



# 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

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tive 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

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

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 3B 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

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

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  $\mu\text{g/L}$  may be computed by the equation

$$W_d = 312 \times 10^{-9} (\text{volume of estuary or lake in cubic feet}). \quad (11)$$

Such estimates are for an average concentration of 1  $\mu\text{g/L}$ . 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

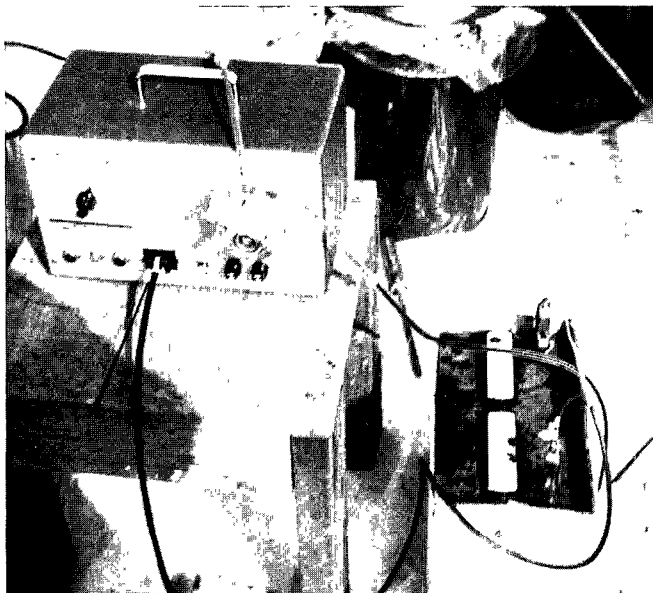


Figure 11.—Battery-powered peristaltic pump being used to pump rhodamine WT dye directly from shipping containers into an estuary.

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



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

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



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

mobility and quickness it provides in moving with and sampling on the high and low slack tides.

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.

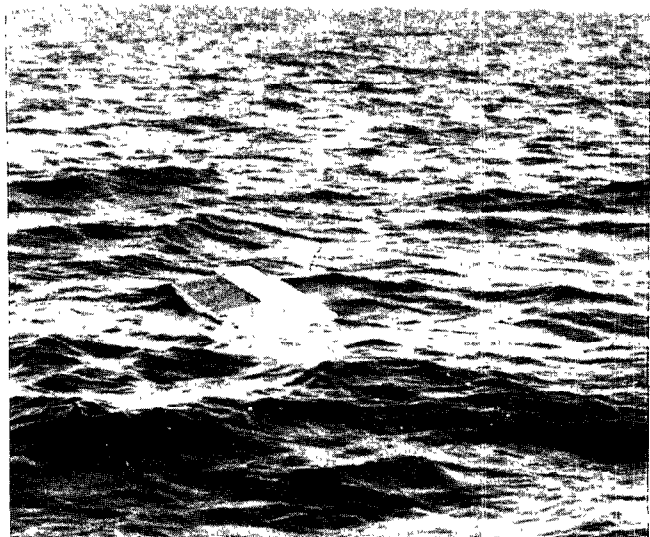


Figure 15.—Automatic floating sampler used to sample at night and under hazardous conditions.

If the tracer injection period is 1 tidal day,  $\Delta T = 24.8$  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  $\Delta T$  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.

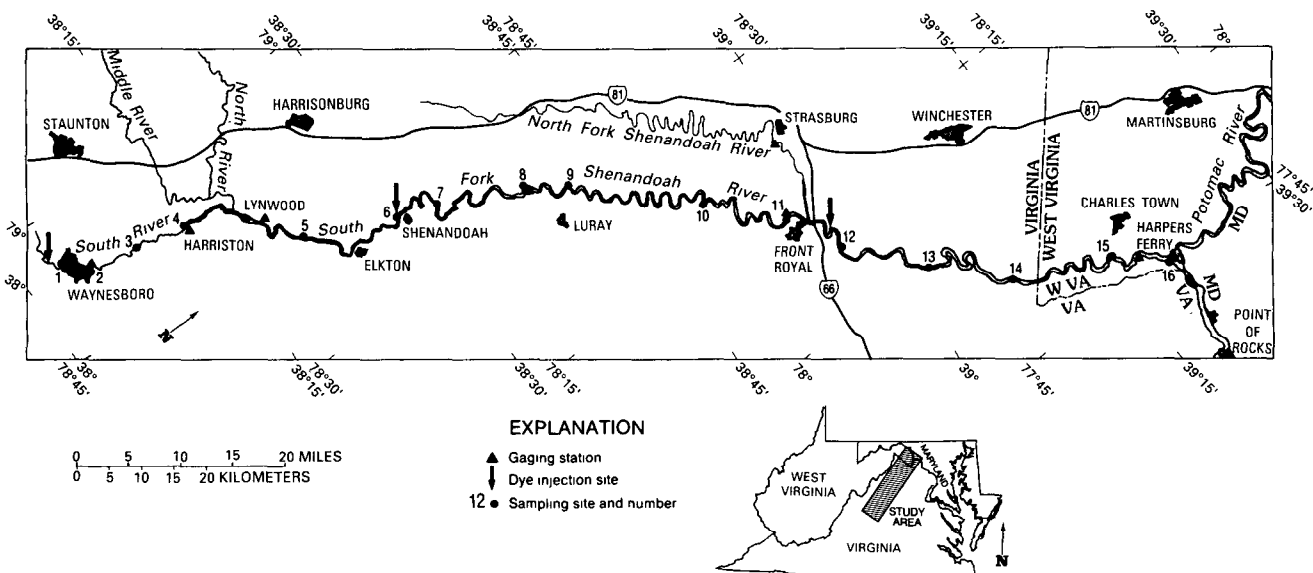


Figure 16.—Study reach for time-of-travel studies on the Shenandoah River in Virginia and West Virginia.

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 18A and 18B. The shaded curves in figure 18A 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

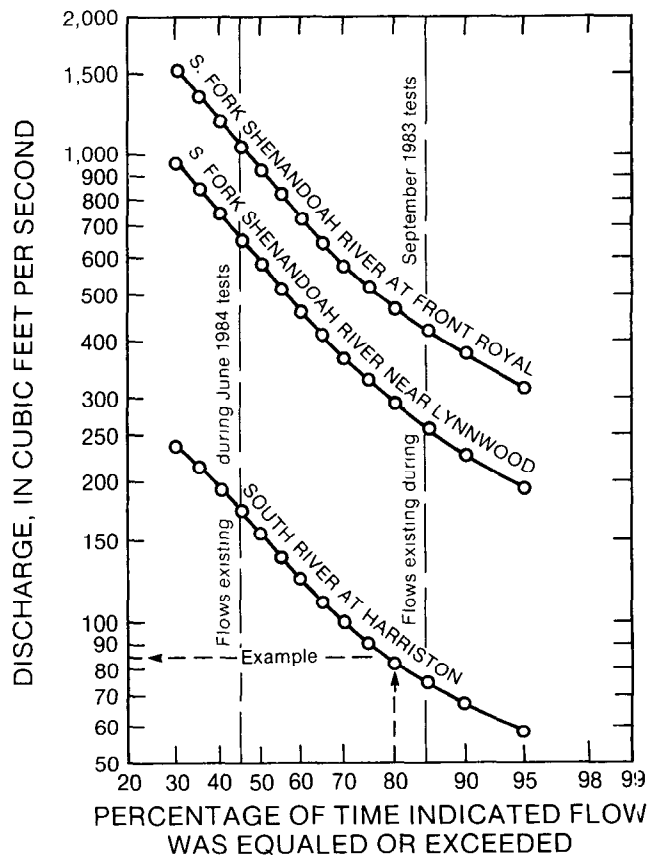


Figure 17.—Flow-duration curves for index gaging stations on the South River and South Fork Shenandoah River, Va.

