

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

**MEASUREMENT OF DISCHARGE
USING TRACERS**

Book 3
CHAPTER A16





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of the United States Geological Survey

Chapter A16

MEASUREMENT OF DISCHARGE
USING TRACERS

By Frederick A. Kilpatrick and Ernest D. Cobb

Book 3

APPLICATIONS OF HYDRAULICS

DEPARTMENT OF THE INTERIOR

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UNIT CONVERSION

<i>Multiply inch-pound unit</i>	<i>By</i>	<i>To obtain SI unit</i>
cubic foot (ft ³)	28.320	cubic meter (m ³)
cubic foot per second (ft ³ /s)	0.028	cubic meter per second (m ³ /s)
degrees Fahrenheit (°F) minus 32°	0.556	degrees Celsius (°C)
foot (ft)	3.048	meter (m)
foot per second (ft/s)	0.305	meter per second (m/s)
gallon (gal)	3.785	liter (L)
gallon (gal)	3785	milliliter (mL)
inch (in)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
pound (lb)	453.6	gram (g)
square foot per second (ft ² /s)	9.290	square meter per second (m ² /s)

SYMBOLS, DEFINITIONS, AND UNITS

<u>Symbol</u>	<u>Definition</u>	<u>Unit</u>
A _c	Area under the time-concentration curve	(μg/L)(min)
B	Average width of stream	ft
c	Plateau concentration	μg/L
c _i	The concentrations at points i across a section	μg/L
\bar{c}	Weighted or average plateau concentration	μg/L
C	Concentration of injected solution	μg/L
C _a	Average concentration for an entire tracer cloud when sampled at a constant rate over a time period, ΔT _c	μg/L
C _i	Initial concentration	μg/L
C _n	New concentration after a dilution	μg/L
C _p	Peak concentration	μg/L
C _s	Concentration of stock solution, generally as obtained from the manufacturer	μg/L
C _{1,2,3,4}	Concentrations resulting from serial dilutions 1 through 2, 3, and 4 dilution steps	μg/L
C _f	Final standard concentration	μg/L
d	Mean depth of stream	ft
D	Diameter of orifice	in
D _T	Total dilution factor; the product of a series of dilutions, D ₁ ×D ₂ ×D ₃ , and so forth	---
D _{1,2,3,4}	Dilutions for each step, 1, 2, 3, and 4 of a serial dilution, respectively	---
D _C	Dilution factor to reduce C _s to C	---
E _z	Transverse mixing coefficient	ft ² /s
g	Acceleration of gravity	ft/s ²
h	Head on orifice	in
K	Mixing length coefficient	ft ²
k	Fluorometer scale factor	---
L	Length of measurement reach	ft
L _m	Mixing length	ft
L _o	Channel length required for optimum mixing; usually corresponds to about 95 percent mixing	ft
M	Mass of tracer injected	g
M _{1,2...n}	Series of slug injections of equal mass	g
P _m	Percentage of mixing	---
q	Rate of constant tracer injection	mL/min
Q	Total stream discharge	ft ³ /s
Q _{a,b,c...n}	Portions of the total stream discharge, Q	ft ³ /s
Q _i	Discharges applicable to the points, i	ft ³ /s
r	Fluorometer dial reading for individual stream sample	---
\bar{r}	Weighted or average fluorometer dial reading for stream samples	---

R	Fluorometer dial reading for a standard prepared from the injection solution or prepared from stock solution used in preparing the injection solution	---
s	Water-surface slope	ft/ft
S_G	Specific gravity	---
ΔT_c	Period during which dye cloud is sampled at a constant rate	min
t_c	Lapsed time between centroids of time concentration curves	s
T_d	Duration in time for tracer cloud to pass any one point in section	min
T_D	Duration in time required for entire tracer cloud to pass a section	min
T_e	Elapsed time to leading edge of dye cloud	min
T_f	Elapsed time to trailing edge of dye cloud	min
T_p	Elapsed time to maximum concentration of dye cloud	min
v	Mean stream velocity	ft/s
v^*	Shear velocity	ft/s
V_d	Volume of dye solution	mL
V_I	Volume of dye solution injected into stream	mL
V_s	Volume of stock dye solution	L
V_w	Volume of diluent, usually distilled water	mL
V	Volume of conduit	ft ³
W_d	Weight of dye	g
W_s	Weight of stock dye solution	g

EQUATIONS

For Slug-Injection Method

$$(1) \quad Q = \frac{M}{A_c} \text{ (without unit conversion factor)}$$

$$(3) \quad Q = 5.89 \times 10^{-7} \frac{S_G V_I C}{A_c}$$

$$(8) \quad Q = 5.89 \times 10^{-7} \frac{S_G V_I C}{\Delta T_c C_a}$$

For Constant-Rate Injection Method

$$(2) \quad qC = Qc \text{ (without unit conversion factor)}$$

$$(9) \quad Q = 5.89 \times 10^{-7} q \frac{C}{\bar{c}}$$

$$(10) \quad Q = 5.89 \times 10^{-7} q \left[\frac{R}{\bar{F}} \times \frac{D_C}{D_T} \right]$$

$$(11) \quad Q = 5.89 \times 10^{-7} q \left[\frac{R}{\bar{F}} \times \frac{1}{S_G D_T} \right]$$

For Mixing Length Determinations

$$(4) \quad L_0 = 0.1 \frac{vB^2}{E_z}$$

$$(5) \quad L_0 = 0.088 \frac{vB^2}{d^{3/2} s^{1/2}}$$

$$(12) \quad L_m = K \frac{vB^2}{E_z}$$

For Volume of Rhodamine WT Dye

$$(6) \quad V_s = 3.79 \times 10^{-5} \frac{QL}{v} C_p$$

For Serial Dilution Determinations

$$(7) \quad C_n = C_i \left[\frac{W_d}{V_w + V_d} \right] = C_i S_G \left[\frac{V_d}{V_w + V_d} \right]$$

For Computing Percentage Mixing

$$(14) \quad P_m = 100 - \frac{50}{\bar{c}Q} \sum_{i=1}^N |c_i - \bar{c}| Q_i$$

For Tracer Velocity Discharge Measurements

$$(13) \quad Q = \frac{V}{t_c}$$

MEASUREMENT OF DISCHARGE USING TRACERS

By Frederick A. Kilpatrick and Ernest D. Cobb

Abstract

The development of fluorescent dyes and fluorometers that can measure these dyes at very low concentrations has made dye-dilution methods practical for measuring discharge. These methods are particularly useful for determining discharge under certain flow conditions that are unfavorable for current meter measurements. These include small streams, canals, and pipes where

1. Turbulence is excessive for current-meter measurement but conducive to good mixing.
2. Moving rocks and debris may damage instruments placed in the flow.
3. Cross-sectional areas or velocities are indeterminate or changing.
4. The flow is unsteady, such as the flow that exists with storm-runoff events on small streams and urban storm-sewer systems.
5. The flow is physically inaccessible or unsafe.

