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

Chapter A9

MEASUREMENT OF TIME OF TRAVEL IN STREAMS BY DYE TRACING

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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.

Book 3

APPLICATIONS OF HYDRAULICS

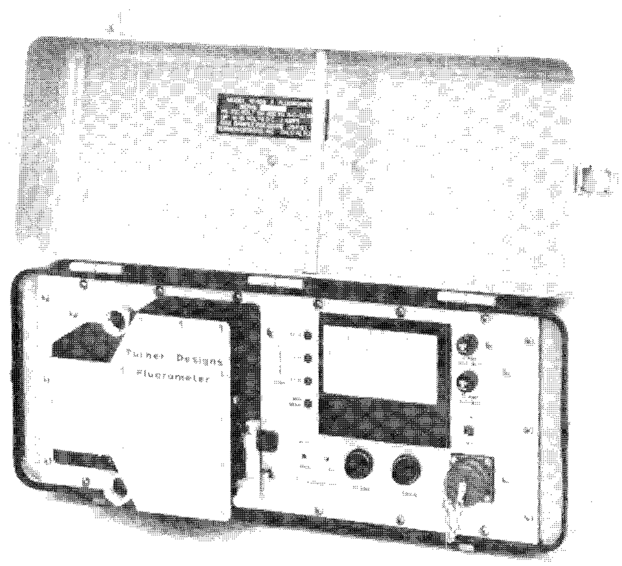


Figure 10.—A modern fluorometer, suitable for field use, having both flow-through and individual-sample analysis capability.

extensive series of time-of-travel tests was performed by Taylor and others (1986) during 1983 and 1984 at flows of 85 percent and 45 percent duration, respectively. The data and techniques used by Taylor and others are used selectively in this manual. Figure 12 shows the relation between flow duration and discharge for four gaging stations or locations on the South Fork Shenandoah River and its tributaries in Virginia. Taylor and others found that during September 1983 discharge on the Shenandoah River increased from 36 cubic feet per second (ft^3/s) at Waynesboro to 570 ft^3/s at Harpers Ferry, although flow duration was at approximately 85 percent throughout the reach. This information made possible comparisons with tests on the Potomac River, which were performed during the fall of 1981 at the flow duration of 90 percent; flow at this duration was 1,800 ft^3/s for the Potomac River at Washington, D.C. As mentioned previously, time of travel commonly varies inversely with discharge. The relation of time of travel to discharge is of the form

$$t=kQ^{-x}, \tag{5}$$

which is a straight line, logarithmically. The constant, k, and the exponent, x, need to be defined for each flow-control condition of interest, that is, pool-and-riffle or channel control. Thus, two or more time-of-travel measurements are usually required for any stream reach.

The first step in planning the time-of-travel study is to study existing streamflow records and to select the one or more flow durations to be sought for the tests. The lower flow (higher flow duration) is usually the most important, as traveltimes are long and the transport and behavior of potential wastes are the most critical. Fall is the most likely season for sufficiently long periods of stable low flows in a large river system. Stable high flows, having flow durations between 40 and 50 percent, sometimes occur during late spring. In either case, careful planning means being alert and ready for the desired periods of stable flows. Manpower may have to be concentrated for intense efforts when the flow "window" for the tests materialize. Plans and logistics need to be ready for implementation when the time comes.

Map and streamflow-data study

The next step in planning the time-of-travel measurement is to make a tentative evaluation of the stream reaches under consideration in terms of hydraulic characteristics and of constraints on the use of dyes. Topographic maps and available streamflow data should be examined to make the initial selection of sites where dye will be injected and sampled. Maps are useful in developing a generalized picture of the stream-channel system in terms of channel geometry, discharge and slope variations, manmade impoundments and diversions, and accessibility of the sites.

Examination of available streamflow data, discharge measurements, and gaging-station records and comparisons of hydrographs assist in selecting sampling and injection sites.

Reconnaissance of the stream

The reconnaissance of the stream will depend on the scope of the measurements being planned and should include the following activities:

1. Inspect the proposed injection site or sites to determine flow conditions, type of dye injection to use, and accessibility for injecting the dye.
2. Inspect the proposed sampling sites (minimum of two per injection is desirable) to determine accessibility and suitability. Decide whether more than one sampling point in the cross section will be necessary and where the sampling points will be located. Measure or estimate the channel width and depth and the mean velocity of the stream reach to the extent possible.
3. Estimate stream velocities to aid in planning sampling schedules. When making a visual reconnaissance of the stream, there is a tendency to give too much weight to the higher velocities observed in riffles compared with the slower

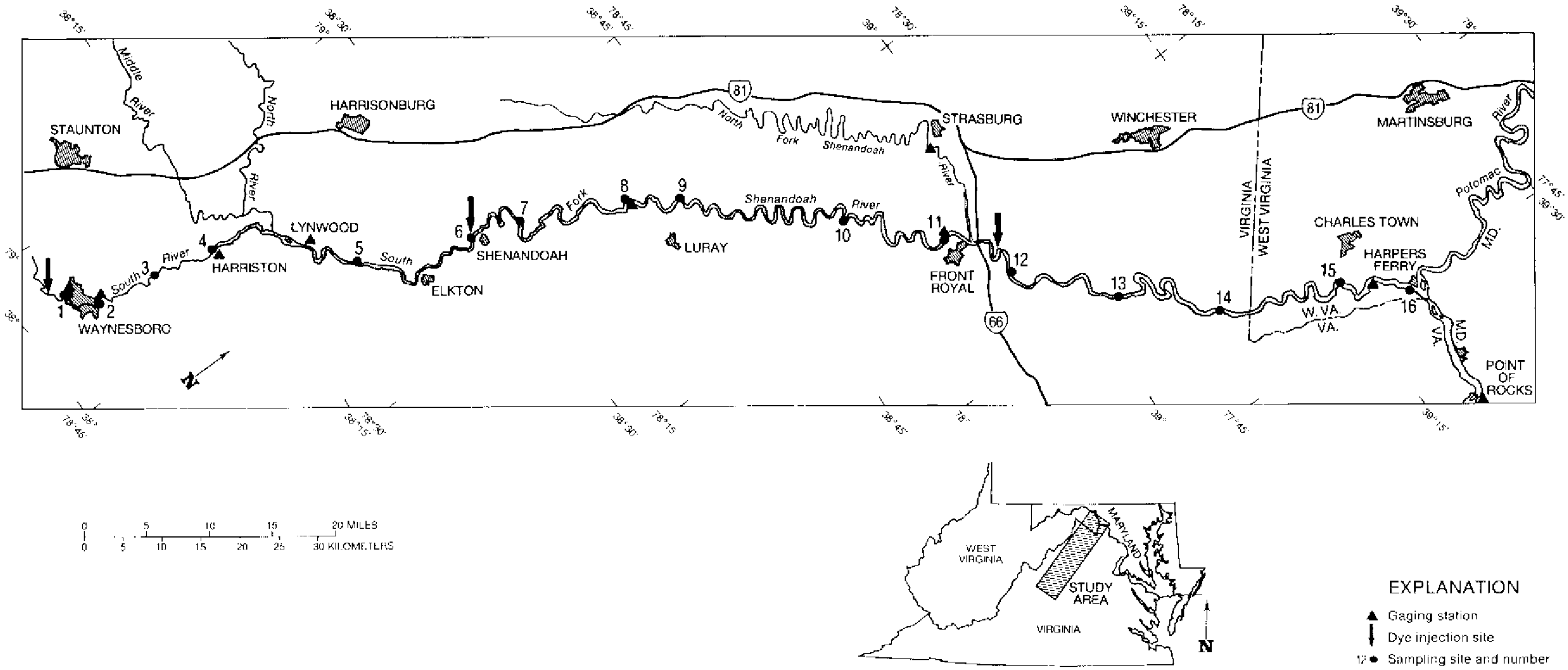


Figure 11.—Study reach for time-of-travel studies on the South Fork Shenandoah River in Virginia and West Virginia (from Taylor and others, 1986).

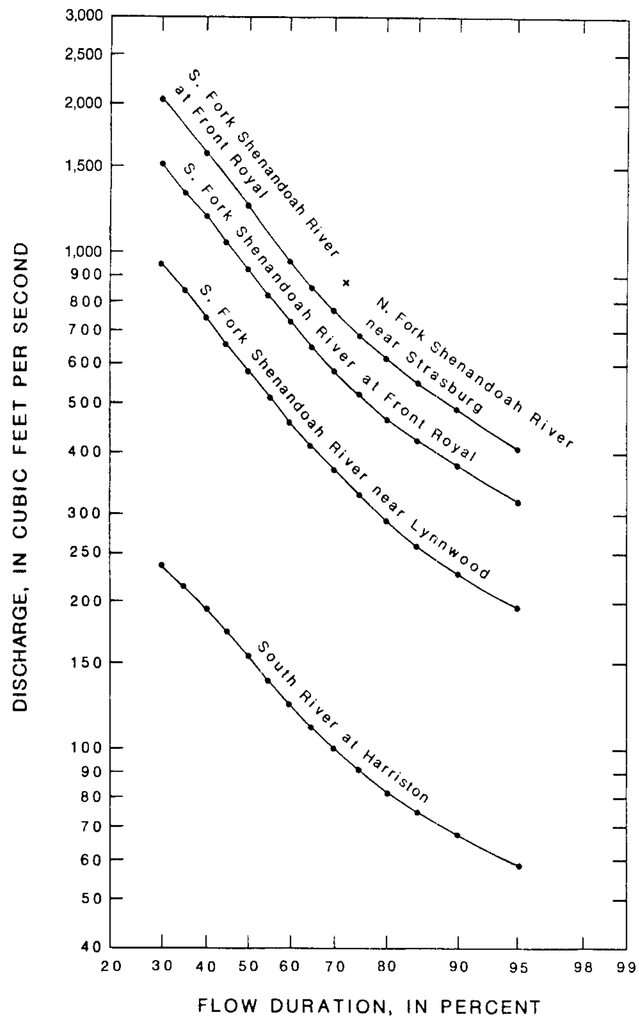


Figure 12.—Relation between flow duration and discharge at index gaging stations on the South Fork Shenandoah River and its tributaries in Virginia and West Virginia (from Taylor and others, 1986).

velocities through the pools, which occupy a larger proportion of the stream. However, the use of conservative estimates, that is, higher velocities, to plan sampling schedules ensures measurement of the leading edge of the dye cloud.