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

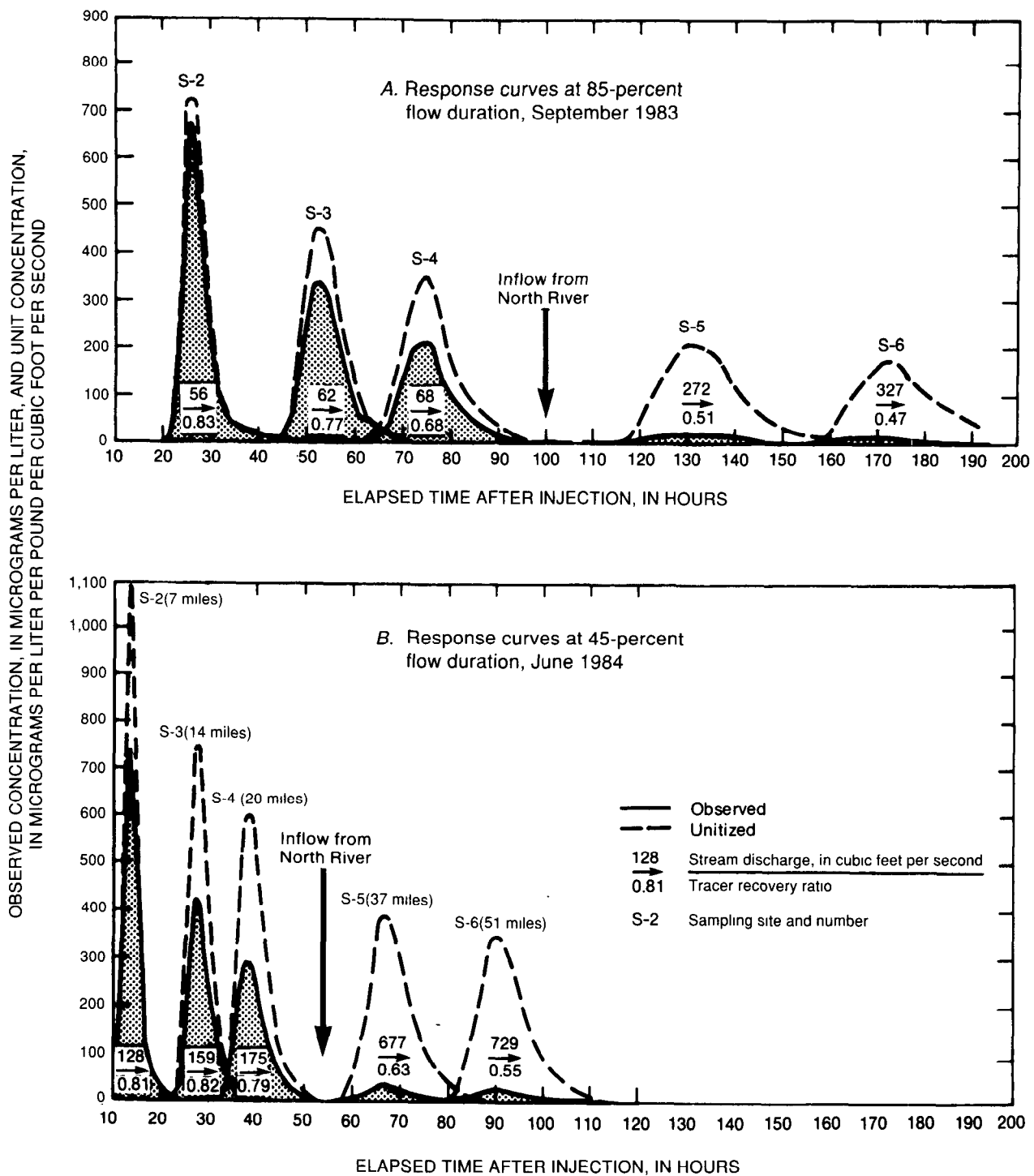


Figure 18.—Observed and unitized tracer-response curves for the South River and South Fork Shenandoah River between Waynesboro and Shenandoah, Va., for two different discharges.

concentration decreased from approximately 67  $\mu\text{g/L}$  at S-2 to less than 2  $\mu\text{g/L}$  at S-6. The diluting effect of an inflow, 3 times as great as that in the South River entering from the North River and S-5, is

apparent as the observed peak concentration dropped from about 22 to 2.5  $\mu\text{g/L}$ , and the areas of the respective observed response curves are reduced accordingly.

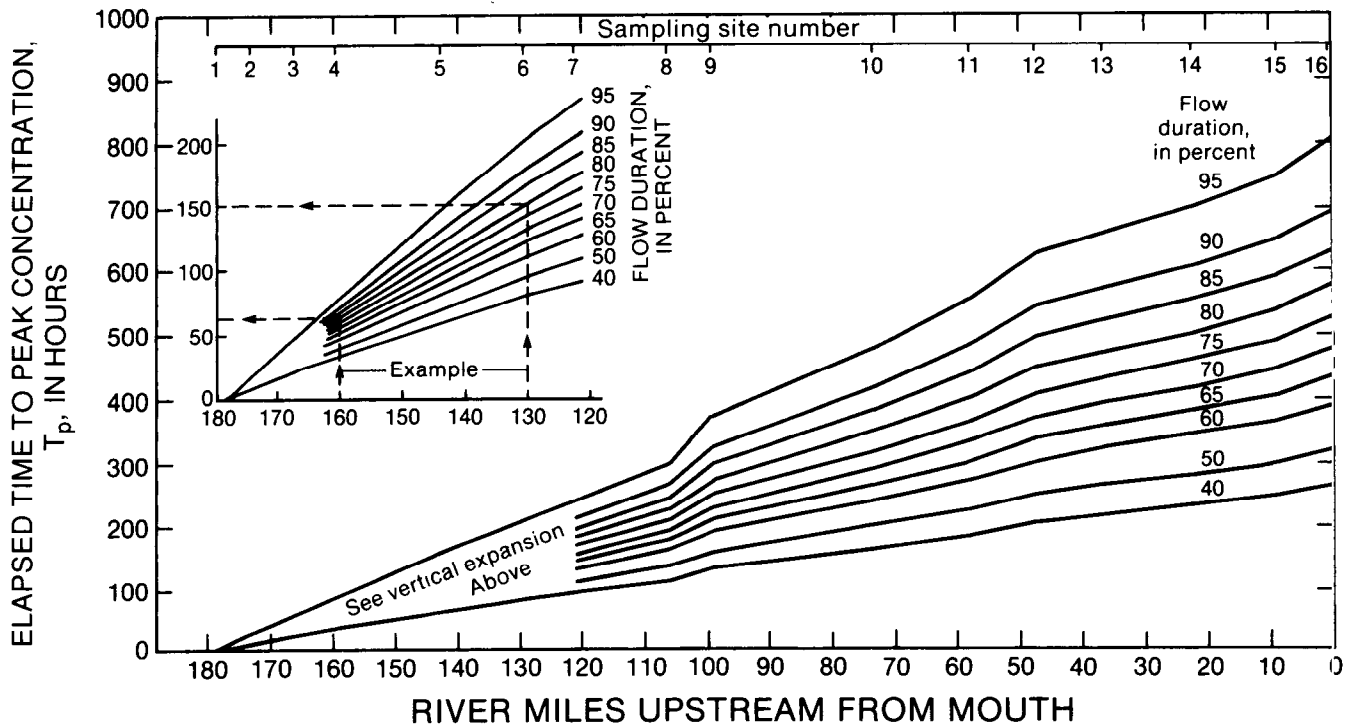


Figure 19.—Relation between travel time and distance for peak concentrations at selected flow durations, Shenandoah River from Waynesboro, Va., to Harpers Ferry, W. Va.