From a practical standpoint, such methods are limited primarily to small streams, because of the excessively long channel-mixing lengths required for larger streams. Very good accuracy can be obtained provided that

1. Adequate mixing length and time are allowed.
2. Careful field and laboratory techniques are used.
3. Dye losses are not significant.

This manual describes the slug-injection and constant-rate injection methods of performing tracer-dilution measurements. Emphasis is on the use of fluorescent dyes as tracers and the equipment, field methods, and laboratory procedures for performing such measurements. The tracer-velocity method is also briefly discussed.

Introduction

Tracer gaging may be divided into two categories: the tracer-dilution method and the tracer-velocity method. The latter is commonly known as the salt-velocity method (Aastad and Reinhardt, 1954), although any tracer may be used. It has the advantage of simple injection, requires a relatively small amount of tracer, and is not critically dependent on the conservativeness of the tracer. Its chief disadvantages are the requirements that the channel reach be uniform and that the channel-flow geometry be defined exactly; it also entails extensive sampling. This method, although not frequently used, can be very accurate in canals and pipes

where the cross-sectional area is uniform and accurately measurable. It is discussed in a later section.

Measurement of stream discharge by dilution methods depends on the determination of the degree of dilution of an added tracer solution by the flowing water. Dilution methods of measuring discharge have been known since at least 1863 (Spencer and Tudhope, 1958, p. 129). Until recently, chemical salts (Ostrem, 1964) were generally used as the tracer injected into the stream. Radioactive tracers have been used successfully, but handling problems have limited widespread use (Schuster and Hansen, 1968). The development of stable fluorescent dyes and fluorometers that can measure them at very low concentrations has greatly enhanced the use of dilution methods (Morgan and others, 1977, and Kilpatrick, 1968, 1969). Hence, this manual addresses the use of fluorescent dyes as the tracer to be used, although the principles discussed apply to any tracer.

Dilution methods are useful under the following flow conditions:

1. Where it is difficult or impossible to use a current meter due to high velocities, turbulence, or debris.
2. Where, for physical reasons, the flow is inaccessible to a current meter or other measuring device.
3. Where, for some conditions, the rate of change of flow is such that the time to make a current-meter measurement is excessive.
4. Where the cross-sectional area cannot be accurately measured as part of the discharge measurement or is changing during the measurement.

Typical examples of situations where the dilution methods might be used are turbulent mountain streams, pipes, canals, sewers, ice-covered streams, and sand-channel streams. The purpose of this manual is to describe the dyes, equipment, and methods used to measure discharge by the dilution method using both the constant-rate injection and the slug-injection technique.

Note that this manual goes beyond what is required to make a simple dilution-type discharge measurement and that the user need read through only the sections on Theory, Slug-Injection Method, and Constant-Rate Injection Method before attempting such measurements. Also bear in mind that while many of the same techniques as those used in time-of-travel studies are used in making dye-dilution discharge measurements, a higher level of accuracy is desired, and therefore greater care in performance is required. The user is urged to perform a dye-dilution discharge measurement on an ordinary small stream before attempting more difficult measurements. The stream chosen for a trial should be one where a good current-meter or weir measurement can be made concurrently to provide verification.

The fluorometric techniques described in this report are oriented toward use of the Turner Model 111 and Turner Designs Model 10 fluorimeters because those instruments are in general use in the United States Geological Survey; however, other brands of fluorimeters may be used. Additional information about tracers and equipment is given in the manual by Wilson and others (1984). The methods and techniques presented in this manual are based on experimental studies by F. A. Kilpatrick and E. D. Cobb, and by B. J. Frederick, J. F. Wilson, Jr., J. F. Bailey, and numerous others.

Theory

Measurement of the degree of dilution of a known quantity of tracer after its mixing in a flowing stream of water is the basis of dilution gaging. There are two main approaches: (1) the slug injection of a known amount of tracer into the flow, which requires that the dilution of the tracer be accounted for by the complete measurement of its mass downstream; for this reason, it is sometimes referred to as the total recovery method; and (2) the constant-rate injection of a tracer solution into the flow, which requires only the measurement of the plateau level of concentration that results downstream after equilibrium has been reached. The principles are simple, yet their successful application in streams, canals, pipes,

and elsewhere requires a good understanding of the dispersion process. No elaborate theoretical treatment is used in explaining these processes; however, the reader is urged to heed the following principles, for they can eliminate many of the problems others have had in performing such measurements and are helpful in understanding the application of tracers in hydrologic studies in general.

Slug injection

The slug injection of a tracer into a flowing stream is the simplest of all methods, from the standpoint of equipment needs. Where radioactive tracers are employed, handling problems make slug injection virtually the only feasible method. Figure 1 shows the resulting response curves at different distances downstream that may result from a single midchannel slug injection of tracer. These response curves are time-concentration curves familiar to many who have been involved in time-of-travel studies; however, stream reaches used for a dilution-discharge measurement are relatively short, and the duration of passage of the entire cloud, T_D , rarely exceeds 1 hour. Large distances such as those in time-of-travel studies may result in significant loss of tracer and, hence, inaccurate measurements of discharge. Significant losses of tracer do not ordinarily occur in the short stream reaches used for dilution-discharge measurements, although the possibility must always be kept in mind.

The discharge as measured by the slug-injection tracer-dilution technique is

$$Q = \frac{M}{A_c} \quad (1)$$

where Q is the volume rate of flow of the stream;

M is the mass of tracer injected; and
 A_c is the area under the response curve obtained after adequate mixing of the tracer in the flow.

