Designation: D5613 – 94 (Reapproved 2014)

Standard Test Method for Open-Channel Measurement of Time of Travel Using Dye Tracers[1]

This standard is issued under the fixed designation D5613; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers a means of measuring the time-of-travel of water and waterborne solutes by the use of dye tracers and tracing techniques. This test method is similar to methods developed by the U.S. Geological Survey and described in other referenced documents.

1.2 This test method describes the dye tracers, measuring equipment used, and field and laboratory procedures customarily used.

1.3 This test method describes the methods of tracer study analysis and data presentation.

1.4 The user of this test method should address the following concerns regarding the use of tracers in water bodies:

1.4.1 Determine whether the chemical has clearance or approval or has potential or preceived impacts relating to potable, industrial, irrigation, or fish and wildlife use.

1.4.2 Determine whether approvals are required by involved agencies.

1.4.3 Document contacts regarding notification.

1.5 The values stated in inch-pound units except for chemical concentrations and liquid volumes for step dilutions, which are stated in SI units, are to be regarded as the standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* For specific hazards statements, see Section 9.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1192 Guide for Equipment for Sampling Water and Steam in Closed Conduits (Withdrawn 2003)[3]

D2777 Practice for Determination of Precision and Bias of Applicable Test Methods of Committee D19 on Water

D3370 Practices for Sampling Water from Closed Conduits

D3858 Test Method for Open-Channel Flow Measurement of Water by Velocity-Area Method

D4411 Guide for Sampling Fluvial Sediment in Motion

2.2 *ISO Standard:*[4]

ISO 555/2-1974 Liquid Flow Measurement in Open Channels—Dilution Methods for Measurement of Steady Flow, Part 2: Integration (Sudden Injection) Method.

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *automatic programmable sampler*—a portable device designed to collect sequential, discrete water samples representative of the water mixture moving in the river in the vicinity of the sampler at a single point in a cross section. Depending on the make and model of the device, water samples can be collected at equal or variable time intervals.

3.1.2 *centroid*—the center of mass of the dye response curve calculated as outlined by Parker and Hunt (**1**).[5]

3.1.3 *depth-integrated sample*—a water sample collected in such a manner as to be representative of the water mixture moving in the river in the vicinity of the sampler at a single vertical in a cross section.

3.1.4 *dispersion*—the three-dimensional process of disseminating the dye within a river's waters.

3.1.5 *flow duration*—the percentage of time during which a specific discharge is equalled or exceeded.

3.1.6 *fluorometer*—an instrument that measures the luminescence of a fluorescent substance when subjected to a light source of a given wave length.

[1] This test method is under the jurisdiction of ASTM Committee D19 on Water and is the direct responsibility of Subcommittee D19.07 on Sediments, Geomorphology, and Open-Channel Flow.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[5] The boldface numbers in parentheses refer to the list of references at the end of this test method.

3.1.7 *injection site*—a study site where the tracer is to be introduced into a parcel of river water. This study site is usually a sufficient distance upstream of the study reach such that complete vertical and lateral mixing of the tracer in a parcel of river water has occurred before the water parcel's entry into the study reach.

3.1.8 *lateral dispersion*—the process of disseminating the dye within a river water's horizontal axis perpendicular to its longitudinal axis. The completion of this process is dependent on the width of the river and velocity variations.

3.1.9 *leading edge*—the first detectable dye concentration observed at a sampling site.

3.1.10 *longitudinal dispersion*—the process of disseminating the dye within a river's waters along its upstream-downstream axis. This component of the dispersion process continues downstream indefinitely.

3.1.11 *mixing*—the blending of two or more substances into one uniform mass.

3.1.12 *peak*—the maximum dye concentration observed at a sampling site.

3.1.13 *point sample*—a water sample collected in such a manner as to be representative of the water mixture moving in the river in the vicinity of the sampler at a single point in a cross section.

3.1.14 *sample site*—a study site where water samples are collected for determination of the tracer-concentration response curve.

3.1.15 *standard integrated depth sampler*—a device designed to accumulate a water sample from a stream vertical at such a rate that the velocity in the nozzle at the point of intake is always as nearly as possible identical with the immediate stream velocity.

3.1.16 *study reach*—the section of a river's length that is to be studied.

3.1.17 *study site*—sections of a river where data are to be determined, monitored, measured, and where tracer is to be introduced into the river.

3.1.18 *tracer response curve*—at each sampling site, the plots of tracer concentration versus time after the tracer injection.

3.1.19 *trailing edge*—the point of the falling limb of the dye response curve that is equal to approximately 2 % of the peak concentration observed at a sampling site.

3.1.20 *vertical dispersion*—the process of disseminating the dye within a river's water's vertical axis perpendicular to its upstream-downstream axis. This dispersion process is usually completed first.

4. Summary of Test Method

4.1 Dye tracers injected into a stream are assumed to behave in the same manner as the water molecules themselves. A measure of the longitudinal movement of a tracer along a given streamline will be a measure of the movement of an element of fluid in the stream and of its dispersion characteristics for that streamline.

4.2 The initial planning of a dye tracer time-of-travel study involves the estimation of stream velocities and the required tracer injection volume. The information necessary for these estimations is obtained by reviewing historical flow data and topographic maps and by making a reconnaissance of the proposed study reach.

4.3 The time-of-travel for a given flow is determined by observing the passage of a slug-injected dye tracer cloud at previously identified locations along the study reach. The dye cloud response curve is defined at each reach location (study site) by measuring the dye concentration in collected water samples and noting the time that each sample was collected since the tracer injection.

4.4 After tracer studies have been conducted at two or more flow durations on the study reach, estimation of the time-of-travel and dispersion of a solute can be made at any flow between those studied. Tracer studies are typically performed at 40 to 90 % flow duration ranges.

5. Significance and Use

5.1 *Purpose:*

5.1.1 This test method covers the use of fluorescent dye tracers in streams to determine the rate that a solute moves along a streamline for a given river reach and the rate at which a solute disperses as it moves downstream.

5.1.2 Accurate measurements of a stream's velocity and dispersion coefficient that can be determined by a tracer study are important parameters for water-quality models.

5.1.3 Determined in advance to potential spilled or released noxious substances, velocity and dispersion rates are used to predict the time of arrival, passage time, and maximum concentration. Public health officials need this information to decide whether, when, and how long to suspend operations of public water-supply intakes in the reach downstream of a spill.

5.2 *Assumptions:*

5.2.1 This test method assumes that the dye tracer behaves in the same manner as the water in which it is injected. Dispersion and mixing of the tracer in the receiving river occur in all three dimensions of the channel. Longitudinal mixing is unending since boundaries do not exist in this direction.

5.2.2 The tracer response curve at a point downstream from the point of tracer injection can be represented by plotting the tracer concentration against elapsed time since the injection (Fig. 1).

5.2.3 A tracer response curve has four important characteristics: the elapsed time to the response curve's leading edge; elapsed time to the response curve's peak concentration; elapsed time to the response curve's centroid; and elapsed time to response curve trailing edge at 2 % of the peak concentration.

5.2.4 Between two monitoring locations separated by a long stream length, the time-of-travel for individual response curve characteristics is the difference in the elapsed times since injection for that characteristic at the two locations.

5.2.5 The duration or time of passage of a tracer response curve at a particular river location is the difference between the

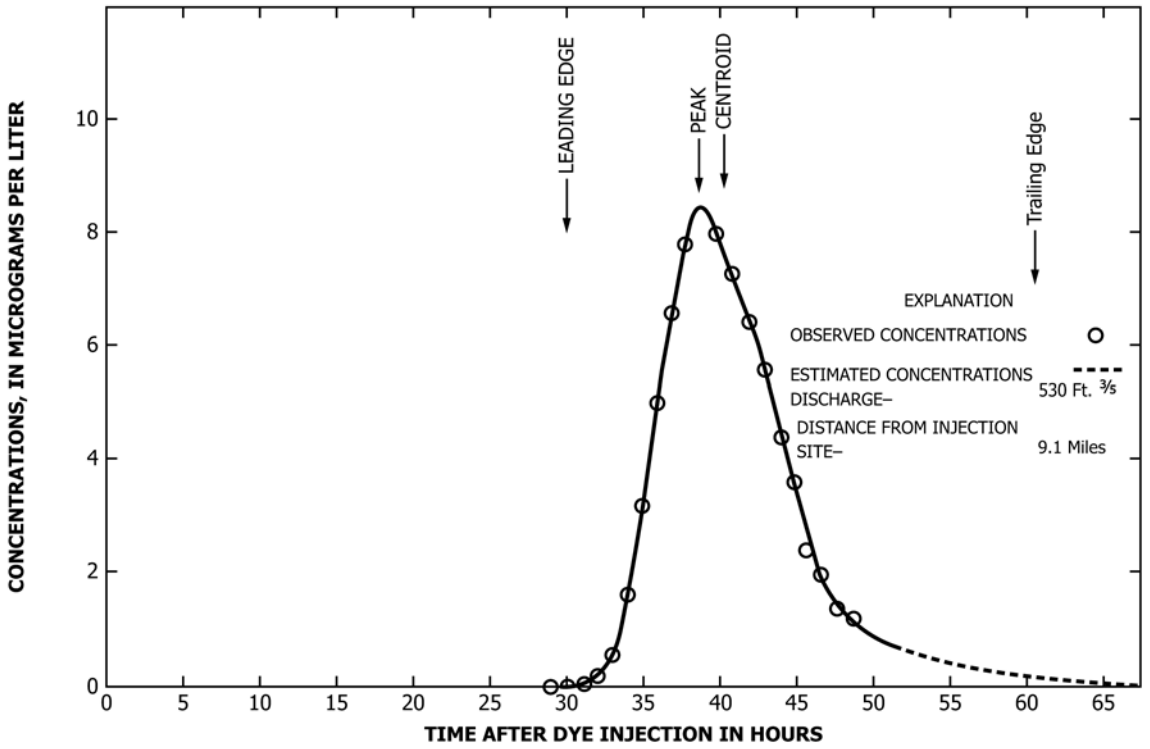


FIG. 1 Travel Time from Burnham Versus Concentration at Clinton, Maine, Sept. 18–20, 1979 (from Parker) (2)

slowest trailing edge elapsed time since injection and the earliest leading edge elapsed time since injection determined in the cross section.

5.3 *Tracers:*

5.3.1 Conservative tracers used to investigate fluid motion are generally extrinsic, artificial, and chemical substances and are usually classified according to the methods of detection used and chemical composition.