At high flows when pools and riffles are drowned out, mean velocities determined from current-meter measurements commonly are in close agreement with the mean velocity of the dye cloud. It should be remembered that the leading edge travels at a velocity faster than the mean. A common mistake is to base the sampling schedule on average velocity, which results in arrival too late to sample the leading edge.

4. Inspect all river reaches for dams, diversion canals, water intakes, sewage outfalls, and any other condition that might affect the measurement or might be affected by the measurement. Where water supplies are withdrawn in the reach under investigation, estimate the mean velocity for the reach and the river discharge at the diversion point, in order to estimate the maximum dye concentration that may be anticipated. Obtain water samples for nitrite determination at any water withdrawal points. If dye concentrations at the withdrawal point are expected to exceed 10 μg/L, or if nitrite concentrations exceed 50 μg/L, less dye will have to be injected or the injection point changed. Frequently the location of a water-supply diversion is selected as the most distant sample point, and an injection for the next subreach is made just below this point. Because it is desirable to overlap subreaches, the water intake should be the next-to-last sampling site for one subreach, and the injection for the next subreach made immediately downstream from the intake.
5. Locate suitable discharge measuring sections at or near each injection and sampling site. Set reference points at the sites if it is desirable to establish stage-discharge relations at the site rather than measuring discharge during the passage of the dye.
6. Estimate the probable discharge at the last sampling section to compute the amount of dye needed. It should be kept in mind that the maximum discharge in the reach is that used in estimating the amount of dye needed.
7. Select a base of operations where shelter and power for the fluorometer are available. This could be the motel or hotel used for accommodations (see activity 8). The use of fluorometers in the field depends primarily on the number of units available, the distance between and access to the sampling sites, and the time interval between samples. If only one fluorometer is available, a central location, such as a laboratory, office, or motel, may be best. Typically, samples from several sites are brought to a centrally located fluorometer.
8. Locate suitable accommodations, such as motels or hotels, noting name, address, and phone number of each. Good communications are vital for a successful time-of-travel study.

Selecting dye-injection and sampling sites

As discussed earlier, a considerable reach length may be required for complete lateral mixing of dye injected in the center of the stream. Mixing-length equations used to compute the length of channel necessary for complete lateral mixing yield widely varying results. Much of the difference is related to the definition of "complete mixing." The length of channel necessary to obtain 100-percent lateral mixing may be twice that necessary to reach 95-percent mixing. In this case, percent mixing refers to the uniformity of tracer mass in transport through a flow section; this is described and formulated by Kilpatrick and Cobb (1985).

Complete mixing is seldom sought in time-of-travel studies; 95-percent mixing is optimum, as it does not require such long channel lengths. Yotsukura and Cobb (1972, eq. 29) and Fischer and others (1979, eqs. 5, 10) derived the following equation to estimate the length of channel necessary for optimum lateral mixing from a single-point midchannel injection:

$$L_o=0.1\frac{vB^2}{E_z} \tag{6}$$

where

- L_o = length of channel required for optimum mixing, in feet;
- v = mean stream velocity, in feet per second;
- B = average stream width, in feet; and
- E_z = lateral mixing coefficient, in feet squared per second.

Table 1 provides values of E_z for selected depths and slopes to aid in estimating the optimum mixing length from equation 6.

Until the dye is mixed laterally, its movement does not represent that of the total flow. Once the dye extends to both banks, so that time-concentration curves for different points across the stream are virtually equal in area, the time of travel of the water is represented by the movement of the dye cloud along the stream course. In a small stream, lateral mixing is ordinarily accomplished in a short distance relative to the distance at which the cloud is sampled, so no significant errors occur if dye is injected at the head of the reach of interest. The length of stream reach necessary to accomplish lateral mixing in wide or shallow streams may be large; to accurately measure the traveltime between two points on such a stream, the dye needs to be injected a distance L_o, or greater, above the head of the reach. Thus, time-of-travel data will be for the interval from cloud to cloud and will accurately measure the characteristics of the desired reach.

Table 1.—*Values of the lateral mixing coefficient, E_z, for selected average flow depths and slopes*

[Note: $E_z=1.13d^{3/2}s^{1/2}$; s, water-surface slope; d, mean depth of the stream]

Depth, d (feet)	Slope, s (foot/foot) 0.001	0.002	0.004	0.006	0.008	0.010
1.0	0.04	0.05	0.07	0.09	0.10	0.11
2.0	.10	.14	.20	.25	.29	.32
3.0	.19	.26	.37	.46	.52	.59
4.0	.29	.40	.57	.70	.81	.90
5.0	.40	.56	.80	.98	1.13	1.26
6.0	.52	.74	1.05	1.29	1.48	1.66
8.0	.81	1.14	1.62	1.98	2.29	2.56
10.0	1.13	1.60	2.26	2.77	3.20	3.57
15.0	2.07	2.94	4.15	5.08	5.87	6.56

Table 2.—*Values for coefficient, K, for different numbers and locations of injection points*

Number and location of injection points	Coefficient, K, for 95-percent mixing
One center injection	0.100
Two injection points[1]	0.025
Three injection points[2]	0.011
One side injection point	0.400

[1] For an injection made at the center of each half of flow.
[2] For an injection made at the center of each third of flow.

To avoid having to make the injection an inconveniently long distance upstream so that natural lateral mixing will occur before the dye cloud arrives at the reach being studied, multiple-point or line injections of the dye can be made. This will more fully tag the entire flow, thus reducing the distance required.

Equation 6 can be written as

$$L_o=K\frac{vB^2}{E_z} \tag{7}$$

where K is a variable whose value depends on the location of injection and the number of injections, and the other variables are as previously defined.

The value of K of 0.1 in equation 6 is for 95-percent mixing with a single center injection. Coefficients (K) for this and other conditions are given in table 2.

The effect of injecting tracer at n points, where each injection is at the center of flow of each n equal flow segments, is that the tracer has to mix throughout an equivalent width of about $(1/n)B$. Since B is squared in the mixing-length equation, the value of K for a single-point injection is modified by the factor $(1/n)^2$.

When two flows merge, they may flow a considerable distance before becoming homogeneously mixed. Therefore, when possible, the last sampling section of a subreach should be just above a tributary.

The flow containing the dye at the junction point of a tributary inflow is analogous to a side injection, and the distance to mixing with the tributary flow may be approximated by equation 7 with a K of 0.4. As can be seen in table 2, this mixing distance may be four times greater than that for a center injection. A sampling site below a major tributary should be located a distance at least equal to L_o below the junction. In such cases, several points across the section should be sampled to define the dye distribution. If analysis of the samples indicates that lateral mixing is not complete, it may be necessary to weigh dye concentrations on the basis of lateral discharge distribution.

Lateral mixing is complete if the area of the time-concentration curves observed at different points in the cross section are the same, irrespective of curve shape and magnitude of the peaks. However, complete lateral mixing is not necessarily a prerequisite to a successful time-of-travel measurement.

The dye cloud should be sampled at a minimum of two sites downstream from the point of optimum mixing. Time-concentration curves defined at two or more points in each subreach not only provide better definition of traveltime, but provide dispersion information as well. By using the automatic sampler described earlier, such data can be acquired with a minimum of personnel.

Sometimes there are considerations that make it necessary to subdivide a long reach into shorter subreaches, for example, excessive total traveltime, long cloud-passage times, limitations on dye concentrations at withdrawal points, tributary inflow, the risk of inclement weather, or changes in flow rates. In effect, separate time-of-travel studies of subreaches, rather than a single study of the entire reach, must be made. Often the injection and sampling are carried out concurrently in all the subreaches for more efficient use of manpower and to reduce the risk of complications from inclement weather. Generally, the limitation on reach length is the amount of time required to sample the ever-lengthening dye cloud. In such cases, the automatic sampler can be very useful and may make it unnecessary to subdivide the study of a long reach.

When concurrent injections are to be made, the subreaches should be long enough that the leading edge of an upstream dye cloud will not overtake the trailing edge of the next cloud downstream. It may be desirable to stagger the injections, the most downstream injection being first.

Inflow to a reach from major tributaries is an important planning consideration with respect to dye-dosage requirements and concentration levels at downstream sampling points. It is emphasized that the maximum discharge in a test reach determines the dye dosage. As with water withdrawal points, major tributaries should be considered in determining subreaches.

Dye requirements

Rhodamine WT dye is recommended for time-of-travel measurements. Several empirical equations have been derived for estimating the quantity of dye necessary for a time-of-travel study. For rhodamine WT 20-percent dye, the dosage formula (Kilpatrick, 1970) is

$$V_s=3.4\times10^{-4}\left(\frac{Q_mL}{v}\right)^{0.94}C_P \tag{8}$$

where

V_s =volume of stock rhodamine WT 20-percent dye, in liters;

Q_m=maximum stream discharge at the downstream site, in cubic feet per second;

L =distance to the downstream site, in miles;

v =mean stream velocity, in feet per second; and

C_p=peak concentration at the downstream sampling site, in micrograms per liter.

The volume of rhodamine WT 20-percent dye required to produce a peak concentration of 1 μg/L can be determined from equation 8 or figure 13 for a range of flow-reach conditions. It should be noted that this equation will yield slightly different results than obtainable using a similar type of equation presented by Kilpatrick and Cobb (1985) for determining dye quantities when making dilution-type discharge measurements. Equation 8 is more applicable to long stream reaches, which are usually involved in time-of-travel tests.

The following example illustrates the method of computing the dye quantity and peak concentrations on a stream having significant tributary flow into the test reach.

Example.—For the stream reach and flow conditions shown in figure 14, calculate the following: A, volume of rhodamine WT 20-percent dye to be injected at mile 0 necessary to produce a peak concentration of 2 μg/L at mile 30; and B, peak concentration to be expected at the water plant at mile 15.

Calculation A:

$$\frac{Q_mL}{v}=\frac{450\ \text{ft}^3/\text{s}\times30\ \text{mi}}{0.5\ \text{ft/s}}=2.7\times10^4.$$

From figure 13, V_s=5.0 L for a peak concentration of 1 μg/L, and V_s=2×5.0=10 L for C_p=2 μg/L.

