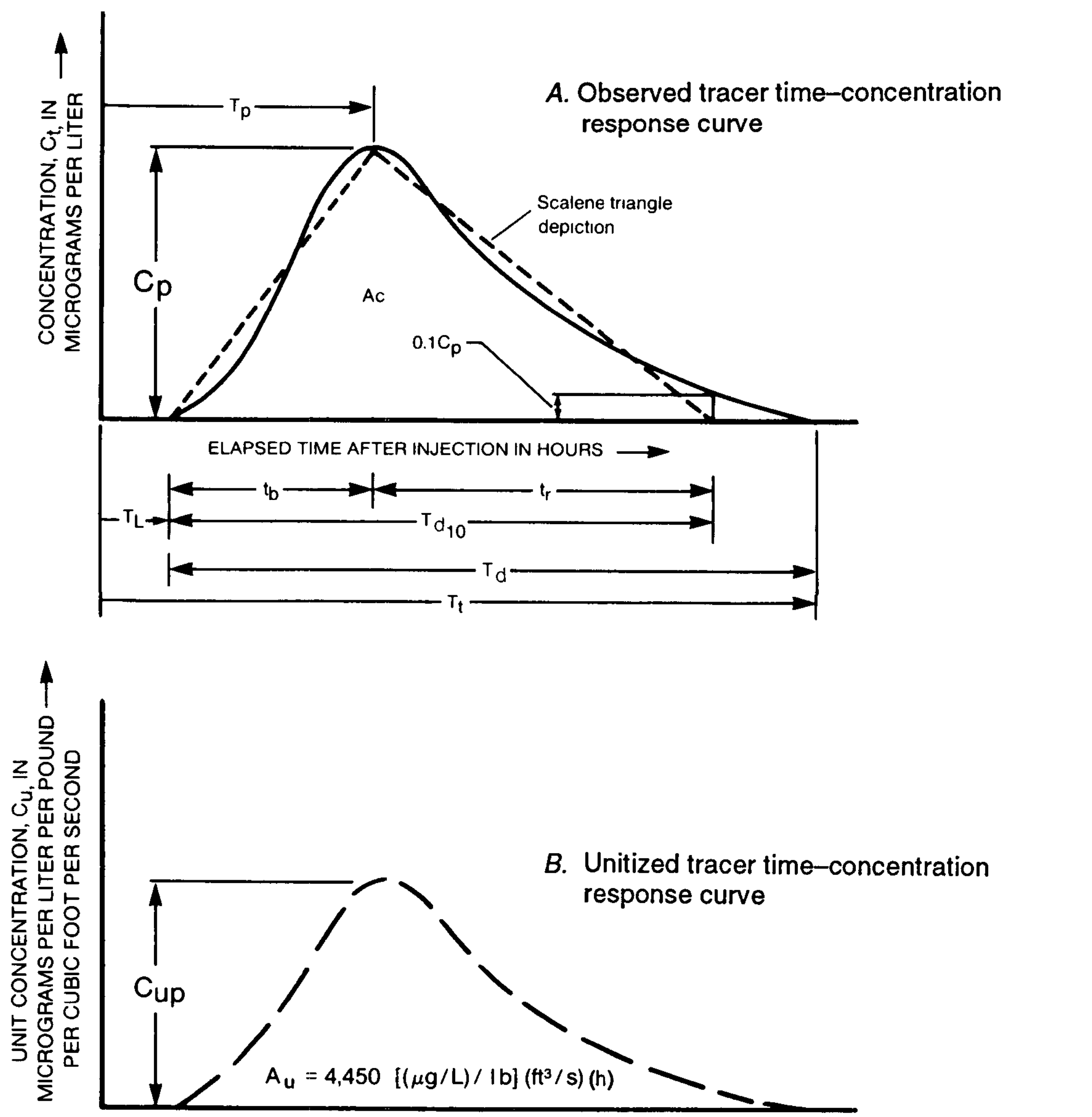


Figure 3.—Observed and unitized time-concentration response curves and scalene triangle depiction.

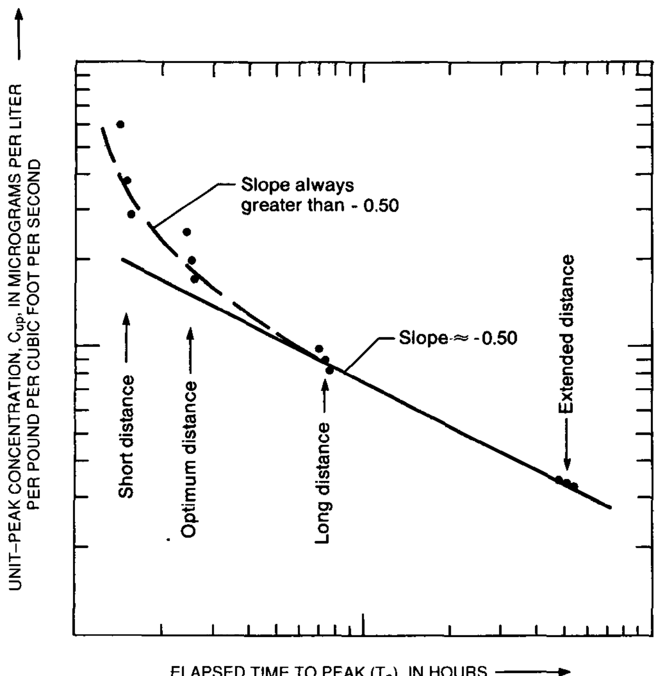


Figure 4.—Theoretical unit-peak-attenuation curve as related to different mixing times.

$$C_{up}=4{,}450\ \frac{C_p}{A_c}\ , \tag{5}$$

where C_p is the observed peak concentration in micrograms per liter.

A plot of the peak concentrations (converted to unit-peak concentrations) with elapsed time for the response curves measured along streamlines b, d, and f at the four distances (figs. 1 and 2) is shown in figure 4. The curve shown in figure 4 is referred to as the unit-peak-attenuation (UPA) curve, as it describes the longitudinal dispersion of a slug of conservative soluble tracer as it moves downstream.

It has been pointed out by Yotsukura (U.S. Geological Survey, written commun., 1976) that, based on the Fickian theory of diffusion (Fischer, 1967), C_{up} is proportional to $t^{-(n)}$, where t is the elapsed time and n is the slope of the UPA curve. Furthermore, ideally $n=0.5$ for the case of steady flow in a straight uniform channel after vertical and lateral mixing are complete and only longitudinal dispersion is continuing. If mixing is in an intermediate stage, where concentrations are uniform in the vertical but not in the lateral, then $n=1.0$; and at extremely short distances and (or) times where neither vertical nor lateral mixing is complete, $n=1.5$. These conditions have been depicted in figure 4; thus the slope of the UPA curve is shown as 0.5 only after nearly complete mixing exists. The ideal case seldom exists in nature, and thus, n typically will be 0.5 or greater. As shown in figure 4, unless the tracer is completely mixed, the slope of the UPA curve will always be greater than 0.5. Where initial mixing is known to be complete, the slope of the UPA curve can be viewed as a measure of the longitudinal dispersion efficiency over and above the ideal. Longitudinal dispersion efficiency refers to the rapidity with which peak concentrations are reduced. The presence of pools and riffles, bends, and other channel and reach characteristics will almost always yield a slope greater than 0.5; the larger the slope the more efficient the reach, in terms of longitudinal dispersion.

The UPA curve, along with the time-of-travel curves, provides a ready means of predicting, at any location, maximum contaminant levels that would be experienced downstream from the spill of any amount of soluble contaminant at any location in the reach after total mixing has been achieved for the range in flows tested. This is accomplished using the equation

$$C_{cp}=\frac{C_{up}W}{Q}\ , \tag{6}$$

which gives the conservative peak concentration, C_{cp}, that would result downstream in discharge Q if W pounds of soluble waste are injected; C_{up} must be obtained from a suitable UPA curve, which requires a knowledge of the elapsed time to the location in question. Elapsed time or time of travel can be thought of as dispersion time; distance is not as significant as the actual time available for dispersion.

It will often be found that if tracer tests are performed in a stream reach at more than one discharge, all the unit-peak-concentration data will define one UPA curve having the same slope. This indicates that longitudinal dispersion is the same for the reach over the range of discharges tested (Kilpatrick and Taylor, 1986). More commonly, different UPA curves are obtained, sometimes having the same slope and sometimes different slopes, but both cases allow interpolation to be made of the results of contaminant spills at other locations and discharges.

Characteristics of tracer movement in estuaries

The techniques involved in simulating the movement and buildup of wastes in an estuary using tracers and the superposition principle will be presented later. An understanding of the complex flow patterns occurring in estuaries is essential in selecting test periods to suit the objectives.

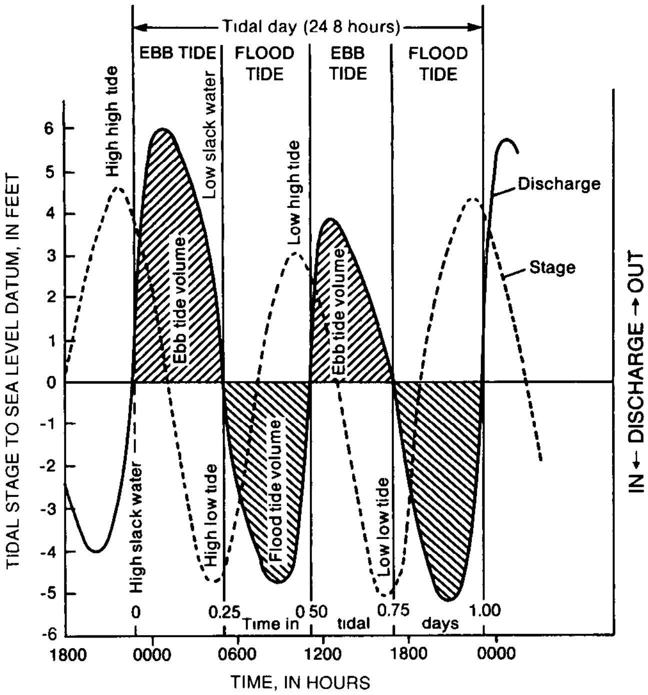


Figure 5.—Typical stage and discharge hydrographs for East Coast estuaries.

Tidal hydraulics

Flows in estuaries are some of the most complex to be encountered. Whereas flow in rivers is essentially steady (or a period may be selected when it is steady), the oscillatory tidal action present in estuaries produces unsteady flow of the most extreme case. To further complicate the hydraulic picture in estuaries, some may have significant freshwater inflow from one or more sources, both surface and ground water. Estuaries are also classified as mixed or unmixed, the latter being characterized by a saltwater wedge that moves inland with changes in freshwater flow and tidal stage. Worse still, the entire picture can change from week to week and season to season due to long-term changes in tidal action and seasonal changes in freshwater inflows.

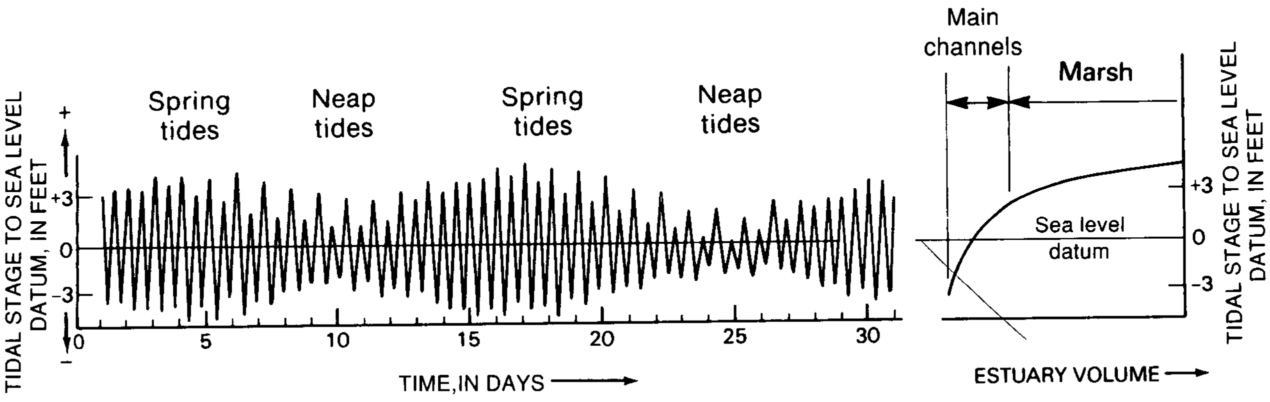
A typical graph of tidal stage, as shown in figure 5 for an East Coast estuary, features two high tides and two low tides per tidal day. These are, as might be observed, at the mouth of an estuary or at any section in an estuary. The tides are driven primarily by the alternating attraction (gravity) of the sun and moon, the moon being the dominant force. One of the high tides will usually be larger (high high tide) than the other (low high tide) within the tidal day as a result of the combined forces of both sun and moon. Note that the maximum discharge in or out of the estuary occurs approximately at zero stage datum (when referenced to mean tide level) as the maximum energy gradient exists in going from high to low or low to high. If the discharge hydrograph is measured as shown in figure 5, its area is a measure of the tidal volume of water flow in (flood tide) and out (ebb tide) of the estuary.

As seen in figure 5, high slack water and high slack tide do not necessarily occur simultaneously. The highest or lowest tidal stage may be on the order of an hour earlier than when flow ceases. As will be seen subsequently, tracer sampling will usually be during high or low slack water and not necessarily at high or low tidal stages.

The data to predict tidal stages and flows are available for selected coastal locations from the Coast and Geodetic Tide Tables. These tables also provide corrections for inland points in the estuaries, since patterns depicted in figure 5 may be significantly different at inland locations.

In general, estuaries experiencing large ranges in tidal stage and, hence, discharges are less apt to be polluted, as contaminants are more likely to be carried seaward. For example, estuaries along the Gulf Coast are less efficient in flushing due to tidal action that is subdued in comparison with that of the Atlantic and Pacific Coasts.

The tidal day is approximately 24.8 hours long, as the moon orbits the Earth in approximately 29.5 days, yielding a tide that occurs about 50 min later each day. The moon's orbit about the Earth must be distinguished from the Earth's own rotation about its axis. Typical tide variations over a month are illustrated in figure 6*A*. The approximately weekly pattern of strong spring and weak neap tides is caused by the 29.5-day orbit of the moon about the Earth. In a general way, the change in estuary volume with tidal stage resulting from flows in and out of the estuary is shown in figure 6*B*. Typically, when the tide is out, water occupies only the main channels of an estuary. At flood tide, flows move inland and laterally out of the main channels and into adjoining marshlands and tidal flats. This cyclic pattern of flooding and dewatering is believed to be critical to the biological community of an estuary (Teal and Teal, 1969). As can be seen by comparing the graphs in figures 6*A* and 6*B*, the degree of marshland flooding may vary significantly between spring and neap tides. More important to the subject of this report, the injection of a tracer into an estuary during spring tide will result in more extensive transport of the tracer (or a soluble contaminant) into the marshlands and, at the same time, the most dilution will occur. Conversely, if injected during a neap tide period, the tracer will be more confined to the main channels and will be diluted the least. Either situation may be undesirable when it comes to injecting contaminants into an estuary.



A. Typical tidal stage variation during one month.

B. Change in affected estuary volume with tidal stage.

Figure 6.—Typical long-term pattern of tidal stage and variation in marshland flooding.

Dispersion and mixing

A typical estuary is depicted in figure 7. This illustration will be used in this report to present the theory and technique of simulating waste buildup in an estuary using a tracer and the superposition principle.

As has been discussed previously, flow in a tidally affected estuary is oscillatory. The magnitude of these flows is determined by the magnitude of the tidal stage changes and the volume of both main channel and marshland areas affected. In a typical East Coast estuary, flows reverse every 6.2 hours, filling inland channels and marshlands on the flood tide and draining out on the ebb tide.

A tracer introduced into an estuary flow system is affected by these flow patterns. Where there is no freshwater inflow, a tracer slug injected inland at location A (fig. 7) will mix with the flow and oscillate back and forth, elongating with time and ultimately dispersing into adjoining lesser channels and the bordering marshlands. A tracer injected on the ebb tide will return on the flood tide, but because of dispersion and advection, will enter adjoining channels and marshland that were bypassed on the ebb tide.

The response to such a slug injection will look like that shown in figure 8*A*, assuming no freshwater inflow. Ultimately, depending on the magnitude of the tidal excursion, the tracer will be flushed into the ocean to be swept away by coastal currents. The tidal excursion, the distance an element of water will move during a tidal cycle, will change from spring tide to neap tide. Note that the tracer-response curve shown in figure 8*A* is essentially symmetrical in contrast to that for a river (fig. 2), which is typically skewed. In an estuary without freshwater inflow, the centroid of the tracer will return to the injection point but will spread as a result of longitudinal dispersion and tidal discharges.

If the point of tracer injection is close to the ocean (location B in fig. 7), the tidal excursion will transport some tracer directly to the ocean, and longitudinal dispersion will eventually move the rest into the ocean (fig. 8*B*). Of the injection made on the ebb tide, large portions, perhaps all, might be carried quickly into the ocean. The dye injected on the flood tide, however, will be carried inland, ultimately returning to the injection point. Eventually, longitudinal dispersion will transport the bulk of the tracer into the ocean. Thus, if a waste effluent was introduced continuously at point B, it would enter both flood and ebb tide flows, the result being some buildup of waste concentrations upstream but a fairly rapid flushing of wastes seaward.

Regardless of the location of the injection, if freshwater inflow exists, it will aid in transporting the tracer seaward (fig. 8*C*). In estuaries experiencing large changes in tidal stage and hence large tidal discharges, the freshwater inflow will normally be small by comparison. Thus, the predominant flushing mechanisms in many estuaries are longitudinal dispersion and tidal discharge.