¹For clarity, units are ignored here; a constant is required to yield a dimensionally correct equation for the units used in this report.

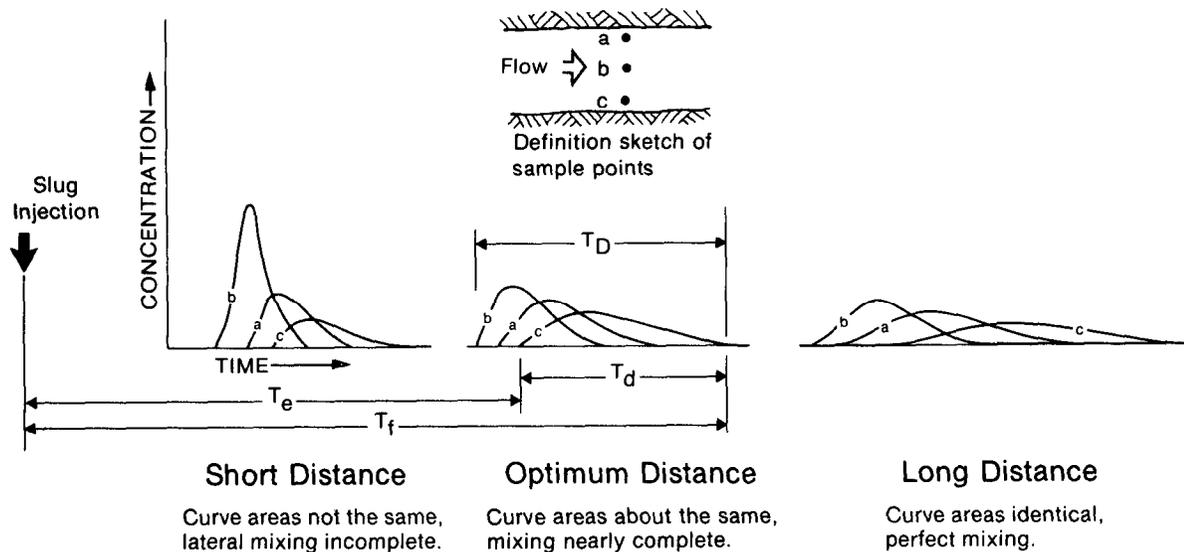


Figure 1.—Typical response curves observed laterally and at different distances downstream from a slug injection of a tracer in the center of a stream.

Most important, therefore, is a measurement of the response curve far enough downstream that mixing is almost complete in a cross section.

At short distances downstream from a slug injection, the tracer is not fully mixed in the total flow of the stream, being more in the center than along the banks (see fig. 1). Furthermore, the response curve measured in the center may be much shorter in duration, T_a , than for those along the banks. This is a common occurrence, because flow along the banks is usually slower and the channel banks tend to slow and elongate the tracer cloud. At such a short distance, an accurate measurement of discharge by dilution cannot be made by ordinary methods. When uniform mixing is reached, the areas under the time-concentration curves are essentially the same regardless of shape; at too short a distance, they are not.

From a practical standpoint, complete mixing does not need to be attained. A good dilution-discharge measurement can be made at what is defined here as an optimum distance, L_o , downstream.² The distance is optimum be-

cause T_D is not too long, and thus sampling of the complete response curves at several points laterally across a section is feasible. Note that the peaks of the response curves are not the same, and that their lengths, or durations, and arrival and departure times are different. Nevertheless, the areas under the individual response curves are nearly the same, which indicates good mixing and allows a good dilution-discharge measurement.

If the response to the tracer slug is measured farther downstream, mixing will be nearly perfect, and the individual time-concentration curves will be nearly identical in area; therefore, a very accurate measurement of discharge may be obtained. That is true, however, only if sampling has been performed for a sufficient time, particularly of the drawn-out tails of the clouds, and if loss of tracer has not occurred because of excessive time of exposure. Frequently, failure to measure the low-level concentrations of the trailing edge of the tracer is misinterpreted as a loss of tracer. It is not a real loss, but merely a sampling or measurement failure.

The foregoing discussion shows that predicting the length of channel for optimum mixing is not a simple task. Formulas to aid in estimating mixing lengths and approaches to reducing the effective reach lengths needed are discussed subsequently.

²The optimum distance is usually where mixing is about 95 percent complete. The concept of degree of mixing and how it is computed is discussed in appendix A.

Constant-rate injection

A continuous, constant-rate injection of tracer may be simulated from the response curve of a slug injection using the superposition principle (Yotsukura and Kilpatrick, 1973). This can best be understood by using any one of the slug-response curves in figure 1 to simulate the response of a continuous injection at the same location. In figure 2, the solid response curve is due to the slug injection, M_1 ; T_e and T_f are the elapsed times to the arrival of the leading edge and trailing edge of the response curve to M_1 . Assuming the streamflow is steady, continuing to inject a series of tracer slugs of equal amounts, M_2, M_3, \dots, M_n , at uniform time intervals (a constant-rate injection), would yield a series of identical response curves. Of course, if the same soluble tracer were continuously injected, the individual response curves would not be distinguishable and there would be an ever-increasing buildup of concentration with time until T_f was reached. In effect, the superimposed slug-response curves are being added as they overlap. At time T_f , corresponding to when the trailing edge of the first slug would have passed the point of observation, a plateau of constant concentration is first reached at that point in the channel. At that time, for a constant injection, an equilibrium condition is reached. Continued injection after T_f would re-

sult in a plateau of constant concentration at that point, so long as the stream discharge and rate of tracer injection did not vary.

The results illustrated in figure 2 are shown also in figure 3 for the same three distances and the three lateral locations used in the example of figure 1. The same slug-response curves used in figure 1 are used in figure 3 to simulate the responses to a continuous injection of tracer as obtained by superimposing the uniformly repeated slug-response curves.

Figure 3 shows that for the short distance, plateaus of different concentrations are obtained laterally. The degree of mixing is poor and identical for the continuous injection and the slug injection.