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. 18B). 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 dilu-

tion 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 20A, 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,  $4,450 [(\mu\text{g/L})/(\text{lb})](\text{ft}^3/\text{s})(\text{h})$ , 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



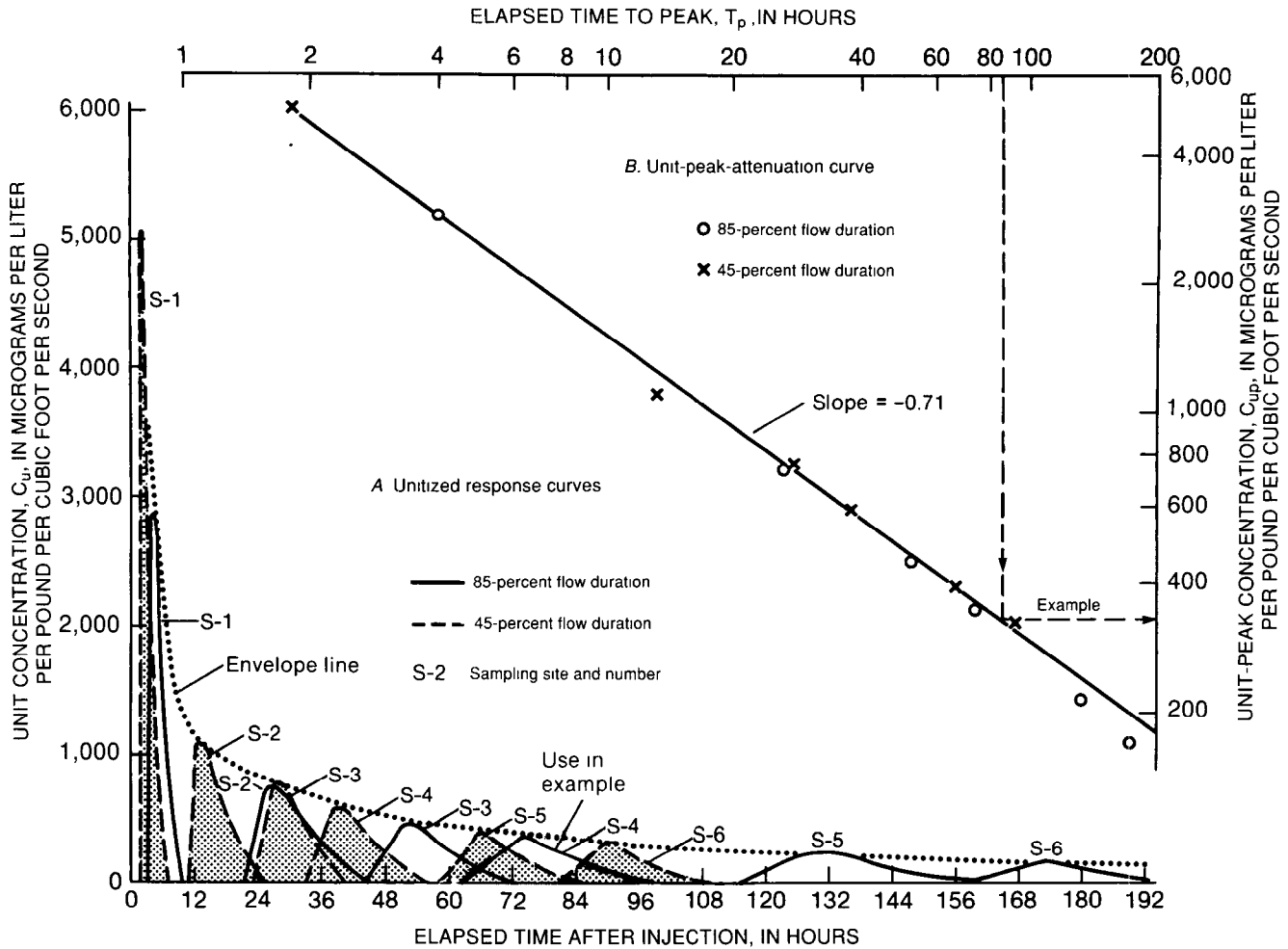


Figure 20.—Unitized tracer-response curves and unit-peak-attenuation curve for the Shenandoah River between Waynesboro and Shenandoah, Va., for two different discharges.

reach sites S-1 through S-6 for the Shenandoah River for flows at both durations is shown in figure 20B. 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 20B, 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.

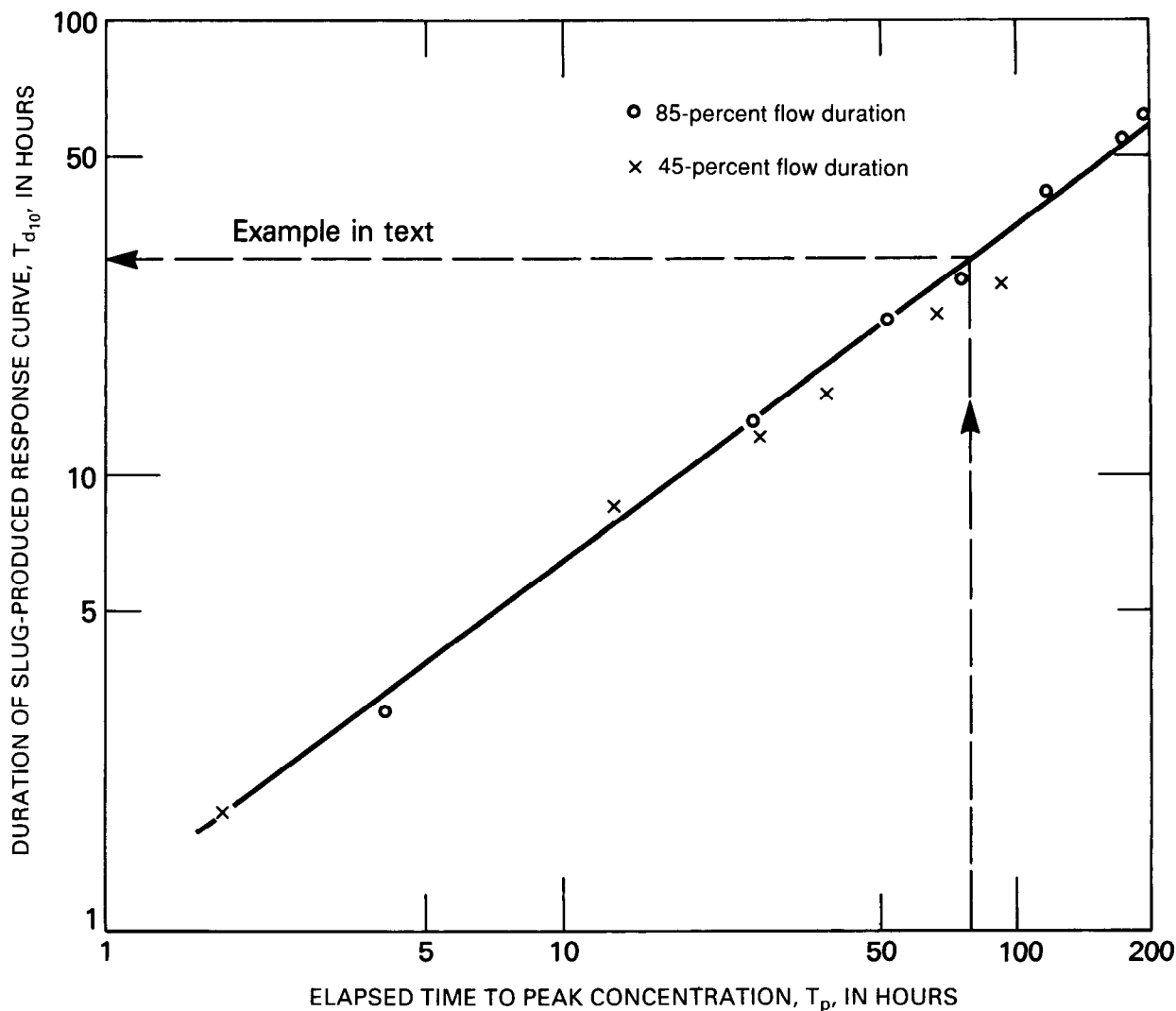


Figure 21.—Relation between peak-concentration elapsed time ( $T_p$ ) and response-curve duration ( $T_{d_{10}}$ ).