The superposition principle

General

One of the most useful tools to hydrologists has been the unit-hydrograph method (Linsley and others, 1958) for predicting stream runoff from precipitation in a drainage basin. The unit-hydrograph theory assumes that the stream-runoff response is linear and that unit hydrographs can be added to synthesize the response to different rainfalls. This approach must be

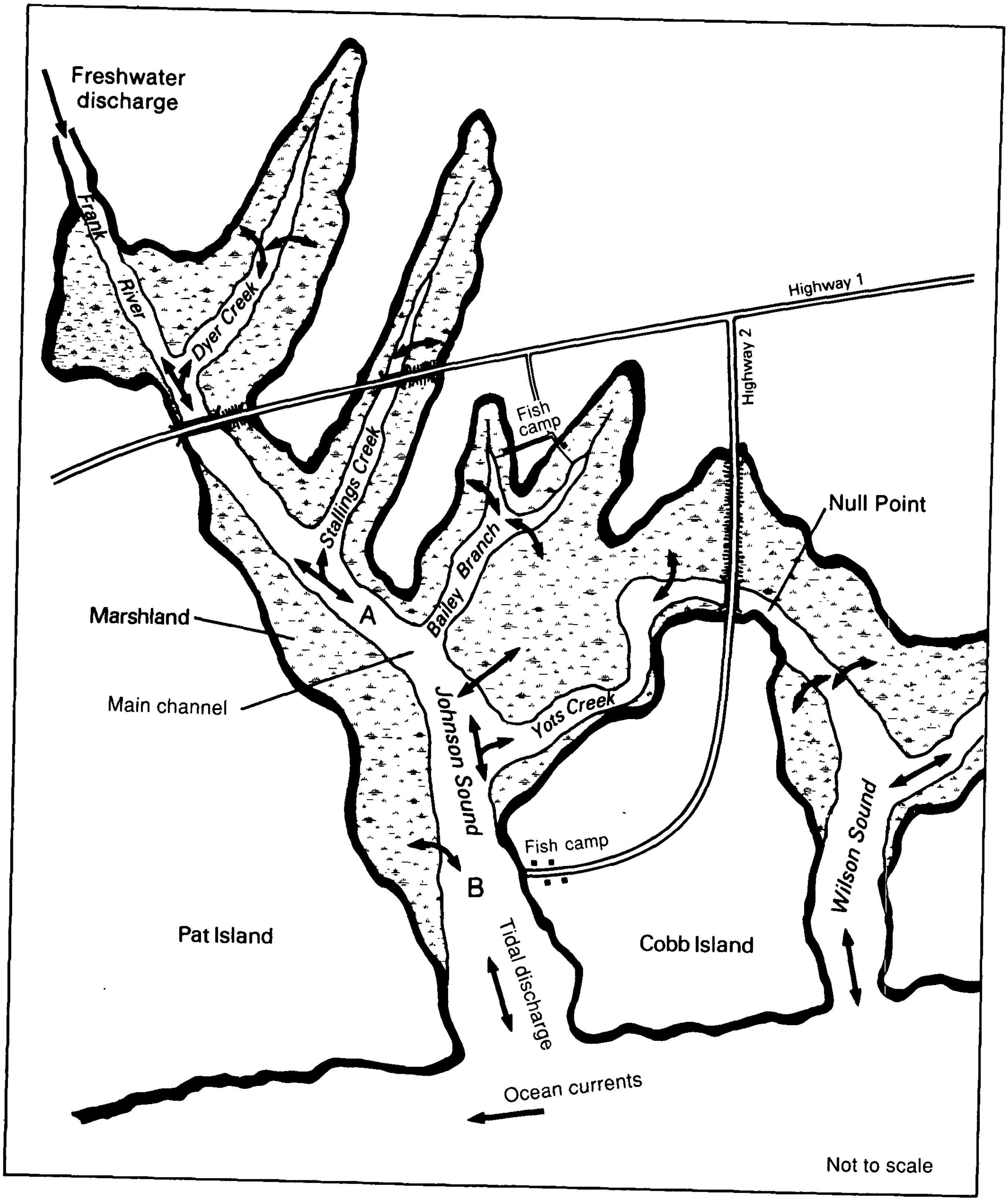
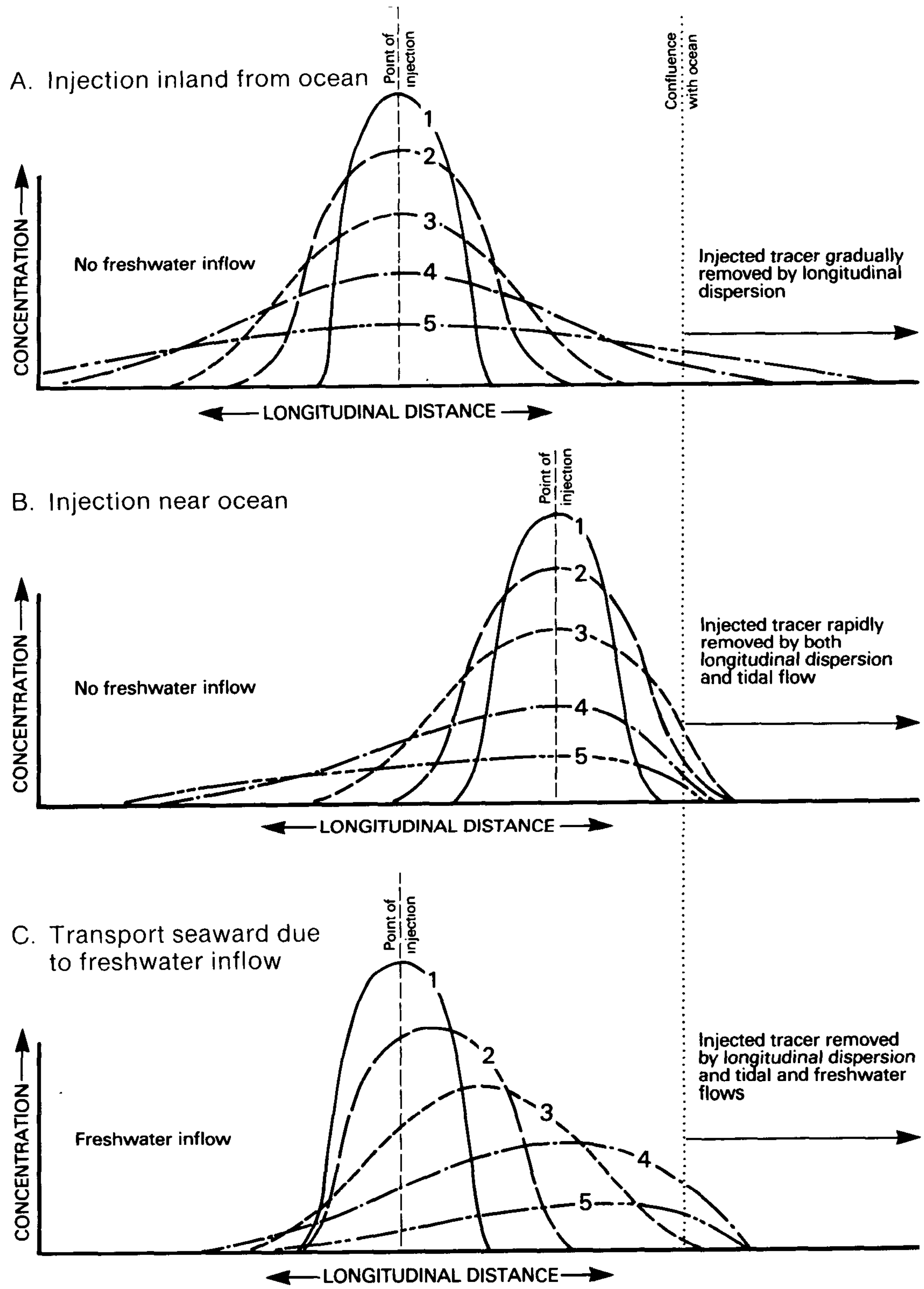


Figure 7.—Typical estuary showing physical geography and flow characteristics.



Note: Numbers refer to time in tidal days. Response curves are from an instantaneous injection observed at times of high slack water; at other times they would be displaced downstream from point of injection as well as be transported seaward by freshwater flow.

Figure 8.—Tracer-response curves in an estuary resulting from different injection points and freshwater and tidal flow conditions.

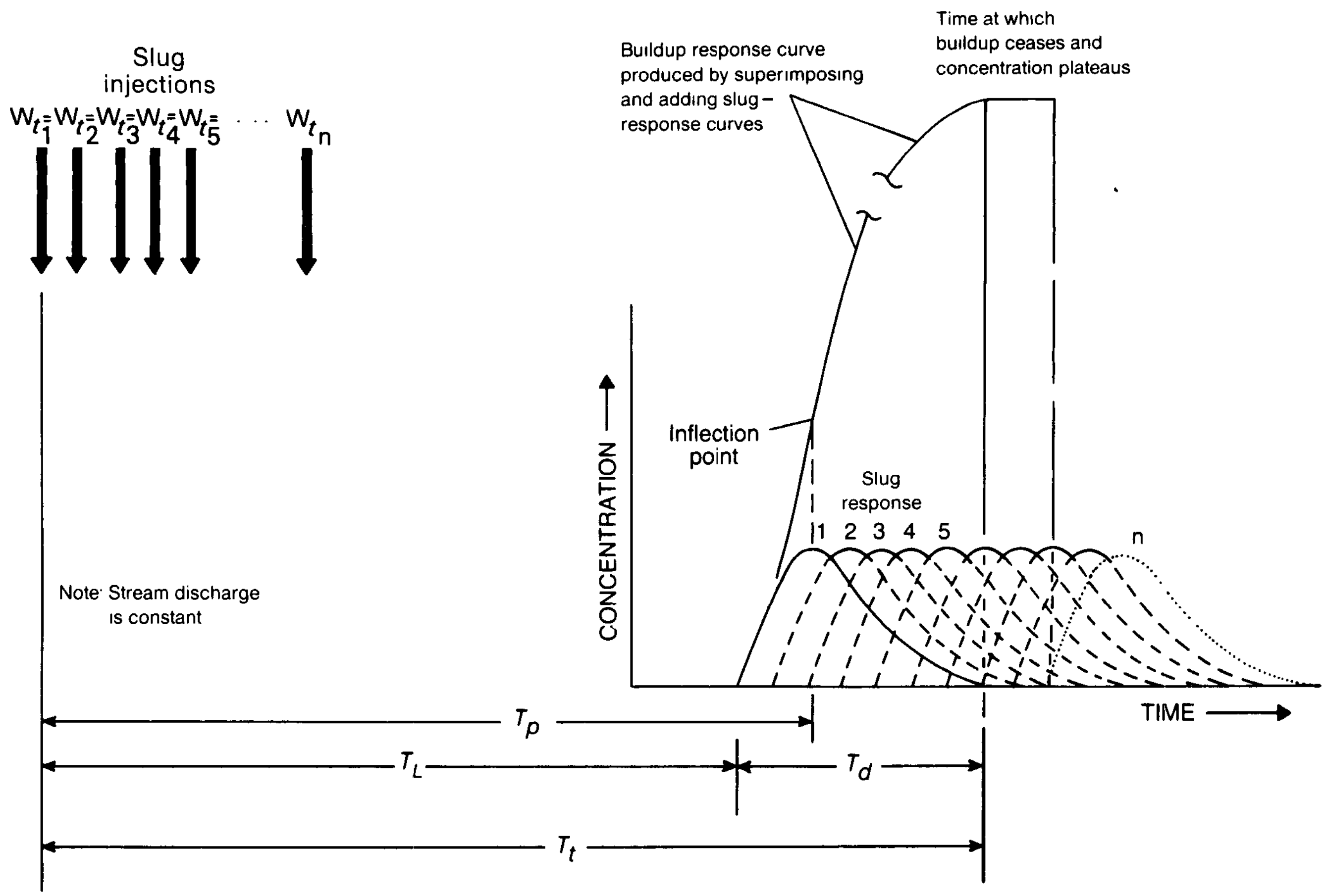


Figure 9.—Superposition of slug-response curves to simulate constant-injection buildup to a plateau at one location in stream section.

used with care, as such systems are seldom completely linear.

Another application of the linear superposition approach is for the simulation of buildup of soluble-waste concentrations in streams and estuaries using tracer tests (Bailey and others, 1966; Yotsukura and Kilpatrick, 1973). By this method, the slug injection of a soluble tracer is assumed to imitate the response of a soluble contaminant and as such can be used to simulate the contaminant. In this instance, the assumption of linearity is correct for any likely test conditions.

In rivers

It was shown by Kilpatrick and Cobb (1985) that the response to a continuous, constant-rate injection of tracer could be simulated by adding a sequence of superimposed response curves from a single slug response as measured for the same stream, location, and discharge. Thus, for example, assume that a series of slug injections of tracer (simulating a constant injection), each of weight W_t, is injected in the stream as depicted in figure 9. As can be envisioned, there would be a repetition of the same responses downstream at the different distances shown in figure 2. As an example, at streamline d for the long distance, there would be a buildup to a constant plateau of concentration as shown in figure 9. The same would occur at every streamline and distance downstream shown in figure 2, so that plateaus of concentration would ultimately exist at every location if the constant injection were continued long enough and the stream discharge remained constant.

Figure 9 shows that for a plateau to be reached at any particular location, a constant injection must be maintained for a length of time equal to the duration of the slug-response curve, T_d, at that location. Furthermore, to fully plateau across a section, injection would have to be maintained for a length of time equal to the response curve of longest duration in the cross section, T_D, probably along one bank or another. Similarly, the duration of the constant injection necessary to establish a plateau in the entire stream reach shown in figure 2 is dictated by the longest duration of slug response at the most downstream location.

The unit-response curve

It becomes apparent that the response curve produced by a slug injection of tracer may be used as a building block with the superposition principle to simulate the buildup of a given soluble waste introduced into the stream. In fact, linearity permits the superposition of varying loads of waste to simulate the resulting response downstream. For convenience, it is practical to reduce the curves of figure 2 to UR curves using equation 4. A UR curve (fig. 3*B*) is for a conservative soluble waste of 1 lb in 1 ft^3/s of discharge. If the UPA curve has been obtained as in figure 4, the peak of the UR curve may be obtained by interpolation for any lapsed peak travel time to the location where the simulation is desired. The UR curve that is being synthesized may be shaped by inspection of the measured UR curves in the reach. When mixing is complete, it will have an area of 4,450 when in units of [(μg/L)/lb](ft^3/s)(h).

It has also been shown by Kilpatrick and Wilson (1989) that the duration of the slug-response curve from the leading edge to the point where the receding concentration reaches 10 percent of the peak, $T_{d_{10}}$, may be approximated by the equation

$$T_{d_{10}}=0.7T_p^{\,0.86}, \qquad (7)$$

where T_p is the elapsed time to the peak in hours (see fig. 3).

Furthermore, Taylor (Kilpatrick and Taylor, 1986) showed that the normal response curve produced by a slug injection could be represented as a scalene triangle (see fig. 3*A*), in which

$$t_r=0.68T_{d_{10}}-0.19. \qquad (8)$$

Thus, as an approximation, about one-third of the duration, $T_{d_{10}}$, is t_b, or the time from the leading edge until concentrations build up to the peak, and about two-thirds of the duration is t_r, or the time from the peak until receding to the trailing edge, when concentrations have reached 10 percent of the peak. A $T_{d_{10}}$ of 4 hours is a lower limit for application of this approximation. In the absence of actual test data, a scalene triangle approximation will yield useful results.

If measured time-concentration response curves are available for a stream reach, it is obviously better to use them rather than scalene triangles because they represent the actual dispersive characteristics of the river in question. It should be borne in mind that an upstream response curve may be thought of as input to the stream producing the responses observed subsequently downstream. The most downstream response to an injection of tracer reflects the cumulative dispersive characteristics of the upstream test reach.

Once the UR curve for the particular location or elapsed time has been synthesized, it may be scaled to suit the particular waste loading and stream discharge involved. Thus, any waste-loading pattern may be divided into convenient increments or "slugs" and the response curves that have been suitably scaled may be superimposed to obtain the additive result. The desired response curves are obtained by multiplying the concentration ordinates of the synthesized UR curve by the pounds of waste and dividing by the stream discharge. The length or duration T_d does not change from that of the UR or observed curves (see fig. 3).

In reservoirs and lakes

It should not be construed that the application of the superposition principle with tracer-response curves measured in the prototype is limited to cases where mixing is complete. The technique is applicable wherever the slug of tracer can be injected at the location of a known point of waste input and the resulting tracer history (response) curves can be measured. This will be best illustrated, later, by example.

Nevertheless, it is cautioned that the results of a tracer simulation test in any body of water reflect prevailing discharges, winds, currents, thermal conditions, and any other factors governing the hydraulics of the system. In rivers and estuaries, this limitation is not too severe; in reservoirs and lakes, some of these conditions may be significant in influencing results. Several tests under different conditions may be necessary, or at least test conditions must be borne in mind when applying and presenting the results.

In estuaries

The superposition principle can only be applied in the unsteady flow of an estuary to simulate the buildup of a waste introduced at a point if tracer injection procedures are tailored to resolve the cyclic nature of the tidal stages and discharges. Advantage can be taken of the repetitive nature of the typical tidal system illustrated in figures 5 and 6. Instead of an instantaneous slug injection, tracer may be continuously and constantly injected over one or more tidal cycles, so as to tag all portions of the tidal hydrograph. Thus unsteadiness can be circumvented and the superposition principle applied to the resulting response curves observed at key locations in the estuary.