5.3.2 Properties to be considered when selecting a tracer for a study include detectability, toxicity, solubility, cost, natural background concentration, and sorption characteristics.

5.3.3 Fluorescent dye tracers such as Rhodamine WT, pontacyl pink, and acid yellow 7 are generally good chemical tracers. Rhodamine WT has the most numerous qualities preferred by many state and federal agencies for open-channel studies.

5.3.4 Other tracers can be used when water-quality or physical conditions are not suitable for the use of fluorescent dyes in a proposed study reach. These include salt-based chemical tracers such as sodium chloride, radioactive tracers such as tritium, and tracers determined with neutron activation analysis such as bromine and lithium (**3**).

5.3.5 These tracers are considered to be generally conservative and, in terms of this test method, differ primarily in the apparatus required to measure the concentrations in the study reach. Discussions in subsequent sections will be limited to fluorescent dye because of the simplicity of fluorometric analysis.

5.3.6 Different tracers require varied levels of permits before being introduced into the environment. For example, radioactive tracers require permits from the Nuclear Regulatory Commission (NRC) and usually state and local permits. Fluorescent dye tracers do not usually require formal permits for use in a study.

6. Interferences

6.1 Natural water may exhibit background fluorescence that is not the result of a fluorescent dye tracer. This background fluorescence may result from scattered light, fluorescence of natural materials or pollutants, or other causes (**4**).

6.2 The fluorescence of Rhodamine WT is stable in solutions having a pH in the range from 5 to 10, which is within the range of most streams. Rhodamine WT fluorescent decreases when in solutions having a pH below 5 (**5**).

6.3 Dye tracer fluorescence may be quenched by the action of other chemicals in the streamwater. The quenching agent may cause any of the following to occur (**6**): absorption of exciting light, absorption of light emitted by the dye, degradation of the excited-state energy, and chemically changing the fluorescent compound of the dye tracer.

6.4 The permanent reduction of Rhodamine dye tracer fluorescence can be caused by photochemical decay as a result of exposure to sunlight (**7**). Sunlight degradation half-lives for the dye at the water surface to a depth of 0.03 ft ranged from 15 to 30 days at 30° North latitude, depending on the season of the year. The degradation half-lives ranged from 15 to 44 days at 40° North latitude, depending on the season of the year. The photochemical decay half-life increases with increased water depth and decreasing light intensity; it is therefore not a concern for most practical problems.

7. Apparatus

7.1 Dye is usually injected by pouring a measured amount as a slug into the center of the flow from a graduated laboratory cylinder. Graduated laboratory cylinders are convenient for measuring and injecting small volumes. Large-volume injections can be measured in terms of full dye containers. The measured volumes of tracer to be injected can be mixed with streamwater in a larger container that can also be used as an injection vessel.

7.1.1 Multiple-point injections across the channel are used on wide streams to shorten the effective length of river required for lateral mixing of the tracer to be completed. The volume of tracer to be injected is divided into several injection vessels that are poured in the stream simultaneously at several points along the cross section. A variation of this approach is to make a line injection by pouring the tracer continuously while crossing the stream. Such an injection should be limited to the center 75 % of the flow. This limitation of injection will optimize the reach length required for complete transverse mixing of the tracer.

7.2 Sample collection apparatuses range in sophistication from hand-held samplers to programmable automatic sample collection systems. The selection of sample collection devices depends on the size of the study, availability of personnel, and hydrologic conditions at each sample site. Any point sampling method may be used where complete mixing has occurred; however, a depth-integrated sample may be necessary where mixing may not have been achieved.

7.2.1 Glass bottles are preferred when long-term storage is anticipated between the sample collection and final tracer concentration analysis. Rhodamine WT dye has an affinity for most plastics. Glass containers are therefore recommended for sample collection and storage. The container should have a tight cap and sufficient volume for six to eight analyses on the fluorometer being used for the study. A volume of at least 100 mL is desirable. Soap- or acid-cleaned containers are not necessary, but rinse the containers three to five times with distilled or non-chlorinated water if precleaned containers are not available.

7.2.2 Depth integrating samplers (Fig. 2) are designed to collect water samples representative of the water column from the bed to surface (**8**). These samplers may vary from hand-held samplers for use in small streams to sampling devices built into heavy weights that are controlled by reels mounted on boats, bridge cranes, or cableways. Use the techniques described in Guide D4411.

7.2.2.1 Automatic sampling equipment collects water at a single point in a cross section. The tracer concentration in point samples can be compared with that in depth-integrated samples. This comparison will also verify complete vertical mixing.

7.2.3 A pump may be used when a continuous recording of fluorescence is being made using a fluorometer with a flow-through device. Periodic samples are collected in glass bottles from the discharge hose for later laboratory verification analysis. This method is considered point sampling.

7.2.4 Many automated, programmable sampling systems are currently available, and these can save significant manpower.

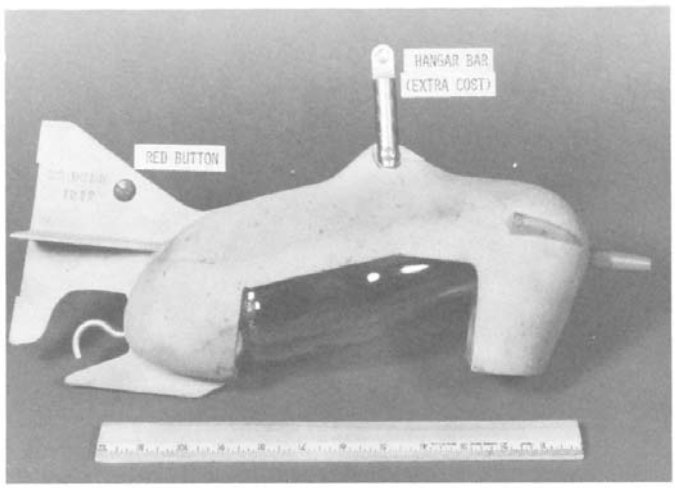


FIG. 2 Depth-Integrating Suspended-Sediment Hand-Type Sampler, US DH-59 (Edwards and Glyason) (8)

The common-type have a peristaltic pump that collects and delivers a predetermined volume of water into a discrete number of sample containers. Samples are collected at the point at which the intake is set. The volume of water collected and the time interval between samples can be programmed by the user. Most systems have a purge cycle to prevent the cross contamination of collected samples by water left in the intake tube.

7.2.5 An automatic sampling boat that uses spring-activated hypodermic syringes is described by Kilpatrick (**9**). The time interval between samples can be preset by the user at a constant frequency for all samples at a given cross section. The sampler also has the advantage of being able to be anchored in the middle of wide rivers.

7.2.6 All samples retained for laboratory analysis must be stored in such a manner as to prevent the permanent reduction of tracer fluorescence by photochemical decay. A common ice chest with bottle racks provides convenient light-tight containers in the field. Any light-tight storage is sufficient once samples have been transferred to a laboratory. No other special handling is required.

7.3 *Fluorometers:*

7.3.1 Fluorometers measure the luminescence of a fluorescent substance when the substance is subjected to a light source of a given wavelength. The higher the concentration of the fluorescent substance, the more emitted light the fluorometer will detect. The use of fluorometers in dye tracing has been described in detail by Wilson, et al. (**4**).

7.3.1.1 The two fundamental types of fluorometers are fluorescence spectrometers used for spectral analysis of fluorescent substances and filter fluorometers used for measuring the relative intensity of light emitted by a sample containing a specific fluorescent substance. Filter fluorometers are the more commonly used instruments for fluorescent dye studies and will be the only types described in this test method. Fluorometers used in time-of-travel studies typically have a primary filter in the 546-nm wavelength and a secondary filter in the 590-nm wavelength.

7.3.1.2 The filter-type fluorometer provides a relative measure of the intensity of light emitted by a water sample containing a specific fluorescent substance. The measured intensity of fluorescence is proportional to the amount of fluorescent substance present in the sample. The fluorometer is calibrated by comparing the measured fluorescent intensities with samples of known dye concentrations at the same temperature conditions. Every fluorometer is different and must be calibrated individually and checked frequently for calibration. All commercial filter fluorometers consist of six basic components (Fig. 3). A more detailed description of fluorometers is given in Wilson, et al. (**4**).

8. Reagents

8.1 Prepare standard solutions of dye by a series of precise dilutions of the dye solution to be injected. Serial dilution is a procedure in which a concentrated tracer solution is reduced in steps to a range of concentration low enough to measure on a fluorometer. Precise measurements of tracer and water volumes are critical to the successful preparation of accurate standards for calibration. Commercial grade distilled or deionized water is acceptable for the preparation of standard solutions.

8.1.1 Time-of-travel studies using fluorescent dye tracers in streams and rivers are generally determined over distances of miles. The "first-arrival-times" of greatly diluted dyes are detected by using highly sensitive fluorometers.

8.1.2 The flow volume is known to within only a few percent in most time-of-travel studies. Consequently, only comparable accuracy of the dye standard concentrations is necessary to evaluate the dilution factors and travel times. That is, the greatest accuracy and precision typically required for quantitative chemical analysis is not necessary.

8.1.3 Adequate accuracy of the dye solution fluorometer calibration standards for time-of-travel studies may consequently be obtained by using graduated cylinders for initial measurements of the dye concentrate. The graduates used should be well rinsed to obtain a complete transfer of the viscious dye concentrate to obtain the first dilution, C_1.

8.2 Using Rhodamine WT as supplied by the manufacturer [6] at a concentration of 20 % by weight, at least a four-step dilution is required to obtain the standard concentrations needed. Assuming the manufacturer specifies the dye concentration as 20 % with a specific gravity of 1.19, calculate the volume required to yield 10.00 g of dye as follows:

[6] Crampton and Knowles Corp. of Skokie, IL, manufactures a suitable product for this purpose.