At the optimum distance, the plateaus laterally tend to converge to the same concentration and reflect dilution by the stream discharge, but their concentrations are not identical; nevertheless, mixing is sufficient to produce a good tracer dilution-discharge measurement. Note that tracer would have to be injected continuously for at least a time, T_D , to first reach a completely stabilized plateau for all points across the channel at that distance. The minimum period corresponds to the difference in time for the earliest arriving tracer (center or point b) and the latest departing tracer (side or point C). Of course, it would be necessary to inject tracer for a time slightly greater than T_D

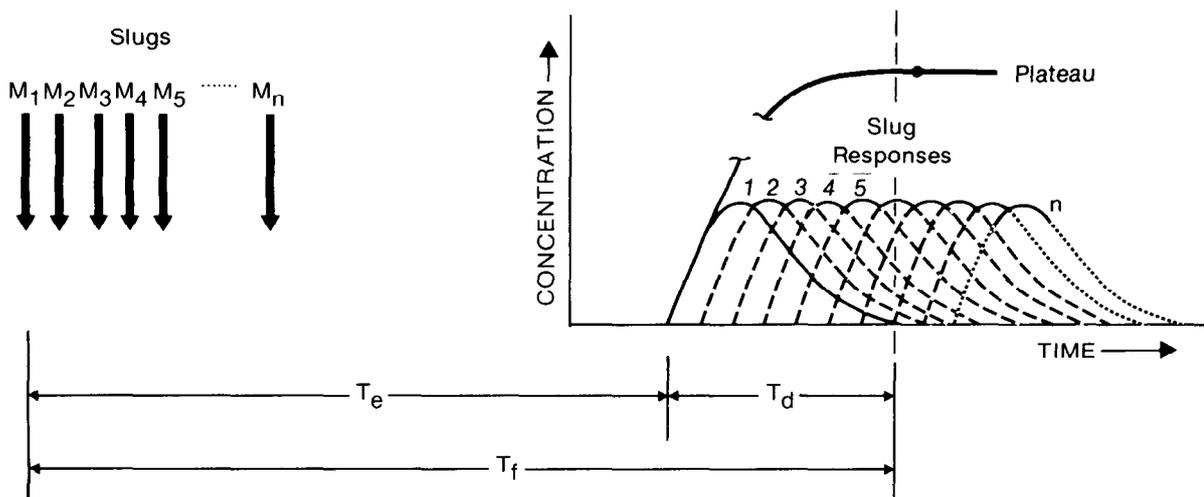
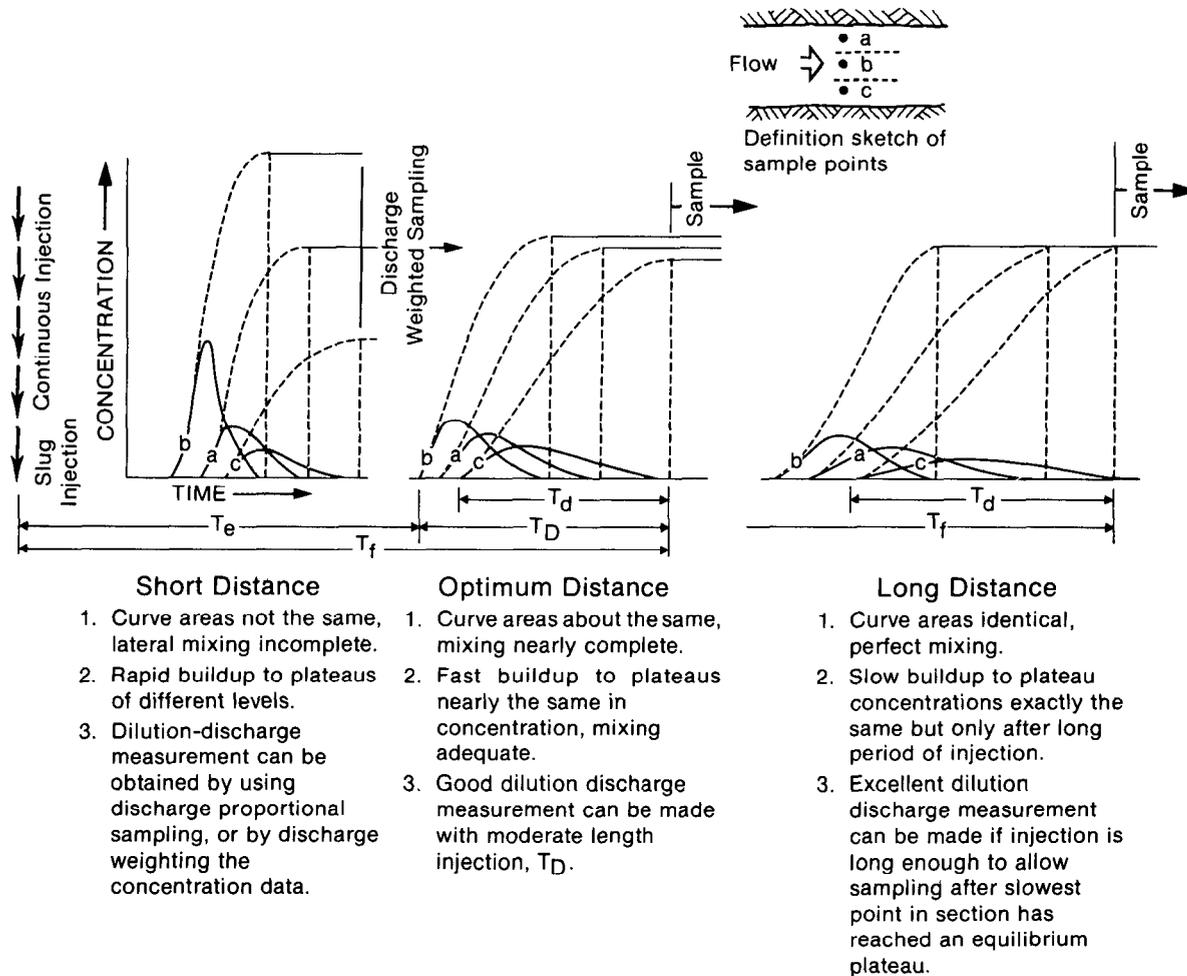


Figure 2.—Superposition of slug-response curves to simulate constant-injection buildup to a plateau at one location in a stream section.