As illustrated in figure 10, a constant-rate injection of tracer may be initiated on a high slack water and continued for either 12.4 hours or 24.8 hours until the next high slack water. As can be seen, injection over a full 24.8-hour tidal day covers a period that more nearly returns to the same hydraulic conditions as at

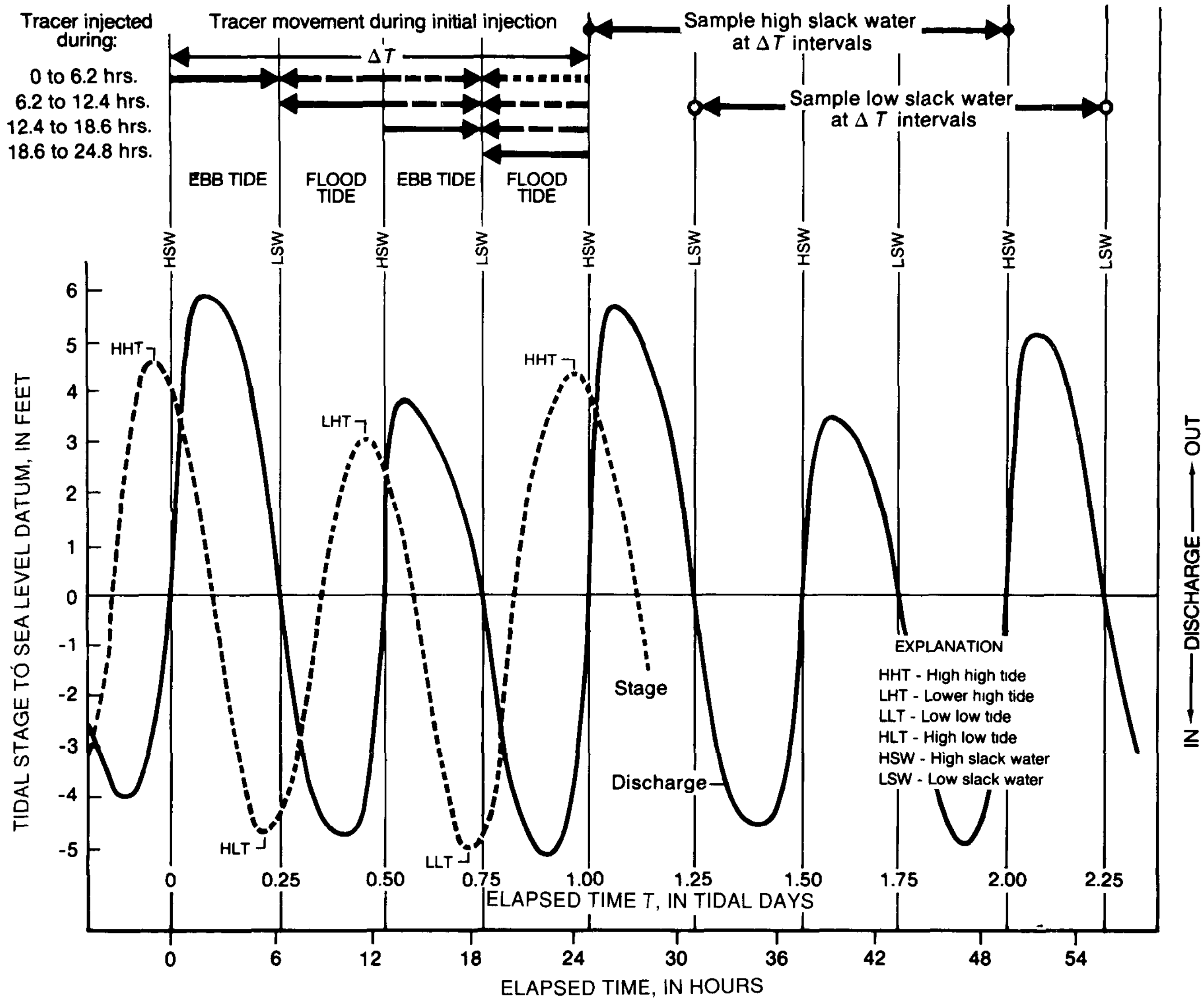


Figure 10.—Discharge and stage hydrographs in an estuary, illustrating a tracer injection over a tidal day, movement with the tides, and initial sampling schedules.

the start. This quasi-steady-state period, ΔT, also determines the integration interval when applying the superposition principle.

Conceptually, the direction of movement of the tracer as it is injected at a point is shown in figure 10. From $T=0$ to 0.25 and from 0.50 to 0.75 tidal days, ebb tide exists and the tracer moves seaward; from $T=0.25$ to 0.50 and from 0.75 to 1.00 tidal days, flood tide exists and the tracer moves upstream. Each quarter tidal day is 6.2 hours long. As the tracer injection progresses, each new 6.2-hour injection may be thought of as being superimposed on previous 6.2-hour tracer clouds that are already in various degrees of dispersion in the estuary.

As may be envisioned, tracer injection could be continued indefinitely until a steady state has been reached. Concentrations could then be measured at selected locations to provide a simulation of what might be expected if a soluble waste were continuously injected. Unfortunately, to reach steady state in most estuaries would require weeks and in some instances months of continuous tracer injection!

It is easy to see, however, that the tracer slug injected over the 24.8-hour tidal day will ultimately experience, as the days progress, the same dispersion, dilution, transport, and flushing from the estuary (see fig. 8) as would a continuously injected tracer or waste. To understand the application of the superposition principle in an estuary, picture the 24.8-hour tracer-response curve for succeeding tidal days, such as depicted in figure 8. The superposition of each new 24.8-hour response curve onto the preceding cumulative responses is the equivalent of what would be measured due to a continuous injection.

Simulation of nonconservative substances

In rivers

By definition, unit concentrations are for a totally conservative solute, hence producing the safest scenario for the prediction of waste concentrations downstream of a spill or other input. To be realistic, it may be desirable to "put back" the decay into the simulation if it is known for the substance involved. The first-order reduction of a substance by decay may be expressed by the equation

$$\frac{W_{rt}}{W}=10^{-kt}=e^{-Kt}, \tag{9}$$

where W_{rt} is the weight of waste remaining after time t, W is the initial weight of waste injected, k is a rate constant to the base 10, and K a rate constant to the base e; hence $k=K/2.3$. The base e is more commonly used, but caution is advised to ascertain which rate constant is being provided.

In application, the concentrations of the UR curve shown in figure 3*B* may be reduced by W_{rt}/W for the time t. If T_d is large, it may be advisable to use elapsed times varying from T_L to T_t and reduce UR concentrations progressively over T_d.

In estuaries

The concept of unit concentration has not been applied to an estuary or lake system because an applicable discharge is not available to determine either recoveries or dilution. The best approach perhaps is to normalize the data by dividing concentrations by the weight of tracer injected.

Since the decay rate of rhodamine WT dye in estuaries has been estimated at about 3.4 percent per day, equation 9 for this dye may be expressed as

$$\frac{W_{rt}}{W}=e^{-0.034t}, \tag{10}$$

where t is elapsed time in days.

Planning, Instrumentation, and Data-Acquisition Techniques

Much of the planning, instrumentation, and data-acquisition techniques needed in tracer studies designed to simulate waste movement and buildup are similar to those needed in performing other types of tracer studies. For example, the techniques used in performing time-of-travel tests in streams are applicable to simulation tests in streams using tracers. The time-of-travel manual (Kilpatrick and Wilson, 1989) should be used by the reader to better understand tracing techniques in rivers. Similarly, the dilution discharge (Kilpatrick and Cobb, 1985) and reaeration manuals (Kilpatrick and others, 1989) are valuable references on the superposition principle and on equipment and techniques needed for constant-rate tracer injection, respectively.

Tracer injection, quantities, and techniques

Slug injection in streams

A slug injection of tracer, usually rhodamine WT dye, is customarily used to obtain the typical series of time-concentration response curves, such as shown in figure 2. The time-of-travel manual provides equations and curves for estimating dye quantities for different stream discharges and reach lengths. For waste simulation tests it is particularly desirable to use as long a test reach as feasible and to select three or more sampling sections, so that UPA curves can be defined. Dye quantities should thus be chosen accordingly.

Slug injection in lakes and estuaries

Where the affected discharge is not readily determined, such as in a lake or estuary, less exact means must be used to estimate the volume of tracer necessary to perform a test. In a lake or estuary, it is best to estimate the volume of water that will ultimately be tagged with tracer and, from this, determine the weight of tracer to produce the desired concentration. If the estuary or lake volume likely to be affected is estimated in cubic feet, the weight of 20-percent rhodamine WT dye, in pounds, required to produce an average concentration of 1 μg/L may be computed by the equation

$$W_d=312\times10^{-9}\text{ (volume of estuary or lake in cubic feet).} \tag{11}$$

Such estimates are for an average concentration of 1 μg/L. Much higher concentrations would exist in the vicinity of the injection and then drop off to zero at the limits of the dye cloud. Therefore, it might be advisable to design for a lesser average concentration and use about 50 to 75 percent of the amount computed by

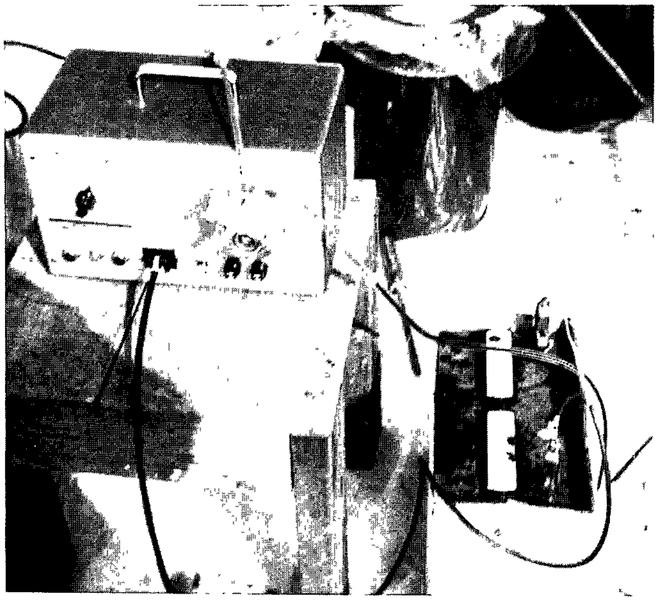


Figure 11.—Battery-powered peristaltic pump being used to pump rhodamine WT dye directly from shipping containers into an estuary.

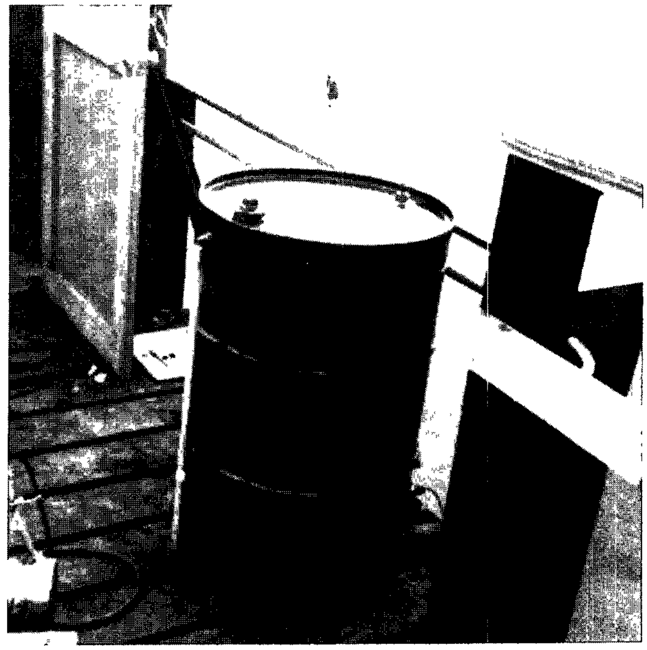


Figure 12.—Fifty-five-gallon drum modified to perform as a constant-rate-injection mariotte tank.

equation 11. At the same time, if the test period is likely to be several weeks, the decay of the dye must be considered.

Injection equipment

Manuals on dilution discharge and reaeration discuss the use of fluid-metering pumps and mariotte vessels. Generally, much larger quantities of tracer are required for major estuary studies than for rivers, so pumps and containers must be sized upward. The 24-V dc fluid-metering pumps are available with discharge capacities up to 1,300 mL/min. Such a discharge could inject 5,000 lbs of 20-percent rhodamine WT dye in a 24.8-hour tidal day.

Peristaltic pumps have also been successfully used for the constant injection of dye solutions. They are usually less expensive than the displacement-type pump but have not been proven quite as accurate in maintaining a constant rate of injection. Operation of these types of pumps on batteries is well suited to injection from remote sites or boats, such as shown in figure 11. Note that protective plastic sheeting has been placed under the injection equipment and dye containers as well as over the transom of the boat to protect against possible dye staining.

It is advisable to have extra batteries to alternate the power supply for injection as long as 24.8 hours. Additional advantages of pumps, as opposed to mariotte vessels, are the ability to switch from one container of dye to another and to inject in any depth of water desired. Injection rates are often checked for amount and constancy by volumetric or weighing techniques described in the dilution discharge manual.

Large mariotte injection tanks have been fabricated from 55-gallon (gal), enamel-coated drums (fig. 12). The design principles discussed in the dilution discharge manual should be followed. Concentrated 20-percent rhodamine WT dye should not be used in a mariotte vessel, as it is too viscous and apt to clog the injection nozzle. The dye should be reduced to a concentration of about 5 percent or less. At this concentration a 55-gal mariotte tank could hold the equivalent of about 140 lbs of 20-percent rhodamine WT dye.

In some instances, it may be necessary to simulate a line injection of waste over all or part of a channel. This may be accomplished by injecting the tracer in a line, via a boat, as shown in figure 13. In this case, a measured amount was injected by boat every 20 min for 24.8 hours. While this method results initially in individual "slug" clouds of tracer moving upstream and downstream, longitudinal dispersion soon melds the individual clouds into one.

Tracer sampling

Sampling in streams

The time-of-travel manual discusses in detail the sampling equipment and procedures to be used in streams. The use of automatic sampling boats (Kil-

Figure 13.—Injection of dye tracer in a line across an estuary at proposed site of factory waste discharge.

patrick, 1972) is particularly desirable where multiple sampling locations over long channel reaches are used. In such instances, the tracer-response curves may be a day or more in passing a site, thus requiring considerable manpower, unless the boats are set on long sampling intervals. The operation of these sampling boats and the determination of sampling frequency are covered in the time-of-travel manual.

Sampling in estuaries

The approach in performing a waste-simulation study in an estuary using tracers is to repeatedly sample at selected points for a sufficient number of tidal cycles to define tracer buildups at those points. Whenever possible, maximum use should be made of bridges and other access points, such as piers, for sampling. Open-water sampling may be by boat or helicopter.

The use of a helicopter (see fig. 14) is highly recommended for larger systems, as boats may be stranded on sand bars and cannot move from one sampling location to the next quickly enough to sample on high or low slack water as required. Furthermore, the several boats required demand considerable manpower. Experience (Kilpatrick and Cummings, 1972) indicates that one helicopter with one pilot and one person to do the sampling can accomplish the work better than several boats. It is usually easier to find the sampling points with a helicopter than with a boat. In this regard, it is advisable to identify each sampling point using anchored buoys. Sections should be identified with panels or blinker lights at their extremities. The main advantage of using a helicopter is the mobility and quickness it provides in moving with and sampling on the high and low slack tides.

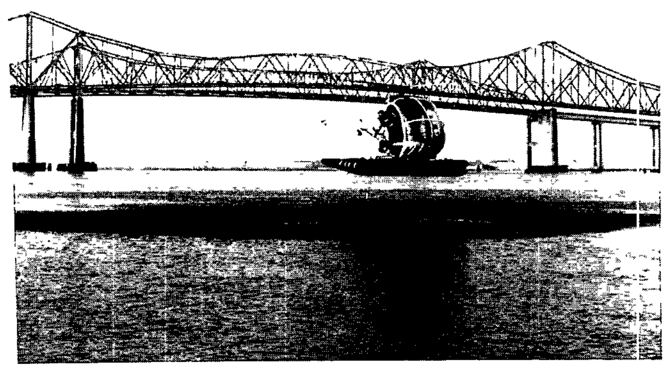


Figure 14.—Helicopter in use to collect dye samples in Charleston Harbor, S.C. (photo courtesy of South Carolina Water Resources Commission).

In most instances, sampling at nighttime should be avoided by boat or helicopter. Careful planning can usually minimize nighttime sampling. Where nighttime sampling or a more complete concentration-time record is needed, the floating automatic sampler (fig. 15) can be used (Kilpatrick, 1972; Kilpatrick and Wilson, 1989). In a saltwater environment, extra care is needed to seal the timing motors and switches in the floating sampler. The user should consult with the U.S. Coast Guard on deploying the floating sampler in navigable waters.

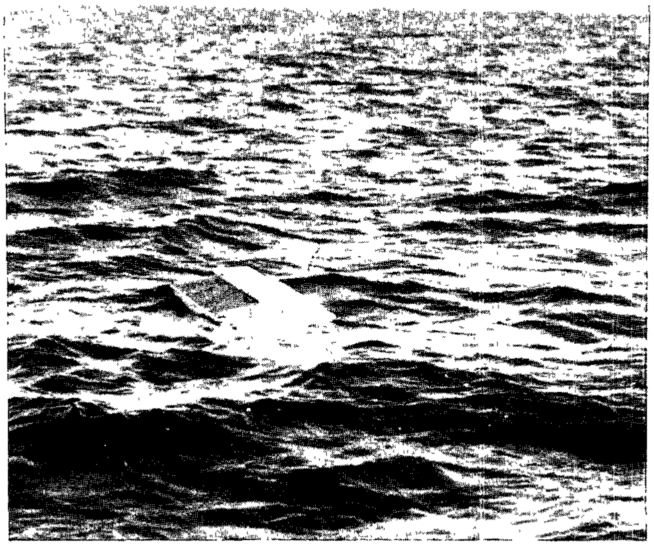


Figure 15.—Automatic floating sampler used to sample at night and under hazardous conditions.

If the tracer injection period is 1 tidal day, ΔT= 24.8 hours, the numerical integration interval in applying the superposition must also be 24.8 hours (see fig. 10). Thus, should the decision be made to inject tracer through only one tidal cycle, 12.4 hours, sampling must be performed initially at the same frequency. An injection period of 2 tidal days would have merit in that sampling could be at 49.6-hour intervals. In the extreme, if tracer were injected continuously and indefinitely, samples would need to be collected only once to evaluate the ultimate levels of concentrations. In effect, each tidal injection is being "added," and nature is doing the superposition. This method is, of course, impractical in most cases, and the superposition principle is applied to a flow period of quasi-steady state, like a tidal day.

The design and planning of a tracer test in an estuary require examining the long-term tidal stage and flow patterns, such as shown in figure 6. Tide tables are invaluable in such planning and are available from the National Ocean Service (1990a, b). The tidal tables are now issued in four volumes: Europe and West Coast of Africa (including the Mediterranean Sea); East Coast of North and South America (including Greenland); West Coast of North and South America (including the Hawaiian Islands); and central and western Pacific Ocean and Indian Ocean. Together they contain daily predictions for 198 reference ports and adjustments for about 6,000 stations. For example, the *Tide Tables, East Coast of North and South America* contain full daily predictions for 48 reference ports and adjustments for about 2,000 stations in North America, South America, and Greenland. The adjustments permit extrapolation to other locations in the estuaries and waterways between and near the reference stations. It is particularly important to know the time of high or low slack water from the mouth of the estuary to more inland locations. This timing may amount to several hours difference in some instances and is beneficial in providing transit time from one sampling location to the next. For example, it is typical practice to start sampling high slack water at the mouth of an estuary, moving inland as high slack water progresses inland.