#### 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<sup>3</sup>/s (80-percent flow duration from fig. 17) near Harriston, which is near the hatchery. Using figure 20B, 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<sup>3</sup>/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<sup>3</sup>/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 23A, the resulting concentration pattern could be simulated as

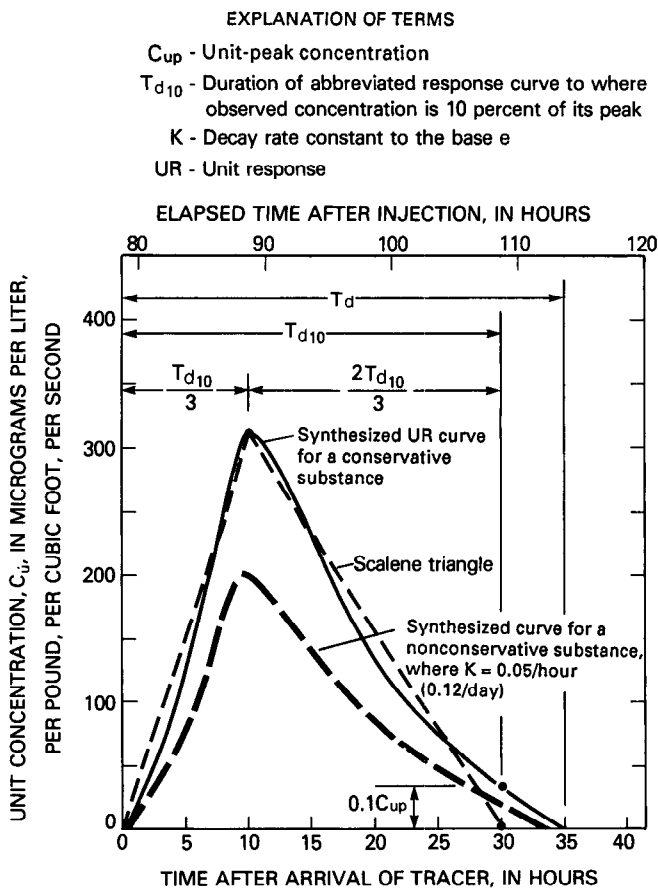
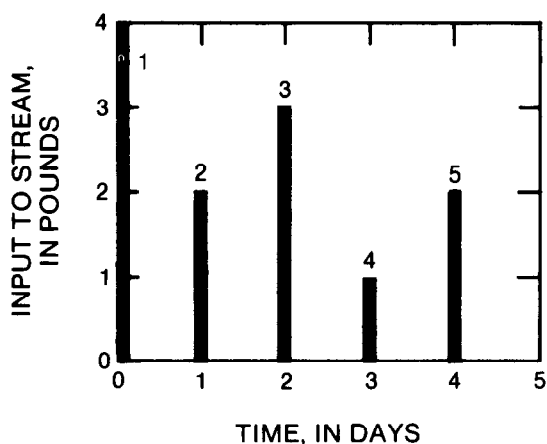


Figure 22.—Unit-response curves for a time of 80 hours, applicable to Shenandoah River from Waynesboro to Shenandoah, Va.

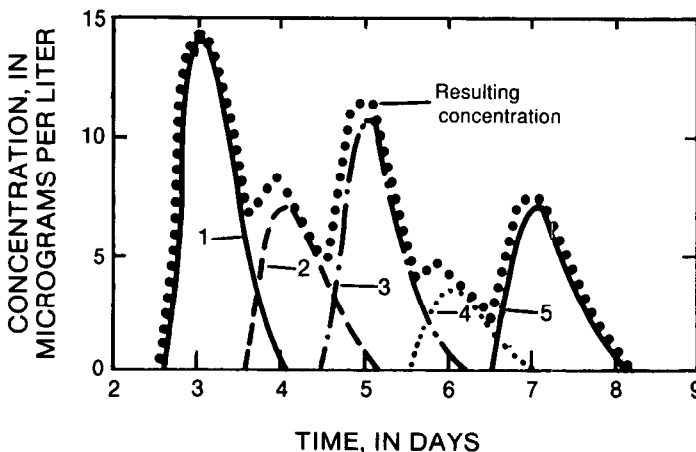
shown in figure 23B. Each response curve shown in figure 23B is obtained by scaling the UR curve in figure 22 upward for the weight and downward for a discharge of 85 ft<sup>3</sup>/s as indicated by equation 6. These data are superimposed at 24-hour intervals and the vertical concentrations added together 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.

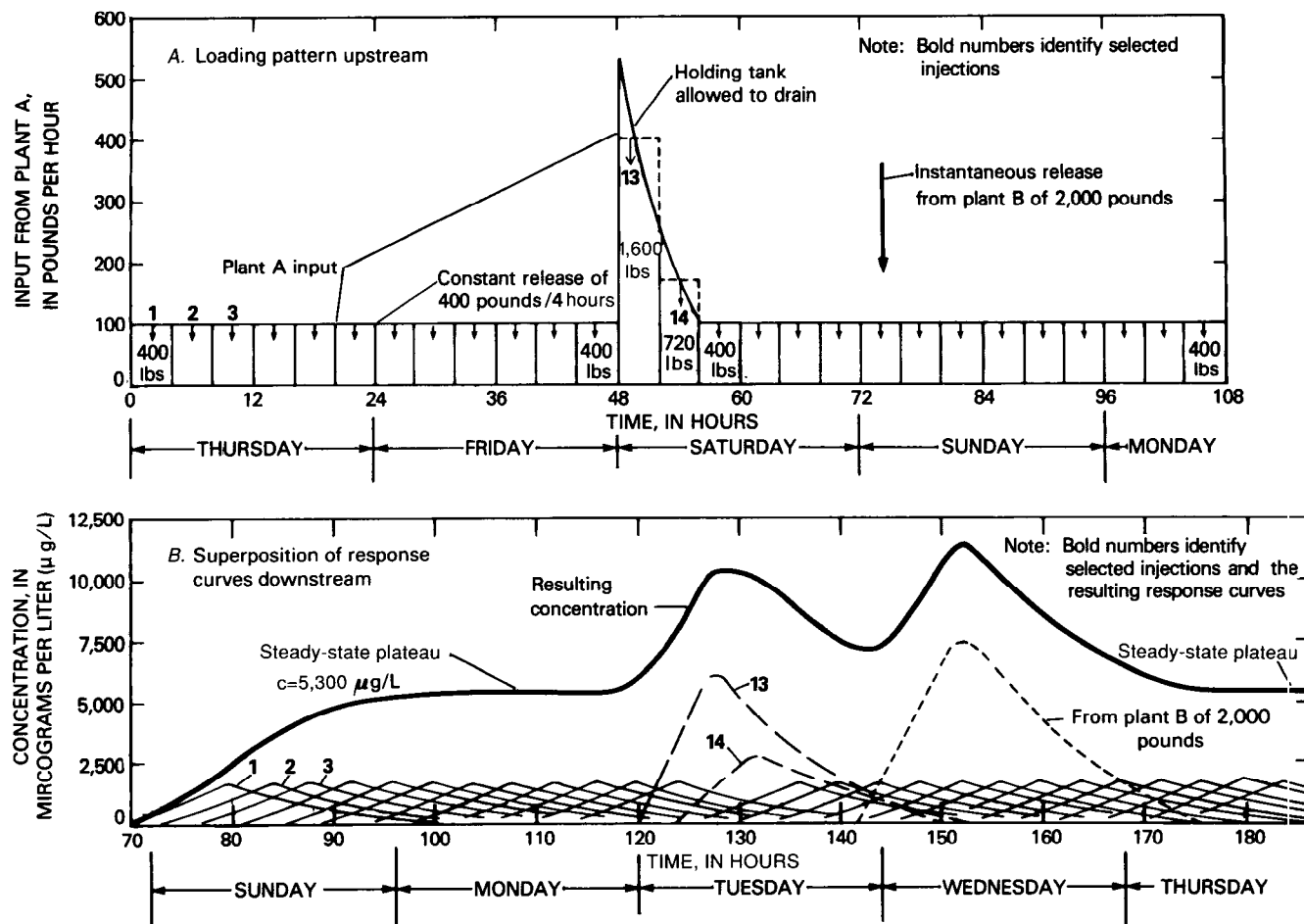


Figure 24.—(A) Waste loading pattern upstream and (B) simulated concentration response curves and resulting superimposed concentration curve downstream in Shenandoah River, Va.