Calculation B:

$$\frac{Q_mL}{v}=\frac{250\ \text{ft}^3/\text{s}\times15\ \text{mi}}{0.5\ \text{ft/s}}=7.5\times10^3.$$

From figure 13, V_s=1.5 L for 1 μg/L; hence,

$$C_p\text{ at the water plant}=\frac{10}{1.5}=6.67\ \mu\text{g/L}.$$

This concentration is less than the maximum permissible under Geological Survey policy, 10 μg/L; had the

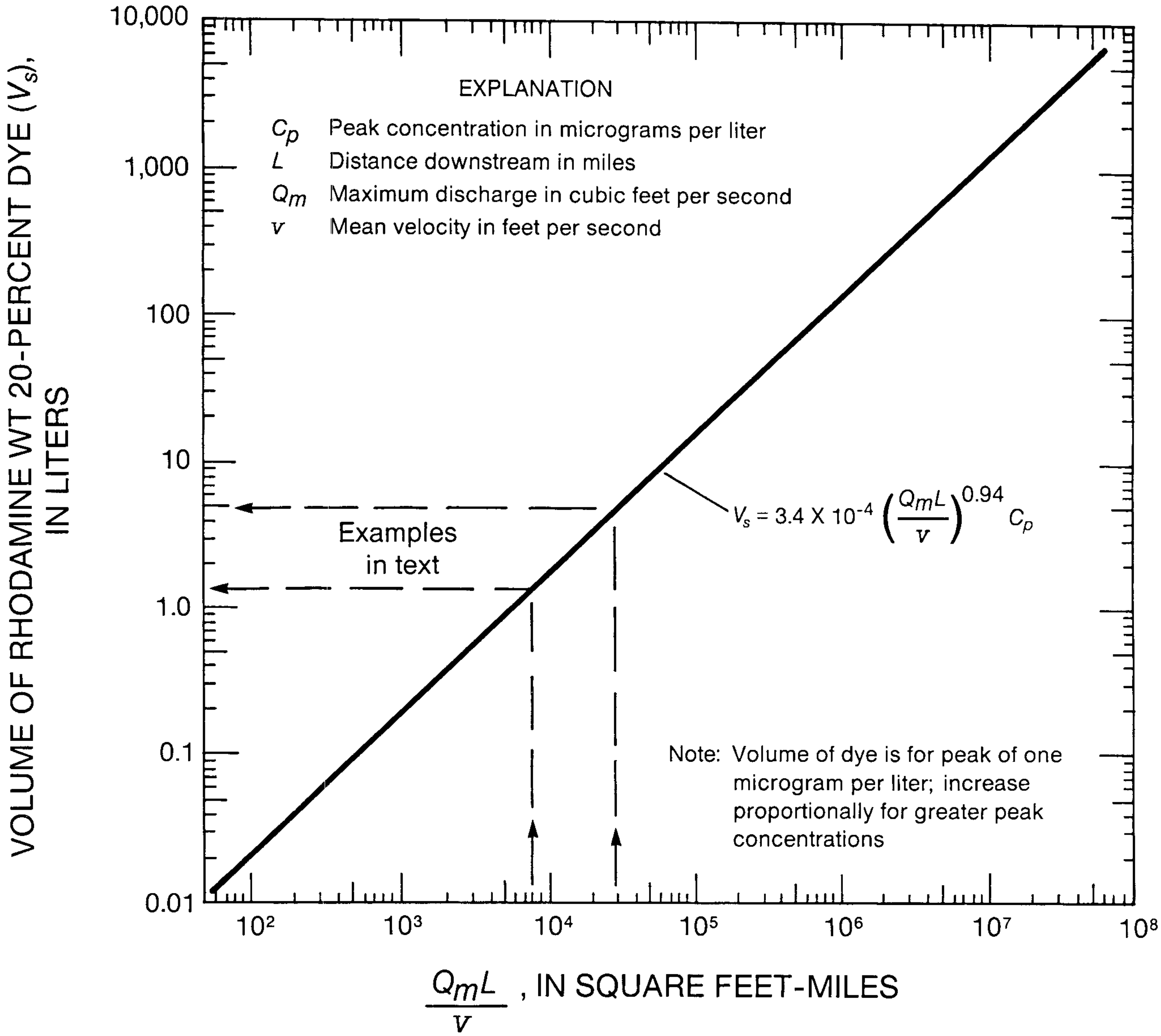


Figure 13.—Quantity of rhodamine WT 20-percent dye required for slug injection to produce a peak concentration of 1 microgram per liter at a distance downstream, L, at a mean velocity, v, and with a maximum discharge, Q_m, in the reach.

concentration been significantly large, the injected volume could have been reduced. Time-of-travel tests have been performed in which the design peak was 0.5 μg/L to reduce dye costs. The use of such low concentrations demands careful fluorometric techniques but is entirely practical with modern fluorometers (Wilson and others, 1986).

In some cases, there may be significant diversions of flow in the test reach that also serve to divert a portion of the injected dye. The following example illustrates the procedure for determining the dye quantity needed when a major diversion of flow takes place in the reach.

Example.—For the stream reach and flow conditions shown in figure 15, determine the volume of rhodamine WT dye to be injected at mile 0 necessary to produce a peak concentration of 2 μg/L at mile 6.

Calculation:

$$\frac{Q_m L}{v} = \frac{195 \text{ ft}^3/\text{s} \times 6 \text{ mi}}{0.5 \text{ ft/s}} = 2.34 \times 10^3.$$

From figure 13, V_s=0.5 L for a peak concentration of 1 μg/L, or 1.0 L for a peak of 2 μg/L.

Only a portion of the dye injected will reach mile 6; therefore, to obtain a peak concentration of 2 μg/L at mile 6, the volume of dye must be increased by the

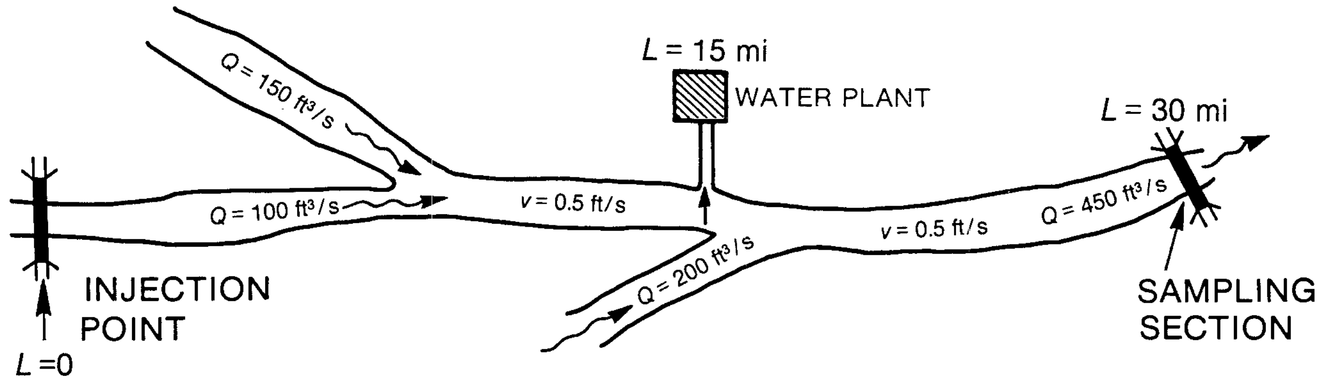


Figure 14.—Stream where a water user is involved and discharge is increasing in the downstream direction. (ft³/s, cubic feet per second; ft/s, foot per second; mi, miles; Q, stream discharge; v, velocity; L, stream length)

ratio of the discharge above the diversion to the discharge in the stream immediately below the diversion. Therefore, the volume of dye required, with the diversion, is

$$V_s=\frac{1.0 \text{ L}\times 250 \text{ ft}^3/\text{s}}{150 \text{ ft}^3/\text{s}}=1.67 \text{ L, with 0.67 L being diverted.}$$

Sampling schedule

The schedule for collecting samples at each sampling site is the most uncertain aspect of the plan. Estimates of the time to begin sampling, the time intervals between samples, and the duration of sampling must be made that will ensure adequate definition of the dye cloud passing each site. In effect, a conservative estimate of the arrival time of the leading edge and the passage time for the dye cloud is required.

The relationship shown in figure 16 was derived from time-of-travel information collected nationwide. It may be used as a guide for estimating the duration of response curves resulting from the slug injection of a tracer and as an aid in preparing sampling schedules. The equation

$$T_{D_{10}}=0.7\ T_p^{\ 0.86} \tag{9}$$

provides an estimate of the duration corresponding to the time when the receding concentration reaches 10 percent of the peak. The duration to the time when concentrations reach zero may be two to four times larger and is the reason sampling down to background is not suggested as necessary for *routine time-of-travel studies*.

Estimation of traveltimes is straightforward and involves examination of any current or previous time-of-travel measurements made in the proposed reach, as well as field reconnaissance of the reach if possible. It should be kept in mind that average velocities determined from current-meter measurements normally are faster than the true reach average; steep mountain streams may be an exception.

As part of a regionalization study, Boning (1974) reported two equations to estimate the velocity of a dye cloud's peak concentration, v_p. For pool-and-riffle reaches having slopes, s, ranging from 0.00012 to 0.0057 feet per foot (ft/ft), the equation is

$$v_p=0.38\ Q^{\ 0.40}\ s^{\ 0.20}, \tag{10}$$

where v_p is in feet per second and Q is discharge in cubic feet per second. For channel-control reaches having slopes ranging from 0.00016 to 0.0023 ft/ft, the equation is

$$v_p=2.69\ Q^{\ 0.26}\ s^{0.28}. \tag{11}$$

Having estimated the velocity of the peak, the time to peak dye concentration, T_p, in hours, is computed as

$$T_p=1.47\frac{L}{v_p}, \tag{12}$$

where L is in miles and v_p is in feet per second. The curve in figure 16 or equation 9 may now be used to estimate the duration of the dye cloud, T_D, to be expected at each sampling section when the trailing edge is defined to just the 10-percent peak concentration.