Two types of tide tables are available, one for high and low stage and one for high and low slack water. Both tidal-stage and tidal-current tables should be examined in planning tracer studies in estuaries.

The timing of the tracer test depends on the objectives of the study. Examining figure 6, if tracer injection starts during a neap tide period, concentrations will be highest in the main channels, and flushing may be minimal due to lower tidal discharges. Conversely, if injection starts during a period of spring tides, dilution and flushing will be the greatest, but tracer buildup may result in adjoining marshlands. Normally, tests will be performed during a period of spring tides, as the extent of waste buildup in the marshes is of particular concern.

The timing of the test should also consider the desirability of having daylight during high and low slack water for the first few days of the test (see fig. 10). After a few days, the trend of the concentrations at each sampling location can be discerned, and interpolation can be used to obtain each value at the required ΔT interval.

Performance and Application of Waste-Simulation Tests in Streams

Example using time-of-travel data

Taylor and others (1986) performed time-of-travel tests on the Shenandoah River and its tributaries in Virginia and West Virginia at two flows. These tests are partially described in the time-of-travel manual and in Kilpatrick and Taylor (1986). These data are expanded here and used to illustrate their application to simulate and predict the transport, dispersion, and buildup of a soluble waste that might be introduced into a river.

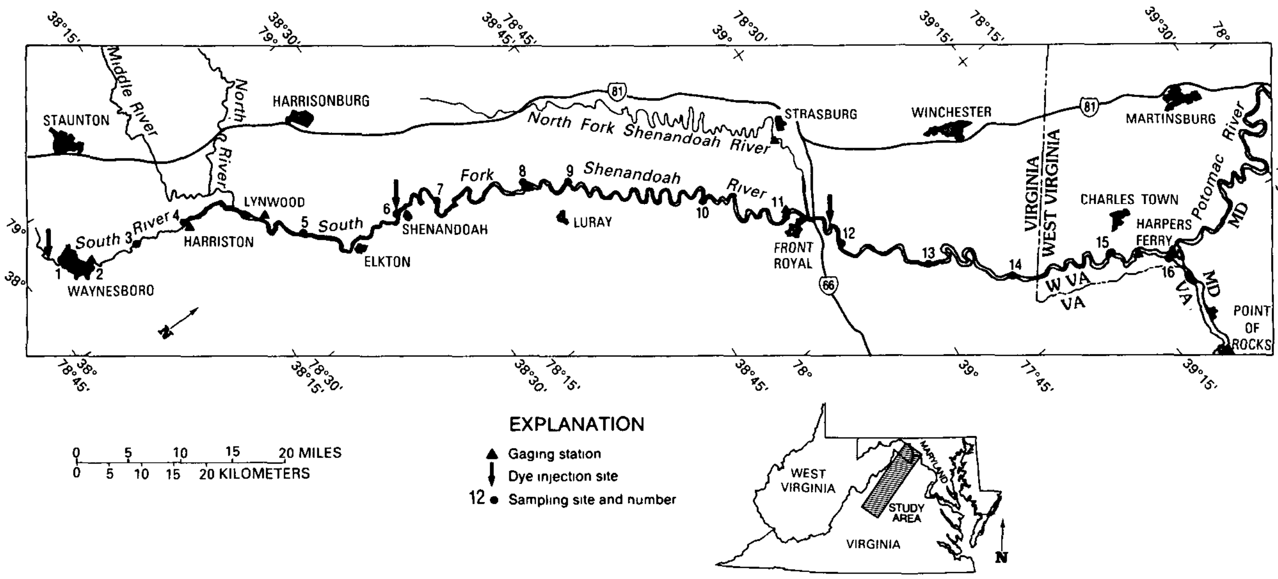


Figure 16.—Study reach for time-of-travel studies on the Shenandoah River in Virginia and West Virginia.

Figure 16 shows the 178-mi reach of the South River, South Fork Shenandoah River, and Shenandoah River from Waynesboro, Va., to Harpers Ferry, W.Va. (henceforth referred to as the Shenandoah River), where two series of tracer tests were performed. These tests were conducted in September 1983 and June 1984 at flows that are exceeded 85 percent of the time and 45 percent of the time, respectively.

The two tests were performed during stable, rainless periods when the flow duration was essentially the same throughout the stream reach, even though actual discharge increased manyfold (see fig. 17). The use of flow duration as an index, instead of actual discharge, is preferable because of the constancy of the index value throughout the study reach.

The reach was subdivided into three subreaches for the 1983 test and four subreaches for the 1984 test. During each test, tracer-response (time-concentration) curves were measured at 16 sites. The first subreach, measurement sites S-1 through S-7, is chosen purposely as an example because there is a large increase in streamflow due to a tributary inflow, in this case the North River (the data for S-1 and S-7 have been omitted to simplify plotting).

The typical response curves, as measured at sampling sites S-2 through S-6, for two different stream discharges are shown in figures 18*A* and 18*B*. The shaded curves in figure 18*A* are in response to the slug injection of 6.3 lbs of rhodamine WT dye 1.4 mi upstream from sampling site S-1 at the lowest discharges (85-percent duration). As might be expected, the curves show a slow rate of movement; the peak at

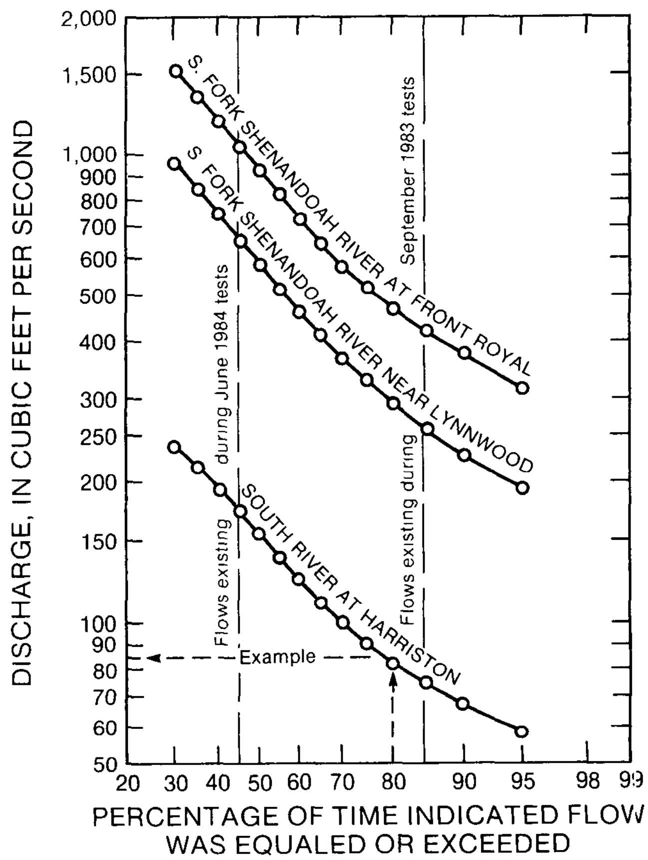


Figure 17.—Flow-duration curves for index gaging stations on the South River and South Fork Shenandoah River, Va.

S-6 required more than 7 days travel time and dispersed longitudinally to the extent that about 2 days were required for passage. Conversely, the peak

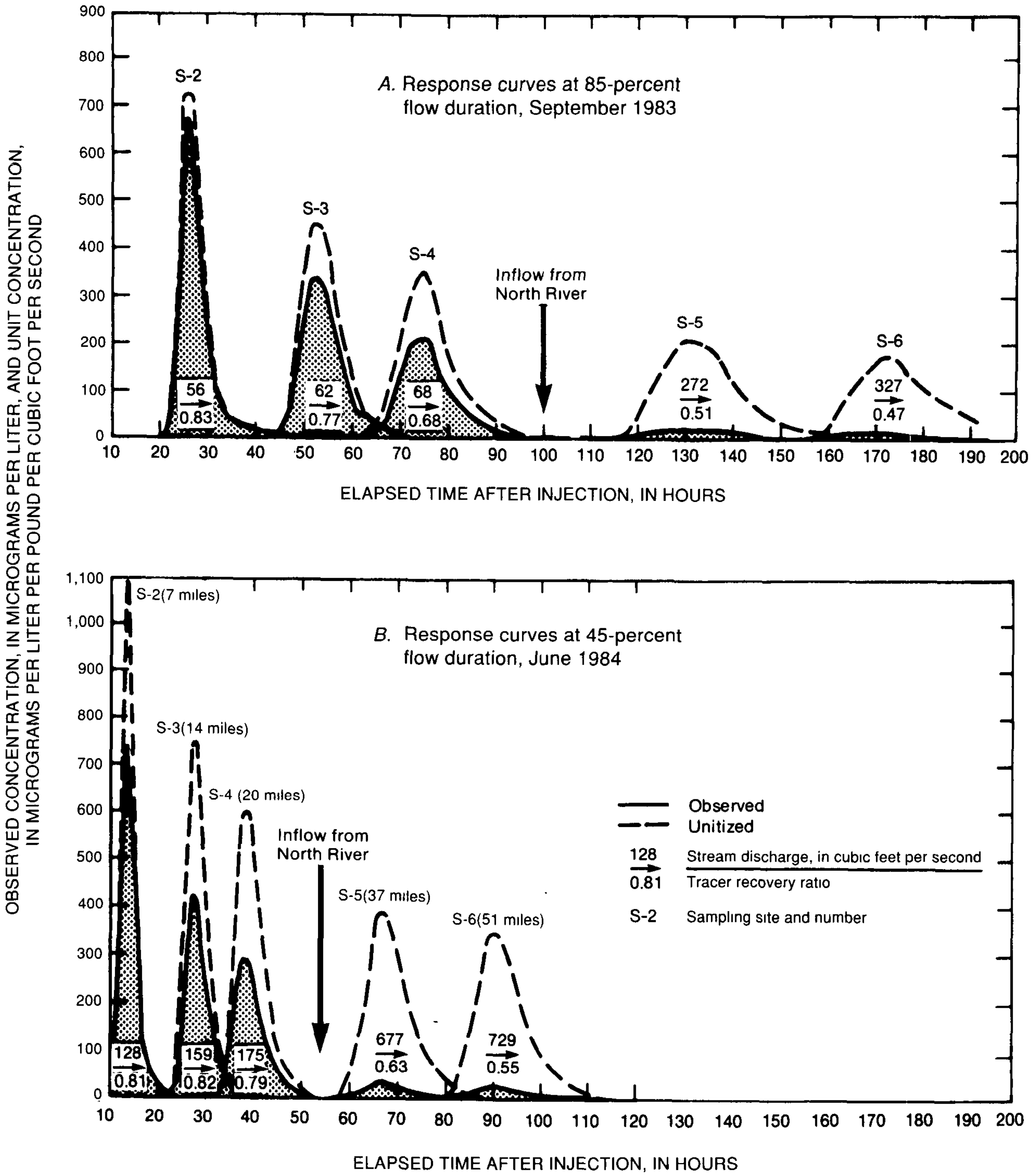


Figure 18.—Observed and unitized tracer-response curves for the South River and South Fork Shenandoah River between Waynesboro and Shenandoah, Va., for two different discharges.

concentration decreased from approximately 67 µg/L at S-2 to less than 2 µg/L at S-6. The diluting effect of an inflow, 3 times as great as that in the South River entering from the North River between S-4 and S-5, is apparent as the observed peak concentration dropped from about 22 to 2.5 µg/L, and the areas of the respective observed response curves are reduced accordingly.

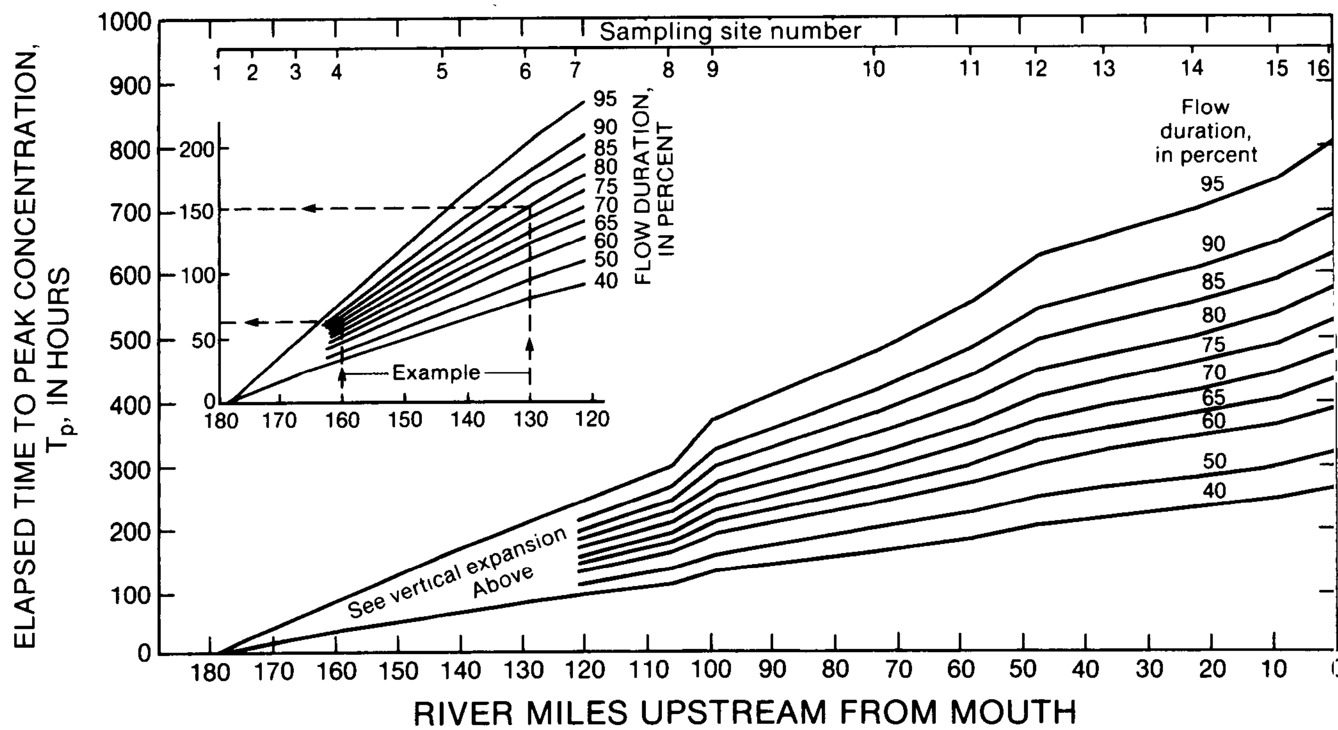


Figure 19.—Relation between travel time and distance for peak concentrations at selected flow durations, Shenandoah River from Waynesboro, Va., to Harpers Ferry, W. Va.

The same kind of longitudinal dispersion and dilution of the response curves is seen to occur with the higher flow in June 1984 (45-percent flow duration), when a 10-lb slug of rhodamine WT dye was injected (see fig. 18*B*). As the curves indicate, the rate of movement was much faster; the peak arrived at S-6 in 3.75 days and passed in about 1.5 days.

From the observed time-of-travel data, such as that shown in figure 18, a family of travel time curves can be constructed for the leading edge, peak, and trailing edge of the slug injection. A family of travel time curves for the entire Shenandoah River for just the peak concentrations is shown in figure 19. The family of curves is based on and interpolated between flow durations. Taylor elaborates on this method in the report on the Shenandoah River tracer studies (Taylor and others, 1986).

Unitizing of tracer data

The unit-response curve

Observed concentrations may be adjusted for (1) the amount of tracer injected, (2) tracer loss, and (3) stream discharge to obtain unit concentrations by using equation 4. The dashed curves shown in figure 18 correspond to the unitized observed data for the Shenandoah River. As can be seen, the drastic dilution effect between sites S-4 and S-5 has been removed, as well as the effect from injecting different quantities of rhodamine WT dye. The tracer losses are about the same (see fig. 18) for both Shenandoah River tests. The unit concentrations now reflect a totally conservative substance.

Most important, the two sets of UR curves form essentially one family or envelope of response curves, as shown in figure 20*A*, where both sets of unitized response curves are shown together. Here, the data for the first sampling site, S-1, is included, as they give a good picture of the process of early longitudinal dispersion. Differences in initial or convective dispersion, as well as longitudinal dispersion for the two different flows, are the only variables that could be expected to cause the two sets of response curves to not coincide or not form a single envelope.

Unitizing the tracer-response curves, in effect, fits one unit weight of tracer into one unit of flow. As such, all UR curves have the same area, 4,450 [(μg/L)/lb](ft^3/s)(h), regardless of location or stream.