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  $1,000 \mu\text{g/L}$  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.

$$\begin{aligned} \text{Input a: Constant injection} &= 20 \text{ gal/min} \times 8.34 \text{ lbs/gal} \times 60 \text{ min/hour} \\ &\quad \times 0.01 \times 1.00 \\ &= 100 \text{ lbs/hour} \\ &= 400 \text{ lbs/4 hours} \end{aligned}$$

$$\begin{aligned} \text{Input b: Holding tank, plant A} \\ \text{Total weight} &= 2,000 \text{ gal} \times 8.34 \text{ lbs/gal} \times 0.08 \times 1.14 = 1,522 \text{ lbs.} \\ \text{Distribute over 8 hours with 1,200 lbs} &\text{ in first 4 hours and 322 lbs in second 4 hours.} \end{aligned}$$

$$\begin{aligned} \text{Input c: Instantaneous slug injection of 17,000 lbs} \\ \text{Total weight of chemical X} &= 17,000 \text{ lbs} \times 0.10 \times 1.18 \approx 2,000 \text{ lbs.} \end{aligned}$$

Figure 24A 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 non-conservative waste

[Unit concentrations are in  $[(\mu\text{g/L})/\text{lb}](\text{ft}^3/\text{s})]$ 

Elapsed time, hours (1)	Unit concentration (from fig. 22) (2)	$e^{-Kt}$ ( $K=0.012/\text{day}=0.005/\text{hour}$ ) (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 ft<sup>3</sup>/s flow and plotted successively, as shown in figure 24B.

Similarly, response curves for 1,600, 722, and 2,000 lbs in 85 ft<sup>3</sup>/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 24B.

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  $\mu\text{g/L}$ . For this period, the plateau concentration may also be computed from the continuity equation:

$$Qc_w = q_w C_w \quad (12)$$

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

$$c_w = \frac{q_w C_w}{Q}$$

$$c_w = \frac{[(20 \text{ gal/min})(0.134 \text{ ft}^3/\text{gal})(0.0167 \text{ min/s})](1 \times 10^7 \mu\text{g/L})}{85 \text{ ft}^3/\text{s}} = 5,265 \mu\text{g/L}$$

Obviously, from the computation and examination of figure 24B, concentrations well exceed the permissible 1,000  $\mu\text{g/L}$  limit at all times. In fact, concentrations on the order of 12,500  $\mu\text{g/L}$  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 ft<sup>3</sup>/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

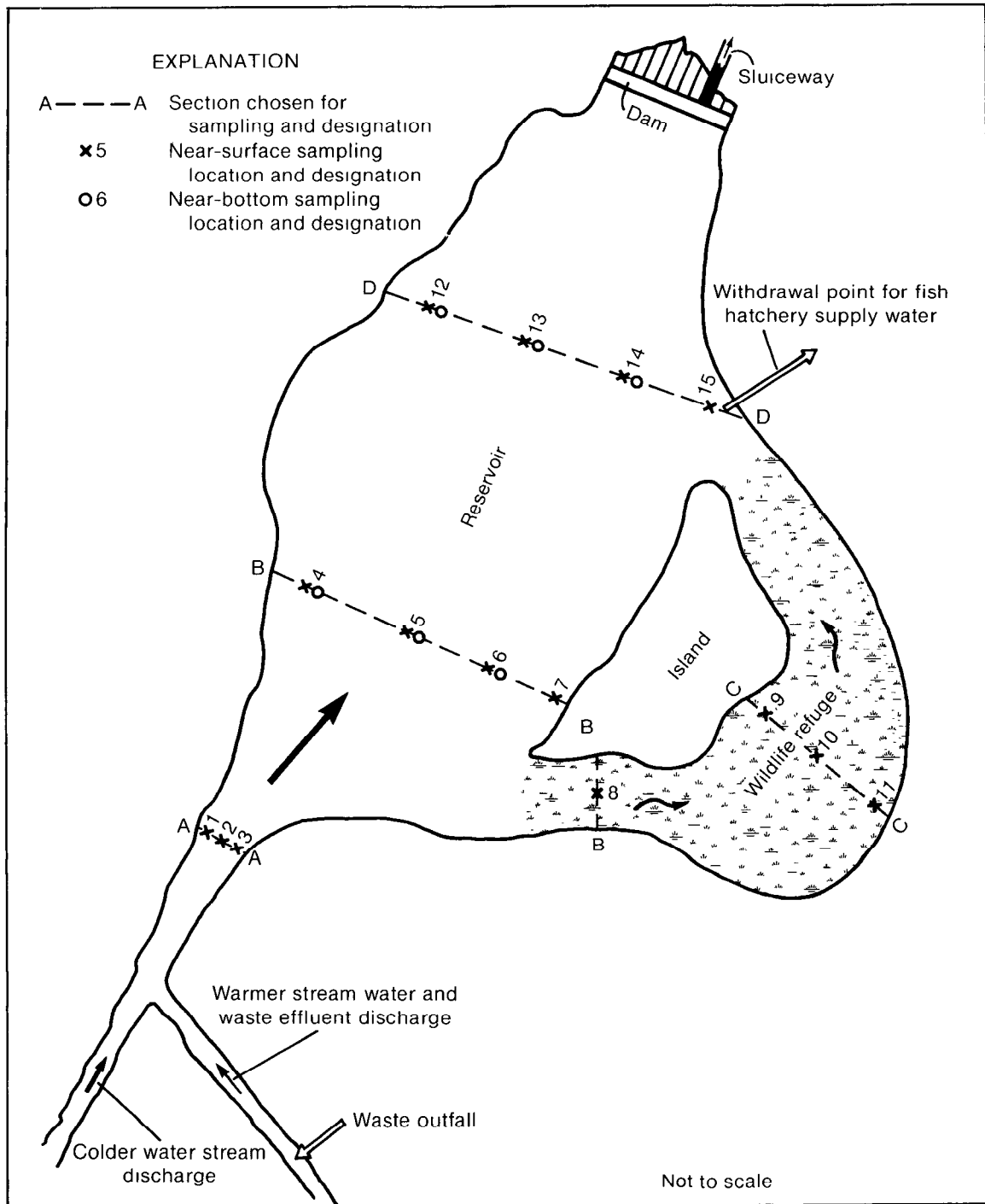


Figure 25.—Hypothetical reservoir used to demonstrate application of superposition principle to predict buildup of wastes at different locations and depths.