Taylor and others (1986) analyzed several hundred sets of time-of-travel data and found that the normal slug-produced time-concentration response curve could be represented as a scalene triangle. In this triangular depiction, one-third of its total duration, $T_{D_{10}}$, was the time, t_b (see fig. 16), from the leading edge to the peak; the remaining two-thirds was the time to recede to a concentration equal to 10 percent of the peak concentration. Referring to figure 16, if $T_{D_{10}}$ is determined for the 10-percent level based on an estimate of T_p, reducing T_p by one-third of $T_{D_{10}}$ will

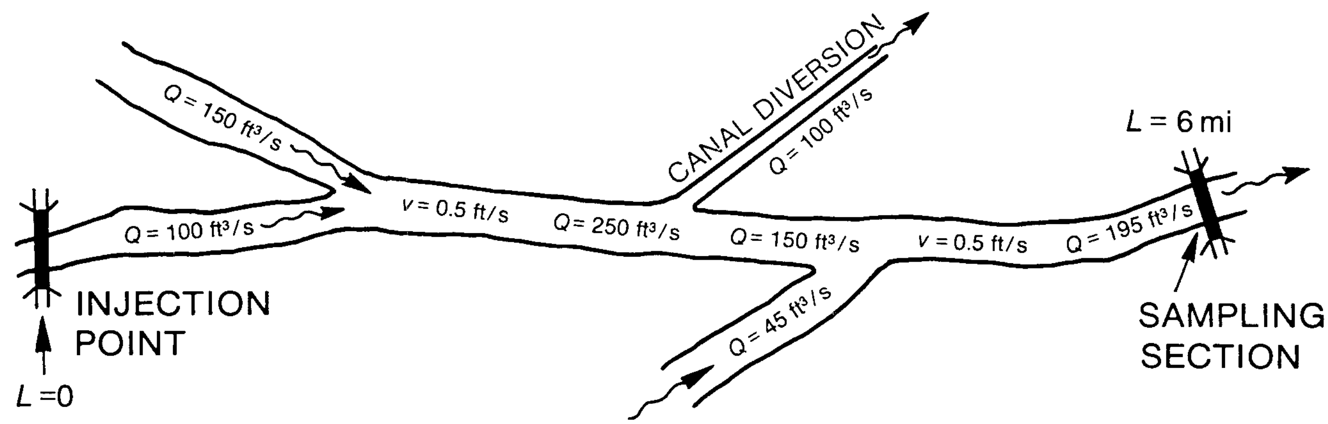


Figure 15.—Stream where flow is increasing in the downstream direction and a major diversion of flow occurs. (ft^3/s, cubic feet per second; ft/s, foot per second; mi, miles; Q, stream discharge; v, velocity; L, stream length)

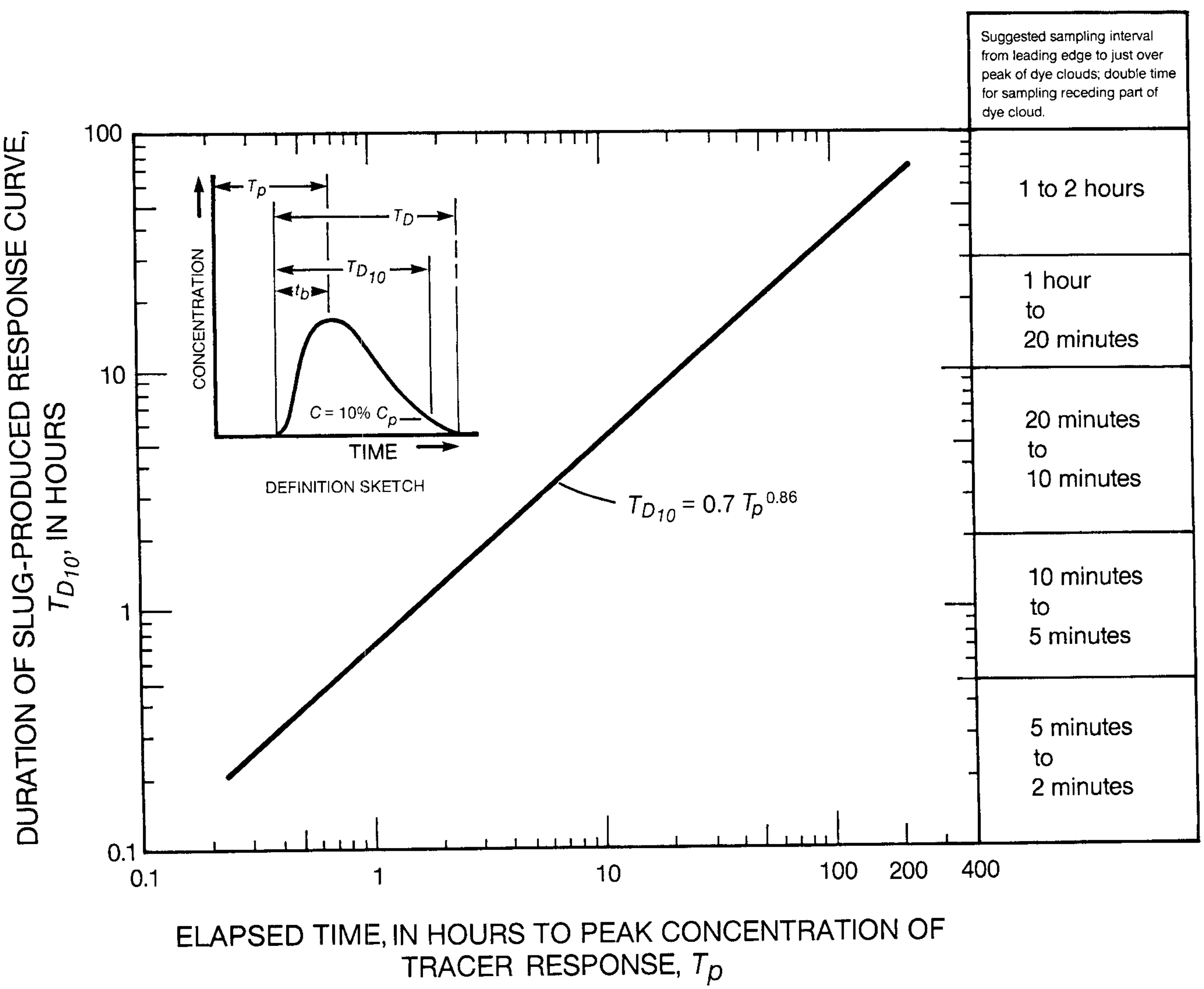


Figure 16.—Relation between traveltime of peak concentration and approximate duration of tracer response. (t_b, time for dye concentration to build up from the leading edge to the peak; C, concentration; C_p, peak dye concentration)

provide an approximation of when the leading edge of the dye will arrive.

Thus the elapsed time to the leading edge of the dye cloud can be estimated as

$$T_L = T_p - \tfrac{1}{3} T_{D_{10}}, \qquad (13)$$

and the trailing edge to the 10-percent level can be estimated as

$$T_{t_{10}} = T_p + \tfrac{2}{3} T_{D_{10}}. \qquad (14)$$

The number and frequency of dye samples also can be approximated from the estimate of $T_{D_{10}}$. The dye slug-response curve can normally be well defined by 30 well-placed data points. Therefore, division of $T_{D_{10}}$ by 30 will give approximately the frequency of sampling needed. More frequent sampling from the leading edge to and *through* the peak and less frequent sampling toward the trailing edge are common practices because of the skewed shape characteristic of most response curves.

The curve in figure 16 and equations 9 through 14 are approximate and should be used for planning purposes only. Rapid fluorometric analysis and plotting of selected samples in the field as quickly as possible after their collection should guide immediate sampling at the first sampling section as well as schedule modification for more downstream sections.

The measurement plan

The measurement plan is an orderly determination of the dye requirements, injection instructions, sampling schedules, sample disposition, and personnel assignments. The plan should include the following:

1. Injection:
   a. A detailed description of each injection site.
   b. The quantity of dye to be injected at each site.
   c. The times of injection.
   d. Instructions for injecting the dye.
2. Sampling:
   a. A detailed description of each sampling site.
   b. The number of points in the cross section to be sampled at each site.
   c. A sampling schedule giving starting time, sampling frequency, and ending time for each site.
   d. Instructions regarding discharge measurement, staff-gage reading, or measurement of distance from a reference point to the water surfaces, if needed.

Personnel and equipment assignments

The number of individuals assigned to each injection site will vary depending on the quantity of dye and the method of injection.

Usually one person can handle the sampling requirements at each sampling site, with assistance from the fluorometer operator as necessary. When sampling is done from a boat, two people should be assigned to that site.

When the measurement reach is divided into subreaches, the party chief usually is responsible for dye injection and the collection and disposition of samples in one or more subreaches.

The measurement plan should list the name, location, and telephone number of lodging accommodations for all personnel. It should also show the assignment of equipment to the various individuals and party chiefs.

Maps and tables are very useful for briefing personnel and for reference. In fact, the entire measurement plan—including injection and sampling instructions, personnel assignments, and equipment disposition—may be put on a map. The map should show sampling sites, injection points, the road and bridge system, lodging, towns, and landmarks. The map should be supplemented with sketches of hard-to-find sites.

Performance of Field Test

Injection of dye

A single slug injection of dye is usually made in the center or in the main thread of flow. As mentioned previously, the injection should be made L_o upstream from the head of the reach, unless L_o is insignificant compared with the test-reach length. Note in figure 11 that two of the three dye injections were made a mile or two upstream from the first sampling site making up the subreach. In the case of the third injection, the first subreach was extended to site 7, overlapping the second subreach. Similarly, multiple-point injections or line injections across the stream may be used where the channel is wide or the flow is shallow. The line injection should be made in the middle half to two-thirds of the flow and not too near the banks. The time required to cross the stream is usually insignificant, and injection may be considered instantaneous. For each injection, the type and amount of dye and the stream stage and discharge should be noted.

The dye cloud will remain visible for some time and distance downstream following injection, depending on the amount of dye used and on stream conditions. While visible, the dye can easily be followed for a short distance, making possible a rough estimate of its arrival time at the first sampling site.