Peak attenuations

Variations in dispersion on the same stream or different streams become most apparent if the unit concentrations for just the peaks, C_{up}, are plotted versus elapsed time to the peaks. Equation 5 may be used to compute the unit-peak concentrations, or they may be found from the UR curves. Such a plot for

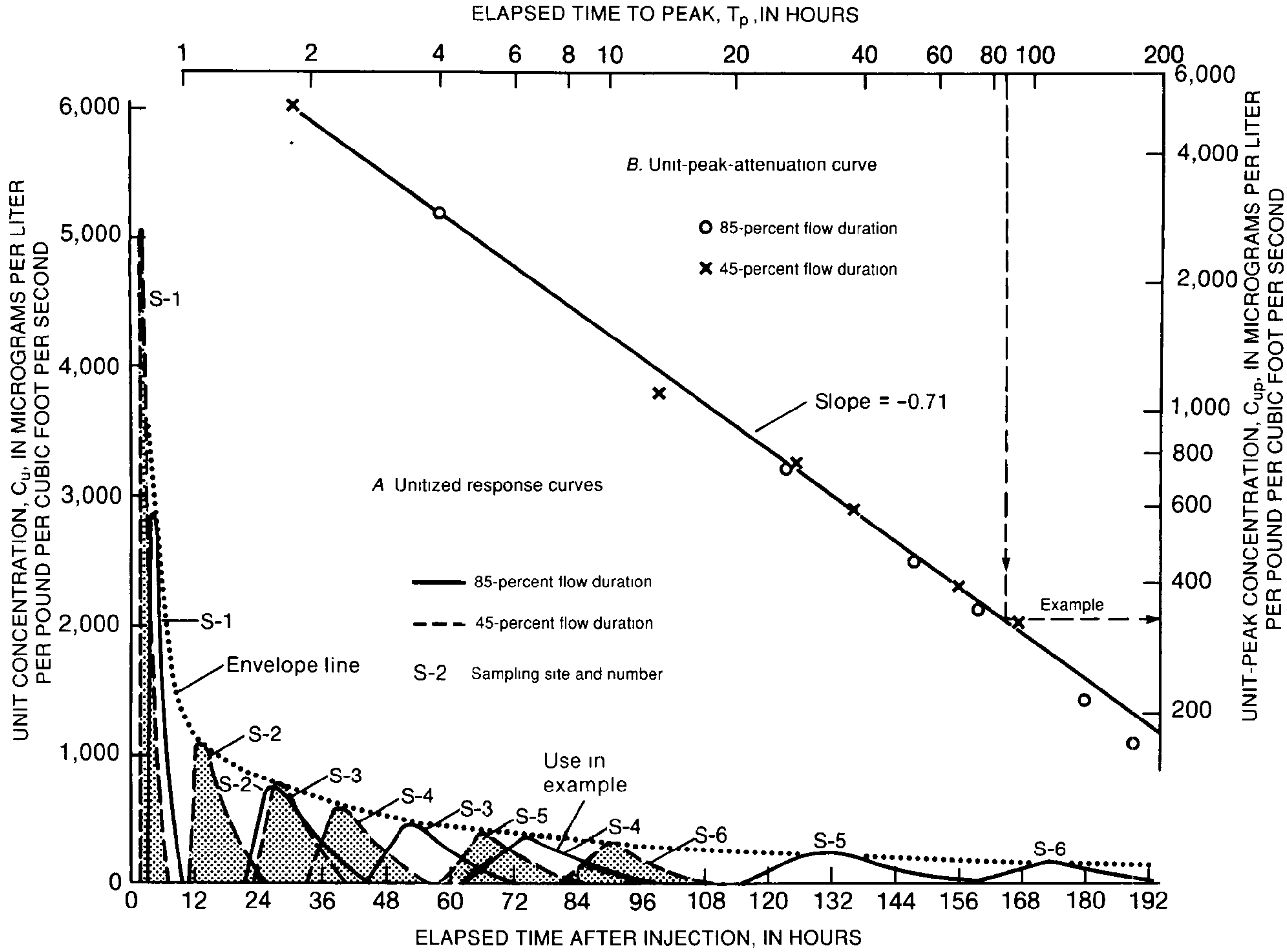


Figure 20.—Unitized tracer-response curves and unit-peak-attenuation curve for the Shenandoah River between Waynesboro and Shenandoah, Va., for two different discharges.

reach sites S-1 through S-6 for the Shenandoah River for flows at both durations is shown in figure 20*B*. For this reach of the Shenandoah River, the dispersion characteristics are the same for flows between 45- and 85-percent flow duration. The UPA curve, shown as figure 20*B*, along with the time-of-travel curves of figure 19, provides a ready means of predicting, at any location, maximum contaminant levels that would be experienced downstream from the spill of any amount of soluble contaminant. This prediction can be done at any location in the reach after total mixing has been achieved for the range in flows tested.

This procedure is accomplished using equation 6, $C_{cp}=C_{up}W/Q$, which gives the conservative peak concentration, C_{cp}, that would result downstream in discharge Q if W pounds of soluble waste are injected; C_{up} must be obtained from a suitable UPA curve, which requires a knowledge of the elapsed time to the location in question.

Simulation of waste concentrations

It becomes apparent from figure 20 that longitudinal dispersion is constant in the reach of the Shenandoah River from Waynesboro (S-1) to Shenandoah (S-6) and, furthermore, that a UR curve can be synthesized for any desired elapsed time.

Example 1

Assume an industrial plant discharges waste into the Shenandoah River at Waynesboro, at mile 160. A fish hatchery is located at Harriston, Va., at mile 130. There is concern for the level of contaminant at the hatchery, which withdraws river water periodically. The analysis is to be made for the condition of 80-percent flow duration in the river.

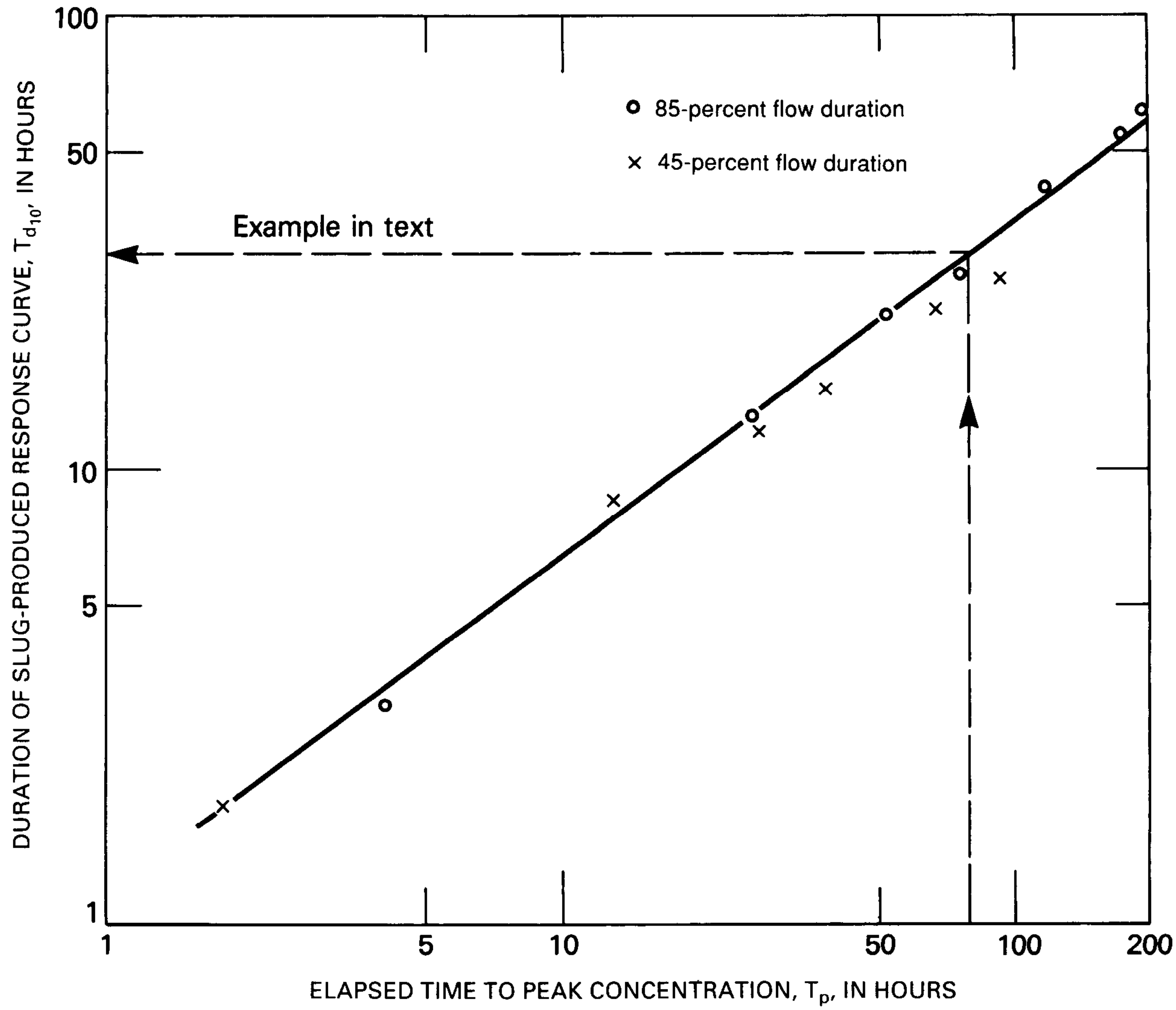


Figure 21.—Relation between peak-concentration elapsed time (T_p) and response-curve duration ($T_{d_{10}}$).

Solution

From the data illustrated in figure 19, determine that the elapsed time of the peak of a response curve would be 88 hours (150 hours minus 62 hours) at a discharge of 85 ft^3/s (80-percent flow duration from fig. 17) near Harriston, which is near the hatchery. Using figure 20*B*, it can be seen that the appropriate UR curve for 88 hours of dispersion time has a unit-peak concentration of 310 [(μg/L)/lb][ft^3/s]. To aid in synthesizing a UR curve for a dispersion time of 88 hours, estimate its duration by interpolating between measured response curves.

A plot of $T_{d_{10}}$ versus elapsed time for this reach is shown in figure 21, from which $T_{d_{10}}$ at 88 hours may be approximated as 30 hours. Thus, T_d is approximately 35 hours total.

Using these data, a scalene triangle may be constructed and the UR curve fitted as shown in figure 22. As an approximate check, the area of the scalene triangle may be computed as 310 [(μg/L)/lb][ft^3/s] × 30 hours/2=4,650. Typically, this area will be slightly greater than the 4,450 for the UR curve; this should influence the shaping of the UR curve in such a way that it fits more inside the scalene triangle to yield an area of 4,450 as nearly as possible. This UR curve is the building block for all superposition simulations at this location. This response curve could be similarly used at any location on this reach of the Shenandoah, if 88 hours were the dispersion time.

In application, "load curves" are synthesized by scaling the UR curve to represent the mass of contaminant being injected and the stream discharge serving to dilute it. Thus, if in the example, the industrial plant were to inject "slugs" of waste once per day in the amounts shown in figure 23*A*, the resulting concentration pattern could be simulated as

EXPLANATION OF TERMS

C_{up} - Unit-peak concentration

$T_{d_{10}}$ - Duration of abbreviated response curve to where observed concentration is 10 percent of its peak

K - Decay rate constant to the base e

UR - Unit response

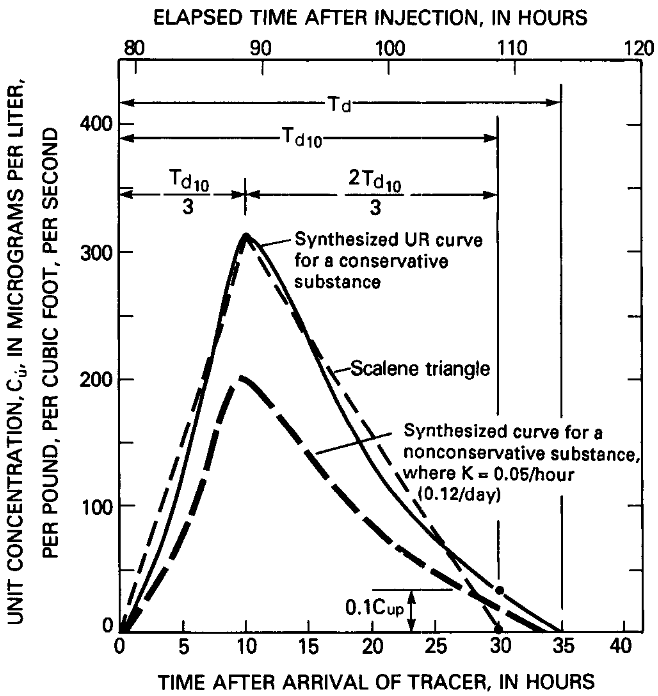
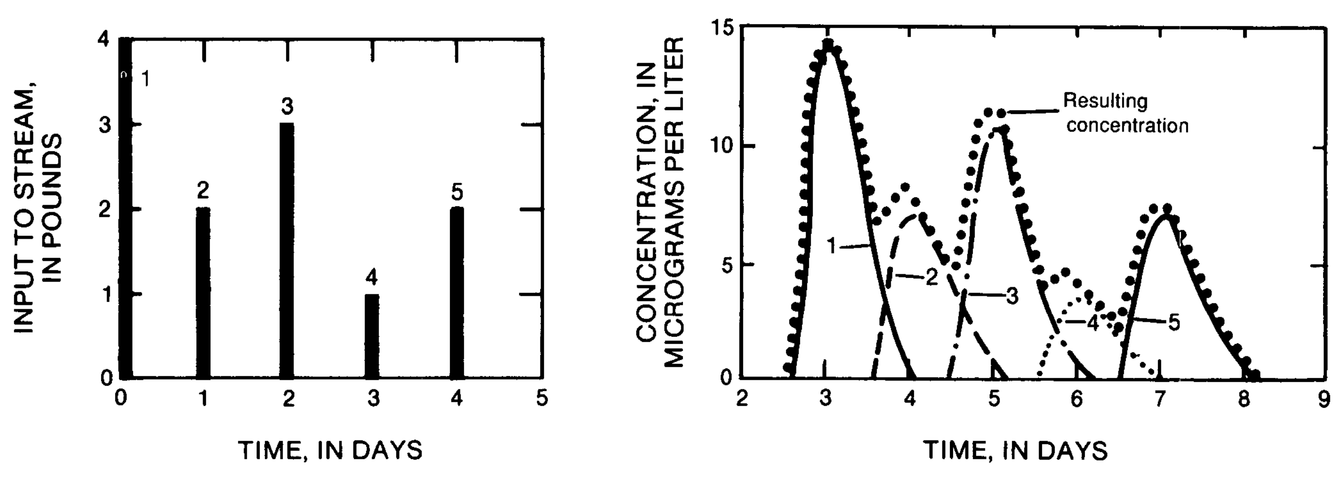


Figure 22.—Unit-response curves for a time of 80 hours, applicable to Shenandoah River from Waynesboro to Shenandoah, Va.

shown in figure 23*B*. Each response curve shown in figure 23*B* is obtained by scaling the UR curve in figure 22 upward for the weight and downward for a discharge of 85 ft^3/s as indicated by equation 6. These data are superimposed at 24-hour intervals and the vertical concentrations added together to produce the cumulative results shown by the dotted curve. As can be seen, the entire slug-response curve is 35 hours in passing or duration (see fig. 22) and curves overlap each other regardless of how much is injected. Therefore, there exists some additive effect of the waste at the fish hatchery at all times, even though plant discharges are 24 hours apart. If plant discharges were 35 hours apart, one response curve would have just departed upon the arrival of the next. Plant discharges every 48 hours would provide 13 hours of uncontaminated river flow.

Example 2

As a further example, assume the industrial complex at Waynesboro consists of a new plant A, which releases continuously a chemical X having a concentration of 1 percent at a constant rate of 20 gal/min. This continuous release has a specific gravity of 1.00. Furthermore, this plant has a 2,000-gal holding tank, which is used to contain the weekly excess of the same chemical, concentrated to an 8-percent solution having a specific gravity of 1.14. This tank is allowed to drain into the Shenandoah River over an 8-hour period starting Saturday at midnight of each week.



A. Loading pattern upstream

B. Superposition of response curves downstream

Note: Numbers identify slug injections and corresponding responses

Figure 23.—Superposition of response curves resulting from once daily, but variable amounts of, slug injections into the Shenandoah River, Va.

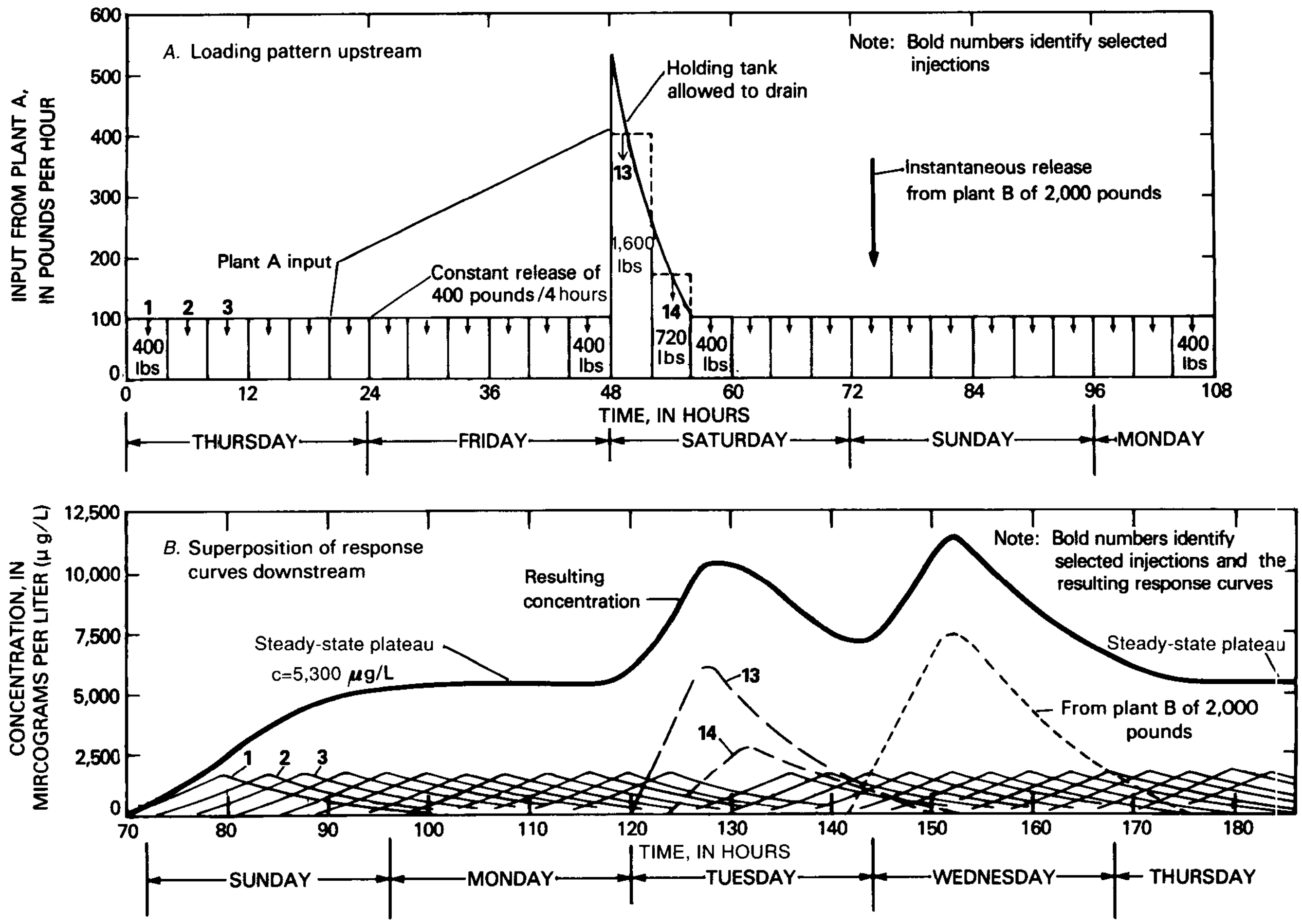


Figure 24.—(*A*) Waste loading pattern upstream and (*B*) simulated concentration response curves and resulting superimposed concentration curve downstream in Shenandoah River, Va.