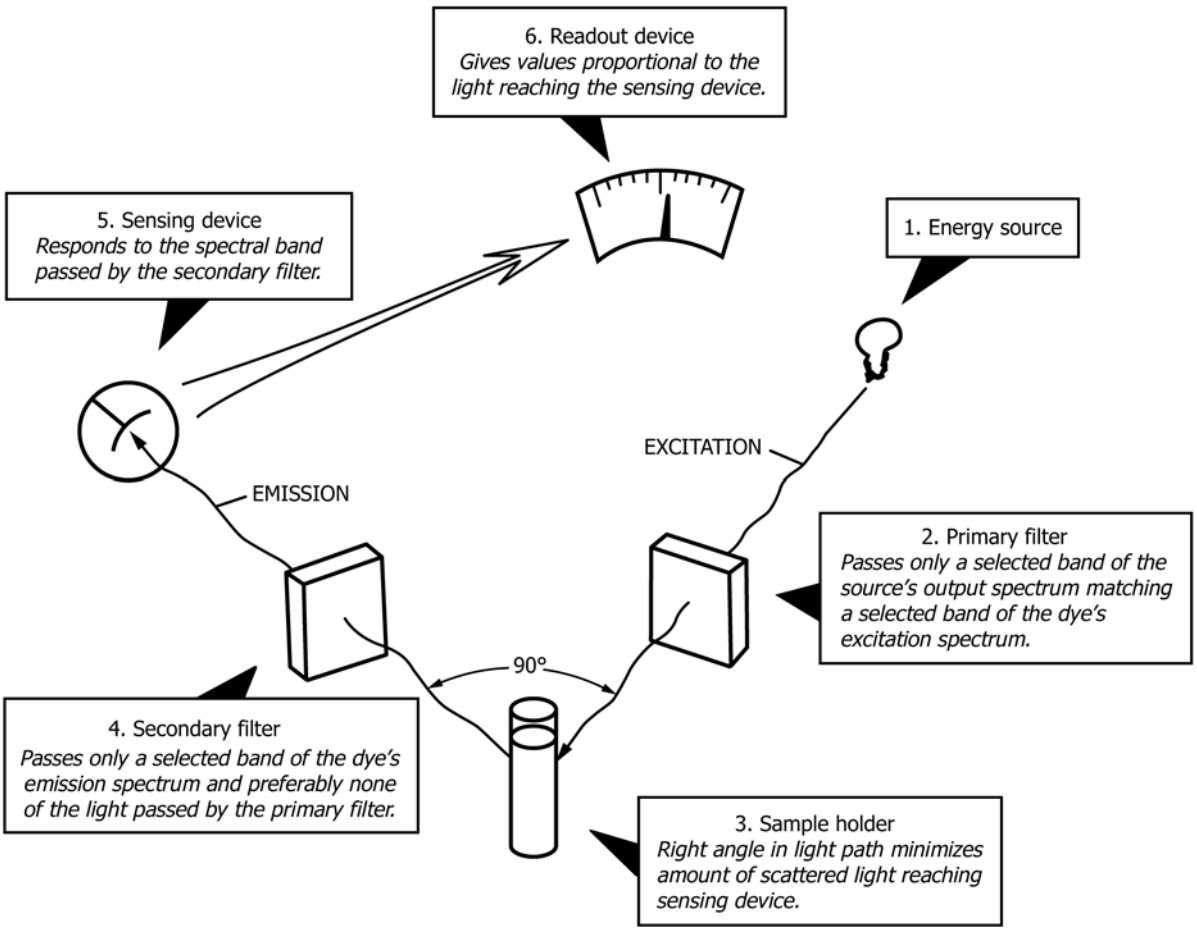


FIG. 3 Basic Structure of Most Filter Fluorometers

$$V_{LD} = \frac{W_{DD}}{W_{PC} \times D} \quad (1)$$

where:

V_{LD} = volume of concentrated liquid dye required,
W_{DD} = weight of dry dye desired, g,
W_{PC} = weight percent of dry dye in liquid dye concentrate, as specified by manufacturer, and
D = density of the dye concentrate (1.19 g/mL) for 20 % Rhodamine WT solution.

$$V_{LD} = \frac{10.0 \text{ g}}{20 \times 1.19 \text{ g/mL}} \times 100 = 42.0 \text{ mL} \quad (2)$$

8.2.1 Measure this volume of dye concentrate as accurately as possible using a 50-mL graduate. Transfer the dye quantitatively to a 1000-mL glass volumetric flask, using distilled or deionized water for rinsing as necessary. Dilute almost to volume, and mix well. Bring to the specified temperature in the volumetric flask and dilute to final volume. This procedure yields 1 L of the initial dilution solution C_i containing 10 000 mg/L of dye. (Larger or smaller volumetric flasks may be used, depending on availability. Make proportional adjustments of the dye volume to be used for dilution, as appropriate.)

8.2.2 The viscosity and drainage characteristics of the C_i dilution from pipets will be comparable to water after the initial dilution to prepare C_i, and normal pipeting procedures can be used.

8.2.3 Make subsequent serial dilutions using the following relationship:

$$V_1 C_1 = V_2 C_2 \quad (3)$$

where:

V_1 = volume of solution, C_1,
C_1 = concentration, mg/L, of solution C_1,
V_2 = volume of solution, C_2, and
C_2 = concentration of solution C_2.

8.2.4 To obtain a solution C_2 containing 100 mg/L and using solution C_1 containing 10 000 mg/L to prepare it, determine V_1 as follows:

$$V_1 \times 10\,000 \text{ mg/L} = 1000 \text{ mL} \times 100 \text{ mg/L} \quad (4)$$

$$V_1 = \frac{1000 \text{ mL} \times 100 \text{ mg/L}}{10\,000 \text{ mg/L}} = 10 \text{ mL}$$

To prepare 1 L of C_2, pipet 10.00 mL of C_1 into a 1000-mL volumetric flask and dilute to volume as previously described.

8.2.4.1 Prepare the following:

(1) C_3 at 1 mg/L by diluting 10 mL of C_2 to 1000 mL;

(2) C_4 at 0.01 mg/L by diluting 10 mL of C_3 to 1000 mL; and

(3) C_5 at 0.001 mg/L by diluting 100 mL of C_4 to 1000 mL.

8.2.5 Transfer the prepared standards into labeled glass (preferably brown) bottles. Prepare additional standards as required (for example, 0.5, 5, 10, 25, and 50 mg/L) in a similar manner.

8.2.6 Store all of the standards in the dark.

9. Hazards

9.1 Direct skin contact with concentrated Rhodamine WT dye should be avoided. Rubber or plastic gloves should be worn when handling dye solutions. Any dye that comes into contact with the skin should be washed off immediately with large quantities of soap and water.

10. Sampling

10.1 Collect samples in accordance with Specification D1192 and Practices D3370.

10.2 In general, select a minimum of three points laterally across each stream study site for sample collection. Select the points on the basis of cumulative discharge and flag or otherwise mark the location for repeated sampling. Use the same cumulative discharge points (streamlines) at all study sites along a stream reach. Table 1 is provided to assist in selecting sample point locations for even discharge increments. More than three sampling points are recommended for wide or shallow streams.

10.2.1 Compare the tracer concentration from depth-integrated samples with that in point samples collected at a consistent, uniform depth by automatic programmable samplers. This procedure will verify whether complete vertical mixing has occurred. Since vertical mixing is usually completed first, once it is verified, point sampling is all that is necessary.

10.2.2 Verify complete lateral mixing by comparing the areas under the time-tracer concentration curves. If the areas are within 95 % of agreement with each other, assume optimum lateral mixing to be complete. Once complete lateral mixing has been verified, center channel or 50 % flow point sampling is sufficient at subsequent downstream cross sections.

10.2.3 If lateral mixing is complete, vertical mixing, a much faster process, is most certainly complete. It is much more important to verify complete lateral mixing than vertical mixing because it is usually the slower process.

TABLE 1 Locations of Sample Collection Points Based on Cumulative Discharge to Verify Complete Transverse Mixing and Define Tracer Response Curve

Number of Sampling Points	Percent of Total Discharge Sampled at Each Point	Locations of Sampling Points									
		1	2	3	4	5	6	7	8	9	10
		Cumulative Discharge in Percent									
3	33.3	16.7	50	83.3							
5	20.0	10.0	30.0	50.0	70.0	90.0					
7	14.3	7.1	21.4	35.7	50	64.3	78.6	92.9			
10	10.0	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0	95.0

10.3 Collect enough samples at each sample point at a study site (30 to 40 samples) to define the shape of the tracer response curve. The samples must be taken at more frequent intervals from the leading edge through the peak tracer concentration due to the typical, skewed shape of a tracer response curve. Less frequent sample collection is common practice to the trailing edge of the response curve. Ideally, no more than 5 % of the dye mass, with a maximum of 10 % of the dye mass, passes a study site between samples.

10.4 A minimum sample volume of 100 mL is required for collection. This will allow at least six to eight concentration determinations in most fluorometers using a 5 to 20-mL cuvette discrete sample holder. All samples should be collected and stored in glass containers since Rhodamine WT has an affinity for many plastics. The samples should also be stored in the dark to avoid photo reduction of the tracer's fluorescence. Plastic bottles can be used only for short-term storage. Plastic tubing used in pumping and flow-through systems are not a problem because the contact times are too short for significant sorption to occur.

11. Calibration

11.1 Calibrate the fluorometer by determining the relationship of fluorometer output units and the dye concentration of standard solutions prepared in Section 8.

11.2 Analyze standards on the fluorometer and record the dial readings in the conventional manner presented as follows. Treat the standard samples in a manner similar to the river samples. For example, allow the standard samples to stand overnight in the same room, or place them in a bath having the same temperature as the river samples.

11.3 Fluorescence varies linearly with dye concentrations below several hundred micrograms per litre. Instrument output is designed to be linear within 1 % of the amount of light reaching the photomultiplier. Fluorometer dial reading should therefore vary linearly with concentration. It is best to plot fluorometer readings for standards on a separate sheet for each fluorometer scale. Record the kind of tracer and tracer lot, sample temperature, date, and fluorometer components on each plot. Label the axes in such a way that there can be no doubt concerning the units used. An example of a set of calibration plots is given in Fig. 4. Once it has been established that the calibration is linear, the number of standards needed for verification is reduced greatly. Some fluorometers are designed such that the instrument readings correspond to direct readings of concentration.