Collection of water samples

At least one water sample is needed for a fluorometer reading of background fluorescence at each site before the dye arrives. If the site is also to be used as an injection site, the background samples should be collected before injecting the dye or should be taken upstream from the point of injection. Sampling should begin early enough to ensure not missing the leading edge of the dye cloud. Usually, it is not necessary to sample more than a few inches below the water surface. If vertical mixing is complete, the concentration will be the same throughout the vertical.

Water samples should also be taken at this time at any water-supply withdrawal points for evaluating and documenting nitrite concentrations during the test.

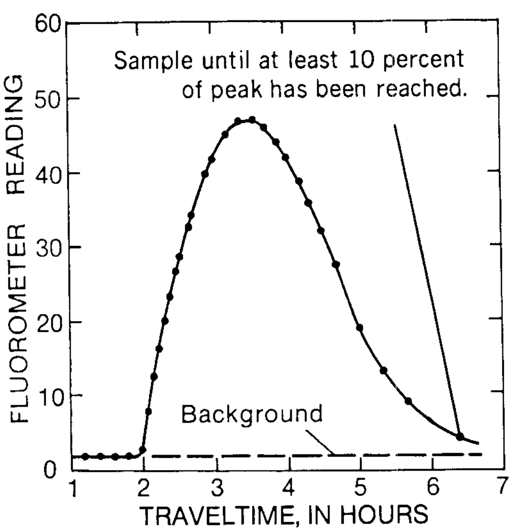
Use of fluorometers

Fluorometric testing of samples in the field is recommended to guide subsequent sampling. The use of a fluorometer at the first sampling section permits on-the-spot detection of dye. The preliminary fluorometer results can be used as a basis for altering the schedule to obtain 20 to 30 samples at proper time intervals to define the time-concentration curve at a sampling point. Field plots of dial readings against time, and of distance against time of leading edge and peak, as illustrated in figure 17, can be extrapolated to check or adjust the downstream sampling schedules. It should be noted that a straight line extrapolation from $t=0$ will yield a larger cloud duration than will actually occur (as defined by fig. 16 and eq. 9). Nevertheless, prompt examination of the data in the field can ensure that data is not missed.

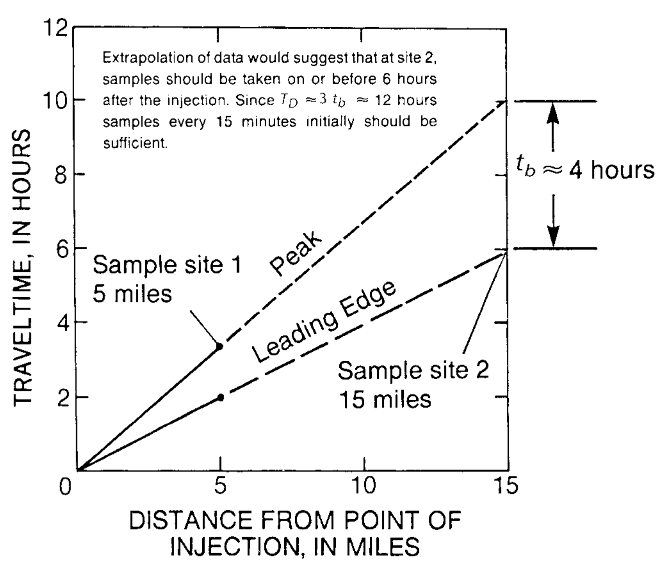
Ideally, sampling should continue until concentrations are down to the background level. If this is not practical, it is recommended that samples be collected until concentrations (or dial readings) have reached either 10 percent of the peak or 0.2 μg/L, whichever is lower.

Unless unusually good conditions exist, accurate fluorometric analysis in the field is not practical using any but the most modern fluorometers. Some of the older fluorometers require shielding from the sun while in use because light may leak into the instrument and cause erroneous responses. Depending on the fluorometer, the need to move from site to site with the movement of the dye cloud may preclude adequate instrument warmup and sample-temperature control, especially the latter. Basic time-of-travel information can be derived from field tests, but accurate measurement of sample concentration ordinarily should be done in an office or laboratory under control conditions. Fluorometer readings for samples tested in the field should be recorded, and the notes should be retained on the data sheet, as shown in figure 6, even though retesting is contemplated.

Some newer fluorometer models are light-tight, require a short warmup time, and do not increase the temperature of the sample. A number of investigators have established field laboratories in a motel, or elsewhere, and have achieved accurate results with



A. Response curve as measured in field at first sample site, mile 5.



B. Time-distance plot extrapolation

Figure 17.—Use of data collected at the first sampling site to schedule sampling at succeeding downstream sites. (T_D, time for entire tracer cloud to pass a section; t_b, time for dye concentration to build up from the leading edge to the peak)

less delay than would be involved in transporting the samples from the field. If standard solutions are on hand and have the same temperature as the stream samples, fluorometer readings obtained in this manner may be considered satisfactory for final use.

Measurement of discharge

The stream discharge should be measured or otherwise determined at each sampling site at the time the dye is present. Stage reference marks at each sampling site can be used in conjunction with current-meter discharge measurements to rate each site; this is helpful if several time-of-travel tests at different discharges are contemplated.

Analysis and Presentation of Data

Laboratory analysis

The samples collected in the field should be reanalyzed if the field analysis was not adequate. This is especially true if more comprehensive interpretations, such as prediction or simulation of waste concentrations and movement (Kilpatrick and Taylor, 1986), are contemplated.

The form shown in figure 6 provides for recording both field and laboratory data. The laboratory work can be expedited, when the Turner model 111 fluorometer is being used, if the analysis can be made using only one fluorometer scale. By inspection of the field data or by trial, select the scale that will yield the maximum reading for the sample representing the peak concentration for the sampling site. All samples for this site can then be analyzed on this one scale, minimizing the number of fluorometer scales that will need calibrating. For this reason, it is convenient to calibrate the fluorometer after the samples for each day have been tested and the scales actually used are known. This is not necessary with the Turner Design model 10, as this fluorometer automatically switches to the most desirable scale. Examination of the field data can guide preparation of calibration standards to best cover just the range of concentrations to be expected.

Time-concentration curves

Time-concentration curves are useful in illustrating the techniques used in the dye study and represent the responses to a given slug injection. The concepts of leading edge, peak, centroid, and trailing edge can easily be explained on these graphs. Although more sophisticated methods of data presentation are available, time-concentration curves show in the simplest way the travel and dispersion of the solute cloud as it moves downstream.

The concentration for each sample should be plotted against elapsed time, and a smooth curve fitted to the points. The typical curve, shown in figure 2, is bell shaped but always slightly steeper on the rising limb than on the falling limb. The tail is usually much longer and flatter than the leading edge and approaches the zero-concentration level asymptotically.

As an example, the time-concentration curves for sampling sites 2 through 12 are shown in figure 18 for the Shenandoah River tests performed in September 1983 (Taylor and others, 1986) at a flow having a duration of 85 percent. These sites make up the two upstream subreaches (see fig. 11). It will be noted that two time-concentration curves were measured at site 7, the last site sampled for the upstream injection and the first for the second subreach. Note the change in the vertical concentration scale between sites 4 and 5; the marked reduction in concentrations resulted from the diluting effect of the major inflow from the North

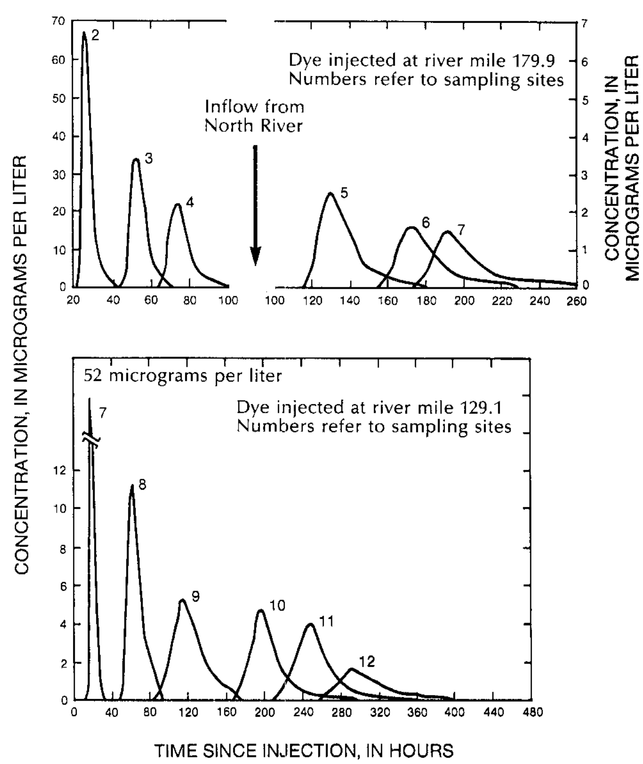


Figure 18.—Observed time-concentration curves for the September 1983 time-of-travel tests on the South Fork Shenandoah River, Virginia; 85-percent flow duration. (See fig. 11 and table 3.)

River. Despite this, longitudinal dispersion in the reach remained relatively constant.

Traveltime

The elapsed times and traveltimes of the leading edge, the peak concentration, and the trailing edge of the dye clouds are determined from the time-concentration curves for each sampling site. Elapsed time is the time from the injection of the dye to the particular part of the response curve of interest. Traveltime is the time of travel between common parts of the response curves: leading edge, peak, centroid, and so forth. It is common practice to define the trailing edge time as the time when the concentration decreases to a level of 10 percent of the peak concentration observed at a sampling site. Typically these data are presented in tabular form, such as table 3. A graphical presentation of these data, as shown in figure 19, provides a clear picture of how dispersion elongates the tracer cloud. Figure 19 shows cumulative traveltime data for both dye studies performed on the Shenandoah. The data used in this summation process are traveltimes from cloud to cloud rather than elapsed times from points of injection. This is why the subreaches were overlapped (see table 3 and fig. 11) or the injections were made a mixing distance upstream from the reach of interest.

The curves in figure 19 are for the two flow durations selected for testing. It is desirable to interpolate between these values to make the results more usable. The velocities of the leading edge, the peak concentration, and the trailing edge of the dye cloud between successive sampling sites can be calculated by dividing the segment lengths by the traveltimes (table 3). In figure 20, these velocities are plotted on log-log paper as a function of the average daily discharge(s) observed at an index gaging station during the time the dye cloud moved between the two sampling sites. Straight lines are drawn through the points derived from the two studies to represent the leading edge, peak concentration, and trailing edge. Such plots are done independently for the discharges at each index station.