To further complicate the problem, an older plant B, located adjacent to plant A, discharges its weekly waste accumulation of 17,000 lbs of chemical X as an instantaneous slug every Sunday morning at 0200 hours (2:00 a.m.) to avoid the waste that plant A injects on Saturday mornings. This chemical solution has a 10-percent concentration with a specific gravity of 1.18. If chemical X is totally conservative, what concentrations will result downstream at mile 130 from this complex series of releases, and will the maximum permissible level of 1,000 µg/L for chemical X be exceeded?

Solution

For purposes of the superposition, distribute the constant waste discharge and varied waste drainage from the holding tank, plant A, as 4-hour slug injections. The slug injection from plant B will be an instantaneous injection. At a dispersion time of 88 hours, the response curve to a 4-hour "slug" injection will be essentially an "instantaneous" injection for superposition purposes.

Input a: Constant injection=20 gal/min×8.34 lbs/gal×60 min/hour × 0.01 ×1.00
=100 lbs/hour
=400 lbs/4 hours

Input b: Holding tank, plant A
Total weight=2,000 gal×8.34 lbs/gal ×0.08×1.14=1,522 lbs.
Distribute over 8 hours with 1,200 lbs in first 4 hours and 322 lbs in second 4 hours.

Input c: Instantaneous slug injection of 17,000 lbs
Total weight of chemical X=17,000 lbs×0.10×1.18≈2,000 lbs.

Figure 24*A* shows the distribution of the three different inputs as determined above. Slug inputs 13 and 14 are the sum of both the constant input and that

Table 1.—Adjustment of unit-response curve for a nonconservative waste

[Unit concentrations are in [(μg/L)/lb](ft³/s)]

Elapsed time, hours (1)	Unit concentration (from fig. 22) (2)	e^{-Kt} (K=0.012/day= 0.005/hour) (3)	Nonconservative unit concentration (4)
78	0	0.68	0
83	125	.66	82
88	310	.64	198
93	227	.63	143
98	130	.61	79
103	72	.60	43
108	32	.58	19
113	0	.57	0

from the holding tank at plant A. The UR curve in figure 22 is scaled up to represent 400 lbs of chemical X in 85 ft³/s flow and plotted successively, as shown in figure 24*B*.

Similarly, response curves for 1,600, 722, and 2,000 lbs in 85 ft³/s are scaled and plotted, using in all cases the 88-hour travel time to the peak of each. All response curves are summed to yield the resulting concentration curve shown in figure 24*B*.

Note that as of 113 hours, a steady-state plateau is reached and sustained until 118 hours, when the response of the input from the holding tank (curve 13) first comes into play. The plateau concentration during this period, based on the superposition, is 5,300 μg/L. For this period, the plateau concentration may also be computed from the continuity equation:

$$Qc_w=q_wC_w \tag{12}$$

where Q is the stream discharge, c_w is the resulting concentration of waste in the stream, q_w is the waste discharge from the plant, and C_w is its concentration. Hence

$$c_w=\frac{q_wC_w}{Q}$$

$$c_w=\frac{[(20\text{ gal/min})(0.134\text{ ft}^3\text{/gal})(0.0167\text{ min/s})](1\times10^7\ \mu\text{g/L})}{85\text{ ft}^3\text{/s}}=5{,}265\mu\text{g/L}.$$

Obviously, from the computation and examination of figure 24*B*, concentrations well exceed the permissible 1,000 μg/L limit at all times. In fact, concentrations on the order of 12,500 μg/L are reached as a result of the combined effect of the instantaneous release from plant B onto the constant 100 lb/hour release from plant A. Note too that the releases from the two holding tanks overlap and reinforce each other as well as the constant injection.

Analysis for a nonconservative waste

The above analysis assumes that chemical X is entirely conservative. This is seldom the case. The same approach as shown above may also be used if the waste is nonconservative. This is done by "decaying" the UR curve of figure 22 if the decay rate is known. For example, if the decay rate K for chemical X is 0.12/day to the base e, the concentrations between 78 and 113 hours (see fig. 22 and column 2 in table 1) may be "decayed" to produce the values shown in column 4 of table 1 and depicted in figure 22 for the nonconservative UR curve. This nonconservative UR curve may be used in the superposition to produce a reduced-concentration profile.

Note that in table 1, column 3, the decay goes from 0.68 to 0.57 over the duration of the UR curve. The average is about 0.63. Inspection of figure 18 indicates that the tracer recovery ratios for rhodamine WT dye at about 80 hours are of the same order of magnitude. Hence, the decay rate for this rhodamine WT dye lot for the two tests is about 12 percent per day.

It should not be construed that time-of-travel data, when unitized, will always reduce to one UPA curve such as shown in figure 20, although this is not uncommon. For example, Kilpatrick and Taylor (1986) showed that one UPA curve was applicable to the Mississippi River for the reach from Baton Rouge to Pointe a La Hache, La., between the discharges of 240,000 and 800,000 ft³/s.

Commonly, a family of UPA curves having the same or different slopes will be obtained, allowing interpolation for different flow durations. In almost all instances, UR and UPA curve relations are obtainable and permit analyses and interpretations similar to what has been presented. Therefore, it is important to realize that ordinary time-of-travel tests, if performed at more than one stream discharge and featuring adequate sampling at three or more sites on a stream, can be used to simulate not only the speed of a soluble contaminant but the concentrations that might result downstream from various waste loadings.

Performance and Application of Waste-Simulation Tests in Reservoirs and Lakes

Example

The use of the superposition principle, in conjunction with observed tracer-response data from tests in the prototype, can be used in any body of water where a soluble waste is to be injected and subsequently dispersed and diluted. It is reemphasized that results

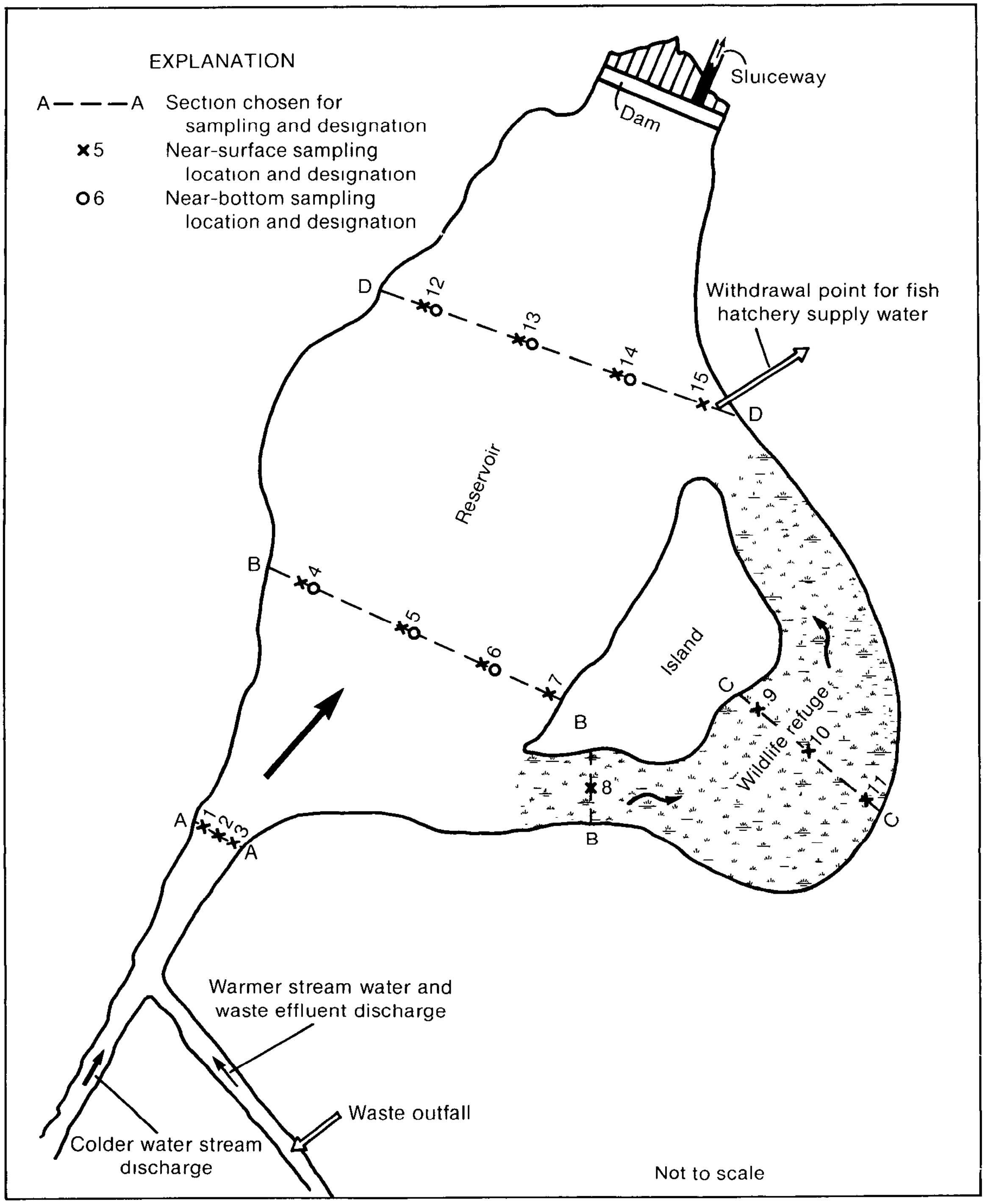


Figure 25.—Hypothetical reservoir used to demonstrate application of superposition principle to predict buildup of wastes at different locations and depths.

reflect the prevailing hydraulic and atmospheric conditions that exist during the tracer tests; this is particularly apt to be true in lakes.

The application of the superposition principle in a reservoir can be understood by examining figure 25, which shows a hypothetical reservoir that is to receive the waste discharge from a plant located upstream on a tributary flowing into the reservoir. In this example, assume the water in the stream receiving the waste is slightly warmer than the stream it mixes with prior to entering the reservoir. Thus, it is suspected that there could be some stratification occurring that might

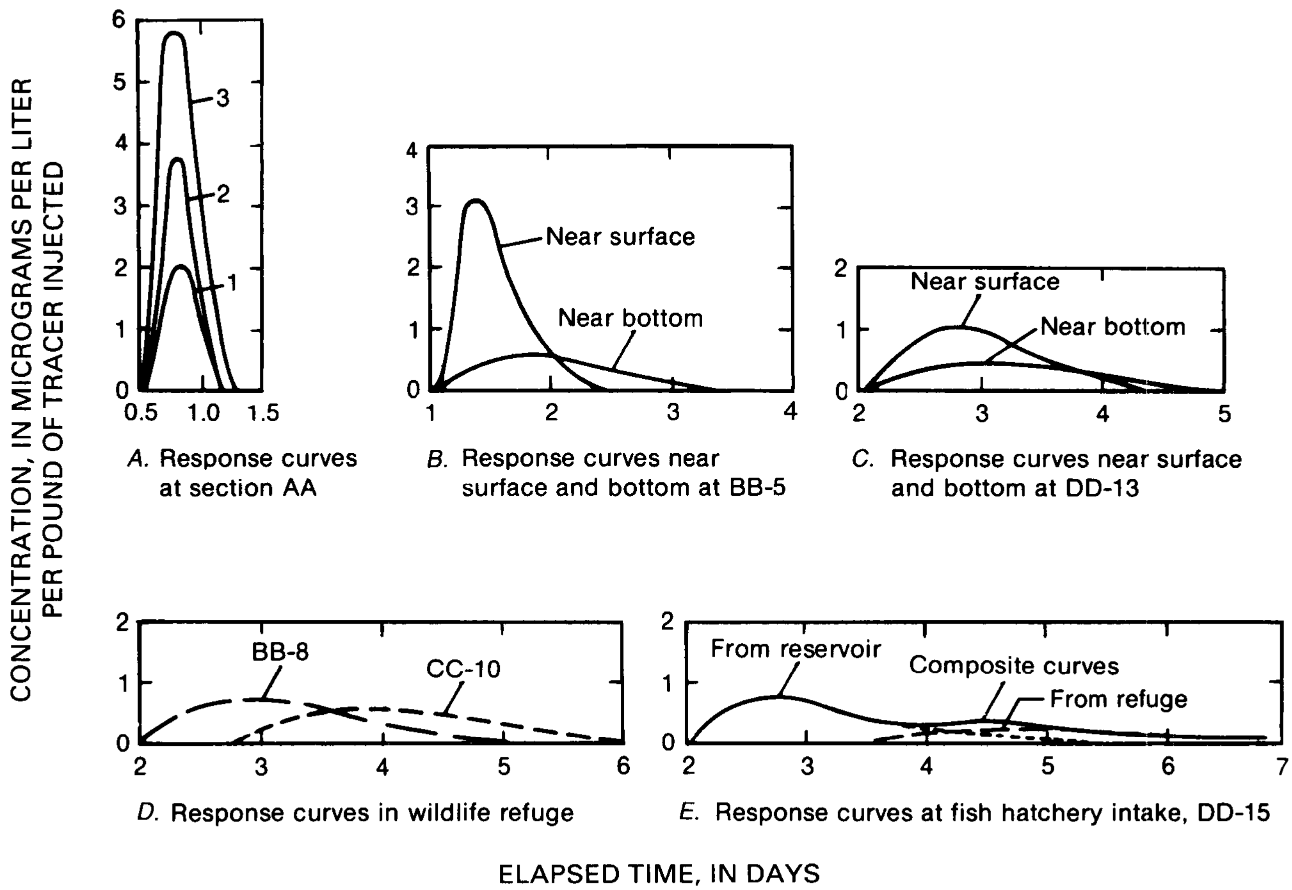


Figure 26.—Response curves obtained at different locations in a reservoir due to slug injection of tracer upstream in incoming flow.

result in higher concentrations of waste in surface than in bottom waters. Furthermore, a large area in the reservoir is shallow and used as a wildlife refuge, where the buildup of wastes would be most undesirable. The same is true for waste that might enter a fish hatchery just below the refuge. The objective, therefore, is to simulate the magnitude of any waste buildups that might occur at these various locations due to a constant injection of a waste upstream.

Performance

To perform a tracer-simulation test, a slug of tracer will be injected at the exact location of the proposed waste outfall and the resulting response curves measured at the locations designated in figure 25. A detailed discussion of the performance of such a test would be redundant, as it would follow practices well described previously.

The response curves observed at certain key locations in the reservoir are shown in figure 26. Relative concentrations, the concentrations per pound of tracer injected, rather than unit concentrations are shown because discharge and tracer losses cannot be precisely evaluated in the reservoir.

Analysis and interpretation

The response curves shown in figure 26 illustrate several points. For example, in figure 26*A* it can be seen that lateral mixing in the main stream is incomplete, as might be expected from a side entrance of the waste-water stream. It is the area of each response curve that is a measure of the waste buildup that would occur with a continuous injection using the superposition principle. Therefore, waste buildup would be greatest on the right bank at section AA, if a soluble waste were continuously injected.

In figure 26*B* the larger-area response curve near the surface upstream in the reservoir compared with that near the bottom would indicate some stratification but, also, that some vertical mixing is occurring. The larger area of the surface-response curve would indicate a larger buildup on the surface than near the bottom from a continuous injection.

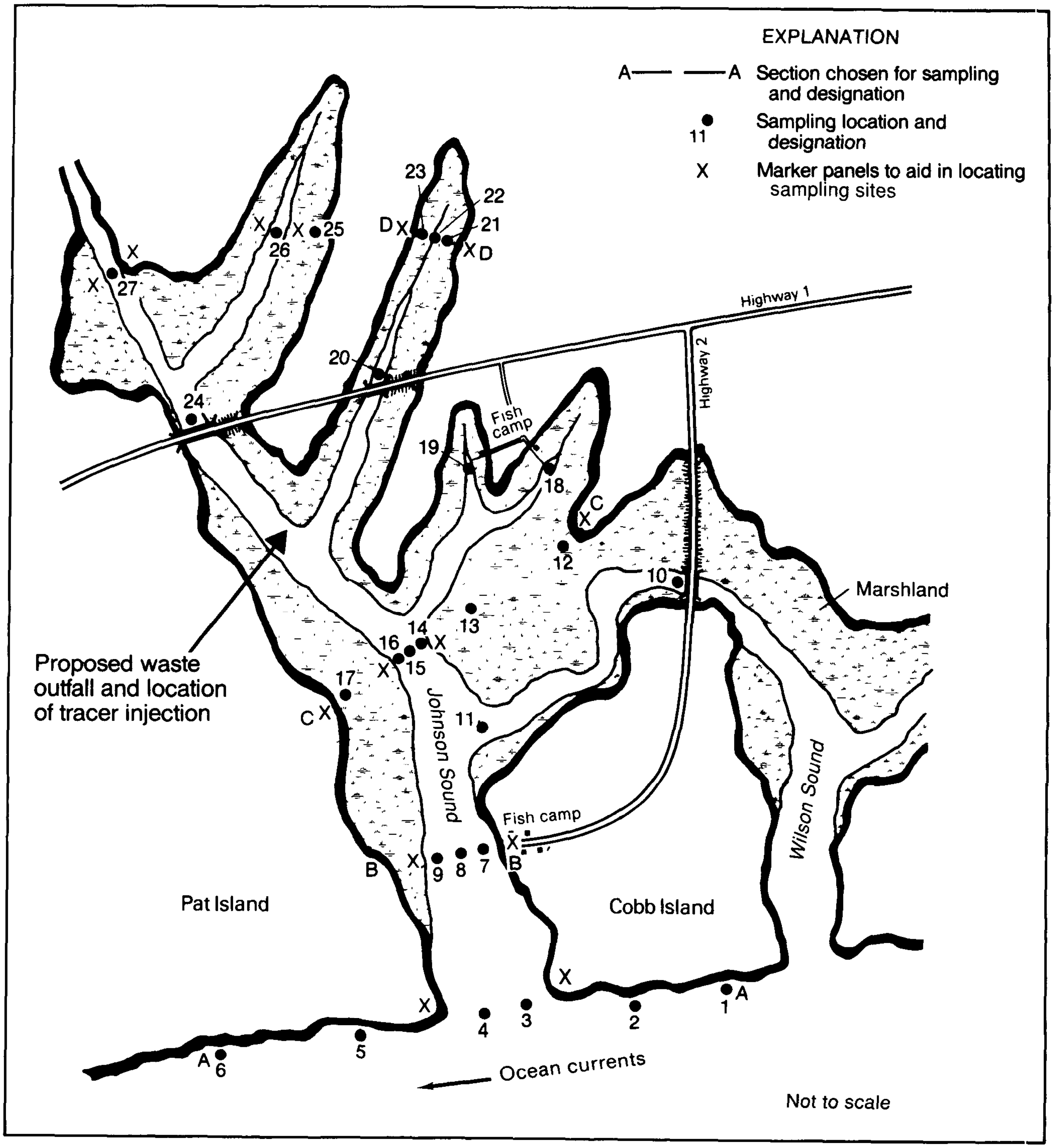


Figure 27.—Layout of tracer injection and sampling locations in Johnson Sound, S.C., for performing simulation tests.

