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

Chapter A9

MEASUREMENT OF TIME OF TRAVEL AND DISPERSION IN STREAMS BY DYE TRACING

By E. F. Hubbard, F. A. Kilpatrick, L. A. Martens,
and J. F. Wilson, Jr.

Book 3

APPLICATIONS OF HYDRAULICS

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

PREFACE

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The unit of publication, the Chapter, is limited to a narrow field of subject matter. This format permits flexibility in revision and publication as the need arises. Chapter A9 deals with the application of dye tracers for the measurement of time of travel and dispersion in streams.

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UNIT CONVERSION

Multiply inch-pound unit	By	To obtain SI unit
ft (foot)	3.048×10^{-1}	m (meter)
mi (mile)	1.609	km (kilometer)
lb (pound)	453.6	g (gram)
gal (gallon)	3.785	L (liter)
ft³ (cubic foot)	28.320	m³ (cubic meter)
ft/s (foot per second)	0.305	m/s (meter per second)
ft³/s (cubic foot per second)	0.028	m³/s (cubic meter per second)

SYMBOLS AND UNITS

Symbol	Explanation	Unit
A_c	Area under the time-concentration curve	(µg/L)h
C	Concentration	µg/L
C_{con}	Conservative concentration	µg/L
C_{obs}	Observed concentration	µg/L
C_p	Peak concentration	µg/L
C_s	Concentration of stock solution	µg/L
C_u	Unit concentration; conservative concentration times discharge per unit weight	(µg/L)(m³/s)/kg
C_{up}	Peak unit concentration	(µg/L)(m³/s)/kg
d	Mean depth of stream	m
E_z	Transverse mixing coefficient	m²/s
g	Acceleration of gravity	m/s²
L	Longitudinal distance from point of injection to sampling site	km
L_m	Channel length required for nearly complete lateral and vertical mixing	m
R_p	Quantity of dye recovered	Percent
Q	Total discharge	m³/s
Q_m	Maximum discharge in test reach	m³/s
s	Water-surface slope	m/m
S_G	Specific gravity	
T_c	Elapsed time to centroid of dye cloud	h
T_e	Elapsed time to leading edge of dye cloud	h
T_f	Elapsed time to trailing edge of dye cloud	h
T_p	Elapsed time to peak concentration	h
t	Time	h
$t_{c,e,f,p}$	Mean traveltimes of centroids, leading edges, trailing edges, and peaks, respectively	h
t_d	Time for dye cloud to pass	h
V	Volume of stock dye solution	L
v	Mean velocity	m/s
v_*	Shear velocity	m/s
W	Average width of stream	m
w_d	Weight of pure dye or tracer	kg
w_s	Weight of stock dye solution	kg

MEASUREMENT OF TIME OF TRAVEL AND DISPERSION IN STREAMS BY DYE TRACING

By E. F. Hubbard, F. A. Kilpatrick, L. A. Martens, and J. F. Wilson, Jr.

Abstract

The use of fluorescent dyes and tracing techniques pro vides a means for measuring the time-of-travel and dispersion characteristics of steady and gradually varied flow in streams. Measurements of the dispersion and concentration of dyes give insight into the behavior of soluble contaminants that may be introduced into a stream.

This manual describes methods of measuring time of travel of water and waterborne solutes by dye tracing. The fluorescent dyes, measuring equipment used, and the field and laboratory procedures are also described.

Methods of analysis and presentation to illustrate time-of-travel and dispersion characteristics of streams are provided.

Introduction

Time of travel refers to the movement of water or waterborne materials from point to point in a stream for steady or gradually varied flow conditions. In recent years, greater accuracy in the determination of time of travel has been made possible by the production of stable fluorescent dyes and the devising of modern dye-tracing procedures (Buchanan, 1964; Wilson, 1967). Previously, most time-of-travel computations were based on the average velocity determined at a number of cross sections along the reach of a stream (Searcy and Davis, 1961; Steacy, 1961).

Dye tracing simply means that a dye is slug injected at some location along the stream and the resulting response, or dye cloud, is measured at other locations downstream. When a fluorescent dye is used as a tracer material, the degree of fluorescence can be determined with a fluorometer. The concentration of dye in the sample is directly proportional to its fluorescence. A plot of concentration against time defines the passage of the dye cloud at each sampling site. Time of travel is measured by observing the time required for movement of the dye cloud between sampling sites. Equally as important,

the dispersion characteristics of the stream can also be determined.

The purpose of this manual is to describe methods, procedures, dyes, and equipment used in planning and making time-of-travel and dispersion measurements in streams.

It is assumed that the reader is familiar with "Fluorometric Procedures for Dye Tracing," by Wilson (1968), which contains the general procedures for the use and measurement of dyes.

General Description of Dye Tracing

Theory

Dyes injected into a stream behave in the same manner as the water particles themselves. A measure of the movement of the tracer will in effect be a measure of the motion of the stream and its dispersion characteristics.

The dispersion of the tracer in the receiving stream takes place in all three dimensions of the channel (fig. 1). Vertical dispersion is normally completed first, lateral later, depending upon the width of the stream and velocity variations. Longitudinal dispersion, having no boundaries, continues indefinitely and is the dispersion component of primary interest.

The movement of a dye cloud past any point downstream from an instantaneous dye injection can be represented by a time-concentration curve (fig. 2). The time-concentration curve, defined by the analysis of water samples taken at selected time intervals during the dye-cloud passage is the basis for determining time-of-travel and dispersion characteristics of streams.