The relations described above are entered with discharges corresponding to selected flow-duration values of 40, 50, 60, 65, 70, 75, 80, 85, 90, and 95 percent for the index gaging station(s) used; table 4 shows these data for the test reach between sites 7 and 8 on the Shenandoah River (see fig. 11) using the Front Royal gaging station as the index station. In a similar manner, incremental velocities are determined at 10 flow durations for an entire test reach.

The distance between sampling sites is then divided by these incremental velocities to provide an incremental traveltime at each of the 10 flow durations for leading edge, peak concentration, and the trailing edge. In table 5, for the Shenandoah River example, incremental times are accumulated from Waynesboro to Harpers Ferry. Figure 21 is a graphical presentation of these data. Similar tables and figures may be presented for the leading and trailing edge traveltimes. These data and curves can be used to estimate the time required for a soluble substance to move from *any* point in the study reach to *any* point downstream. The similarity between figures 19 and 21 should be noted. Figure 21 provides the information for an entire range of flows, in contrast to figure 19, which is the observed data for the two test flows. The graphical presentations allow a straight-line interpolation between sampling sites and may be easier to use than the tabular data in situations in which the points of interest are not at the sampling sites used in the study.

Numerous approaches have been used to present time-of-travel information. The approach chosen should be readily usable in predicting the rate of movement of a solute, which might be spilled at *any location* and at *any discharge*, and should be related to some index gaging station. Thus, except in certain worst case scenarios (usually extreme low flow), it is highly advisable to perform field tests at more than one stream discharge. For example, Jack (1986) found that the traveltime of a solute peak on the South Branch Potomac River from Petersburg, W. Va., to its confluence with the North Branch Potomac River, a distance of 69 mi, would vary from about 3 days at 1,500 ft^3/s to 18 days at 70 ft^3/s! Jack performed time-of-travel tests at two flow durations, 32 and 95 percent, and therefore was able to provide curves for predicting the rate of solute movement over a broad range of flows. A single time-of-travel test would be of little predictive value.

Regionalization

Time-of-travel and dispersion data have been regionalized with some success. Boning (1974) regionalized data from 873 studies on streams—for a variety of sizes, slopes, and discharges—throughout the United States. Separating the study reaches into three categories—pool and riffle, channel controlled, and lock and dam—Boning regressed leading edge and peak velocities with channel length and slope, discharge, and channel storage (for lock-and-dam reaches). He was able to derive empirical predictive equations with standard errors of ± 50 percent or less. In fact, the relations for estimating the velocities of the peak and leading edge in channel-controlled reaches had a standard error of only ± 26 percent.

Table 3.—*Traveltime data for dye study of September 1983 on the South Fork Shenandoah River, Virginia and West Virginia*

[Site locations shown in fig. 11. mi, mile; h, hour; mi/h, mile per hour]

		Distance			Leading edge				Peak concentration				Trailing edge			
Site No.	Site name	Upstream from mouth (mi)	Sub-reach length (mi)	From point of injection (mi)	Time since injection (h)	Travel-time (h)	Cumulative travel-time (h)	Velocity (mi/h)	Time since injection (h)	Travel-time (h)	Cumulative travel-time (h)	Velocity (mi/h)	Time since injection (h)[1]	Travel-time (h)	Cumulative travel-time (h)	Velocity (mi/h)
Injected 12 liters of 20-percent rhodamine WT dye at 1700 hours on September 6, 1983, at Mile 179.9																
1	Waynesboro	178.5		1.4	3		0		4		0		6		0	
			5.3			18		0.294		22		0.241		28		0.189
2	Hopeman Parkway	173.2		6.7	21		18		26		22		34		28	
			7.4			23		.322		26		.285		32		.231
3	Crimora	165.8		14.1	44		41		52		48		66		60	
			6.4			20		.320		23		.278		25		.256
4	Harriston	159.4		20.5	64		61		75		71		91		85	
			16.8			52		.323		56		.300		67		.251
5	Island Ford	142.6		37.3	116		113		131		127		158		152	
			13.5			40		.338		42		.321		52		.260
6	Shenandoah	129.1		50.8	156		153		173		169		210		204	
			7.9			18		.439		20		.395		26		.304
7	Grove Hill	121.2		58.7	174		171		193		189		236		230	
Injected 35 liters of 20-percent rhodamine WT dye at 1455 hours on September 6, 1983, at Mile 129.1																
7	Grove Hill	121.2		7.9	14		---		17		---		24		---	
			15.0			36		.417		46		.326		63		.238
8	U.S. Highway 211	106.2		22.9	50		207		63		235		87		293	
			7.0			34		.206		52		.135		76		.092
9	Bixler Bridge	99.2		29.9	84		241		115		287		163		369	
			26.1			78		.335		81		.322		85		.307
10	Bentonville	73.1		56.0	162		319		196		368		248		454	
			15.4			46		.335		50		.308		57		.270
11	Front Royal	57.7		71.4	208		365		246		418		305		511	
			10.2			48		.212		46		.222		73		.140
12	Morgan Ford	47.5		81.6	256		413		292		464		378		584	
Injected 57 liters of 20-percent rhodamine WT dye at 1100 hours on September 6, 1983, at Mile 52.4																
12	Morgan Ford	47.5		4.9	13		---		23		---		111		---	
			10.9			23		.474		35		.311		32		.341
13	U.S. Highway 17 & 50	36.6		15.8	36		436		58		499		143		616	
			14.5			28		.518		31		.468		33		.439
14	State Highway 7	22.1		30.3	64		464		89		530		176		649	
			13.7			35		.391		38		.360		43		.319
15	State Highway 9	8.4		44.0	99		499		127		568		219		692	
			7.6			32		.238		38		.200		43		.177
16	Harpers Ferry	0.8		51.6	131		531		165		606		262		735	

[1] Determined at 10 percent of peak concentration.

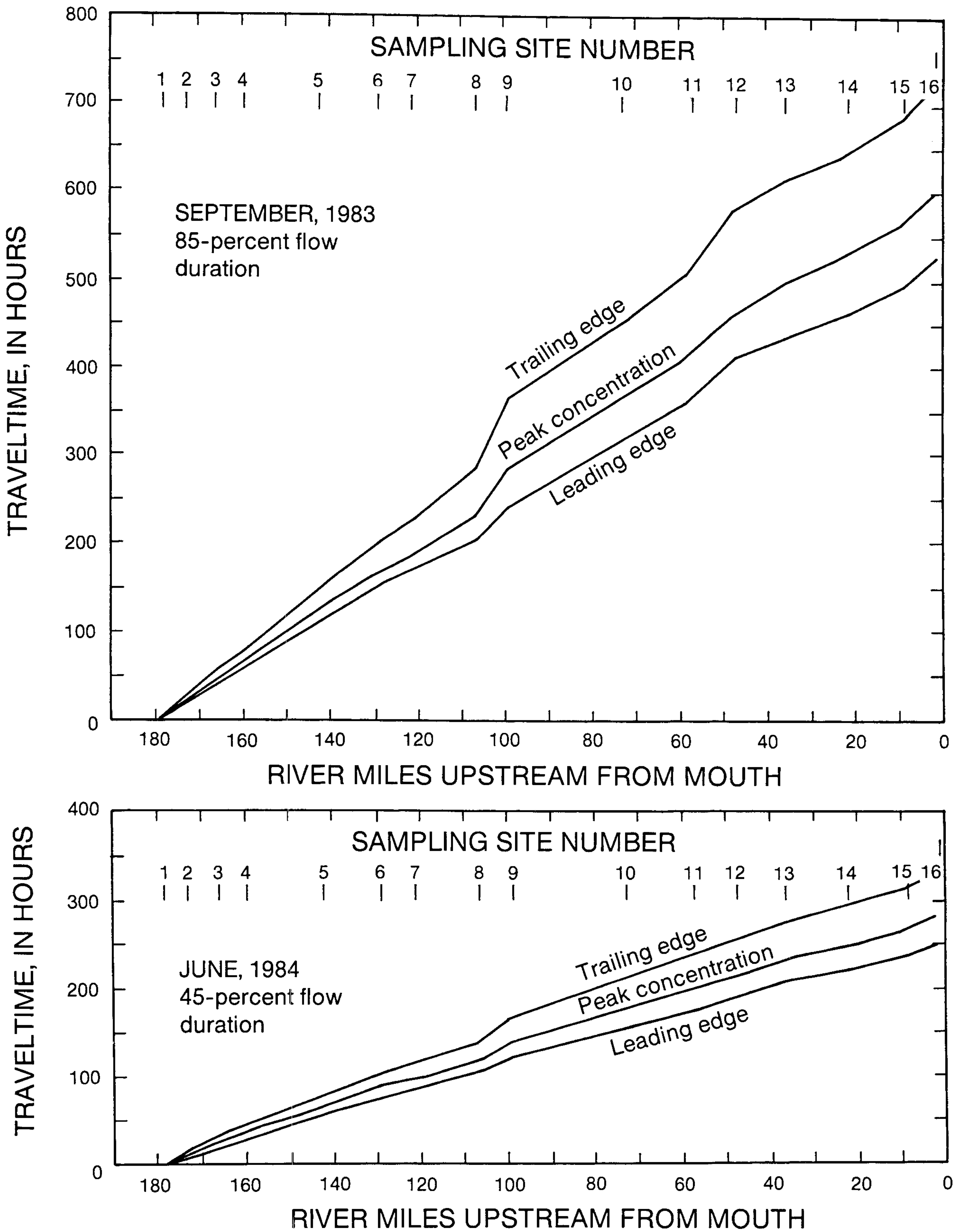


Figure 19.—Cumulative traveltime for the South Fork Shenandoah River, Virginia and West Virginia (from Taylor and others, 1986).