11.4 A calibration should remain valid for weeks or months of normal use if the fluorometer is not moved and none of the electronic components are touched. However, spot checks are desirable. A different calibration will be necessary for each dye lot used. Some of the more common causes of change in calibration are as follows:

11.4.1 Jarring the fluorometer, as might be expected when it is used in the field;

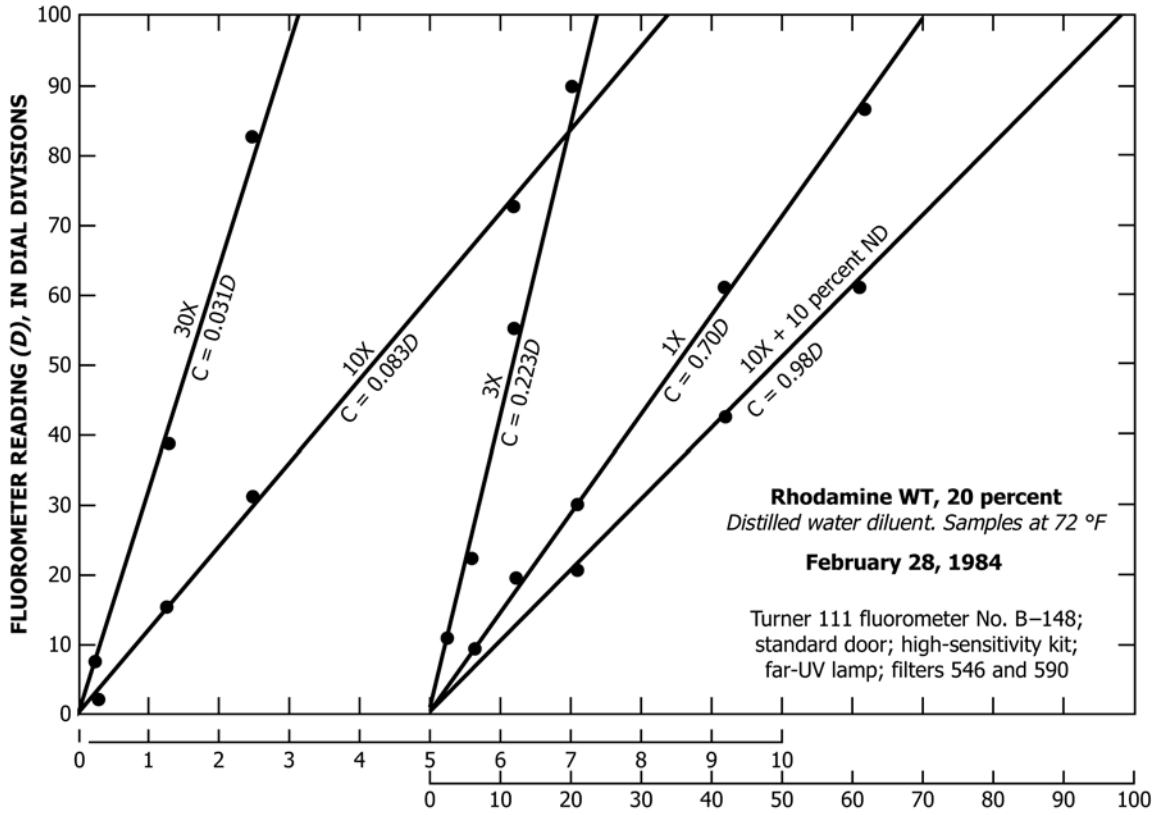


FIG. 4 Typical Set of Calibration Curves

11.4.2 Removing the lamp temporarily;
11.4.3 Changing the lamp or photomultiplier;
11.4.4 Damage to the lamp or photomultiplier;
11.4.5 Clouding and deterioration of filters with time;
11.4.6 Changes in optical alignment;
11.4.7 Changes in the temperature of standard samples (the application of temperature-correction curves using Fig. 5 will eliminate this problem); and
11.4.8 Accumulation of dust or film on exposed optical components on the fluorometer (lamps, filters, mirrors, or cuvettes); etching or scratches on the cuvettes may also cause problems.

12. Procedure and Calculation

12.1 *Planning:*
12.1.1 The primary goal of a time-of-travel tracer study is to characterize how stream reach average velocity varies with discharge. Over a long reach, stream discharge generally increases in the downstream direction, but most increases are uniform with distance except at points at which tributaries enter the river. An absolute discharge for a river is not an ideal variable to index the travel times for a whole system for this reason. Flow duration is an index of river discharge that is nearly constant with distance throughout a reach of stream in the absence of a flood wave moving through the system. Flow duration is a good indication of the general reach discharge for developing a system relationship with time-of-travel for this reason (see Fig. 6).
12.1.2 Review all existing streamflow records as the first step in planning a time-of-travel study. Determine the selection of the desired range of flow durations critical to answer the objective of the study for the series of planned tracer tests. Selection of the higher flow duration (smaller discharge) is usually the most important because the travel times are long and the transport and dispersion characteristics most critical. Low-discharge periods generally coincide with low suspended-sediment concentrations, which is desirable. Sediment sorbs the dye, resulting in higher dilution rates.
12.1.3 Make a tentative evaluation of the stream reaches under consideration in terms of hydraulic characteristics and

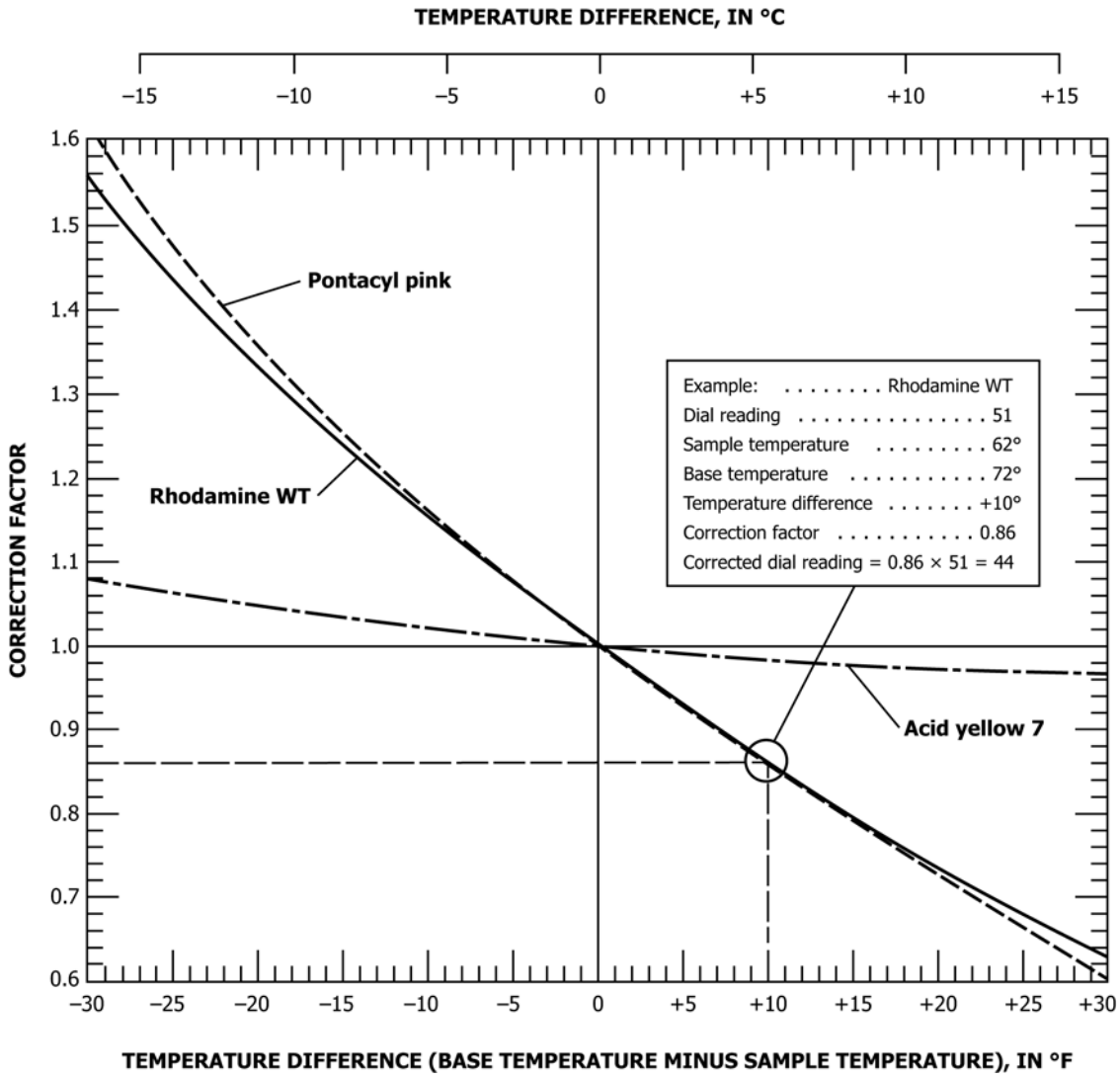


FIG. 5 Temperature-Correction Curves for Rhodamine WT, Pontacyl Pink and Acid Yellow 7 Dyes; Curve for Acid Yellow 7 Modified from Smart and Laidlaw (5)

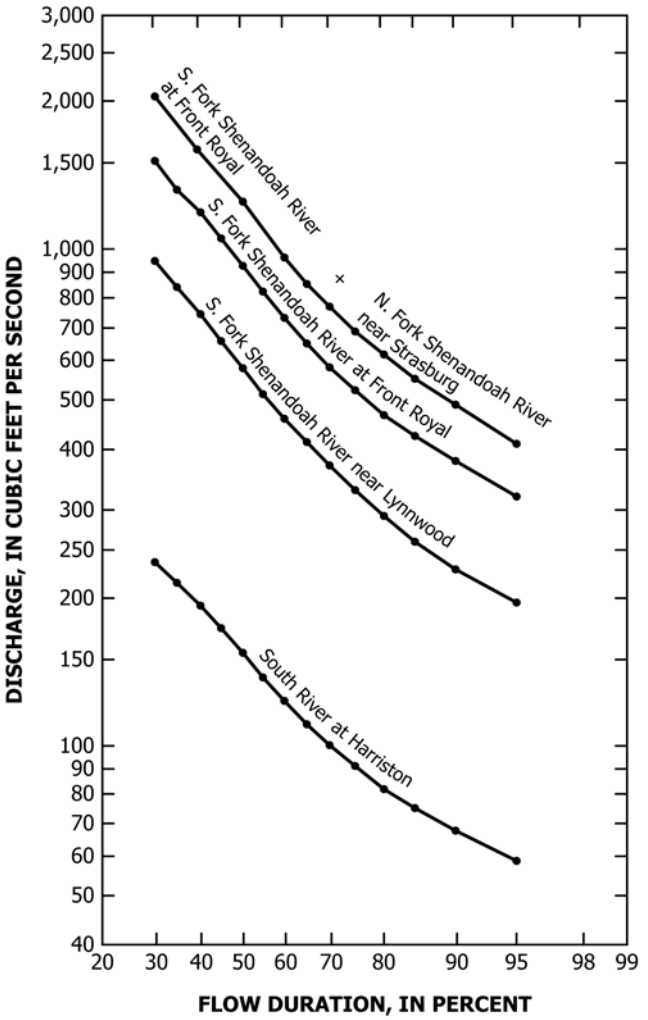


FIG. 6 Relation Between Flow Duration and Discharge at Index Gaging Stations on the South Fork Shenandoah River and its Tributaries in Virginia and West Virginia (from Taylor, et al.) (10)

constraints on the use of dye as the next step in planning the time-of-travel study. Topographic maps and available streamflow data should be examined to make the initial selection of the sites at which dye will be injected and sampled. Maps are useful for 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. Examinations of available streamflow data, discharge measurements, and gaging-station records and hydrographic comparisons assist when selecting sampling and injection sites.