1

5   Lateral mixing complete,
    time-concentration curve areas the
    same, longitudinal mixing continues

4   "Foldback" of dye from banks

3   Dye reaches banks,
    vertical mixing probably complete

2   Vertical, lateral, longititudal mixing
    (vertical not shown)

1   Single point injection at midstream.
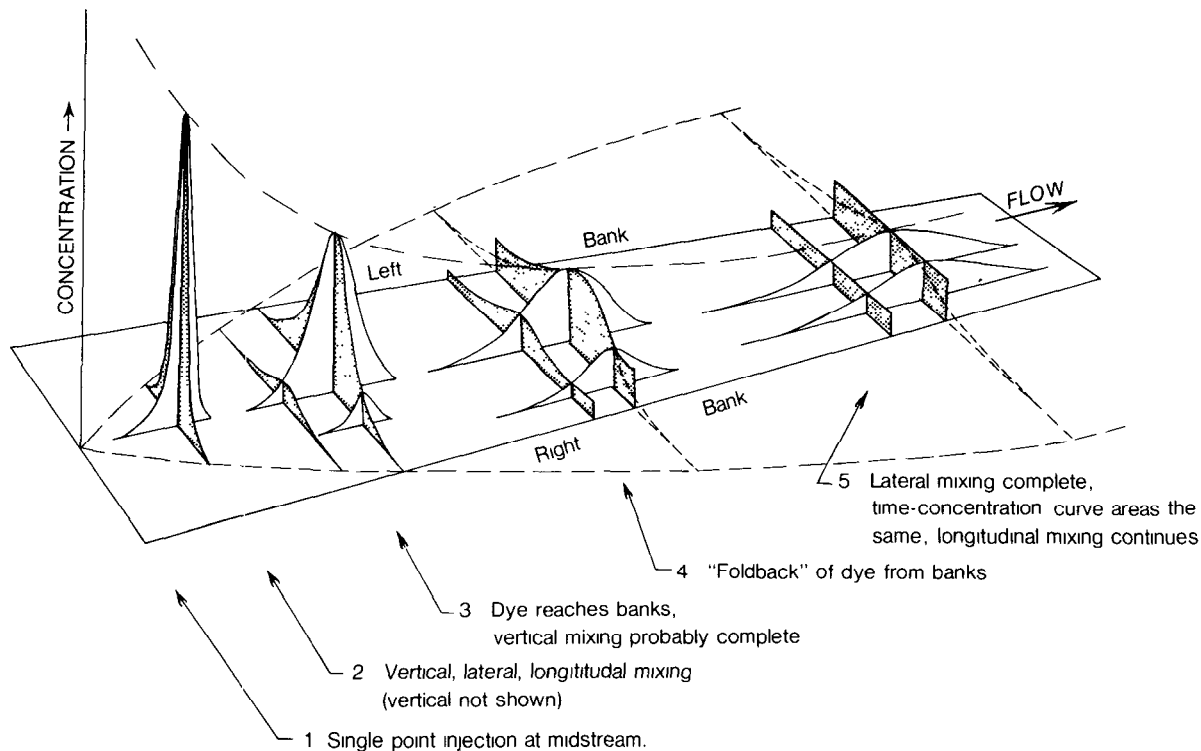
Figure 1.—Lateral and longitudinal mixing patterns and changes in distribution of dye concentration downstream from an injection point.

The characteristics of the concentration-time curves shown in figure 2 are described in terms of elapsed time after an instantaneous dye injection:

T_e , elapsed time to the arrival of the leading edge of a dye cloud at a sampling location;

T_p , elapsed time to the peak concentration of the dye cloud;

T_c , elapsed time to the centroid of the dye cloud, indicated by the centroid of the time-concentration curve; and

T_f , elapsed time to the trailing edge of the dye cloud.

The mean traveltime for the flow in a reach is defined as the difference in elapsed time of the centroids of the time-concentration curves defined for the upstream and downstream sections of the reach:

$$t_c = T_{c_{(n + 1)}} - T_{c_n},$$

where n is number of the sampling site.

Similarly, the traveltimes of the leading edge, peak concentration, and trailing edge are, respectively,

$$t_e = T_{e_{(n + 1)}} - T_{e_n},$$

$$t_p = T_{p_{(n + 1)}} - T_{p_n}, \text{ and}$$

$$t_f = T_{f_{(n + 1)}} - T_{f_n}.$$

The time, t_d , necessary for the entire dye cloud to pass a sampling point is

$$t_d = T_{f_n} - T_{e_n}.$$

The area under the time-concentration curve is

$$A_{c_n} = \int_0^\infty C dt,$$
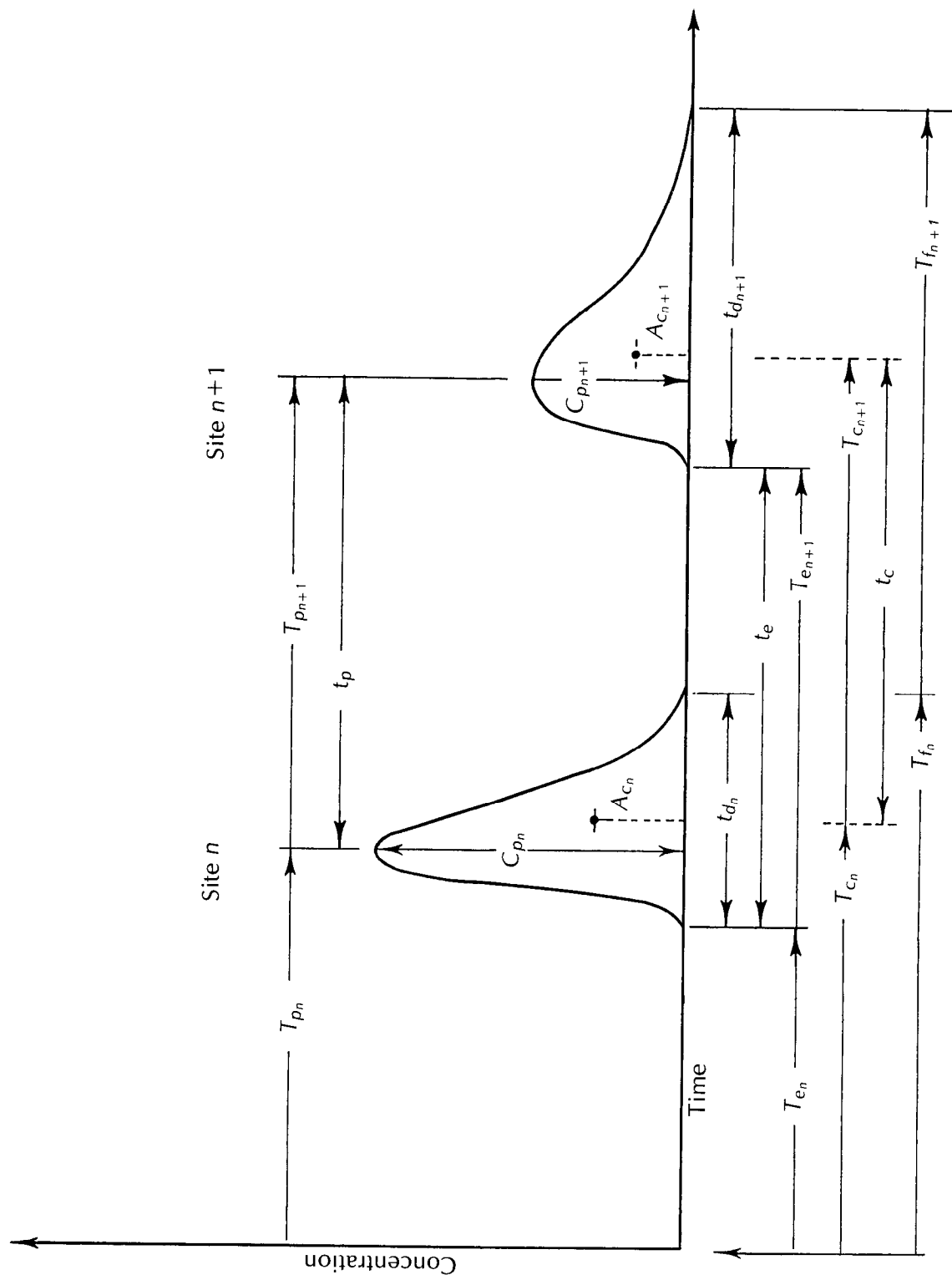
Figure 2.—Definition sketch of the time-concentration curves resulting from an instantaneous dye injection.

where C is the dye concentration measured at the sampling site at a given time, t.