The information shown in figure 26*C* indicates that surface buildup concentrations would still exceed bottom buildup from a continuous waste injection, but that vertical mixing is substantial between sections BB and DD, as the waste moves further down the reservoir.

The potential for a very slow but definite transport and dispersion of waste through the refuge is indicated in figure 26*D*. Furthermore, while the peak concentrations of the tracer-response curves are low, the total areas of the response curves are substantial. Hence potential waste buildup could be substantial.

As the data in figure 26*E* indicate, tracer from the main reservoir overlapping the slow-moving tracer from the refuge side of the island would form a response curve having a double peak and a very long drawn-out tail. Again, the combined area is substantial, indicating that a continuous injection of waste would possibly affect the fish hatchery.

The magnitude of the buildups that could occur throughout the reservoir would be directly in proportion to the magnitude of the waste input. In addition, changes in stream discharges, water temperatures, wind direction, and magnitudes could change the entire picture and could require retesting under other conditions to acquire characteristic slug-response curves. These changes would have to be substantial though to alter buildup computations, as the long duration of the response curves in figure 26 indicates that minor short-term changes would be dampened. Longitudinal dispersion becomes the smoothing agent in the superposition process. No example of the superposition of the response curves of figure 26, to simulate a particular waste input, will be made here, as this procedure is identical to that described for a river. The normalized concentrations would have to be increased to represent the load inputs in pounds.

If it was known that the waste in question was highly conservative, concentrations would have to be adjusted upward. Experience indicates that the decay rate for rhodamine WT dye in larger, deeper bodies of water would be about 3 to 4 percent per day. This is considerably less than most chemicals that might be spilled; thus, the use of observed dye concentrations would normally be on the conservative or safe side.

Performance of Waste-Simulation Tests in Estuaries

Example

Assume a discharge of soluble waste is proposed for the location in Johnson Sound, shown in figure 27. The proposed waste discharge will be continuous, at a constant rate, and from a single location. The objective is to simulate the consequences of such an injection on the water quality of the estuary both in the main channel and, particularly, in the marshland.

Planning

Tracer tests in estuaries require more careful planning than probably any other such study. The unsteady nature of the flow requires careful selection of the test period so that sampling is done during daylight hours and during the period that will give the best results. For example, it is almost always best to choose a period when flood tidal stages are high to assure that marshes and low areas are flooded. Furthermore, sampling might be necessary for as long as 1 or 2 months (but not every day), so the tidal pattern should be carefully examined.

Test period

The test period can best be selected by examination of the National Ocean Service tidal stage and slack water tables for the reference station(s) nearest Johnson Sound. The tables also provide the adjustments that must be made to these data so that they apply to the entrance as well as to selected subordinate stations in Johnson Sound. The tidal stage tables (National Ocean Service, 1990b) are examined for three criteria in choosing the test period:

1. A period when tidal stages are high and marsh areas can be expected to be flooded.
2. A period immediately following cessation of tracer injection, when high high tides are occurring in the early morning hours as well as during daylight hours, for about 1 week during the early phase of the test. Remember that the times of high and low tides move progressively from daytime to nighttime over a period of months.
3. A period in the spring, summer, or fall when daylight hours are longest to permit the work of sampling to be most effective and safest.

On the basis of these criteria, a period in early September 1990 was chosen as the best time to perform the test, as spring tides existed (see fig. 6) and caused extensive flooding of marsh areas at high tides. Table 2, columns 2 and 3, show the times and tidal stages for September 6 through 12, as derived from the tide tables to apply to Johnson Sound at the location of the injection.

Although the tidal stage graph is important in deciding on the test period, the times of high and low slack waters are essential in selecting the actual injection period and sampling times. High and low slack waters will normally occur within a few minutes of the corresponding high and low tidal stages.

The times predicted by the tide tables have been found to be quite close to those measured in the field. Nevertheless, sampling schedules should be developed to assure accurate sampling of the high and low slack waters. A field reconnaissance should thus include observations of the time of the slack waters at various locations in the estuary, especially in the more distant arms, such as at sampling locations 18, 19,

Table 2.—Tidal stages and times for high and low slack waters and injection and sampling schedules for Johnson Sound, S.C.

[F, flood tide; E, ebb tide; solid and open symbols are shown in figure 28 for clarity; times are in hours and minutes; for example, 0259 is 2:59 a.m.]

Date and day in September 1990 (1)	Times of high and low tidal stages for injection site in Johnson Sound (2)	Height to sea level datum (ft) (3)	Times of high and low slack waters for injection site in Johnson Sound (4)	Tracer injection and sampling schedule at injection site in Johnson Sound (5)
6	0259	−0.2	0324E	
Thursday	0904	8.2	0900F	
	1521	0.0	1545E	┬
	2127	8.0	2123F	Injection
7	0342	−0.3	0402E	↓
Friday	0947	8.4	0948F	●F
	1607	0.1	1631E	oE
	2214	7.7	2203F	
8	0426	−0.3	0444E	
Saturday	1036	8.4	1030F	●F
	1655	0.3	1721E	oE
	2300	7.4	2246F	
9	0511	−0.2	0530E	
Sunday	1130	8.3	1122F	●F
	1746	0.6	1816E	oE
	2357	7.1	2334F	
10	0601	0.0	0612E	oE
Monday	1228	8.1	1221F	●F
	1844	0.9	1918E	
11	0057	6.8	0031F	
Tuesday	0658	0.3	0722E	oE
	1332	7.9	1328F	●F
	1950	1.2	2027E	
12	0201	6.6	0140F	
Wednesday	0803	0.6	0830E	oE
	1436	7.8	1441F	●F
	2101	1.3	2140E	

Data in columns 2–4 are from National Ocean Service (1990b), high and low water predictions, and National Ocean Service (1990a), high and low slack water predictions, as adjusted from reference station to injection site in Johnson Sound.

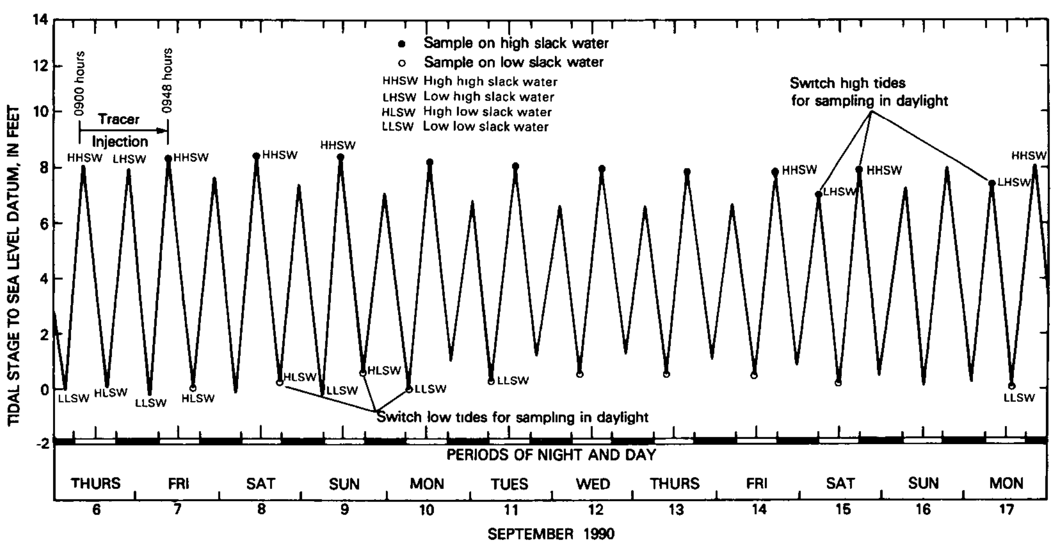


Figure 28.—Tidal stage–slack water diagram for the Frank River, Johnson Sound, S.C., showing tracer injection and sampling schedule derived from analysis of tide tables.

21–23, and 27 (see fig. 27). Use of the tide current tables in advance for the day of the reconnaissance will expedite observation of actual times of slack water. In some instances, a current meter suspended at middepth at a proposed sampling site will show when slack water occurs. Observation of floats, such as oranges, will also help in determining times of slack water. Table 2, column 4, shows the times of high and low slack waters for the period September 6 through 12, 1990, as developed from the slack water tables adjusted to apply to Johnson Sound at the location of the injection. The tidal stage-slack water diagram for Johnson Sound at the proposed injection site for September 6 through 17 is shown in figure 28. To present a clearer picture, high and low tidal stages (column 3 in table 2) have been plotted at the corresponding slack water times (column 4 in table 2). Such a diagram provides a clear picture of the magnitude of the tides and the corresponding times of their slack waters, which is vital in determining the injection period and subsequent sampling times.

Injection schedule and location

The tracer-injection period selected is one tidal day starting at 0900, September 6, 1990, and terminating at 0948 on the morning of September 7. Thus, a constant rate injection would be for 24.8 hours, or one tidal day. The injection will be made from a boat anchored at the proposed waste-injection site about 1 mi downstream of the Highway 1 bridge, as shown in figure 27.

Sampling locations

The proposed locations for sampling the tracer on high and low slack waters are shown in figure 27. They were chosen so that the tracer-concentration measurements could be used with the superposition principle to delineate the pattern of waste dispersion and buildup throughout the estuary. Sampling locations at bridges and docks were sought as much as possible, but most sampling would be by helicopter.

Sampling schedule

On the basis of the tide table calculations and observations of the slack tides, a sampling schedule is developed that "moves" inland from the mouth on flood slack water and seaward in the estuary on ebb slack water. Although this progressive change in slack water times will not always be the case, it will be typical of most East Coast estuaries. The tidal stages and slack water times in table 2 and plotted in figure 28 are for the injection site in Johnson Sound. Hence, flood tide and its corresponding slack water will occur earlier at the mouth of the sound and later inland from the injection site than shown in table 2 and figure 28. The Tide Current Tables (National Ocean Service, 1990a) and field observations provide a means of adjusting these times for flood and ebb slack waters. Based on the times at the injection site (column 4, table 2) as reference, these adjustments are shown in table 3.

Study of the diagram of tidal slack water and of column 4 in table 2 permits selection of the sampling schedule, which will produce the data needed for the superposition analysis. Furthermore, sampling will be confined primarily to the daylight hours. As seen in figure 28, the first set of samples must be collected on the high high slack water (HHSW) simultaneous with the termination of tracer injection. These are the most crucial samples to be taken. HHSW sampling would continue until Saturday, September 15. No samples would be needed on Sunday. Low high slack water (LHSW) samples would be taken on Monday and from then on to allow collection during daylight hours. Because of this tidal "switch," samples should also be taken at LHSW on Saturday, September 15. Sampling is able to switch tides because after a week of dispersion in the estuary, there will be few, if any, distinguishing differences in the tracer concentrations between HHSW and LHSW.

As seen in figure 28, the first sampling on low slack water must take place immediately following termination of tracer injection and must be on an HLSW. HLSW sampling can continue through Sunday, September 9, and then switch to LLSW to permit sampling in daylight hours.

Quantity of tracer and injection rate

The tracer test in Johnson Sound is to use 20-percent rhodamine WT dye. The quantity needed can be determined using equation 11 and an estimate of the estuary volume likely to be tagged. It is estimated that the tracer test could take 3 weeks.

Estimated estuary volumes at HHSW are as follows:

a. Main channel:

10 mi long × 5,280 ft/mi × 1,000 ft average width × 17 ft average depth $\approx 9.0\times10^8$ ft^3

b. Marshland:

Area planimetered from topographic map	$\approx 3.0\times10^8$ ft^3
Average depth	≈ 2.5 ft
Estimated volume	$\approx 7.5\times10^8$ ft^3

Total estimated volume of affected estuary at high high tide $\approx 1.65\times10^9$ ft^3

By use of equation 11,

$W_d=312\times10^{-9}(1.65\times10^9\ \text{ft}^3)=515$ lbs of 20-percent rhodamine WT dye.

Table 3.—Adjustments for sampling high and low slack waters for different locations in Johnson Sound, S.C.

Flood slack water		Ebb slack water	
Location (see fig. 27) (1)	Lapsed time from flood slack water, relative to injection site[1] (min) (2)	Location (see fig. 27) (3)	Lapsed time from ebb slack water, relative to injection site[1] (min) (4)
Sect. AA	−11	Pt. 26	−13
Sect. BB	−8	Pt. 25	dry
Pt. 11	−6	Sect. DD	dry
Sect. CC	−2	Pt. 27	−10
Injection site	0	Pt. 24	−6
Pt. 24 (Hwy. 1)	+3	Pt. 20	−3
Pt. 18	+5	Injection site	0
Pt. 19	+7	Sect. CC	+5
Pt. 20	+9	Pts. 12, 13, 17	dry
Pt. 12	+14	Pts. 18, 19	+11
Pt. 10 (Hwy. 2)	+29	Sect. BB	+12
Pt. 27	+37	Sect. AA	+17
Pts. 25 and 26	+42	Pt. 10	+36
Sect. DD	+48		

Note: A given high slack water occurs earliest at the entrance to the sound and moves inland. A given low slack water occurs earliest inland and moves seaward.

[1]Adjustments in minutes shown in columns 2 and 4 of table 3 should be added or subtracted from the times of flood (high) and ebb (low) slack water times occurring at the injection site (column 4, table 2).

The estimate is based on the concentration averaging 1 μg/L. Much higher concentrations might be expected to exist in the vicinity of the injection and to drop off to zero at the limits of the dye cloud. This amount of 20-percent rhodamine WT dye, if injected over a 24.8-hour tidal day, would be the equivalent of 100 lbs/day of soluble waste (515 lbs×0.2×24 hours/24.8 hours). The 515 lbs of 20-percent rhodamine WT dye must be injected at a constant rate over a tidal day. The injection rate to accomplish this can be computed as

$$q=\frac{V_s}{\Delta T} \tag{13}$$

where

q is the injection rate in mL/min,

V_s is the volume of stock dye solution, and

ΔT is the duration of the injection in hours.

$$q=\frac{(515 \text{ lbs})453.6 \text{ g/lb}(1 \text{ mL}/1.19 \text{ g})}{(24.8 \text{ hours})\times(60 \text{ min/hour})}=132 \text{ mL/min.}$$

This is well within the capacity of the battery-driven fluid-metering pumps available.

Sampling and concurrent data analysis

The day before tracer injection begins, large background samples are taken at all sampling locations in the sound. These are carefully labeled, stored out of daylight, and kept cool to avoid algae growth.

All tracer samples are analyzed within a few hours of collection. The fluorometric analysis of dye tracer samples has been well documented by Wilson and others (1986). In tracer studies in estuaries it is very important to plot the data concurrent with collection as a guide for when to sample and, in particular, when to stop sampling. Sampling is performed on every other high or low slack water for about a week following termination of injection as shown in figure 28. Usually, by this time, it is possible to go to 2- and 3-day sampling intervals and to select the high or low slack water that comes during daylight hours.

Tracer concentrations will be continually reduced as the test progresses due to dilution and dispersion, flushing out of the estuary, and decay or loss of the tracer. Sampling should continue at all locations until concentrations are reduced to at least 0.2 μg/L.