12.1.4 Make a reconnaissance of the stream including the following activities:

12.1.4.1 Obtain pH information for the study reach.

12.1.4.2 Inspect the proposed injection site, or sites, to determine the flow conditions, type of dye injection to use, and accessibility for injecting the dye.

12.1.4.3 Inspect the proposed sampling sites (minimum of two per injection being desirable) to determine accessibility and suitability. Measure or estimate the channel width and depth and the mean velocity of the stream reach to the extent possible.

12.1.4.4 Estimate the 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 velocites through the pools, which occupy a larger proportion of the stream. At high flows, when pools and riffles are drowned out, mean velocities determined from current-meter measurements are commonly in close aggreement with the mean velocity of the dye cloud. The leading edge travels at a faster velocity 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.

12.1.5 A considerable upstream reach length may be required for the lateral mixing of an injected tracer to be completed before the tracer reaches the first study site. Complete 100 % mixing is seldom obtained in time-of-travel studies; 95 % mixing is assumed to be adequate for time-of-travel because it does not require such long channel lengths. This mixing will be defined as optimum mixing. Until the tracer is mixed laterally, its movement does not represent that of the total flow. Once the dye extends to both banks, so that the time-tracer concentration curves for different points across the stream have areas that are within 5 % of each other, the time-of-travel data for the interval from tracer cloud to tracer cloud will accurately represent the movement and dispersion of a solute along the reach. For this reason, it is desirable for optimum mixing of the tracer to occur prior to entry of the tracer cloud into the study reach.

12.1.6 Yotsukura and Cobb (**11**) and Fischer and others (**12**) (Eq 4 and Eq 9) derived the following equation to estimate the length of channel necessary for optimum lateral mixing from a single-point midchannel injection:

$$L_o = 0.1\,\frac{vB^2}{E_z} \tag{5}$$

where:

L_o = length of channel required for optimum mixing, ft,
v = mean stream velocity, ft/s,
B = average stream width, ft, and
E_z = lateral mixing coefficient, ft ^{2}/s.

Table 2 provides values of E_z for selected depths and slopes to aid in estimating the optimum mixing length from Eq 1. See Table 3.

12.1.7 The length of stream reach necessary to accomplish lateral mixing in wide or shallow streams may be great; to measure the travel time between two points on such a stream accurately, inject the dye at distance L_o or greater above the head of the reach. Make multiple-point or line injections of the dye to avoid having to make the injection an inconveniently long distance upstream such that natural lateral mixing will occur before the dye cloud arrives at the reach being studied. This will tag the entire flow more fully, thus reducing the distance required.

12.1.7.1 To estimate the mixing length for a multiple-point injection, Eq 5 can be written as follows (see Table 3):

TABLE 2 Values of the Lateral Mixing Coefficient, E_z, for Selected Average Flow Depths and Slopes

NOTE 1—$E_z = 1.13 d^{2/3} s^{1/2}$; s = water-surface slope; d = mean depth of the stream.

Depth, d (ft)	Slope, s(ft/ft)					
	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	0.10	0.14	0.20	0.25	0.29	0.32
3.0	0.19	0.26	0.37	0.46	0.52	0.59
4.0	0.29	0.40	0.57	0.70	0.81	0.90
5.0	0.40	0.56	0.80	0.98	1.13	1.26
6.0	0.52	0.74	1.05	1.29	1.48	1.66
8.0	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 3 Values for Coefficient, K, for Different Numbers and Locations of Injection Points

Number and Location of Injection Points	Coefficient, K, for 95 % Mixing
One center injection	0.100
Two injection points [A]	0.025
Three injection points [B]	0.011
One side injection point	0.400

[A] For an injection made at the center of each half of flow.
[B] For an injection made at the center of each third of flow.

$$L_o = K \frac{VB^2}{E_z} \quad (6)$$

where:

K = variable whose value depends on the location of injection and number of injections, and the other variables are as defined previously. Values of the coefficient K for various numbers of injection points and locations are given in Table 3.

12.1.7.2 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 approximately $(1/n)B$. Since B is squared in the mixing-length equation, modify the value of K for a single-point injection by the factor $(1/n)^2$.

12.1.8 Selection of the study site for tracer study water sample collection should reflect the physical characteristicsof the reach being studied. There are sometimes considerations that make it necessary to subdivide a long reach into shorter subreaches, for example, excessive total travel time, long cloud passage times, limitations on dye concentrations at water withdrawal points, tributary inflow, the risk of inclement weather, or changes in flow rates. In effect, make separate time-of-travel studies of subreaches rather than a single study of the entire reach. The limitation on reach length is generally the amount of time required to sample the ever-lengthening dye cloud.

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

12.1.8.2 The flow containing the dye at the junction point of a tributary inflow is analogous to a side injection and the approximate distance to mixing with the tributary flow by Eq 6 with a K value of 0.4. A sampling site below a major tributary should be located a distance at least equal to L_o below the junction. Sample several points across the section to define the dye distribution in such cases. Weighted dye concentrations on the basis of lateral discharge distribution must be made if analysis of the samples indicates that lateral mixing is not complete.

12.1.8.3 Sample the dye cloud at or below the point of optimum mixing and a minimum of one site downstream from this initial point study site. Define time-concentration curves at two study sites in each study reach to determine time-of-travel. Time-concentration curves defined at more than two study sites in each study reach not only provide better definitions of travel time, but also provide dispersion information.

12.1.8.4 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. The maximum discharge in a test reach determines the dye dosage. As with water-withdrawal points, consider major tributaries when determining study reaches.

12.1.9 Estimate the quantity of Rhodamine WT 20 % dye tracer required for injection (Kilpatrick) **(13)** using

$$V_s = 3.4 \times 10^{-4} \left(\frac{Q_{mL}}{v} \right)^{0.94} C_p \quad (7)$$

where:

V_s = volume of Rhodamine WT 20 % dye, L,
Q_m = maximum stream discharge in the study reach, ft^3/s,
L = distance to the downstream site, miles,
v = mean stream velocity, ft^3/s, and
C_p = peak concentration at the downstream sampling site, µg/L

Determine the volume of Rhodamine WT 20 % dye required to produce a peak concentration of 1 µg/L from Eq 7 or Fig. 7 for a range of discharge and reach conditions.

12.1.10 The schedule for collecting samples at each sampling site is the most uncertain aspect of the plan. Make estimates of the time to begin sampling, time intervals between samples, and duration of sampling made that will ensure adequate definition of the dye cloud passing each site. A conservative estimate of the arrival time of the leading edge and the passage time for the dye cloud is required to ensure sampling of the complete dye mass.

12.1.10.1 The relationship shown in Fig. 8 for estimating the elapsed time from the peak concentration to trailing edge concentration of 10 % of the peak concentration was derived

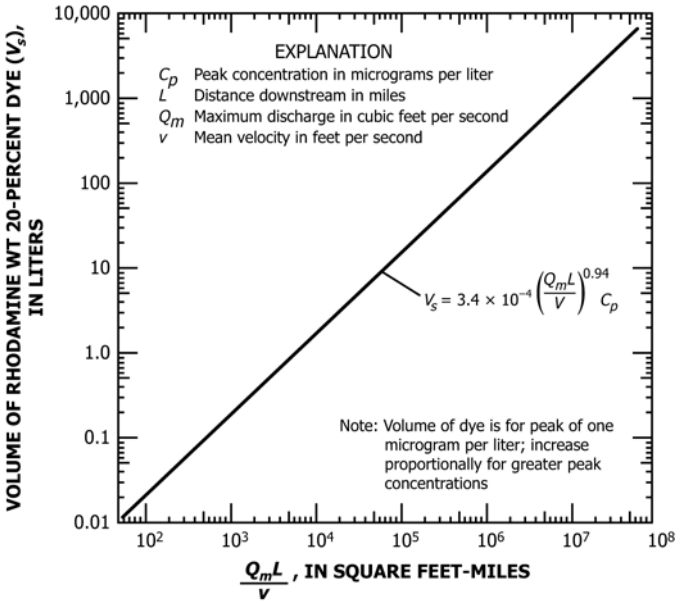


FIG. 7 Quantity of Rhodamine WT 20 % Dye Required for Slug Injection to Produce a Peak Concentration of 1 µg/L at a Distance Downstream, *L*, at a Mean Velocity, *v*, and with a Maximum Discharge, Q_m, in the Reach

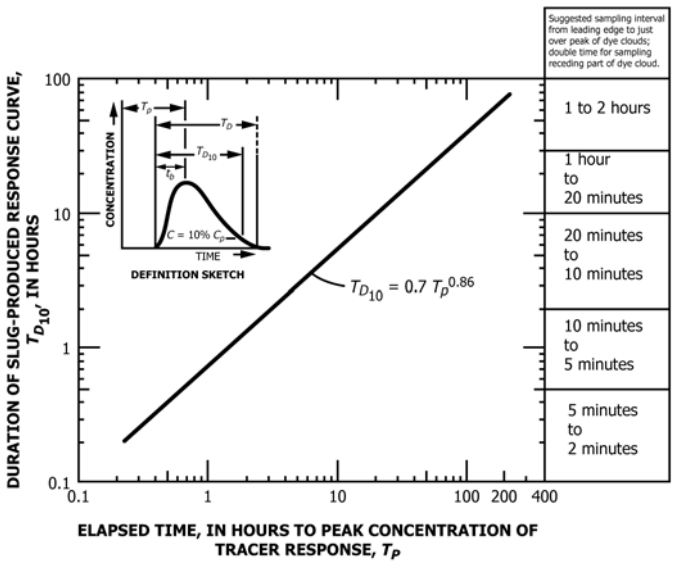


FIG. 8 Relation Between Approximate Duration of the Tracer Response and Travel Time of Peak Concentration of (t_b, Time for Dye Concentration to Build Up from the Leading Edge to the Peak; *C*, Concentration; C_p, Peak Dye Concentration)

from time-of-travel information collected nationwide. While a 10 % trailing edge occurs sooner than the 2 % trailing edge, it may be used for planning purposes as a guide for estimating the duration of response curves resulting from the slug injection of a tracer and as an aid for preparing sampling schedules. The equation is as follows:

$$T_{D_{10}} = 0.7 T_p^{\,086} \quad (8)$$

where:

$T_{D_{10}}$ = duration of the response curve to 10 % of the peak concentration, h, and

T_p = time-of-travel to the response curve peak concentration, h.