Once vertical and lateral dispersion are complete, the area under this curve would be equal at all sampling sites downstream from the injection point for a conservative dye (one with no losses) if the discharge is constant for the reach. However, commonly used fluorescent dyes are not conservative and

$$A_{c_n} = A_{c_{(n+1)}} + \text{dye loss.}$$

The dye losses can be determined if the entire dye cloud is measured at each sampling point and the discharge is known. The time-concentration curve, adjusted for dye losses, then represents the dispersion characteristics for flow conditions in the reach. These characteristics serve as a basis for predicting the response of streams when contaminants are released into the flow.

Stream velocity and, consequently, time of travel commonly vary with discharge. The relation of time of travel to discharge takes the form

$$t = KQ^{-x},$$

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

Fluorometry

Fluorometers measure the luminescence of a fluorescent substance when the substance is subjected to a light source of a given wave length. 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 (1968).

Fluorescent dyes

Several dyes are available that can be used as tracers in time-of-travel measurements. The basic characteristics of dyes now being used by the U.S. Geological Survey have been discussed by Wilson (1968). Properties to be considered in selecting a tracer are detectability, toxicity, solubility, cost, and sorption characteristics.

Both rhodamine BA and rhodamine WT have been used successfully as tracers in time-of-travel studies. The basic differences between the two are that (1) the loss rate of rhodamine BA is higher, (2) rhodamine WT is easier to handle, and (3) the unit price of rhodamine BA is less. Rhodamine BA is adsorbed or absorbed quite readily by almost anything it comes in contact with. It is especially susceptible to loss by contact with aquatic plants, suspended clays, and the streambed and banks. It has been found to adhere to sample bottles, both glass and plastic, resulting in erratic data. Because of its higher loss rate, measurements with rhodamine BA usually require more dye at injection than do measurements with rhodamine WT to obtain the same concentration at the sampling site. Thus, despite its greater initial cost, rhodamine WT has been proved to be more economical. Presently, rhodamine WT dye is the tracer recommended and the one involved in subsequent discussions.

Purposes of Tracer Studies

As described in this manual, dye studies in streams usually are to provide data for two reasons: to determine time-of-travel for use in water-quality models and to define relations that will enable those charged with public safety, or others having interest in transient water-quality problems, to predict the time of arrival, passage time, and peak concentration of a noxious substance released or spilled upstream.

Water-quality models are, typically, no better quantitatively than the traveltime data used in their formation. Travel time estimated from low-flow discharge measurements or from a few cross sections in a reach may be subject to large error. Thus, a more accurate measurement of time of travel, such as can be made using dye tracers, is needed.

The headlines are full of reports of spills of hazardous materials into streams: a truck goes into a river; a barge sinks or starts leaking; a holding tank at a riverside facility ruptures; an industry accidentally releases a dangerous substance into their normal effluent; or a pipeline ruptures near a river. Many times public-health officials must make a decision whether, when, and how long to suspend operations of public water-supply intakes in the reach downstream from the spill. Likewise, other users of the water must decide on an appropriate course of action. On one hand, suspension of water use may have economic penalties and may cause widespread discomfort if it involves a public water supply. On the other hand, a public-health official cannot afford to take unfounded risks when the safety of large numbers of people are involved. Clearly, good time-of-travel and dispersion information is needed, in advance of the spill, to provide a reasonable basis for such decisions.

Stewart (1967) made such a study on short notice when a chlorine barge sank in the Mississippi River near Baton Rouge, causing officials to fear that the poisonous substance would leak into the river. Perhaps spurred by this incident, the Louisiana Department of Public Works has acquired, through its cooperative program with the U.S. Geological Survey, an extensive set of data on time of travel and dispersion for streams in the State (Colandro, 1978; Shindel and others, 1977).

Level of Study

Dye studies may be conducted at different levels of completeness depending on the objectives of the investigation, policy considerations, and manpower and financial constraints. If, for instance, only time-of-travel data are needed, the data requirements of a study to produce this information would be considerably less than when dispersion data are needed. Although each situation or set of study objectives will dictate the data requirements and, consequently, the difficulty level of a study, this section outlines two possible levels of effort. Only by understanding the data requirements of a particular set of objectives, gained through experience or through study of a manual such as this one, can

an investigator insure that the data collected will be sufficient to produce the desired end result.

High level

In a high-level study, where data are collected to produce a full suite of time-of-travel and dispersion information, the study should include the following at each of two or more stream discharges:

1. Independently measure or evaluate stream discharges at every sampling point during the passage of the dye cloud.
2. Carefully measure the amount of dye injected.
3. Retain a sample of the same dye as injected for later use in the laboratory in preparing standards.
4. Measure the entire dye cloud or until at least a concentration equal to or less than 10 percent of the peak or 0.20 $\mu g/L$ (microgram per liter) is reached, (whichever is lowest).
5. Measure the dye cloud at several points across each sampling section to better account for the entire mass and to be a measure of the completeness of lateral dispersion;
6a. Inject dye at a sufficient distance upstream of the stream reach being tested so that mixing is accomplished prior to entering the test reach; hence the dye cloud is measured at the head of the test reach, as well at one or more locations downstream, or
b. Inject the dye at several locations laterally at the head of the test reach to more completely tag the flow mass and subsequently take samples at two or more downstream locations.

A high-level study similar to the one just described will provide data sufficient to allow making nearly every kind of applicable analysis in the literature. It will meet the present U.S. Geological Survey policy requirement that the absolute concentration of dye in a stream that passed a public water-supply intake be documented. This documentation will provide

pertinent evidence in the event that a water user alleges adverse effects from the dye.