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

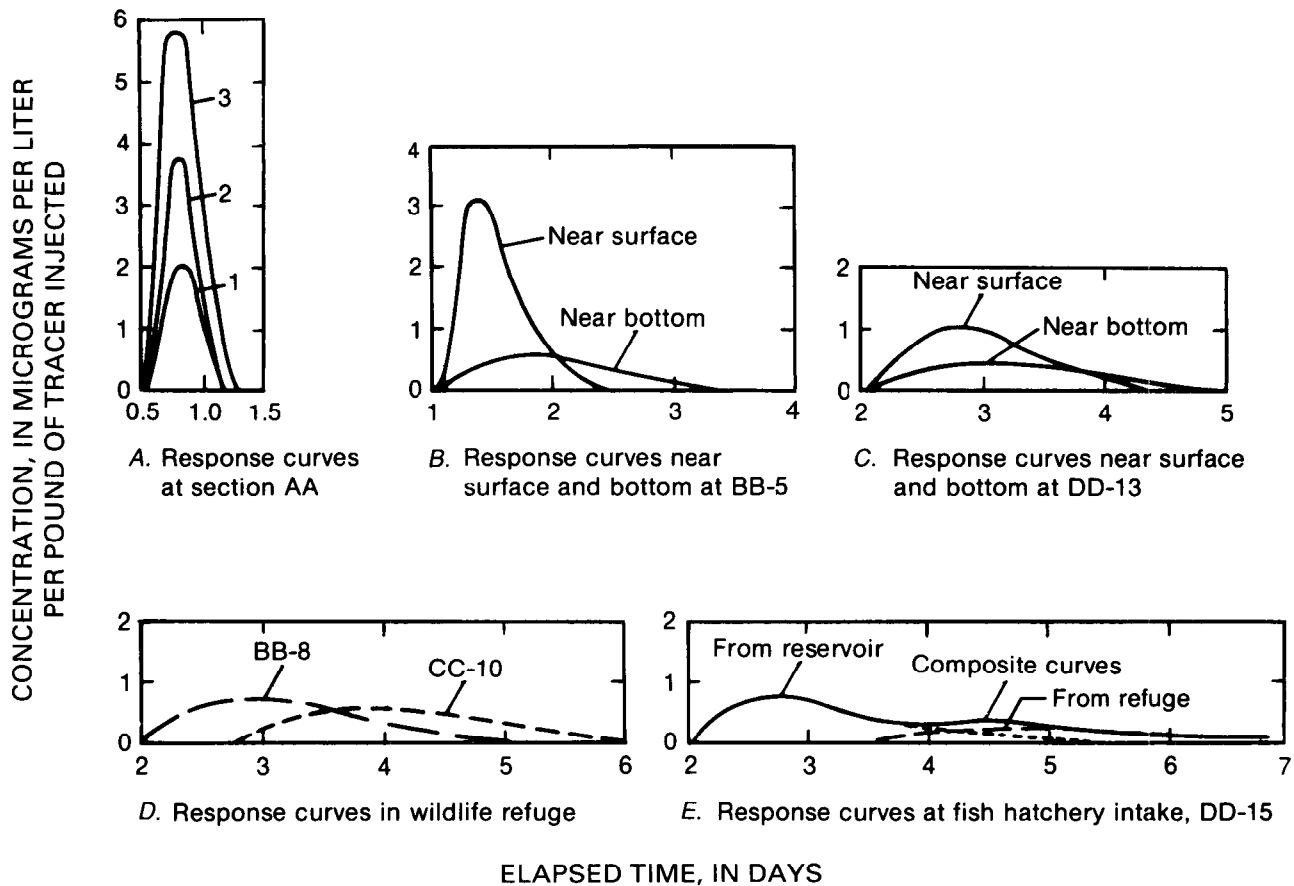


Figure 26.—Response curves obtained at different locations in a reservoir due to slug injection of tracer upstream in incoming flow.

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 26A 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 26B 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.

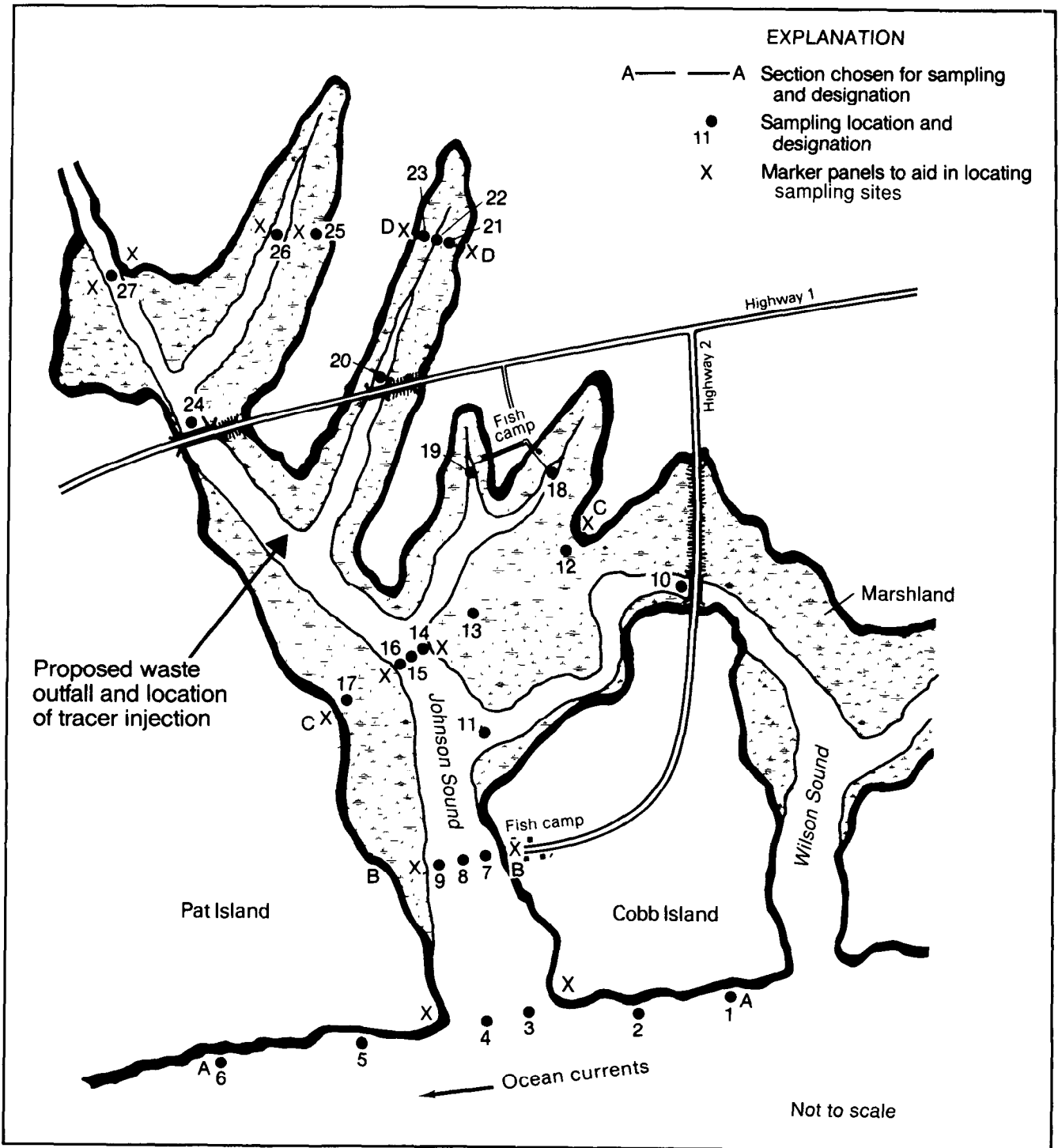


Figure 27.—Layout of tracer injection and sampling locations in Johnson Sound, S.C., for performing simulation tests.

The information shown in figure 26C 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 26D. 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 26E 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)
Thursday	0259	-0.2	0324E	
	0904	8.2	0900F	
	1521	0.0	1545E	
Friday	2127	8.0	2123F	
	0342	-0.3	0402E	
	0947	8.4	0948F	●F
Saturday	1607	0.1	1631E	○E
	2214	7.7	2203F	
	0426	-0.3	0444E	
Sunday	1036	8.4	1030F	●F
	1655	0.3	1721E	○E
	2300	7.4	2246F	
Monday	0511	-0.2	0530E	
	1130	8.3	1122F	●F
	1746	0.6	1816E	○E
Tuesday	2357	7.1	2334F	
	0601	0.0	0612E	○E
	1228	8.1	1221F	●F
Wednesday	1844	0.9	1918E	
	0057	6.8	0031F	
	0658	0.3	0722E	○E
Thursday	1332	7.9	1328F	●F
	1950	1.2	2027E	
	0201	6.6	0140F	○E
Friday	0803	0.6	0830E	
	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.