Eq 8 provides an estimate of the duration corresponding to the time at which the receding concentration reaches 10 % of the peak.

12.1.10.2 The estimation of travel times involves examination of any current or previous time-of-travel measurements made in the study reach as well as field reconnaissance of the reach, if possible. Average water velocities determined from current-meter measurements are normally faster than true reach average; steep mountain streams may be an exception.

12.1.10.3 As part of a multiple regression analysis study of time-of-travel data from all over the United States, Boning **(14)** 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 ft/ft, the equation is as follows:

$$V_p = 0.38\ Q^{0.40} s^{0.20} \quad (9)$$

where:

V_p = ft/s, and

Q = discharge, ft ^{3}/s.

For channel-control reaches having slopes ranging from 0.00016 to 0.0023 ft/ft, the equation is as follows:

$$V_p = 2.69\ Q^{0.26} s^{0.28} \quad (10)$$

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

$$T_p = 1.47\ \frac{L}{V_p} \quad (11)$$

where:

L = miles.

Use the line in Fig. 8 or Eq 9 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 % peak concentration. The 2 % trailing edge will occur later in the cloud durations that may be as much as three times longer than those estimated using this procedure.

12.1.10.4 Taylor, et al. **(10)** 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. 8), from the leading edge to the peak; the remaining two thirds was the time to recede to a concentration equal to 10 % of the peak concentration. Referring to Fig. 8, if $T_{D_{10}}$ is determined for the 10 % level based on an estimate of T_p, reducing T_p by one third of $T_{D_{10}}$ will provide an approximation of the time at which the leading edge of the dye will arrive.

12.1.10.5 Estimate the elapsed time to the leading edge of the dye cloud T_L as follows:

$$T_L = T_p - \frac{1}{3} T_{D_{10}} \quad (12)$$

and estimate the trailing edge to the 10 % level as follows:

$$T_{s_{10}} = T_p + \frac{2}{3} T_{D_{10}} \quad (13)$$

12.1.10.6 The number and frequency of dye samples can also be approximated from the estimate of $T_{D_{10}}$. The dye slug-response curve can normally be well defined by 30 to 40 well-placed data points. Division of $T_{D_{10}}$ by 30 will yield the approximate 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 line in Fig. 8 and Eq 8-13 are approximate and should be used for planning purposes only. Use fluorometric analysis and plotting of the dial reading for selected samples as a function of time in the field as soon as possible after their collection to guide immediate sampling at the first sampling section and to schedule sampling for downstream sections.

12.1.11 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 required to be injected at each site for discharge conditions expected.

(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 and their internal locations in the cross section to be sampled at each site.

(c) A proposed sampling schedule providing the starting time, sampling frequency, and ending time for each site. This schedule is for initial planning purposes only. Guide all sampling by the field measurements of dye concentration with the fluorometer.

(d) Instructions regarding discharge measurements, staff-gage readings, or measurements from a reference point to water surface, if necessary.

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

TABLE 4 Study Reach Personnel Assignment

Study Site	Personnel
Injection	John Doe
A	Susan Smith
B	Fred Smith
C	Lisa Doe
D	Richard Doe, Leslie Smith
E	John Doe [A]
F	Susan Smith [B]

[A] Personnel who make the Injection should be allowed to collect samples only if sufficient time is given to clean hands and the clothing of dye traces.
[B] Move to the second site after work is completed at the first site.

12.1.11.2 One person can usually handle the sampling requirements at each sampling site, with assistance from the fluorometer operator as necessary. Assign two people to that site (Table 4) when sampling is conducted from a boat.

12.1.11.3 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.

12.1.11.4 Maps and tables are very useful for briefing personnel and reference. Place the entire measurement plan, including injection and sampling instructions, personnel assignments, and equipment disposition, on a map. The map should show the sampling sites, injection points, road and bridge system, lodging, towns, and landmarks. Supplement the map with sketches of hard-to-find sites. Even a simple, hand-drawn map such as that shown in Fig. 9 will be useful and convey a lot of information very simply.

12.2 *Field Tests:*

12.2.1 *Injection of Dye:*

12.2.1.1 Make a single slug injection of dye in the center or in the main thread of flow. As mentioned previously, make the injection L_o (Eq 6) feet upstream from the head of the study reach and first sample site. Use multiple-point injections or line injections across the stream where the channel is wide or the flow shallow. Make the line injection in the center 75 % 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. Note the type and amount of dye and the stream stage and discharge for each injection.

12.2.1.2 The dye cloud will remain visible for some time and distance downstream following injection, depending on the amount of dye used and stream conditions. The dye can be

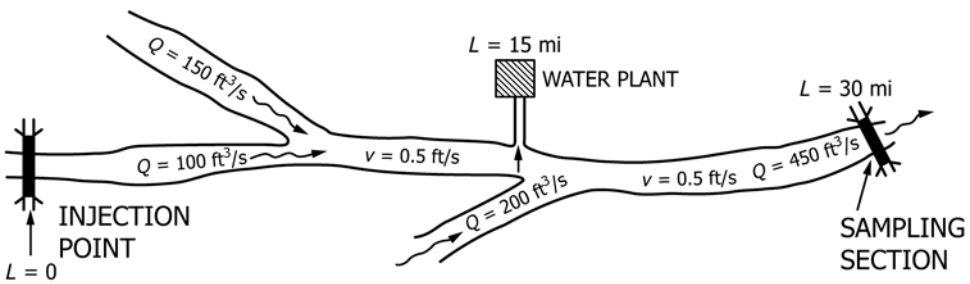


FIG. 9 Study Reach Where a Water User Is Involved and Discharge is Increasing in the Downstream Direction mi, miles; *Q*, Stream Discharge; *v*, Velocity; *L*, Stream Length

followed for a short distance easily while visible, making a rough estimate of its arrival time at the first sampling site possible.

12.2.2 *Collection of Water Samples*—At least one water sample is necessary for a fluorometer reading of background fluorescence at each site before the dye arrives. Sampling should begin early enough to ensure that the leading edge of the dye cloud is not missed. If vertical mixing is complete, the concentration will be the same throughout the vertical.

12.2.3 *Measurement of Discharge*—Measure the stream discharge (see Practice D3858) or otherwise determine it at each sampling site at the time when the dye is present. Use stage reference marks at each sampling site 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.

12.2.4 *Determination of Tracer Concentration During Studies:*

12.2.4.1 Fluorometric testing of samples in the field is necessary to guide subsequent sampling. The use of a fluorometer at the first sampling site permits on-the-spot determination of the dye concentration. Use the preliminary fluorometer results as a basis for altering the schedule to obtain 30 to 40 samples at proper time intervals to define the time-concentration curve at a sampling site. Extrapolate field plots of the fluorometer reading against time, and of distance against time of the leading edge and peak, as illustrated in Fig. 10, to check or adjust the downstream sampling schedules. In Fig. 10b, a straight line extrapolation from $t = 0$ will yield estimates of the leading edge and peak arrival times at downstream sample sites. Prompt examination of the data in the field can ensure that data are not missed.

12.2.4.2 Sampling should ideally continue until concentrations are down to near the background level. If this is not practical, it is recommended that samples be collected until the concentrations (or dial readings) have reached either 2 % of the peak or 0.2 µg/L, whichever is lower.

12.2.4.3 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, especially sample-temperature control. Basic time-of-travel information can be derived from field tests, but accurate measurements of sample concentrations should ordinarily be performed in an office or laboratory under controlled conditions. Record the fluorometer readings for samples tested in the field, and retain notes on the data sheet as shown in Fig. 11.

12.3 *Analysis and Presentation of Data:*

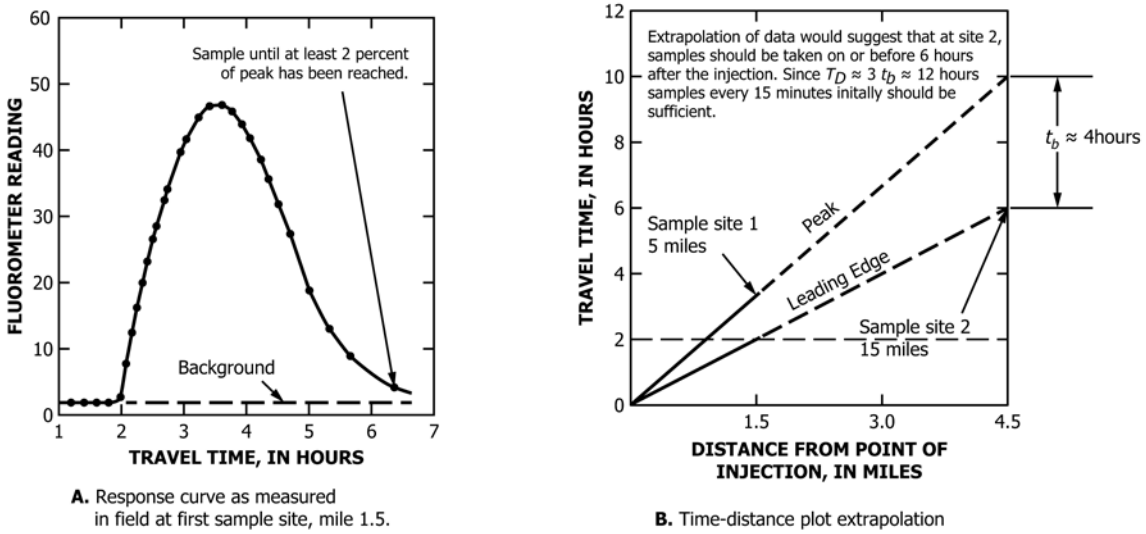
12.3.1 *Laboratory Analysis:*

12.3.1.1 Reanalyze all samples collected in the field in the laboratory under controlled temperature conditions (see Fig. 5). This is especially important if more comprehensive interpretations, such as the prediction or simulation of waste concentrations and movement, are contemplated (Kilpatrick and Taylor) (**15**).