GENERAL: Minimum length of constant injection required, T_D , is equal to longest time slug dye cloud would be present at any location in the stream. Danger is in not injecting long enough and not sampling late enough, samples taken prior to T_f would give impression mixing was poor and (or) yield data suggesting, incorrectly, a tracer loss

Figure 3.—Time-concentration curves for slug and simulated constant injections observed at three points laterally across the channel at three different distances downstream from the injection point.

(shown only for the optimum distance) to allow for sampling the fully developed plateau. At a long distance (fig. 3), the resulting plateau concentrations are virtually identical if the constant injection is made over sufficient time and if sufficient time is allowed for buildup across the entire channel before sampling. Depending on the nature of the channel and the mixing distance selected, the injection duration and the lapsed time necessary before sampling the correct plateau concentration may be greater than anticipated.

Unlike the slug-injection method, the entire response curves need not be measured, only the plateau concentrations. Once equilibrium plateau conditions have been reached, the conservation-of-mass principle and the continuity equation

$$qC = Qc \quad (2)$$

³For clarity, units are ignored here; a constant is required to yield a dimensionally correct equation for the units used in this report.

apply, whereby the amount of tracer being injected, qC , equals that passing the sampling section, Qc ,

where q is the rate of tracer injection and is assumed to be very small relative to Q ;

C is the concentration of the tracer being injected; and

c is the resulting plateau concentration after dilution by Q .

Certain conclusions can be drawn from examination of figures 1, 2, and 3 for a given stream and flow:

1. Sampling of the response curves from a slug injection must be for a period of time, T_D , and until time T_f ; T_f is the earliest time at which the plateau resulting from a constant injection can be sampled. Thus, the effective elapsed time required to make a discharge measurement is essentially the same by either method.
2. The duration of a continuous injection needed to reach equilibrium plateau concentrations can be determined accurately by examination of the slug-response curves for a given site. The injection time must be at least equal to the time at which tracer is last present in the stream minus the earliest time of arrival of the leading edge of the tracer for that section, T_D . For practical purposes, the injection time must be slightly longer than T_D to allow for sampling.
3. For the constant-injection method, plateaus develop earlier in the main flow than they do close to the streambanks, where the flow is slower.

Slug-Injection Method

Overview

The slug-injection method is sometimes preferred because of the simplicity of injection and because less tracer is needed. Equation 1 may be written as

$$Q = 5.89 \times 10^{-7} \frac{S_G V_I C}{A_c} \quad (3)$$

where Q is the discharge of the stream, in cubic feet per second;

V_I is the volume of concentrated dye solution injected into the stream, in milliliters;

C is the concentration of the dye solution injected into the stream, in micrograms per liter;

A_c is the area under the time-concentration curve, in units of minutes time micrograms per liter; and

S_G is the specific gravity of the injected solution.

Successful application of equation 3 requires that the mass of tracer injected be fully recovered at the sampling point. This recovery consists in multiplying the area of the response curve or time-concentration curve, A_c , by the discharge, Q . Thus it is vital that A_c accurately represent the dilution of the injected tracer. To recover the injected tracer totally, therefore, requires complete measurement of the time-concentration curve at each of several locations laterally, such as at a, b, and c as depicted in figure 1. The necessity for extensive sampling is the reason this method has found less favor in the United States than the constant-injection method. Nevertheless, the method may be used where a constant-rate injection apparatus is not available or its use is not feasible. Modification of the method to decrease the number of samples required can make it more attractive. Such modification is discussed after presentation of the basic method.

Preparation

Reach selection

The reach where the discharge measurement is to be made should be close to the stream-gaging station or other point of interest. There should not be inflow or outflow within the measurement reach or between the measurement reach and the gage.

The measurement reach should contain a minimum of dead-water areas. Such areas can greatly extend the time required for the tracer to pass a downstream section and, hence, the measurement time. Also, extensive deadwater

Table 1.—Values of the transverse mixing coefficient, E_z , for selected average flow depths and slopes.[Note: $E_z=1.13d^{3/2}s^{1/2}$]

Depth, d (ft)	Slope, s, (ft/ft)				
	0.001	0.005	0.010	0.050	0.100
1.0	0.04	0.08	0.1	0.3	0.4
2.0	.1	.2	.3	.7	1.0
3.0	.2	.4	.6	1.3	1.9
4.0	.3	.6	.9	2.0	2.9
5.0	.4	.9	1.3	2.8	4.0

areas will elongate the trailing edge of the tracer cloud and result in long-duration, low-concentration tails that it is difficult to define accurately.

Rapid lateral (cross-channel) mixing is desired in the stream reach to reduce measurement time and length of reach. A stream with good mixing characteristics will be narrow and deep. Mixing will usually take place rapidly in pool-and-riffle streams--the pools generally being more effective for lateral mixing than the riffles. The volume of the pools should not be too great relative to the volume of flow; otherwise it will take excessive time for the tracer to move through them. Contractions and bends within the reach may help speed up the mixing process. Lateral mixing in shallow whitewater streams is poor, and its mixing effectiveness is apt to be deceiving; depth is needed for good lateral mixing. For the same reason, braided reaches should be avoided. Small islands generally will not significantly slow the mixing process, provided that flow characteristics are similar on both sides of an island.

The optimum distance required for adequate lateral mixing of a tracer injected in the middle of the streamflow may be estimated by the following equation (adapted from Yotsukura and Cobb, 1972, eq. 29, and Fischer and others, 1979, eqs. 5 and 10):

$$L_0 = 0.1 \frac{vB^2}{E_z} \quad (4)$$

where E_z is the transverse mixing coefficient (table 1) in feet squared per second, given by

$$E_z = 0.2 d v_*$$

where v_* is the shear velocity, in feet per second, given by $v_* = (g d s)^{1/2}$;

L_0 is the distance required for optimum mixing, in feet;

d is the mean depth of the stream, in feet;

g is the acceleration of gravity (32.17 ft/s²);

s is the water-surface slope, in feet per foot;

v is the mean stream velocity, in feet per second; and

B is the average stream width, in feet.

The transverse mixing coefficient may therefore be expressed as

$$E_z = 1.13 d^{3/2} s^{1/2}$$

Hence, the optimum mixing length may also be expressed as

$$L_0 = 0.088 \frac{vB^2}{d^{3/2}s^{1/2}} \quad (5)$$

Table 1 provides values of E_z for selected depths and slopes to aid in estimating the optimum mixing length from equation 4.