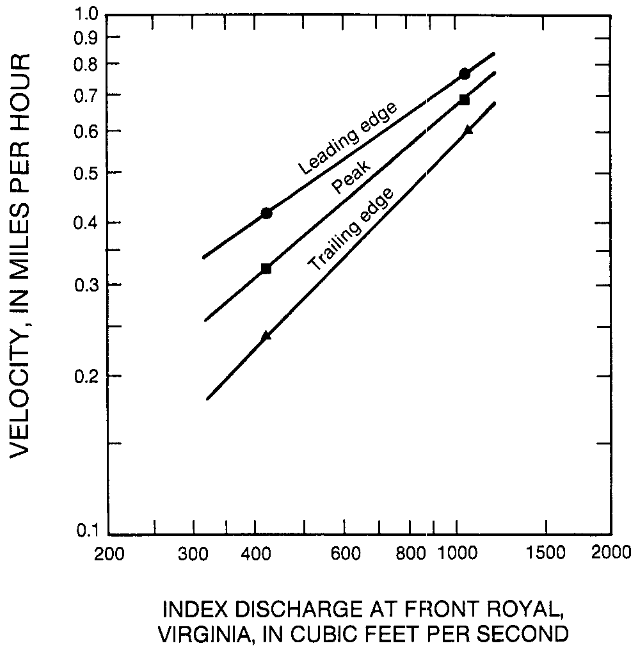


Figure 20.—Plot of traveltime velocities in reach between sites 7 and 8 as a function of index discharges at the Front Royal station on the South Fork Shenandoah River, Virginia (from Taylor and others, 1986).

Table 4.—*Example showing velocities as computed for a 15-mile test reach between sites 7 and 8 on the Shenandoah River versus selected flow durations at the Front Royal, Virginia, index station*

[ft^3/s, cubic feet per second; mi/h, mile per hour; Q, stream discharge]

Flow duration		Velocity, mi/h		
Percent	Q, in ft^3/s	Peak	Leading edge	Trailing edge
40	1,190	0.770	0.830	0.670
50	930	.620	.700	.520
60	728	.505	.595	.405
65	647	.460	.550	.365
70	579	.420	.510	.330
75	521	.385	.470	.295
80	468	.350	.440	.265
85	421	.315	.410	.235
90	377	.295	.380	.213
95	318	.255	.335	.178

In view of the uncertainties of applying time-of-travel data to an emergency situation, these standard errors of estimate might be acceptable because many spills occur on streams or stream reaches where no previous studies have been made. In such situations, regionalized data would be very useful.

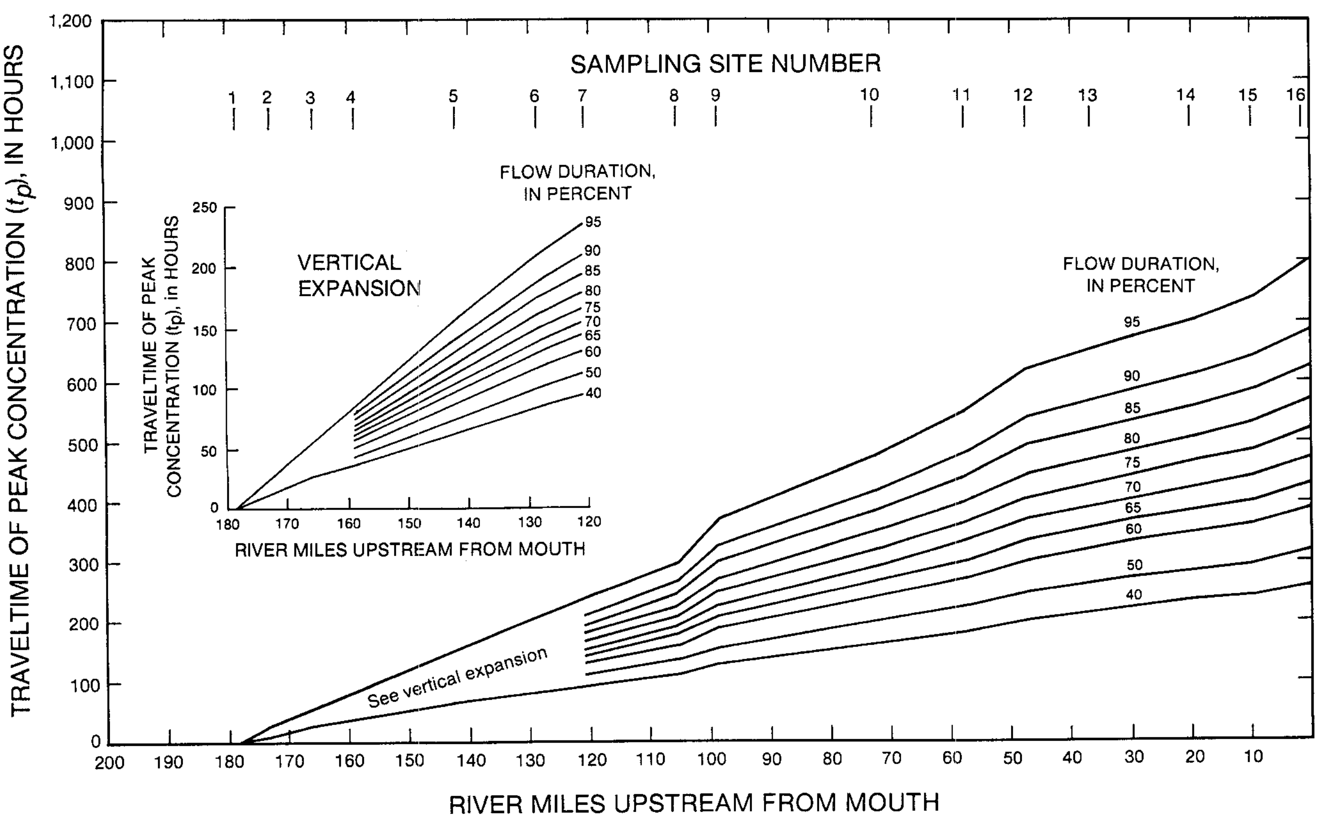


Figure 21.—Traveltime-distance relation for peak concentrations of a solute at selected flow durations, South Fork Shenandoah River from Waynesboro, Virginia, to Harpers Ferry, West Virginia (from Taylor and others, 1986).

Table 5.—*Traveltimes for peak concentration of a solute on the South Fork Shenandoah River at selected flow durations*

[Site locations shown in fig. 11]

Site No.	Site name	Miles upstream from mouth	Distance between sampling sites (miles)	Traveltime of peak concentration of dye cloud, in hours, for indicated flow duration, in percent									
				40	50	60	65	70	75	80	85	90	95
1	Waynesboro	178.5		0	0	0	0	0	0	0	0	0	0
			5.3										
2	Hopeman Parkway	173.2		12	14	16	17	19	20	21	22	24	26
			7.4										
3	Crimora	165.8		26	30	35	38	41	43	46	49	52	57
			6.4										
4	Harriston (index gage)	159.4		37	43	51	56	60	64	68	72	77	85
			16.8										
5	Island Ford	142.6		63	74	87	96	104	112	120	130	140	157
			13.5										
6	Shenandoah	129.1		84	99	116	128	138	149	160	173	186	209
			7.9										
7	Grove Hill	121.2		94	111	131	144	155	168	181	196	211	237
			15.0										
8	U.S. Highway 211	106.2		114	136	161	177	192	208	225	245	265	299
			7.0										
9	Bixler Bridge	99.2		132	159	190	210	229	250	272	298	325	370
			26.1										
10	Bentonville	73.1		165	200	242	267	292	319	349	383	418	479
			15.4										
11	Front Royal (index gage)	57.7		186	227	274	304	333	365	400	441	482	554
			10.2										
12	Morgan Ford	47.5		206	252	306	339	373	410	449	495	542	625
			10.9										
13	U.S. Highway 17 & 50	36.6		219	267	324	359	394	433	474	522	571	658
			14.5										
14	State Highway 7	22.1		233	284	344	381	418	460	503	554	605	697
			13.7										
15	State Highway 9	8.4		249	303	368	408	448	492	539	593	648	748
			7.6										
16	Harpers Ferry	.8		263	321	390	432	475	522	571	629	688	794

The standard errors of estimate in the Boning study are not extremely large when the problem of application of the predictive relation and the noise inherent in the data are considered.

Regionalization in a more limited area, such as a State or a river basin, would probably reduce standard error to even lower levels than those attained by Boning. For example, in an Indiana study, Eikenberry and Davis (1976) derived predictive equations to estimate traveltime of peak concentrations for selected discharges in streams having drainage areas of 80 square miles or more. The standard error of these equations ranged from ±16 to ±18 percent for tributary streams and from only ±11 to ±15 percent for main-stem streams.

Calandro (1978) developed regional relationships for Louisiana streams using data from tests on 18 streams. Multiple tests at different discharges were performed on 9 of the 18 streams. Calandro found that for Louisiana streams, traveltime (as contrasted with velocity) was most significantly related to reach length, drainage area, and discharge. He depicted this using nomographs for the leading edge, peak, and trailing edge traveltimes, as illustrated in figure 22.

Parker and Gay (1987) performed a similar type of regionalization for Massachusetts streams using 30 sets of tracer test data from 16 river reaches. They were able to relate mean velocity to discharge, slope, and channel width.