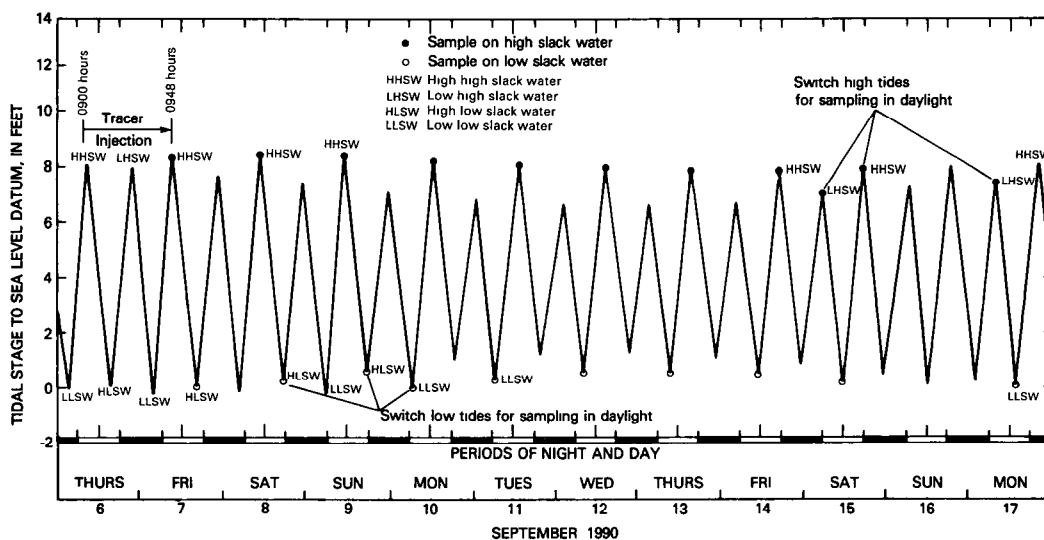


Figure 28.—Tidal stage-slack water diagram for the Frank River, Johnson Sound, S.C., showing tracer injection and sampling schedule derived from analysis of tide tables.

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 mid-depth 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  $\times$  5,280 ft/mi  $\times$  1,000 ft average width  $\times$  17 ft average depth  $\approx 9.0 \times 10^8$  ft<sup>3</sup>

##### b. Marshland:

Area planimetered from topographic map  $\approx 3.0 \times 10^8$  ft<sup>2</sup>

Average depth  $\approx 2.5$  ft

Estimated volume  $\approx 7.5 \times 10^8$  ft<sup>3</sup>

Total estimated volume of affected estuary at high tide  $\approx 1.65 \times 10^9$  ft<sup>3</sup>

By use of equation 11,

$$W_d = 312 \times 10^{-9} (1.65 \times 10^9 \text{ ft}^3) = 515 \text{ lbs of 20-percent rhodamine WT dye.}$$

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 <sup>1</sup> (min) (2)	Location (see fig. 27) (3)	Lapsed time from ebb slack water, relative to injection site <sup>1</sup> (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.

<sup>1</sup>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  $\mu\text{g/L}$ . 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  $\times$  0.2  $\times$  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

$$q = \frac{V_s}{\Delta T} \quad (13)$$

where

$q$  is the injection rate in mL/min,  
 $V_s$  is the volume of stock dye solution, and  
 $\Delta T$  is the duration of the injection in hours.

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

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  $\mu\text{g/L}$ .

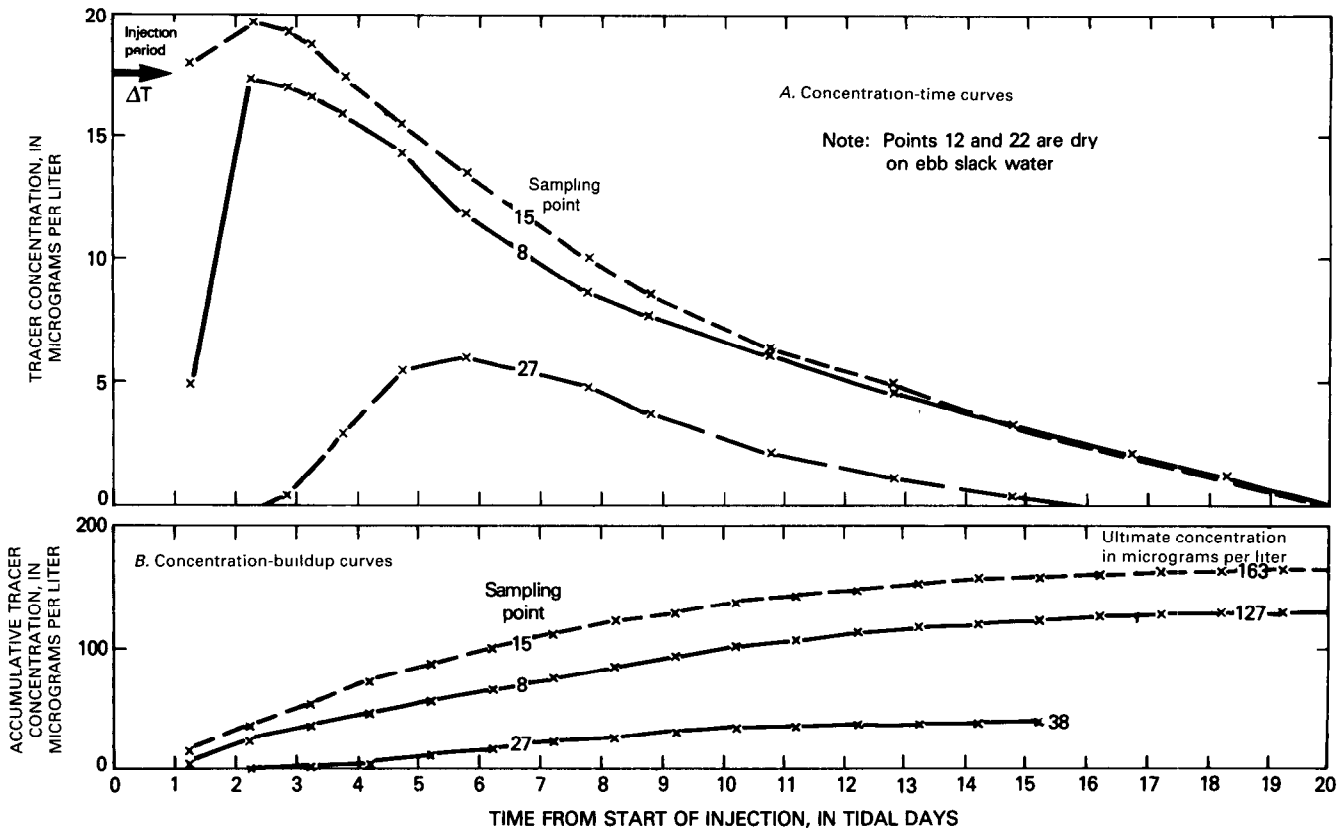


Figure 29.—(A) High slack water concentration versus time and (B) buildup curves for three sampling points in Johnson Sound, S.C.

### 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  $\Delta T$  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  $\Delta T$  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.