The data from studies conducted at this level will be sufficient to

1. determine time of travel of the leading edge, peak, centroid, and trailing edge of a solute for a range in stream discharges;
2. determine peak concentrations for any amount of conservative solute spilled for a range in discharges;
3. permit the assessment of the longitudinal dispersion characteristics of the stream for a range of index flows or river stages;
4. permit the prediction for a range in flows of the effects of the spillage of a soluble waste as it moves downstream; and
5. permit the regression analyses using stream characteristics to obtain equations that regionalize time-of-travel and dispersion characteristics.

In the real world, however, compromises must be made. Not every study will yield data worthy of the high-level approach. In fact, some studies could not be made at all unless some concessions were made to reduce the cost or time requirements. Under some circumstances, a lower level study might be warranted.

Low level

A low-level study would include the following measurements:

1. One dye test at a single stream discharge, but it is more desirable to conduct even the simpler tests at two or more discharges.
2. Determine an index discharge, perhaps at a gaging station in or near the study reach, but not necessarily measure the discharge at each sampling site.
3. Carefully measure the amount of dye injected.
4. Determine the absolute dye concentrations

in the laboratory or field using existing fluorometer calibrations and reasonable quality control appropriate to the operating circumstances.

5. Measure the dye cloud only long enough to be sure the true peak has passed.
6. Measure the dye cloud in the center of the flow, additional lateral measurements being optional.
7. Measure the dye cloud at only one location below the injection point; measurements at more than one place are to be encouraged, though.

This low level of study will provide the following:

1. Basic definition of time-of-travel data for one discharge. This can be expanded for a range in discharges by performing a low-level study at two or more discharges; this is usually highly desirable.
2. Peak concentrations would be available, but they would not represent a conservative tracer.

In considering the appropriate level for a proposed dye study, it is important to recognize that manpower, cost, and technical-expertise requirements increase as the study level increases. However, dye-study data often have uses beyond the immediate objectives of a single study. The results from many individual studies have been used on a regional basis to define the effects of channel characteristics on traveltime and dispersion. Other investigators have used results of many individual studies to provide information on the dispersion rates of natural streams. Such data have also been employed in modeling time-of-travel and dispersion characteristics.

Boning (1974), in a generalization of stream travel rates and dispersion characteristics, found that of 1,500 individual time-of-travel measurements only 873 had data complete enough to use in his analysis. Perhaps, with just a little more data, many more of the measurements could have also been used.

Dye-Tracing Equipment and Supplies

Injection

Injections are usually made by pouring a measured amount of dye into the part of the stream having the highest velocities. Graduated laboratory cylinders, as those shown in figure 3, are recommended for measuring small quantities of dye. Large injections can be measured in terms of full dye containers; the net weight of dye is usually stamped on its container.

Injections at multiple points across the stream are sometimes used on wide or shallow streams to shorten the effective mixing length. The dye is measured and divided into a number of containers and poured simultaneously at several points along the cross section. Special boat-mounted devices, such as those shown in figure 4, may be useful for line injections of very large doses. A line injection is made by pouring dye continuously while crossing the stream; in such instances avoid injecting dye at the immediate stream banks in dead or slow-moving sections. As a rule, dye should be injected in only about the central 75 percent of the flow.

Sampling

Tests have indicated that all dyes, particularly rhodamine BA, have an affinity for most plastics; therefore, glass bottles are recommended in preference to polyethylene bottles.

Figure 3.—Volumetric measuring of dye dosage in the field.

Figure 4.—Special boat-mounted apparatus for making a line injection of a large dosage (Missouri District).

The 8-dram (approximately 32-mL or 1-oz) polyseal-cap glass bottles shown in figure 5 are stock items. This bottle has sufficient volume for six to eight analyses on the fluorometer, is easy to clean and handle, and is compatible with temperature-bath control systems. Excessively large samples create storage problems in both the field vehicle and office. Large-volume samples also require a longer time to come to the desired temperature where temperature-control apparatus are used. Glass bottles are often permanently numbered so that the sample data can be kept on separate data sheets referred to only by sample number (see fig. 6). Permanent numbers may be placed on the glass with a vibrator-etcher tool, or temporary numbers may be added by writing on masking or transparent tape affixed to the bottle. Soap or acid cleansing of bottles is not recommended; flushing and then rinsing twice in plain water is sufficient.

The chest shown in figure 5 contains six trays of 50 bottles each and is sufficient for most tests. Information pertaining to the purchase and fabrication of this equipment can be obtained from the Operations Section, Water-Resources Division, at National Headquarters in Reston, Va.

Standard samplers such as the depth-integrating water-quality samplers can be used for point sampling, although smaller, lighter samplers designed specifically for the size and type of sample bottle are best. The sample bottle holder for the standard glass bottle, shown in figure 5, is intended for use from bridges. It is fabricated by mounting a utility clamp or a split
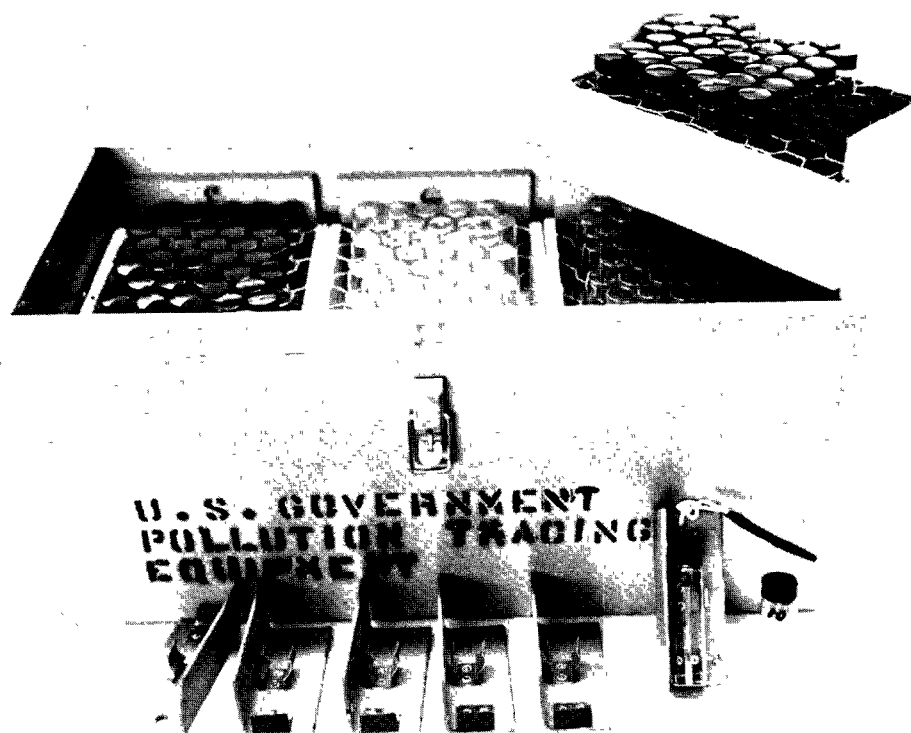
Figure 5.—Sampling equipment for use in dye-tracer studies.

section of rubber hose to angle iron or to some other support, which serves to hold and protect the bottle.