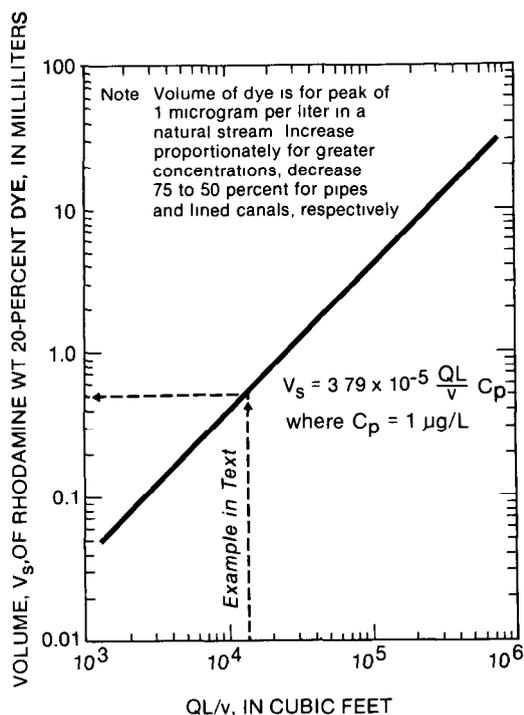


Figure 4.—Quantity of rhodamine WT 20-percent dye required for slug injection to produce a peak concentration of 1 microgram per liter at a distance downstream, L , at a mean velocity, v , and with a discharge, Q , in the reach.

Estimation of needed tracer amounts

The volume of tracer required for a slug-injection discharge measurement is a function of the stream discharge, the measurement-reach length, the stream velocity, and the peak concentration to be achieved at the sampling site. Henceforth, this manual will describe the use of rhodamine WT and pontacyl pink dye tracers, particularly the former. The following easy-to-use empirical equation for estimating the dosage requirements of rhodamine WT 20-percent dye for natural streams was developed by Kilpatrick (1970):

$$V_s = 3.79 \times 10^{-5} \frac{QL}{v} C_p \quad (6)$$

where C_p is the peak concentration at the sampling site, in micrograms per liter;

L is the length of the measurement reach, in feet;

Q is the stream discharge, in cubic feet per second;

V_s is the volume of rhodamine WT 20-percent dye, in milliliters; and

v is the mean-stream velocity, in feet per second.

A plot of equation 6 for a value of $C_p = 1.0 \mu\text{g/L}$ is shown in figure 4. For most discharge measurements, a peak concentration of 10 to 20 $\mu\text{g/L}$ is recommended. Experience indicates that in lined channels and smooth pipes flowing full, the dosages may be reduced to one half to one fourth, respectively, of the amount needed in a natural stream, as defined by equation 6. In such cases, longitudinal dispersion is less and, hence, less dye is required to produce a desired peak.

Pontacyl pink dye comes as a 100-percent pure powder. It compares favorably with rhodamine WT as a water tracer and can be analyzed on most fluorometers using the same lamps and filters as for rhodamine WT. The weight in grams of pontacyl pink needed for a slug injection can be determined from equation 6 or figure 4 by multiplying the volume, in milliliters, for V_s by 0.24.

Preparation of injection solutions

The dosage required for a slug injection is determined from equation 6 or directly from figure 4. Care should be taken to mix the contents of the container thoroughly before withdrawal. For very small quantities, graduated "To Contain" pipets should be used. Special dye pipets of tough borasilicate glass, with white graduations, are available for use in the field. They range typically from 1 to 25 mL total capacity with accuracies of ± 2 percent. Rhodamine WT 20-percent dye is rather viscous and tends to cling to the sides of graduated cylinders and other laboratory glassware; mixing with a larger quantity of water before injection will help to obtain an accurate injection of the amount measured.

Just before withdrawing the concentrated dye, 10 L or so of river water should be measured accurately into a container (most buckets will readily contain 10 to 12 L). The exact

amount of dye withdrawn (it will probably be slightly different from the amount computed) should be measured and delivered to the larger container. When using a "To Contain" pipet, the contents should be blown out into the container, care being taken not to allow droplets of dye on the outside of the pipet to spill into the container. The exact volume of rhodamine WT 20-percent dye and water mixture to be injected into the stream must be recorded.

A sample of the mixed tracer solution must be retained in the event standards are to be prepared from it; 50 mL is a desirable sample amount. The removal of the sample from the total amount injected must be noted.

Field equipment

The equipment required for a slug-dye injection is minimal; a container of stock solution, laboratory glassware for the measurement of volumes, a range of graduated pipets, a container to dilute the mixture in preparation for injection, sample bottles, sample bottle holders, a watch, and note sheets.

Glass sample bottles are recommended in preference to plastic bottles, because the dye may have a slight affinity for plastics. A convenient bottle is an 8-dr (approximately 32 mL or 1 oz) polyseal-cap glass bottle. This bottle has sufficient volume for six to eight analyses on a fluorometer and is easy to clean and handle.

Equipment required for collecting the sample will vary with the method of collection, that is, from a bridge or a boat, or by wading. The sampler shown in figure 5 holds the 1-oz bottle mentioned earlier and may be easily lowered from bridges or cableways or tossed out into the flow if necessary (fig. 6).

Generally, a fluorometer is neither needed nor desirable in the field for most dilution-type discharge measurements.

Fluorometer calibration

It is recommended that a calibration be prepared for each lot of dye and fluorometer in use, and that the results be kept in the laboratory with the fluorometer. A copy of the calibration should be provided to those doing dye-discharge measurements as an aid in selecting

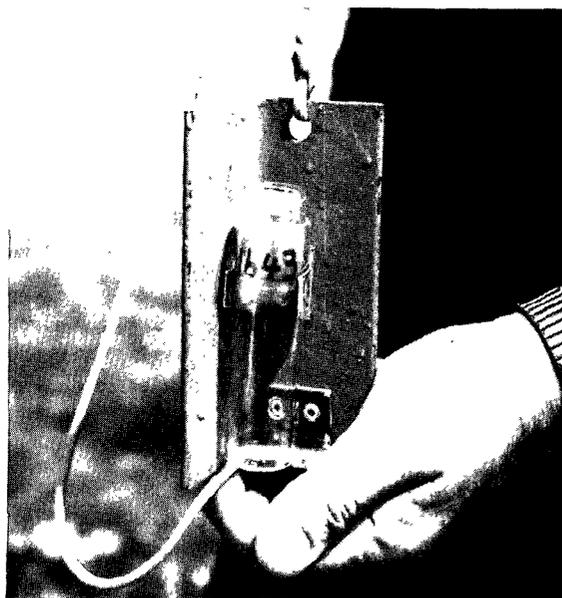


Figure 5.—Dye sampler constructed from a section of angle iron and a broom clamp.

the most suitable concentrations. For example, the graph of the fluorometer calibration in figure 7 shows that if a peak concentration of $20 \mu\text{g/L}$ were chosen, it would probably fall conveniently on the high end of scale III; thus, all smaller concentrations to be expected could also be measured using just this one fluorometer scale.