12.3.1.2 The form shown in Fig. 11 provides for recording both field and laboratory data. Expedite the laboratory work if all of the analyses that can be made using any one fluorometer scale are made at the same time. By inspection of the field data or trial, select the scale that will yield the maximum reading for the sample representing the peak concentration for all sampling sites. Analyze all samples on this one scale, minimizing the number of fluorometer scales that will require calibrating at any one time. Examination of the field data can guide the preparation of calibration standards to cover the range of concentrations to be expected in the field samples.

12.3.2 *Time-Concentration Curves:*

12.3.2.1 Final dye concentration versus time since injection is the simplest presentation of the travel time and dispersion of



A. Response curve as measured in field at first sample site, mile 1.5.

B. Time-distance plot extrapolation

FIG. 10 Use of Data Collected at the First Sampling Site to Schedule Sampling at 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)

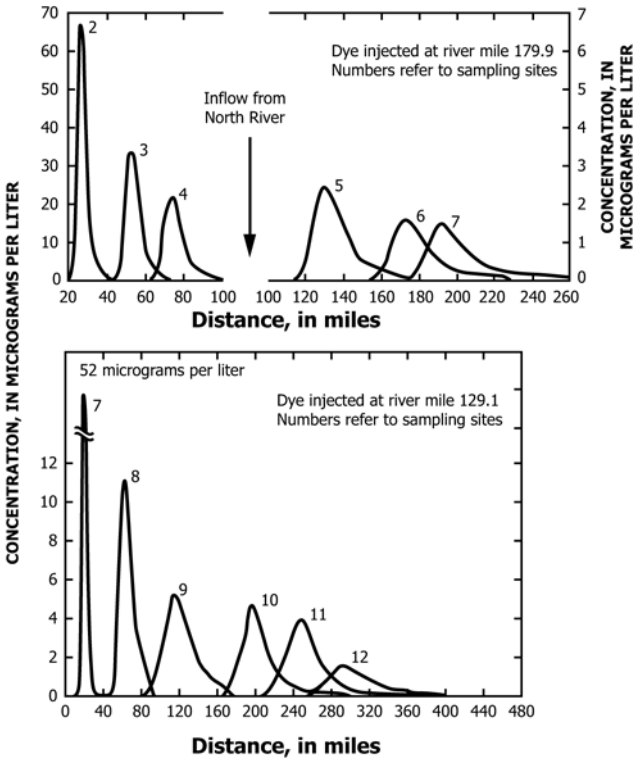


FIG. 11 Observed Time-Concentration Curves for the September 1983 Time-of-Travel Tests on the South Fork Shenandoah River, Virginia; 85 % Chance of Excedence Flow Duration

the dye cloud as it moves through the study reach. These time-concentration curves are useful for illustrating the techniques used in the dye study and represent the responses to a slug injection. The concepts of leading edge, peak, centroid, and trailing edge can be explained on these graphs easily.

12.3.2.2 Plot the concentration for each sample against elapsed time and a smooth curve fitted to the points. Shown in Fig. 10, the typical curve 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.

12.3.2.3 As an example, the time-concentration curves for sampling Sites 2 through 12 are shown in Fig. 11 for the Shenandoah River tests performed in September 1983 (Taylor, et al.) (**10**) at a flow having a duration with an 85 % chance of exceedence. These sites comprise the two upstream subreaches. It will be noted that two time-concentration curves were measured at Site 7, with 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 River. Longitudinal dispersion in the reach remained relatively constant despite this.

12.3.3 *Travel Time:*

12.3.3.1 Determine the elapsed times and travel times of the leading edge, peak concentration, centroid, and trailing edge of the dye clouds from the time-concentration curves for each sampling site. Elapsed time is the time from injection of the dye to the particular part of the response curve of interest. Travel time is the time-of-travel between common parts of the response curves: leading edge, peak, centroid, and trailing edge. These data are typically presented in tabular form, such as Table 5. As it is defined in this test method, the trailing edge time is the time at which the concentration decreases to a level of 2 % of the peak concentration observed at a sampling site. In Table 5, the trailing edge times reported for the study are those occurring when the dye concentration decreased to a level equivalent to 10 % of the peak concentration. As shown in Fig. 12, a graphical presentation of these data provides a clear picture of how dispersion elongates the tracer cloud. Fig. 13 shows cumulative travel time data for the 1983 dye studies performed on the Shenandoah. The data used in this summation process are travel times from cloud to cloud rather than elapsed times from points of injection. This is why the subreaches were overlapped or the injections were made a mixing distance upstream from the reach of interest.

12.3.3.2 The curves in Fig. 13 are for the two flow durations selected for testing. It is desirable to interpolate between these values to obtain velocity estimates for other discharges. Calculate the velocities of the leading edge, peak concentration, and trailing edge of the dye cloud between successive sampling sites by dividing the segment lengths by the travel times (Table 5). These velocities are plotted in Fig. 14 on log-log coordinates as a function of the average daily discharge(s) indexed to records for a edging station during the time the dye cloud moved between the two sampling sites. The lines represent the velocities of leading edge, peak concentration, and trailing edge as a function of discharge at the index gaging station. Prepare plots for the discharges expected at each index gaging station.

12.3.3.3 The relations described above and illustrated in Fig. 14 are entered with discharges corresponding to selected flow-duration values of 40, 50, 60, 65, 70, 75, 80, 85, 90, and 95 % for the index gaging station(s) used; Table 6 gives these data for the test reach between Sites 7 and 8 on the Shenandoah River using the Front Royal gaging station as the index station. Incremental velocities can be determined at ten flow durations for an entire reach in a similar manner.

12.3.3.4 The distance between sampling sites is then divided by these incremental velocities to provide an incremental travel time at each of the ten flow durations for leading edge, peak concentration, and trailing edge. In Table 7, incremental times are accumulated from Waynesboro to Harpers Ferry for the Shenandoah River example. Fig. 15 is a graphical presentation of these data. Similar tables and figures may be presented for the leading and trailing edge travel times. Use these data and curves 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 Fig. 13 and Fig. 15 should be noted. Fig. 15 provides the information for an entire range of flows, in contrast to Fig. 13, 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.

TABLE 5 Travel Time Data for Dye Study of September 1983 on the South Fork Shenandoah River, Virginia and West Virginia (from Taylor and Others)

Site No.	Site Name	Distance			Leading Edge			Peak Concentration				Trailing Edge			
		Upstream from Mouth, miles	Subreach Length, miles	From Point of Injection, miles	Time Since Injection, h	Travel Time, h	Cumulative Travel Time, h	Velocity, miles/h	Time Since Injection, h	Travel Time, h	Cumulative Travel Time, h	Velocity, miles/h	Time Since Injection, h [A]	Travel Time, h	Cumulative Travel Time, h	Velocity, miles/h
Injected 12 L of 20 % Rhodamine WT Dye at 1700 h 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		0.322		26		0.285		32		0.231
3	Crimora	165.8		14.1	44		41		52		48		66		60	
			6.4			20		0.320		23		0.278		25		0.256
4	Harriston	159.4		20.5	64		61		75		71		91		85	
			16.8			52		0.323		56		0.300		67		0.251
5	Island Ford	142.6		37.3	116		113		131		127		158		152	
			13.5			40		0.338		42		0.321		52		0.260
6	Shenandoah	129.1		50.8	156		153		173		169		210		204	
			7.9			18		0.439		20		0.395		26		0.304
7	Grove Hill	121.2		58.7	174		171		193		189		236		230	
Injected 35 L of 20 % Rhodamine WT Dye at 1700 h on September 6, 1983, at Mile 129.1																
7	Grove Hill	121.2		7.9	14		...		17		...		24		...	
			15.0			36		0.417		46		0.326		83		0.238
8	U.S. Highway 211	106.2		22.9	50		207		63		235		87		293	
			7.0			34		0.206		52		0.135		76		0.092
9	Bixler Bridge	99.2		29.9	84		241		115		287		163		369	
			26.1			78		0.335		81		0.322		85		0.307
10	Bentonville	73.1		56.0	162		319		196		368		248		454	
			15.4			48		0.335		50		0.308		57		0.270
11	Front Royal	57.7		71.4	208		365		246		418		305		511	
			10.2			48		0.212		46		0.222		73		0.140
12	Morgan Ford	47.5		81.6	256		413		292		464		378		584	
Injected 57 L of 20 % Rhodamine WT Dye at 1100 h on September 6, 1983, at Mile 52.4																
12	Morgan Ford	47.5		4.9	13		...		23		...		111		...	
			10.9			23		0.474		35		0.311		32		0.341
13	U.S. Highway 17650	36.6		15.0	36		436		58		499		143		616	
			14.5			28		0.518		31		0.468		33		0.439
14	State Highway 7	22.1		30.3	64		464		89		530		176		649	
			13.7			35		0.391		38		0.360		43		0.319
15	State Highway 9	8.4		44.8	99		499		127		568		219		692	
			7.6			32		0.238		38		0.200		43		0.177
16	Harpers Ferry	0.8		51.6	131		531		165		606		262		735	

[A] Determined at 10 % of peak concentration.

12.3.3.5 Numerous approaches have been used to present time-of-travel information. The approach chosen should be readily usable when 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. Except in certain worst case scenarios (usually extreme low flow), it is thus highly advisable to perform field tests at more than one stream discharge. For example, Jack (**16**) found that the travel time of a solute peak on the South Branch Potomac River from Petersburg, WV to its confluence with the North Branch Potomac River, a distance of 69 miles, would vary from approximately 3 days at 1500 ft /s to 18 days at 70 ft /s. Jack performed time-of-travel tests at two flow durations, 32 and 95 %, and therefore was able to provide curves for predicting the rate of solute movement. A single time-of-travel test would be of little predictive value. Three or more tests spaced evenly over the same range of flow durations would provide improved confidence for predicting the rate of solute movement over such a broad range of flows.

13. Precision and Bias

13.1 Determination of the precision and bias of this test method is not usually conducted.

13.2 In accordance with 1.6 of Practice D2777, an exemption to the required precision and bias statement was recommended by the Results Advisor and concurred with by the Technical Operations Section of the Executive Subcommittee on June 24, 1992.

13.3 The accuracy of measured tracer concentration is related to the accuracy of the standards prepared for fluorometer calibration and the consistency of temperatures between samples and standards. However, concentration accuracy is not important in time-of-travel studies because only relative concentrations (leading edge, peak, and so forth) are used for determining the travel times.

13.3.1 Using at least the minimum numbers of dilutions required to prepare standards decreases the potential for error in measurement.