Hand sampling during dye studies is quite effective, but it often involves many people, some of whom must work during the night. Long hours with little relief is more the rule than the exception. Consequently, manpower costs are high. A recent development, the automatic dye-sampling boat, shown in figure 7, has reduced the manpower required for a dye study. Kilpatrick (1972) described the apparatus, which he was instrumental in designing. The sampler consists of a series of spring-actuated hypodermic syringes mounted verti-cally in a metal rack. When installed in the floating fiberglass boat, the tips of the syringes are slightly immersed in water. A worm gear,

rotated by a small electric motor, advances a tripping mechanism, which releases the preset syringes one by one in sequence. As they are released, the syringes fill with water from the action of the spring that withdraws the plunger the necessary distance. Following use, the syringes should be rinsed only with clear water; laboratory detergent will cause the syringes to stick in subsequent use. Bench-testing the timing mechanism to accurately determine the sampling interval at various combinations of drive gears is recommended.

The use of dye-sampling boats can reduce the personnel required to do a fairly extensive dye study to just two people. The first sampling site is usually sampled by hand because the dye passes quickly, and these data provide an oppor-tunity to reestimate the time of arrival of the

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.

Figure 6.—Form for recording dye-sample data.
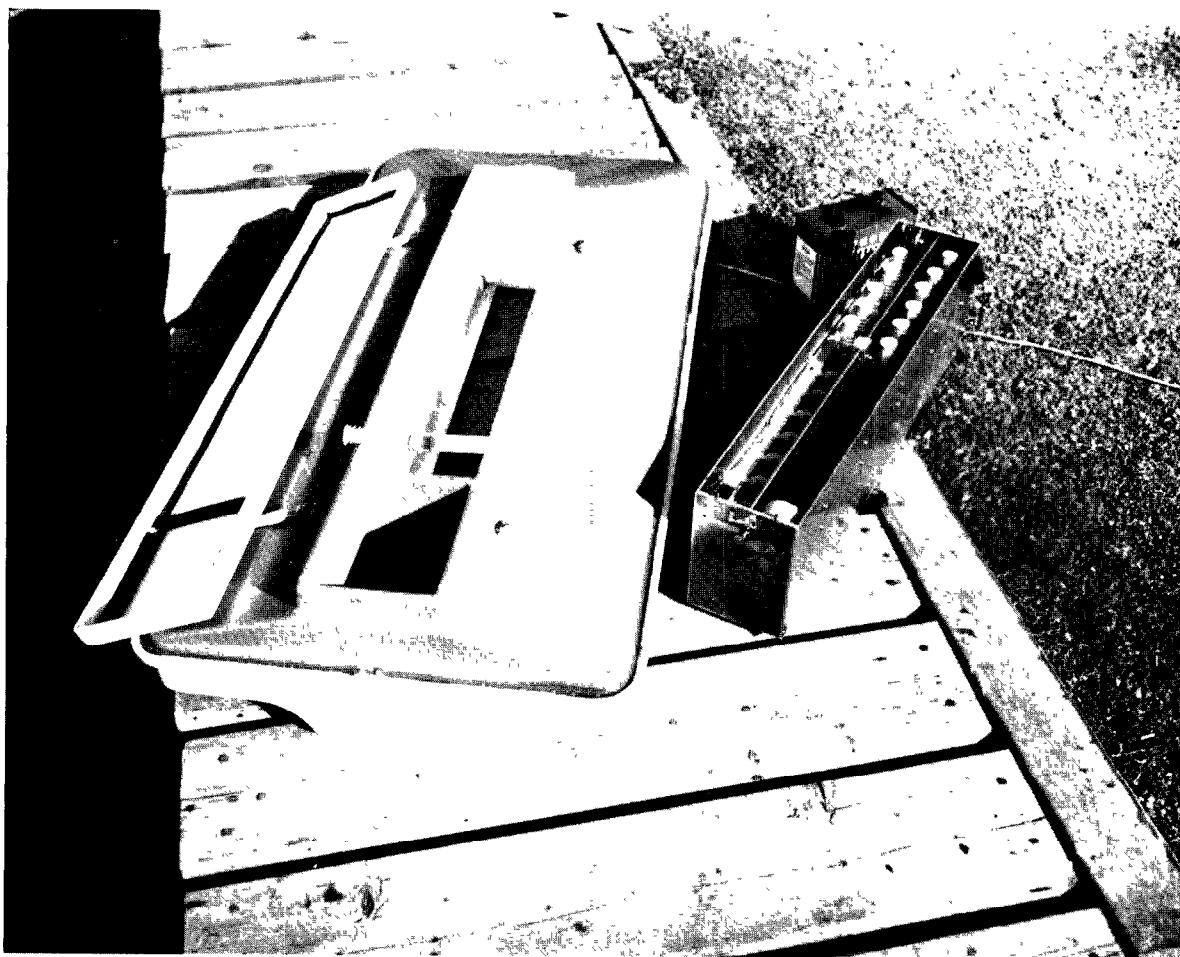
Figure 7.—Automatic dye-sampling boat, with the sampling mechanism and battery removed.

dye cloud at downstream sampling points. Then the sampling boat is tied or anchored at the next sampling site and set to sample during a period of time that will insure that the dye cloud is sampled when it passes. The frequency of sampling is set to obtain enough samples to define the dye cloud.

Although most investigators check the boats during the sampling process, they are typically left unattended for long periods of time to allow the personnel time for meals or rest. There have been few reports of vandalism or theft. Some studies have been made with the sampler boats chained and locked to bridge pilings, but they are, of course, still subject to vandalism. Either way, the number of cases of vandalism and theft have been very low nationwide.

It may be necessary to have two boats for studies if the leading edge of the dye reaches a sampling site before the dye cloud has completely passed the next site upstream or if the dye cloud will pass two sites during the time set aside for the field crew to rest. Where it is necessary to use two sampling boats, they may be leapfrogged to alternate sites as the dye moves through the study reach. In a high-level study, several boats may be needed to obtain samples at more than one point across each site.

In securing the boats by a bottom anchor in streams with swift velocities, enough anchor rope should be provided to prevent the boats from sinking. When tied at the front, where an eyebolt is installed for this purpose, the boats may be pulled under and sunk because the front

end, affected by the force of the anchor rope, tends to float a little lower than the rear.