A new calibration using the serial-dilution process should be performed for any new dye lot. This procedure is explained fully in the manual on "Fluorometric Procedures for Dye Tracing" by Wilson and others (1984) and is reiterated here because the methods involved are important in understanding dilution-measuring techniques.

Serial dilution is a procedure for reducing a concentrated dye solution step by step to concentrations low enough to measure on a fluorometer. Precise measurements of dye and water in each step of the serial-dilution procedure are necessary to prepare a set of standards for accurate calibration of a fluorometer. Distilled water is usually recommended for the preparation of standards. The serial dilution procedure is based on the equation



Figure 6.—Sampling a turbulent stream by tossing a dye sampler into the flow.

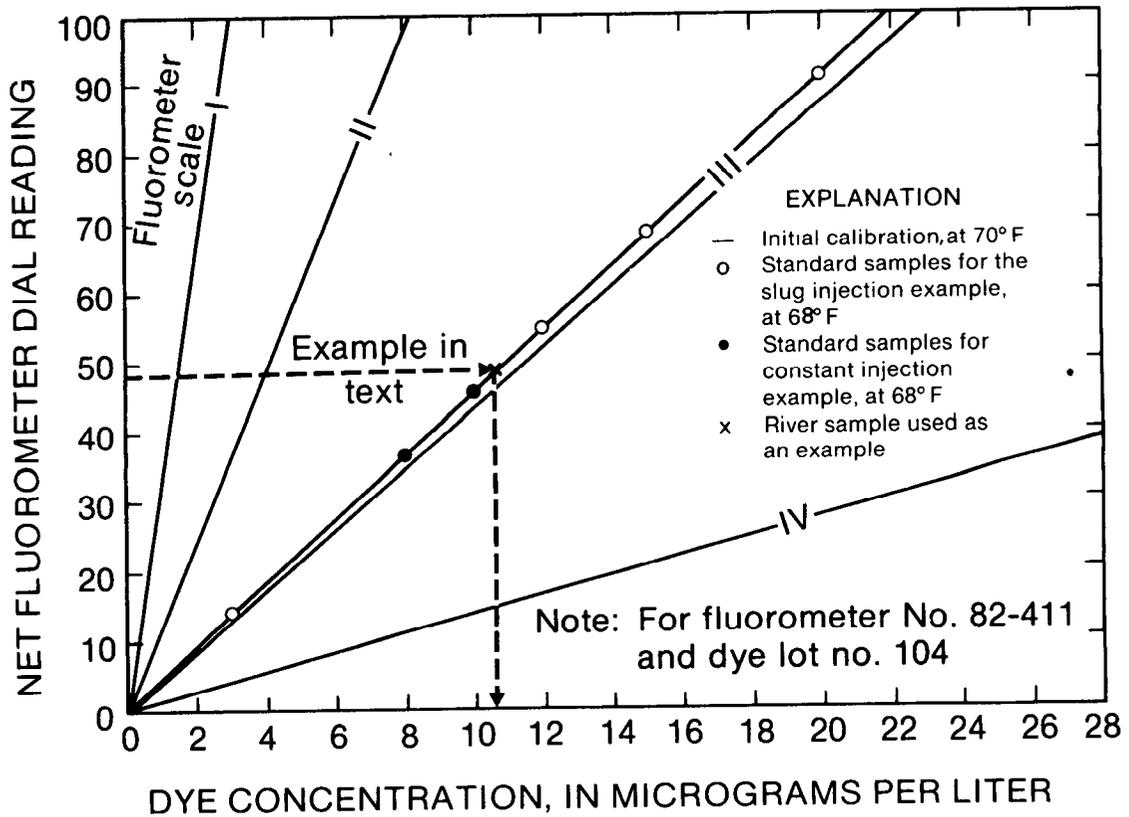


Figure 7.—Typical calibration curves for a fluorometer.

$$C_n = C_i \left[\frac{W_d}{V_w + V_d} \right] = C_i S_G \left[\frac{V_d}{V_w + V_d} \right] \quad (7)$$

where C_i is the initial concentration;
 C_n is the new concentration;
 S_G is the specific gravity of the initial dye solution, 1.19 for rhodamine WT 20-percent solution;
 V_w is the volume of the added water;
 V_d is the volume of dye solution added;
 and
 W_d is the weight of dye added.

If rhodamine WT 20 percent is used, it is necessary to perform three dilutions to obtain concentrations on the order of 100 $\mu\text{g/L}$ (see table 2A). In each step, the preceding C_n becomes the new initial concentration, C_i . It is recommended that this third solution (100 $\mu\text{g/L}$) be retained in quantity and that specific standards of smaller concentration be prepared (a fourth dilution) for the original calibration of a given dye lot as well as for the preparation of selected standards in the future when the same dye lot is used. This 100- $\mu\text{g/L}$ solution, referred to henceforth as a "working solution," should be kept sealed and stored out of direct light. The practice of retaining a working solution of 100 $\mu\text{g/L}$ for each dye lot eliminates the need to

perform a complete serial dilution each time the fluorometer is calibrated. Nevertheless, the calibration should be confirmed each time a measurement is made, as it may have changed or may be for a different sample temperature.

An infinite number of combinations of water and dye may be used to prepare standards. Table 2A provides convenient combinations for three dilutions to produce a working solution of 100 $\mu\text{g/L}$. Table 2B provides convenient combinations (columns 2 and 3) for the fourth dilution to obtain the final standard concentrations (column 4).