TIME-OF-TRAVEL STUDY ON _____

SAMPLING SITE _____

Dye injected at _____ Time _____ Date _____

Amount injected _____ Type of dye _____ Conc. in % _____

Sampling section discharge _____ cfs; width _____ ; mean depth _____

			Field Sampling and Analysis				Final Laboratory Analysis					
Sample No.	Sample Point	Sample Time	Fluorometer Readings				Fluorometer Readings				Dye Conc. (μg/L)	
			1X	3X	10X	30X	1X	3X	10X	30X		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	

Column 1. Number on sample bottle.

2. When more than one point in section is sampled, indicate as "A," "B," "C," etc., from left to right bank.

3. Military time.

4–11. Fluorometer dial readings on scales used.

12. Based on fluorometer calibration--show dye concentration in microgram per liter in stream. If background has not been suppressed on the fluorometer, subtract background reading prior to using calibration curve.

FIG. 12 Form for Recording Dye-Sample Data

13.3.2 The individual time intervals between sample concentrations at each study site should be such that each sample represents less than 5 % of the total mass of tracer injected.

13.4 The accuracy of measured indexed river discharges is detailed in Practice D3858.

14. Keywords

14.1 dispersion; fluorometry; mixing; surface water; time-of-travel; tracers

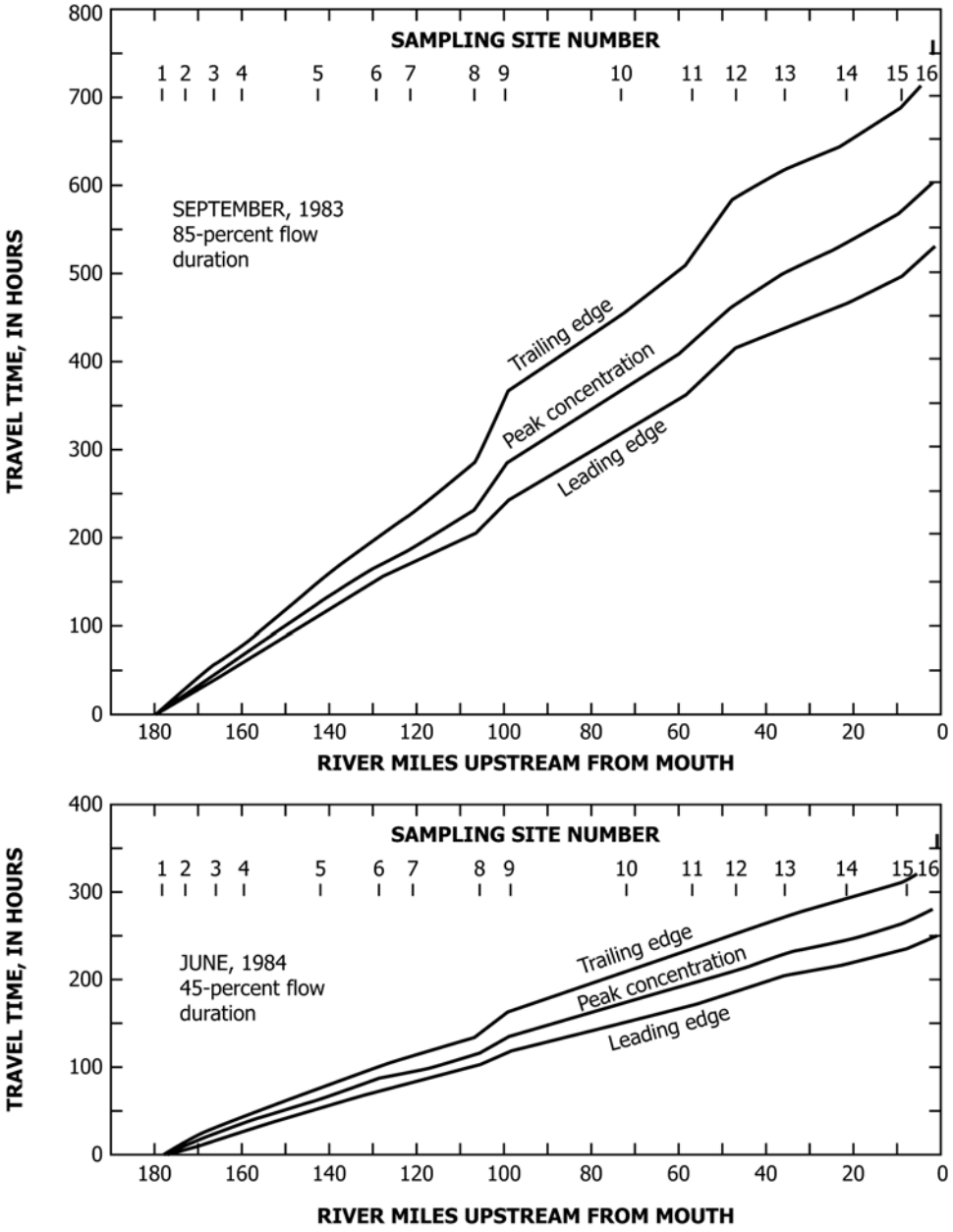


FIG. 13 Cumulative Travel Time for the South Fork Shenandoah River, Virginia, and West Virginia (from Taylor, et al.) (10)

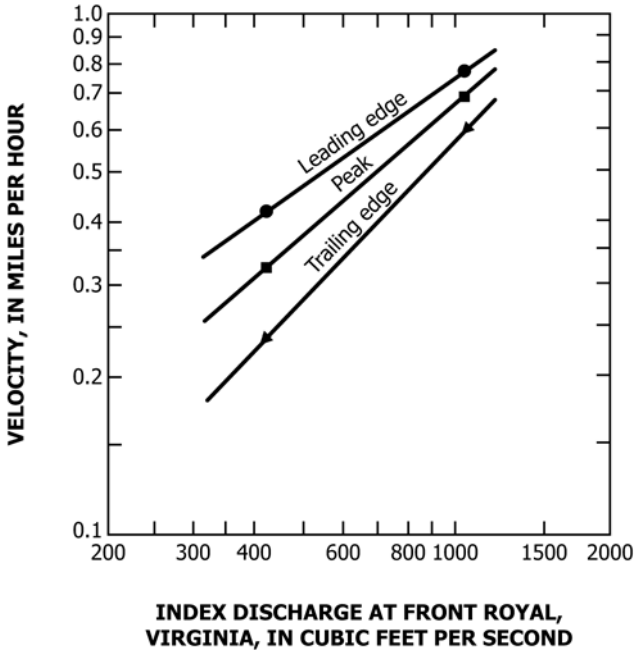


FIG. 14 Travel Time Velocities in the Reach Between Sites 7 and 8 as a Function of Index Discharges at the Front Royal Station on the South Fork Shenandoah River, Virginia (from Taylor, et al.) (10)

TABLE 6 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

Flow Duration		Velocity, miles/h		
Percent Q, [A]	ft ^{3}/s	Peak	Leading Edge	Trailing Edge
40	1190	0.770	0.830	0.670
50	930	0.620	0.700	0.520
60	728	0.505	0.595	0.405
65	647	0.460	0.550	0.365
70	579	0.420	0.510	0.330
75	521	0.385	0.470	0.295
80	468	0.350	0.440	0.265
85	421	0.315	0.410	0.235
90	377	0.295	0.380	0.213
95	318	0.255	0.335	0.178

[A] Q = stream discharge.

TABLE 7 Travel Time for Peak Concentration of a Solute on the South Fork Shenandoah River at Selected Flow Durations

Site No.	Site Name	Miles Upstream from Mouth	Distance Between Sampling Sites, miles	Travel Time of Peak Concentration of Dye Cloud, h, for Indicated Flow Duration, %									
				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	Bixter 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. Highways 17 and 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	0.8		263	321	390	432	475	522	571	629	688	794

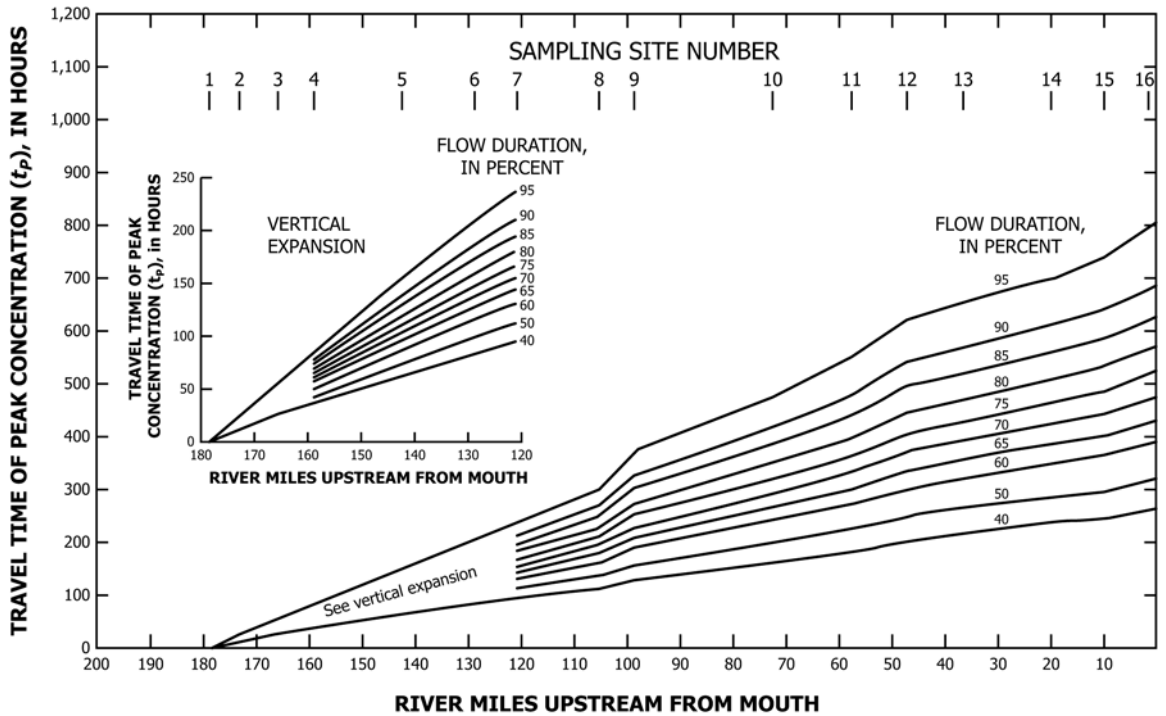


FIG. 15 Travel Time-Distance Relation for Peak Concentrations of a Solute at Selected Flow Durations, South Fork Shenandoah River from Waynesboro, Virginia, to Harpers Ferry, West Virginia (from Taylor, et al.) (10)

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