Although periodic grab sampling manually or with the automatic sampler described have proved more satisfactory for most applications, continuous sampling and recording may be accomplished by use of a flow-through device on the fluorometer and a strip-chart recorder, such as that shown in figure 8. Typically, the intake hose is attached to a small electrically operated pump, which pumps the sample through the flow-through fluorometer door and out the discharge hose.

Continuous sampling from a boat is particularly applicable to dispersion studies in estuaries and lakes where the dye-cloud movement is multidimensional and perhaps oscillating. Depth sampling can be accomplished by traversing vertically with the intake hose. High pump rates and short hose lengths should be employed to minimize lag errors and dispersion taking place in the hose itself.

The strip-chart record of fluorescence plotted against time can be calibrated by periodically collecting bottle samples from the fluorometer discharge line and noting the collection time directly on the chart. Subsequently, these samples are analyzed, and concentrations are plotted against chart reading to define a calibration curve, as shown in figure 9.

Fluorometers

The description, accessory equipment, calibration, and operation of fluorometers are described by Wilson (1968). Since publication of
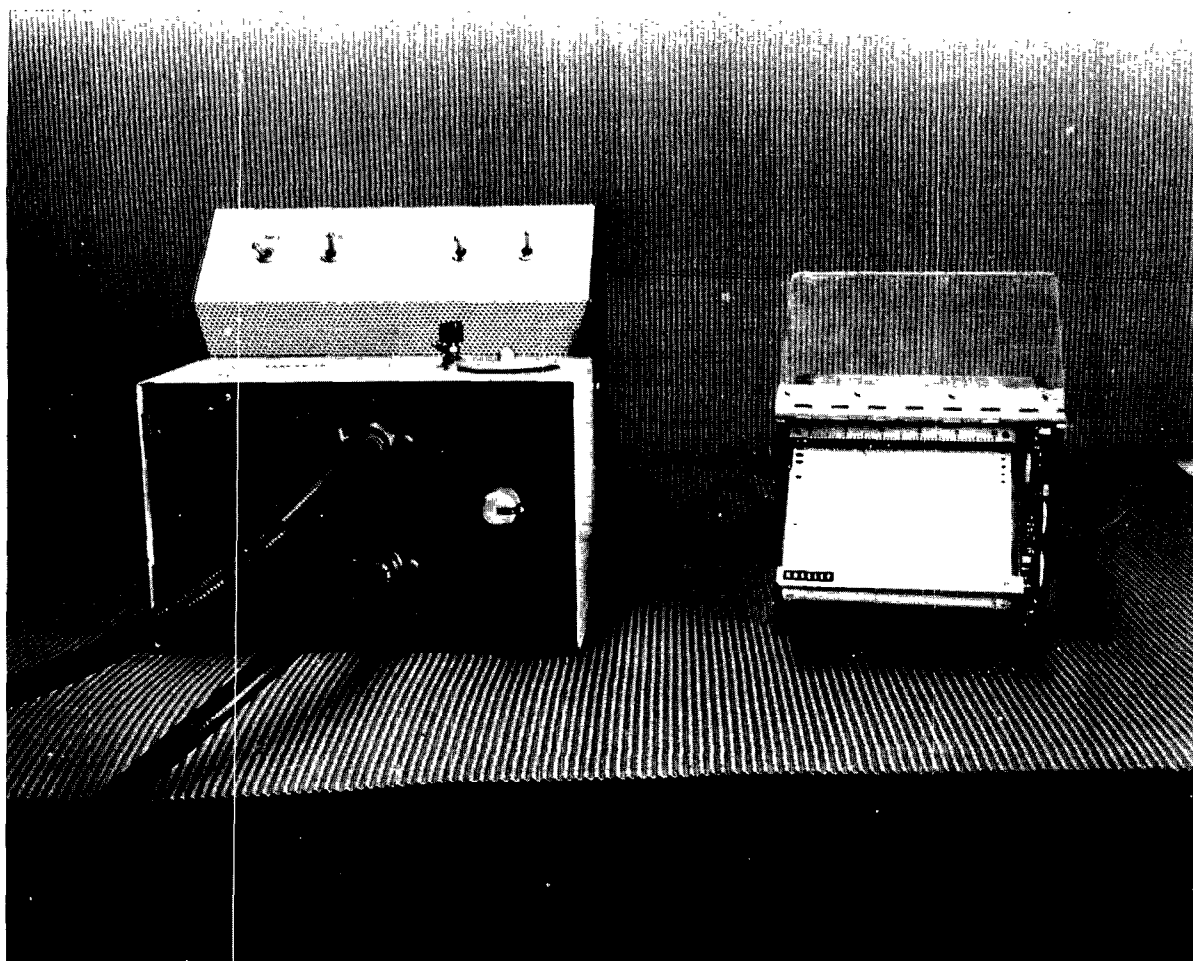
Figure 8.—Fluorometer equipped with a flow-through device and a strip-chart recorder for continuous sampling and recording.
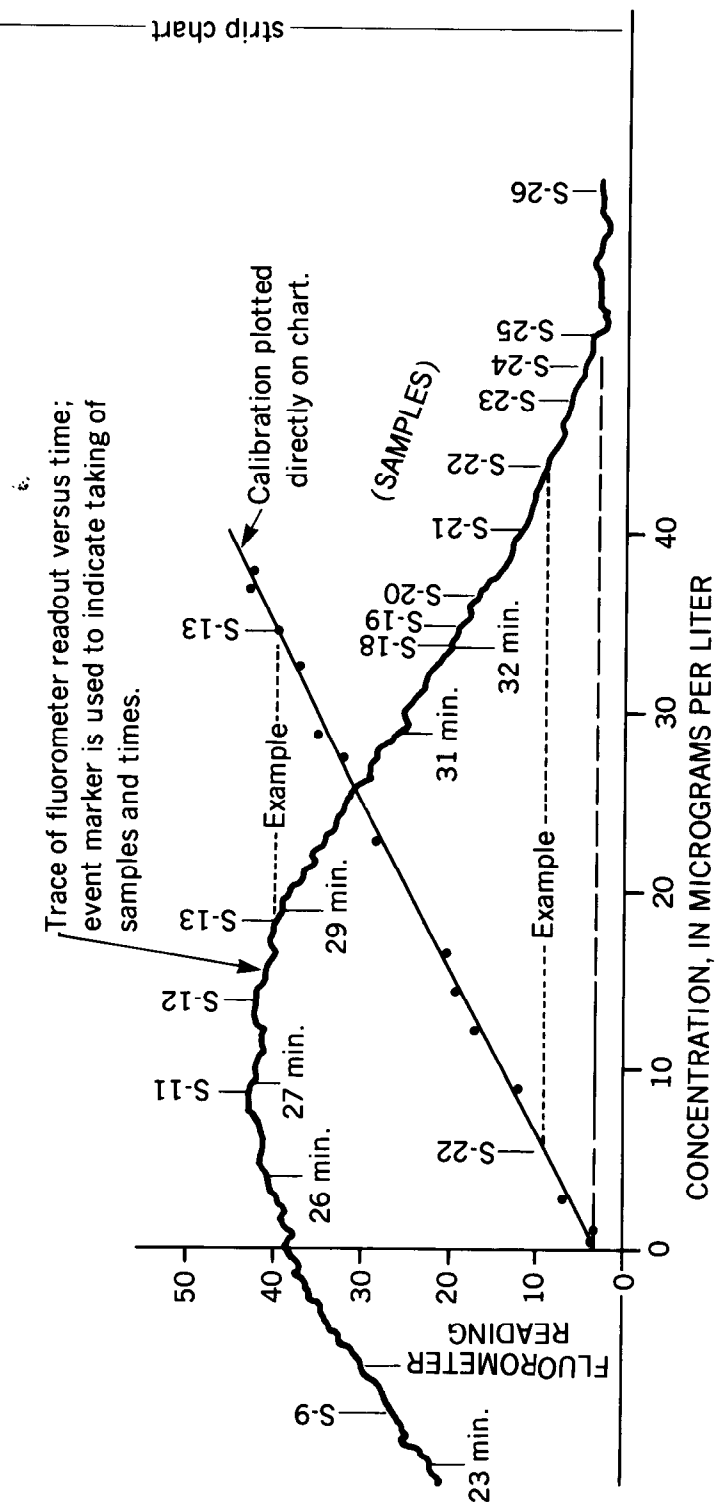
Figure 9.—Example of calibration of strip-chart trace. Selected samples from the fluorometer flow-through discharge are subsequently analyzed in the laboratory and concentrations are plotted against the strip-chart reading directly on the graph.
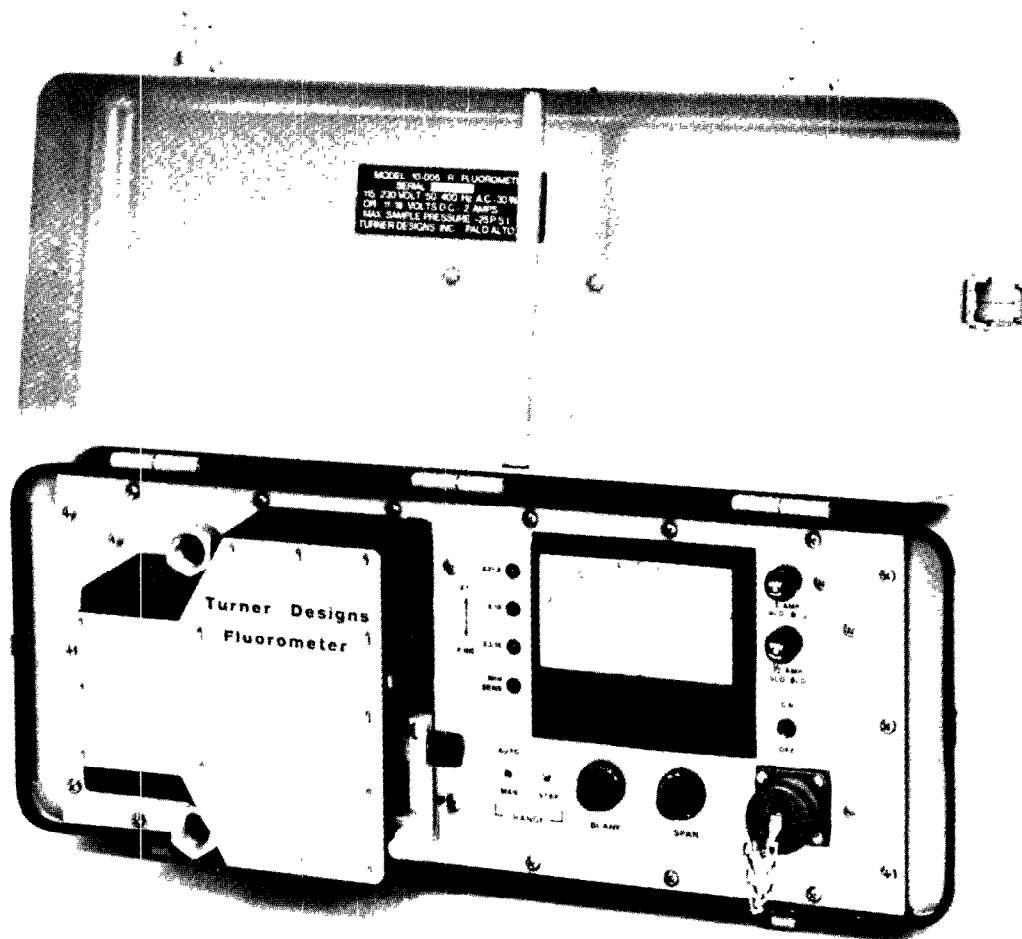
Figure 10.—A modern fluorometer, suitable for field use, having both flow-through and individual-sample analysis capability.