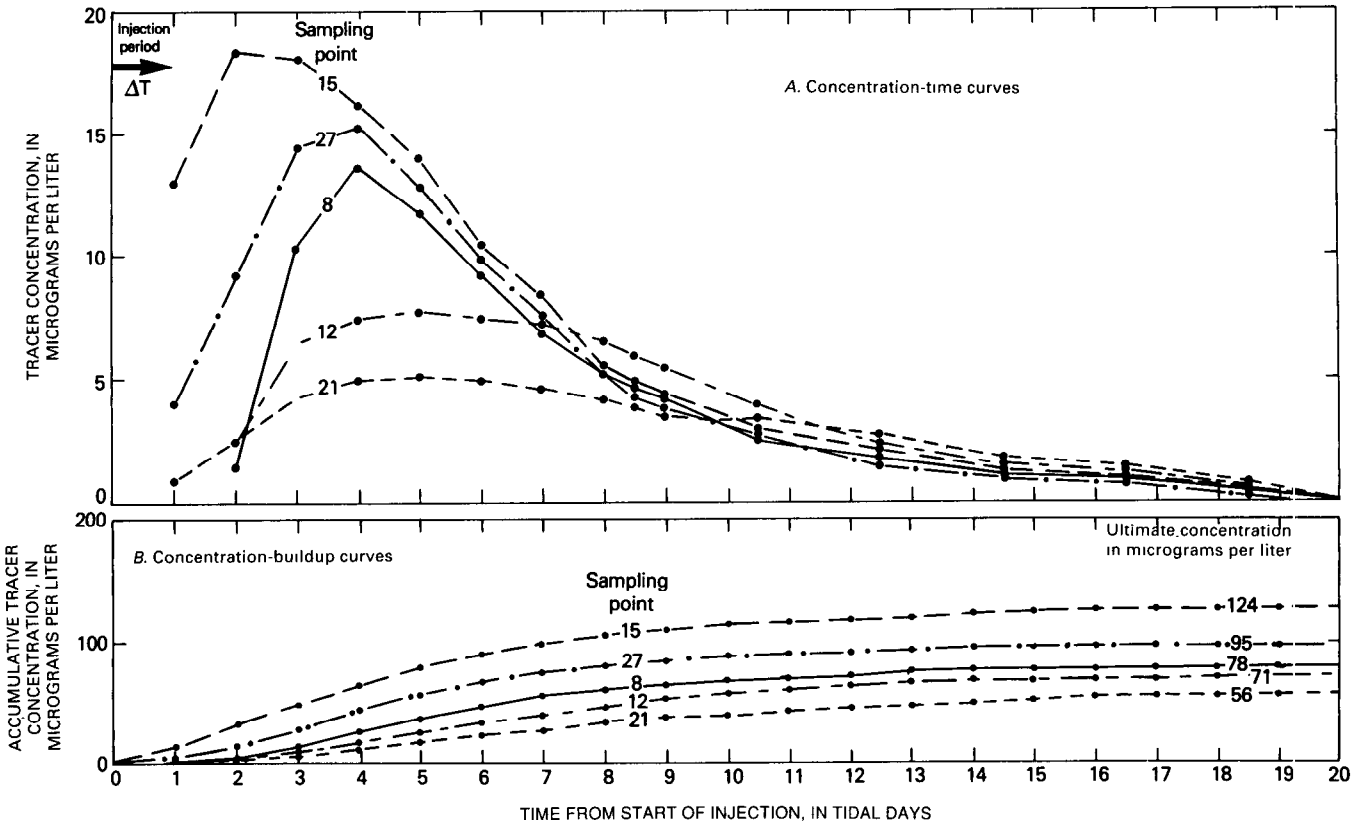


Figure 30.—(A) Low slack water concentration versus time and (B) buildup curves for five sampling points in Johnson Sound, S.C.

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

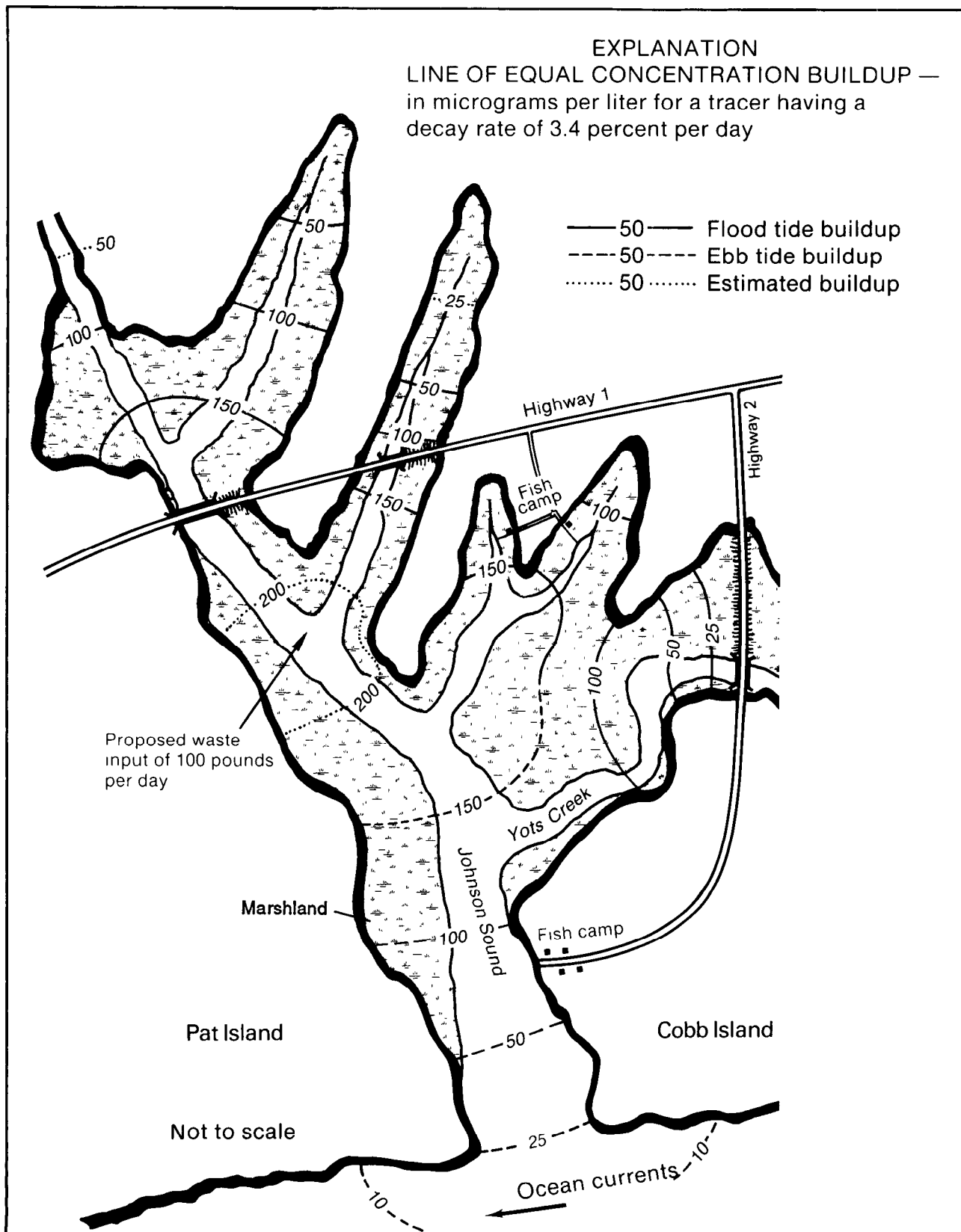


Figure 31.—Maximum buildup of concentrations resulting from continuous injection of 100 pounds per day of tracer in Johnson Sound, S.C.

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  $e$ ;  $\mu\text{g/L}$ , 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 $C_d$ ( $\mu\text{g/L}$ )  ( $K=0.034/\text{tidal day}$ )	Cumulative buildup concentration ( $\mu\text{g/L}$ )	Conservative dye concentration $C_c$ for $K=0/\text{tidal day}^1$ ( $\mu\text{g/L}$ )	Simulated concentration for waste having $K=0.10/\text{tidal day}$				
				Decay factor for each tidal day	Waste concentration <sup>2</sup> ( $\mu\text{g/L}$ )	Waste discharge on tidal day	Relative waste discharge <sup>3</sup>	Waste concentration <sup>4</sup> ( $\mu\text{g/L}$ )
(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

$${}^1C_c = C_d e^{-KT} = C_d e^{-(0-0.034)T} = C_d e^{+0.034T}$$

$${}^2\text{Waste concentration} = C_d [\text{tidal day decay factor}] = C_d [e^{(-0.100-0.034)T}] = C_d e^{-0.066T} \text{ (multiply values in column 2 by values in column 5).}$$

<sup>3</sup>Relative to 100 lbs/day.

<sup>4</sup>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  $\mu\text{g/L}$  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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