The following steps should be taken in analyzing standards for calibration of the fluorometer:

1. Allow all standards, including the distilled-water background samples to reach a common temperature; measurement of sample temperatures will then be unnecessary (Dunn and Vaupel, 1965).
2. Allow the fluorometer to warm up adequately, about 2 hours for the Turner Model 111 and 10 minutes for the Turner Designs Model 10.
3. Analyze all standards in the fluorometer in an identical manner: same cuvette and same temperature.

Table 2A.—Convenient three-step serial dilutions for preparation of a working solution.

(Data in milliliters except as otherwise indicated)

Dye used in test	Line	Dilutions						Working solution, in $\mu\text{g/L}$ (7)
		First		Second		Third		
		V_d (1)	V_w (2)	V_d (3)	V_w (4)	V_d (5)	V_w (6)	
Rhodamine WT (20 percent, $S_G = 1.19$)	a	50	3792	20	3500	20	3500	100
	b	25	2585	20	3000	20	3000	
	c	20	2068	20	3000	20	3000	
	d	20	1158	10	2000	10	2000	
		W_d in gms						
Pontacyl pink and acid yellow 7 (powder)	e	10	3218	20	3500	20	3500	100
	f	5	2188	20	3000	20	3000	
	g	5	1233	10	2000	10	2000	

Table 2B.—Convenient fourth-step dilutions for preparation of dye standards using a 100- $\mu\text{g/L}$ working solution.

Final standard number (1)	V_d (mL) (2)	V_w (mL) (3)	Final standard concentration C_f , ($\mu\text{g/L}$) (4)	Total dilution factor $D_T \times 10^{-8}$ (5)	Fluorometer scale			
					I (6)	II (7)	III (8)	IV (9)
1	300	100	75	31.51				
2 a	200	200	50	21.01				
b	250	250						
3 a	100	150	40	16.81				
b	200	300						
4	100	233	30	12.62				
5 a	50	150	25	10.50				
b	100	300						
*6 a	50	200	20	8.40				
b	100	400						
c	125	500						
*7 a	50	283	15	6.31				
b	100	566						
*8 a	20	147	12	5.03				
b	25	183		5.05				
c	50	366		5.05				
**9 a	20	180	10	4.20				
b	25	225						
c	50	450						
d	100	900						
**10 a	20	230	8	3.36				
b	25	288						
c	50	575						
11 a	20	313	6	2.52				
b	25	392						
c	50	784						
12 a	20	380	5	2.10				
b	25	475						
c	50	950						
13 a	20	480	4	1.68				
b	25	600						
c	50	1200						
*14 a	20	647	3	1.26				
b	25	808						
c	50	1617						
15 a	10	490	2	0.84				
b	20	980						
c	25	1225						
d	50	2450						
16 a	10	990	1	0.42				
b	20	1980						
c	25	2475						
17 a	10	1240	0.8	0.336				
b	20	2480						
c	25	3100						
18 a	10	1657	0.6	0.252				
b	20	3313						
19 a	10	1990	0.5	0.210				

* Used in example of slug-injection test.

**Used in example of constant-injection test.

4. Plot the fluorometer calibration on rectangular graph paper, and reconcile any data points that do not conform to the curve by reanalysis of fresh samples on the fluorometer and, if necessary, by preparation and analysis of new samples.

Performance

A schematic diagram of the step-by-step performance of a slug-injection type dye-dilution measurement is shown in figure 8. The steps in performing such a test use the example shown.

Selection of measurement reach (1)

The stream discharge and the other stream characteristics listed in figure 8, are estimated; using equation 4, compute an optimum stream reach length of about 700 ft. It is desirable to avoid any gain or loss in flow relative to that at the gage, so injection is to be made upstream with sampling close to the gage.

Background samples (2)

Samples of the stream water—at least one, preferably two—are needed before dye injection in order to obtain a reading of the background. The samples should be obtained just before the tracer is injected into the stream, preferably before the dye is handled at all (see sample number 202 on the note form in fig. 8).

Dye injection (3)

For the channel and flow conditions shown, it was decided to try for a peak concentration of about 20 $\mu\text{g/L}$, using rhodamine WT 20 percent. From figure 4, a volume of 0.5 mL is obtained for a peak of 1 $\mu\text{g/L}$; thus, for a peak of 20 $\mu\text{g/L}$, 10 mL of rhodamine WT dye is required.

Next, 10 L of river water is carefully measured into a clean bucket to which the 10 mL of dye is added and mixed. A 50-mL sample of this mixture is retained for future use. The entire contents (9,960 mL) are dumped as a slug into what is judged to be the centroid of the flow.

The time is noted, and the person at the sampling site is notified. A good practice is to start a stopwatch at the instant of injection so that all samples are recorded with respect to lapsed time from injection (see the notes and data plots of fig. 8).

Sampling the dye cloud (4)

The passage of the entire tracer cloud must be monitored for the slug-injection method of discharge measurement. Sampling should begin before the tracer arrives at the section and continue until it has entirely passed. Large numbers of samples are normally required to make certain the entire cloud is measured. Samples should be taken from at least three points in the section in what is estimated to be equal increments of flow. For example, if three points in the section are to be sampled, the samples should be taken at the 1/6, 3/6, and 5/6 points of cumulative flow across the section. Samples 203 through 241 are those taken to define the dye cloud at points a, b, and c across the channel.

Because the samples are not usually analyzed in the field, the length of time for complete passage is an estimate. As a rough approximation, sampling past the peak should continue for two to four times as long as it takes for the peak to arrive. In some instances, the arrival of the peak can be ascertained visually. Hence, if the peak was estimated to have arrived 5 minutes after injection, sampling should continue for a minimum of an additional 10 minutes and preferably 20 to 25 minutes. On this small stream, samples must be taken at very short time intervals; therefore two people are needed, one sampling and one noting the exact time and recording the data. Sampling may be less frequent as the dye cloud recedes. All samples are sealed and stored out of direct sunlight. Notes describing the measurement accompany the samples to the laboratory.

Fluorometric analysis (5)

The single scale that will accommodate the maximum concentrations expected in the field samples should be set on the fluorometer. The quantity of dye injected in step (3) was predicated on obtaining a peak of about 20 $\mu\text{g/L}$.