Wilson's manual, a new fluorometer has been manufactured by Turner Designs, which should be added to the list of available instruments (see fig. 10). It should be noted that the standard 1-oz bottle described earlier and the 20-mL syringe sample obtained with the boat sampler requires the 13 by 100 mm cuvette holder to permit analysis on this fluorometer.

Fluorometer readings for samples are relative values of fluorescence intensity and cannot be directly converted into dye concentrations unless the fluorometer is one of the newer models designed to be read directly in concentration values. In order to obtain the actual concentration of the samples, the fluorometer must be calibrated using a set of standard solutions of known concentration. The standard dye solutions should be made from the same dye lot used

in the field test. Thus, the concentration in samples for all tests using the same lot of dye can readily be determined.

Planning the Time-of-Travel Study

Map and streamflow-data study

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

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

In 1966, the Geological Survey adopted a policy (Water-Resources Division Memorandum 66.90) that prohibits the injection of fluorescent dyes into streams in quantities that would result in dye concentrations exceeding 10 μg/L at water-user withdrawal points. Similarly, all water users in the reach must be identified and press releases issued describing the purpose, time, and location of tests. If there is any possibility that the water containing dye will be used for human consumption, dye concentrations should be as low as possible. The quantities of dye injected and measured peak concentrations must be reported as stipulated in Water-Resources Division Memorandum 72.63.