In the initial planning of any time-of-travel study, consideration should be given to collecting the additional data that would permit regionalization in the future; these data should be acquired *at the time of each test*. It may be concluded that discharge, slope, mean depth and width, and storage where significant, as well as type of flow, are the principal variables and information to be considered in any regionalization. If mean width is determined or estimated, mean depth can be calculated using the continuity equation, with the velocity obtained from the time-of-travel tests:

$$d = Q/Bv. \qquad (15)$$

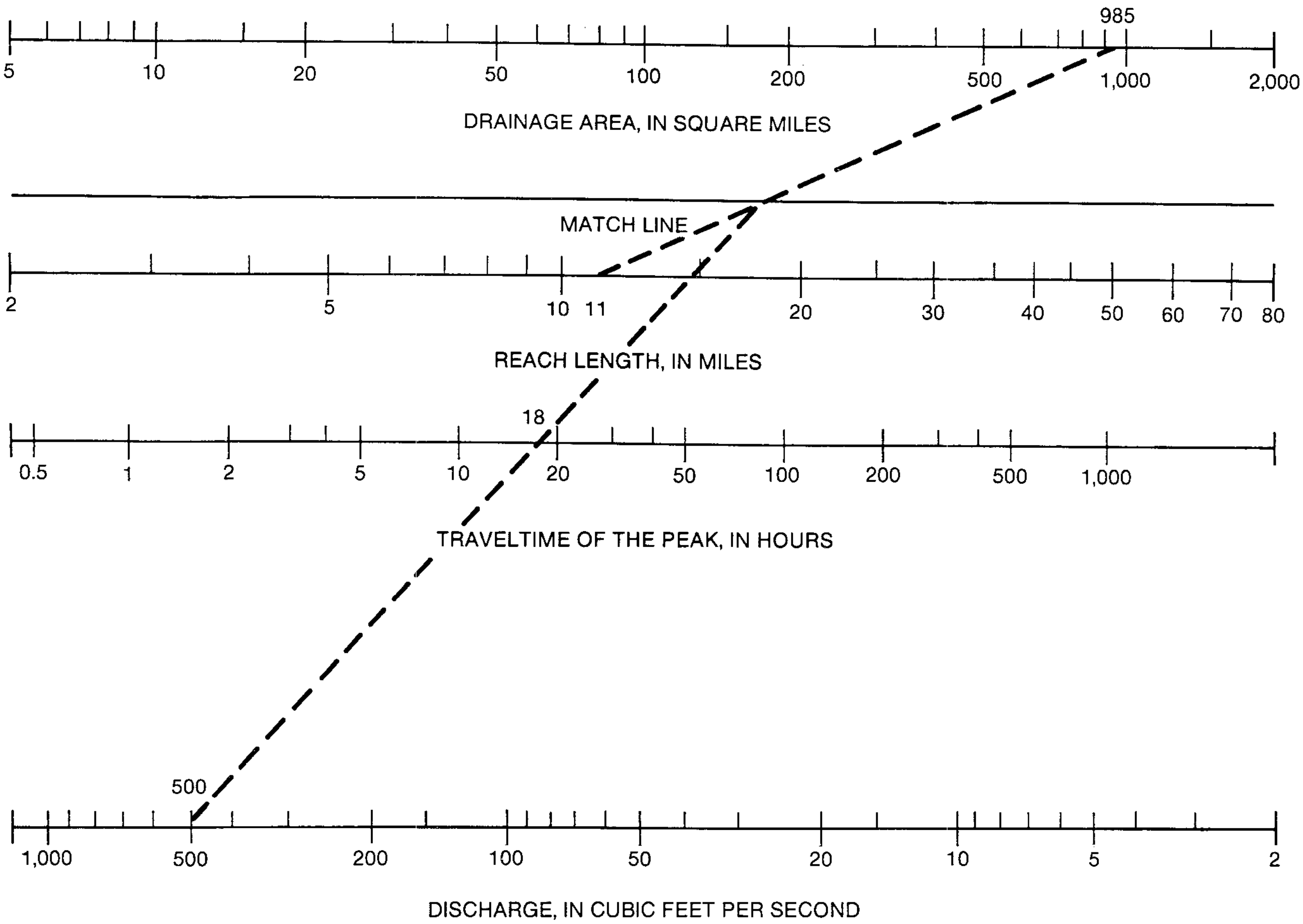


Figure 22.—Relation of traveltime of the peak concentration to drainage area, reach length, and discharge for Louisiana streams (from Calandro, 1978).

Summary

Dye tracing has proved to be a practical means of measuring time of travel during either steady or gradually varied flow in streams. Dye injected into a stream behaves much the same as water molecules, moving on the average at the same rate as the water.

When dye is released in a stream, it disperses in three directions—vertically, laterally, and longitudinally. After an initial mixing period, dispersion is complete in the vertical and lateral directions and disperses only longitudinally, a process that continues indefinitely.

Although a number of dyes are available for water tracing, rhodamine WT, specifically formulated for water tracing, is recommended, principally because it is the most conservative of the dyes available.

Significant effort is usually necessary in planning a successful dye study. Tests should be planned for two or more flow durations. The next step is acquisition and assimilation of available data, including maps and previous discharge measurements. The investigator should conduct a reconnaissance of the stream to inspect sampling and injection sites, to locate dams, diversions, and water intakes, and to work out logistical problems. The discharge, length, and water velocity of the reach must be measured or estimated to determine the minimum reach length required for completion of initial mixing and to calculate the amount of dye to be injected. A study plan must be devised, which includes sampling and dye-injection schedules, descriptions of the sampling and injection sites, personnel assignments, equipment assignments, and maps.

Dye is usually injected near the main thread of flow in a narrow stream or, in a wide stream, in a series of injections or by continuous pouring across the width of the stream to achieve the quickest possible lateral mixing. A sample of water should be taken at a sampling site prior to the arrival of the dye to obtain a background fluorometer reading, which is to be subtracted from recorded readings measured during the passage of the dye cloud. Having a fluorometer available at the sampling site enables the sampler to monitor the passage of the dye and to estimate the time of arrival of the leading edge at the next sampling site downstream. However, depending on the fluorometer, final dye concentrations may have to be determined under more controlled conditions because ambient temperature, light, and other factors affect fluorescence and fluorometer performance. The sampling at a site should continue until the dye concentration is 10 percent or less of the peak concentration. To meet the objectives of most studies, it is necessary to determine stream discharge during passage of the dye.

Typically, final concentrations of dye in the samples are determined under carefully controlled conditions. Samples are brought to a uniform temperature, commonly using a constant temperature bath. Due care must be exercised to ensure that the fluorometer is working properly and is accurately calibrated by using a sample from the same lot as the dye that was injected.

Traveltime-distance curves are used to show the time required for a solute to move through the study reach. They can be for any or all the features of a solute cloud—leading edge, peak, centroid, and trailing edge. Preferably, studies are conducted for two or more discharges to permit preparation of traveltime-discharge curves.

Time-of-travel data can be regionalized by using multiple-regression techniques to derive empirical equations, using discharge, slope, reach length, channel width and depth, and storage as parameters.

References

Abidi, S.L., 1982, Detection of diethylnitrosamine in nitrite-rich water following treatment with rhodamine flow tracers: Water Research, v. 16, p. 199–204.

Boning, C.W., 1974, Generalization of stream travel rates and dispersion characteristics from time-of-travel measurements: U.S. Geological Survey Journal of Research, v. 2, no. 4, p. 495–499.

Buchanan, T.J., 1964, Time of travel of soluble contaminants in streams: American Society of Civil Engineers Proceedings, Journal of the Hydraulics Division, v. 90, no. SA3, p. 1–12.

Calandro, A.J., 1978, Time of travel of solutes in Louisiana streams: Louisiana Department of Public Works, Water Resources Technical Report 17, 32 p.

Eikenberry, S.E., and Davis, L.G., 1976, A technique for estimating the time of travel of water in Indiana streams: U.S. Geological Survey Water-Resources Investigations Report 76–9, 39 p.

Fischer, H.B., and others, 1979, Mixing in inland and coastal waters: New York, Academic Press, 483 p.

Jack, A.R., 1986, Traveltime and dispersion of a soluble dye in the South Branch Potomac River, Petersburg to Green Spring, West Virginia: U.S. Geological Survey Water-Resources Investigations Report 84–4167, 14 p.

Johnson, S.M., and Steinheimer, T.R., 1984, Potential for nitrosamine formation resulting from the use of rhodamine WT for time of travel studies: A combined laboratory and field investigation: National meeting, Division of Environmental Chemistry, American Chemistry Society, 18th, Philadelphia, Preprint extended abstract, v. 24, no. 2, p. 70–71.

Kilpatrick, F.A., 1970, Dosage requirements for slug injections of rhodamine BA and WT dyes, *in* Geological Survey research 1970: U.S. Geological Survey Professional Paper 700–B, p. 250–253.

———1972, Automatic sampler for dye tracer studies: Water Resources Research, v. 8, no. 3, p. 737–742.

Kilpatrick, F.A., and Cobb, E.D., 1985, Measurement of discharge using tracers: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A16, 52 p.

Kilpatrick, F.A., and Taylor, K.R., 1986, Applications of dispersion data: Water Resources Bulletin of the American Water Resources Association, v. 22, no. 4, p. 537–548.

Parker, G.W., and Gay, F.B., 1987, A procedure for estimating reaeration coefficients for Massachusetts streams: U.S. Geological Survey Water-Resources Investigations Report 86–4111, 34 p.

Shindel, H.L., Wagner, L.A., and Hamecher, P.H., 1977, Time of travel and dye-dispersion studies of selected streams and lakes in the Oswego River basin, New York, 1967–75: New York Department of Environmental Conservation Report of Investigation RI–17, 153 p.

Steinheimer, T.R., and Johnson, S.M., 1986, Investigation of the possible formation of diethylnitrosamine resulting from the use of rhodamine WT dye as a tracer in river waters, *in* Subitzky, Seymour, ed., Selected papers in the hydrologic sciences 1986: U.S. Geological Survey Water-Supply Paper 2290, p. 37–49.

Stewart, M.R., 1967, Time of travel of solutes in Mississippi River from Baton Rouge to New Orleans, Louisiana: U.S. Geological Survey Hydrologic Investigations Atlas HA–260.

Taylor, K.R., James, R.W., Jr., and Helinsky, B.M., 1984, Traveltime and dispersion in the Potomac River, Cumberland, Maryland, to Washington, D.C.: U.S. Geological Survey Open-File Report 83–861, 55 p.

———1986, Traveltime and dispersion in the Shenandoah River and its tributaries, Waynesboro, Virginia, to Harpers Ferry, West Virginia: U.S. Geological Survey Water-Resources Investigations Report 86–4065, 60 p.

Wilson, J.F., Jr., 1967, Time-of-travel measurements and other applications of dye tracing, *in* Hydrologic aspects of the utilization of water: International Association of Scientific Hydrology Publication 76, p. 252–265.

Wilson, J.F., Jr., Cobb, E.D., and Kilpatrick, F.A., 1986, Fluorometric procedures for dye tracing (rev.): U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A12, 41 p.

Yotsukura, Nobuhiro, and Cobb, E.D., 1972, Transverse diffusion of solutes in natural streams: U.S. Geological Survey Professional Paper 582–C, 19 p.