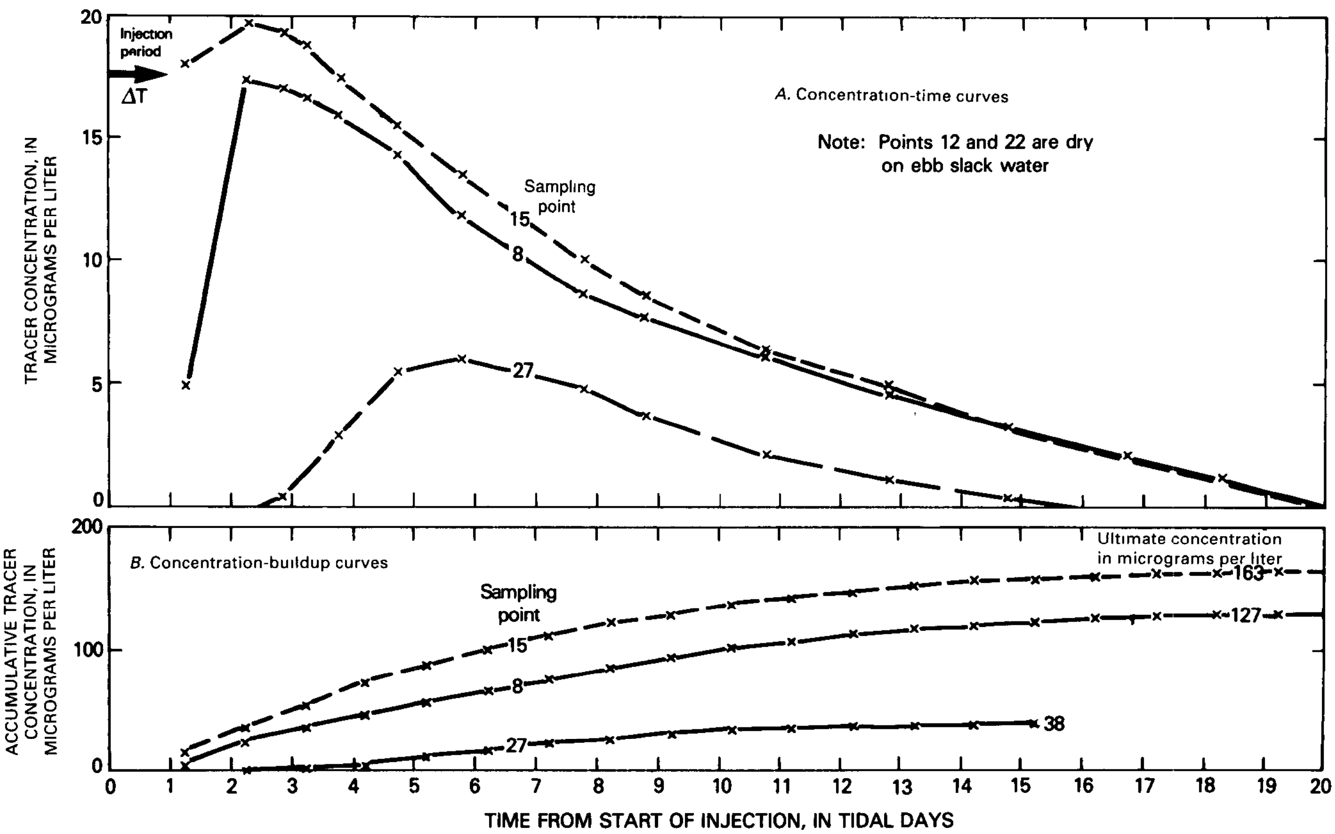


Figure 29.—(*A*) High slack water concentration versus time and (*B*) buildup curves for three sampling points in Johnson Sound, S.C.

Analysis and interpretation

Concentration-time curves are prepared for all 27 points in the estuary shown in figure 27 for both high and low slack water, exceptions being points 12, 13, 17, 21–22, and 25, which are dry at low slack water. Concentration-time curves for 19 tidal days, for selected locations, for high and low slack water are shown in figures 29 and 30.

For high slack water, dye does not reach the mouth of the sound (point 8 in fig. 27) until a tidal day after terminating injection and does not peak until 4 tidal days. This delay occurs because the tidal excursions of the water volume that received dye for 24.8 hours do not extend to the mouth; longitudinal dispersion and the advective affect of any freshwater inflow are necessary to cause seaward transport and eventual flushing. However, point 15 is close enough to the injection point to have substantial dye concentrations at 1 tidal day when the dye injection is terminated. By contrast, on low slack water, the dye peak has reached point 3, the mouth, in 2 1/4 tidal days. The opposite is true of upstream points, for example, point 27. The peak is 4 tidal days on high slack water and about 6 days for low slack water. The marshland areas are flooded only during high tide, so that, as shown by points 12 and 21, there is a gradual buildup of dye concentrations in these areas.

The area under the curves in figures 29 and 30 is indicative of the magnitude of the buildup that would occur at each point if there was a continuous input of 100 lbs/day of soluble waste at the location shown for at least 19 days. Thus, even though the dye is slower to build up in the marsh areas, it is not insignificant.

Superposition

The superposition of the concentration data is accomplished by adding or accumulating the concentrations obtained at each point at ΔT intervals. For high slack water, concentration data would be selected at 1, 2, 3 (and so forth) tidal days, even though actual samples might not have been collected at such times. No data prior to $T=1$ should be used. For low slack water data, the addition interval is still ΔT but starts at 1 1/4 tidal days from the start of injection. This addition or superposition for point 8 is shown in column 3 of table 4.

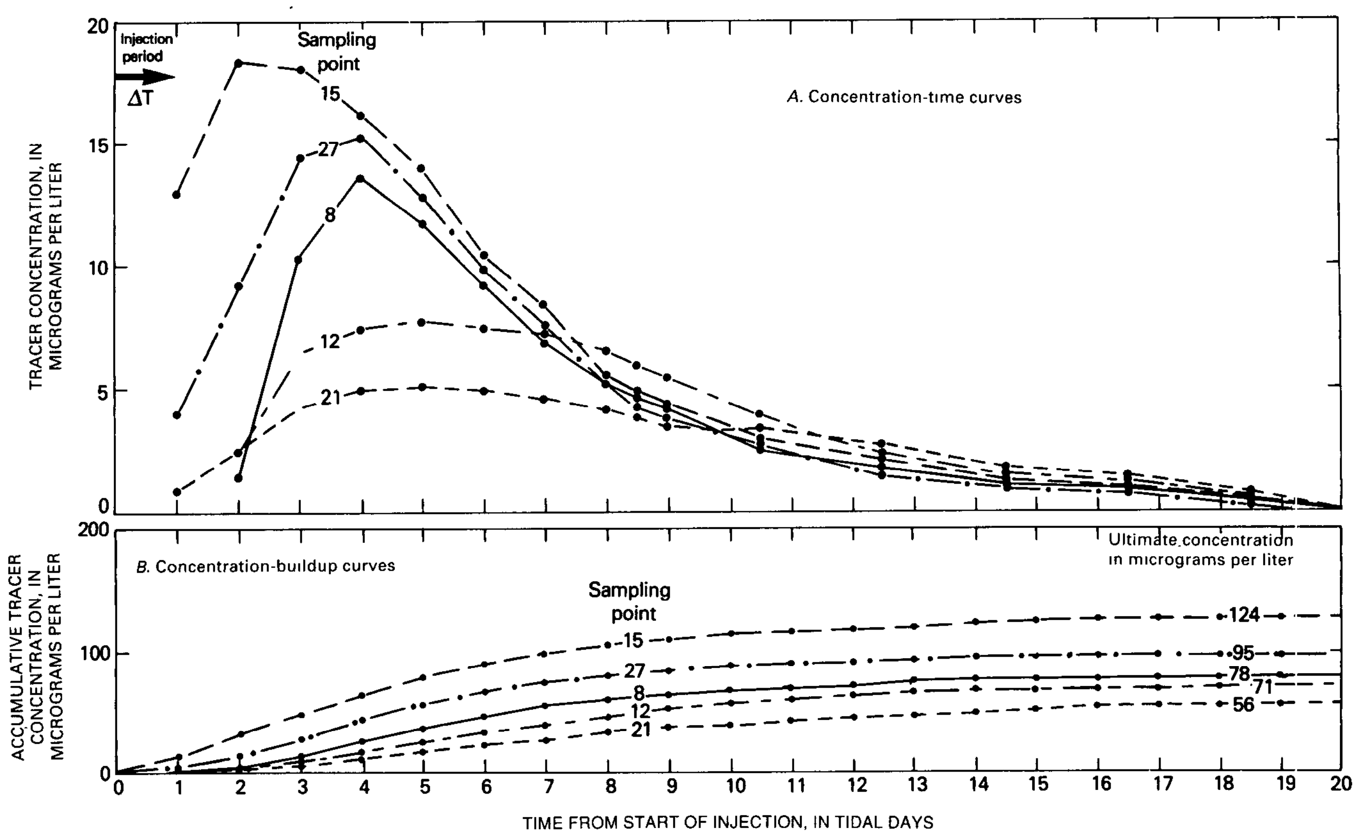


Figure 30.—(*A*) Low slack water concentration versus time and (*B*) buildup curves for five sampling points in Johnson Sound, S.C.

The buildup or superposition of concentrations at selected points until ultimate concentrations are reached is shown in figures 29 and 30. As can be seen, buildup concentrations tend to be lower at high slack water than at low slack water except in upstream areas. As a rule, greater dilution occurring on high slack water results in lower buildup concentrations. Initially, the dye mass occupies essentially the main channel and concentrations are highest due to less dilution. No hard-and-fast rule can be used to say definitely which data set will produce the highest buildup concentrations, but in general, in marsh areas, the highest are at low slack water downstream and at high slack water inland.

Flushing time

In the example presented, the flushing time of the estuary is approximately 20 days for the injection location shown and the tidal conditions existing during the test. In the absence of freshwater inflow, longitudinal dispersion is the principle mechanism producing flushing; each excursion seaward carries a portion of the dispersed solute into the ocean.

Presentation of results

A map showing lines of equal buildup of concentrations from a given dye input is a useful means of presenting the data. Such a map, where the maximum buildup concentrations are presented, regardless of which slack water produced them, is shown in figure 31. This presentation is for 100 lbs/day (103 lbs/tidal day) of dye input. It must be borne in mind that this is not for a conservative waste but for a dye tracer having a decay rate of about 3.4 percent per day. If desired, the buildup concentrations could be made to apply to a conservative waste by the adjustment of each day's concentrations prior to the superposition summation. This computation for point 8 is shown in column 4 of table 4. Thus, the buildup concentration for a conservative substance is 99 μg/L for point 8 based on high slack water data compared with 78 μg/L for a dye or solute having K=0.034/tidal day (see fig. 29). No correction is made here for K values for the time difference between a 24-hour day and a 24.8-hour tidal day because there is too much uncertainty in K values in general to justify such refinement. Most wastes have larger decay rates than the dye tracer, so

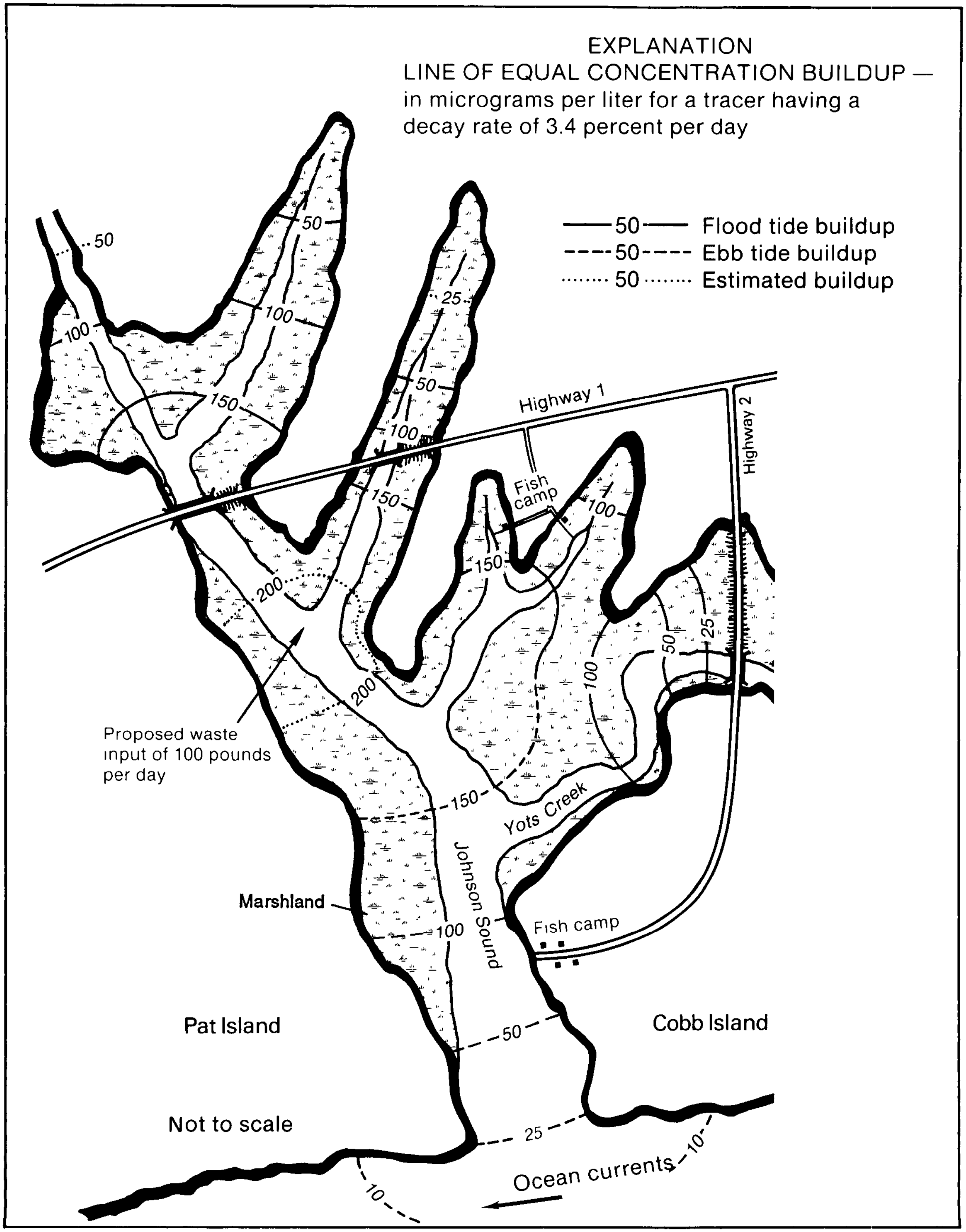


Figure 31.—Maximum buildup of concentrations resulting from continuous injection of 100 pounds per day of tracer in Johnson Sound, S.C.

Table 4.—Application of dye tracer data and superposition principle to estimate waste concentrations from constant and variable waste inputs

[Computation is for point 8 on high slack water, Johnson Sound, S.C.; K is decay rate constant to the base e; μg/L, micrograms per liter; computation for T=8 to T=15 is omitted for brevity]

Elapsed time, T (tidal days)	Constant rate of 100 lbs/day of dye or waste					Variable waste input		
	Measured dye concentration C_d (μg/L) (K=0.034/tidal day)	Cumulative buildup concentration (μg/L) (K=0.034/tidal day)	Conservative dye concentration C_c for K=0/tidal day[1] (μg/L)	Simulated concentration for waste having K=0.10/tidal day: Decay factor for each tidal day	Waste concentration[2] (μg/L)	Waste discharge on tidal day	Relative waste discharge[3]	Waste concentration[4] (μg/L)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	0	0	0	0.94	0	20	1.0	0
2	1.5	1.5	1.6	.88	1.3	19	1.2	1.6
3	10.5	12.0	11.6	.82	8.6	18	1.4	12.0
4	13.6	25.6	15.6	.77	10.5	17	1.5	15.8
5	11.8	37.4	14.0	.72	8.5	16	1.2	10.2
6	11.3	48.7	11.3	.67	6.2	15	.8	5.0
7	7.0	53.6	8.9	.63	4.4	14	.6	2.6
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
16	1.1	76.0	1.7	.35	.4	5	1.0	.4
17	.8	76.7	1.4	.30	.2	4	1.0	.2
18	.6	77.4	1.1	.29	.2	3	.8	.2
19	.4	77.7	.8	.28	.1	2	.9	.1
20	.2	78.0	.4	.27	.1	1	1.0	.1
Superposition totals		78.0	99.0		51.0			61.0

[1] $C_c = C_d e^{-KT} = C_d e^{-(0-0.034)T} = C_d e^{+0.034T}$.
[2] Waste concentration=C_d[tidal day decay factor]=$C_d[e^{(-0.100-0.034)T}] = C_d e^{-0.066T}$ (multiply values in column 2 by values in column 5).
[3] Relative to 100 lbs/day.
[4] Multiply values in column 6 by values in column 8.

the concentrations shown on the map in figure 31 are generally on the conservative side.

If the decay rate of the waste is known, it is possible to compute its buildup concentration at any location by "decaying" the data, tidal day by tidal day, and then summing. For example, suppose that the waste in question has a decay coefficient of 0.10/tidal day compared to 0.034/tidal day for rhodamine WT dye. Columns 5 and 6 in table 4 show the computation of the waste concentration for point 8. As can be seen, the buildup concentration for the 100 lbs of waste per day is 51 μg/L after 20 tidal days, which is about half of the conservative concentration. Note also, that if the waste input varied over 20 tidal days, as shown in column 8, the resulting computations and summation in column 9 reflect both the input variation and the decay. Note that in all the superpositions, the concentrations produced the first few days are the largest and, hence, the most significant in the summation. Thus, if 20 tidal days is the buildup time to produce maximum concentrations, it is the waste injection on tidal days 16, 17, and 18 that is most important (see column 7 of table 4). The dye concentrations measured on the first few days of the tracer test are the most crucial.

Summary and Conclusions

Dye tracers were initially used in the 1960's to perform time-of-travel studies that simulated the speed of a flowing river or of a soluble waste spilled or otherwise injected therein. This report shows that in addition to speed, waste concentrations can be simulated using tracer data and the superposition principle. This approach permits simulation of waste dilution, dispersion, and transport not only in rivers, lakes, and estuaries, but in any water body where the tracer can be used to imitate the waste.

This report focuses on three primary areas. First, a more extensive treatment of conventional time-of-travel data is encouraged as well as more extensive data collection. It is shown that the conventional response curve of concentration versus time can be used in the superposition process as a building block to predict waste concentrations at different locations on a river as a result of different waste loadings.

Second, the same process can be applied to a lake, where the time-concentration curves, in response to a tracer injection, become the building blocks to simulate any manner of waste injection as long as the substance is soluble. But, the user is cautioned that tracer tests in lakes and reservoirs reflect prevailing hydraulic and atmospheric conditions and are conditional to them.

Third, it is shown that by taking advantage of the repetitive nature of tides in estuaries, quasi-steady-state conditions can be tested by injecting a tracer over an entire tidal day and by sampling the high and low slack water periods that follow. Such tracer tests in estuaries can require lengthy sampling but can yield reliable information on flushing times and on the ultimate concentrations, which could be expected for a given waste input to an estuary.

In all of the cases considered, the tracer is testing the prototype, so that the complex flow and dispersion phenomena that might exist, especially in estuaries, are reflected in the observed data. No elaborate flow data or physical characteristics of the water course need be measured, just the resulting responses of the tracer injection. Using these tracer-concentration data from the prototype in conjunction with the superposition principle is a powerful method for simulating waste movement in the water environment.

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