Preliminary estimates of discharges and mean velocities throughout the reach are necessary to make the first estimate of traveltime, dye requirements, and sampling period for each sampling site. Discharge measurements at gaging stations and at partial-record sites in the study reach are useful in estimating stream velocities, although measurements made at low

flow tend to have average velocities considerably greater than the average for a reach.

Reconnaissance of the stream

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

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

2. Inspect the proposed sampling sites (minimum of two per injection is recommended) to determine accessibility and suitability. Decide whether more than one sampling point in the cross section will be necessary and where they will be located. Measure or estimate the channel width, depth, and mean velocity of the stream reach to the extent possible.

3. Check all reaches for dams, diversion canals, water intakes, sewage outfalls, and any other condition that may affect the measurement or be affected by the measurement. Where water supplies are withdrawn in the reach under investigation, make estimates of the mean velocity for the reach, and the river discharge at the diversion point to estimate the maximum dye concentration that may be anticipated. If dye concentrations at the withdrawal point are in excess of 10 μg/L, less dye will have to be injected or the injection point changed. Frequently the location of water-supply diversions are selected as the most distant sample point, and a subsequent injection is made just below this point for the next subreach. It is desirable to overlap subreaches. In this situation, the water intake should be the next-to-last sampling site, and the injection can be made immediately downstream from the diversion.

4. Locate suitable discharge measuring sections at or near each injection and sampling site. Set reference points at the sites if it is desirable to establish stage-

discharge relations at the sites rather than having to measure discharge during the passage of the dye.

5. Estimate the probable discharge at the last sampling section to compute the amount of dye needed. It should be kept in mind that the maximum discharge in the reach is that used in estimating the amount of dye needed.

6. Note locations where there are shelter and power for the fluorometer. These facilities could be at the motel or hotel used for accommodations, as noted in item 7. The utilization of fluorometers in the field depends primarily on the number of units available, the distance between and access to the sampling sites, and the time interval between samples. If only one fluorometer is available, a central location, such as a laboratory, office, or motel may be best. Typically samples from several sites are brought to a centrally located fluorometer.

7. Locate motel and hotel accommodations, noting name, address, and phone number of each. Good communications are vital to a successful time-of-travel study.

Recognition of potential problems

A successful dye study requires some attention in advance to problems that may arise. This observation is particularly true in large or complex studies where many people are involved, some of whom may not be familiar with the procedures, the equipment, and the study area.

Hard-to-find sampling or injection sites should be sketched to help the personnel assigned to that location find the site. During the reconnaissance, the investigator should determine the driving time from the place of lodging to the study area under actual traffic conditions.

The safety of the sampling locations should be considered and traffic warning devices provided, if needed. The location of the nearest hospital emergency room should be found, and maps should be provided to all field personnel unfamiliar with its location.

Wherever possible, backup equipment should be provided for essential equipment. Glassware, fluorometers, generators, sample boats, and hand samplers are all subject to breakage, malfunctions, or loss.

Plans should be made to avoid potential contamination of the water samples. Personnel involved in mixing or injecting the dye may get so much on their hands and clothes that they should not handle the samples. While they are being transported, the dye and the injection equipment should be kept separated from the sample bottles, samplers, and fluorometers. Good cleanliness practices should be followed to every extent possible.

Another potential problem is the possibility of loss of dye through uptake by vascular water plants. D. G. Jordon (oral commun., 1976) cited a study in Puerto Rico, where the dye cloud flowing through thick aquatic growth was completely lost due to plant uptake. An article in "Water and Wastes Engineering" (Dinges, 1976) described the efficiency of water hyacinths and duckweed in removing nutrients and other chemical constituents, including trace organics and metals from water containing sewage. Donaldson and Robinson (1971) found that rhodamine WT was particularly susceptible to uptake by plants.

Estimating mean velocities

The planning of sampling schedules and determining dye quantities require estimates of mean velocity and traveltime for each subreach. Generally, the estimates of mean velocities are greater than those eventually measured. The examination of current-meter measurements of low flows made in the reach commonly indicates a mean velocity greater than the mean for a reach, because measurements are usually made at selected channel sections where velocities are swift. 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 velocities through the pools, which occupy a larger proportion of the stream. However, the use of safe estimates, that is, higher velocities, to plan sampling

schedules insures measurement of the leading edge of the dye cloud.

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

Dye-injection and sampling sites

As discussed earlier, following the injection of dye in the center of a stream, a considerable reach length may be required to complete lateral mixing. Yotsukura and Cobb (1972, eq. 29) and Fischer and others (1979, eq. 5, 10) suggested the following equation to estimate the length of channel necessary for complete lateral mixing from a single-point midchannel injection:

$$L_m = 0.1 \frac{vW^2}{E_z} , \qquad (1)$$

where

E_z is the transverse mixing coefficient, in meters squared per second, given by

$$E_z = 0.2dv_*;$$

v_* is the shear velocity, in meters per second, given by

$$v_* = gds;$$

v is the mean velocity, in meters per second;

W is the average channel width, in meters;

d is the mean depth, in meters;

g is the acceleration of gravity (9.8 m/s²); and

s is the water-surface slope, in meters per meter.

The length of channel for complete lateral mixing from a single-point side injection from a bank is estimated to be

$$L_m = 0.4 \frac{vW^2}{E_z} . \qquad (2)$$

Equations 1 and 2 are dimensionally correct and may be used with units other than those of the SI system, such as foot-pound units, if done consistently.

Until the dye is mixed laterally its movement does not represent that of the total flow. Once the dye extends to both banks so that time-concentration curves for different points across the stream are essentially equal in area, the time of travel of the water is represented by the movement of the dye cloud along the stream course. In a small stream this is ordinarily accomplished in a short distance relative to the distance at which the cloud is sampled, such that no significant errors exist if dye injection is made at the head of the reach of interest. This may not be the case on wide or shallow streams, and it is highly recommended that in order to more accurately measure the traveltime between two points on such a stream, the dye be injected a distance L_m, or greater, above the head of the reach. Thus, time-of-travel data will be for the interval from cloud to cloud and will accurately measure the characteristics of the desired reach.

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

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

Sometimes there are considerations that make it necessary to subdivide a long reach into

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

Where concurrent injections are to be made, the subreaches should be of sufficient length to avoid the possibility of the leading edge of an upstream dye cloud overtaking the trailing edge of the next one downstream. In some instances, it may be desirable to stagger the timing of the injections, the most downstream one being first.

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

The mergence of two flows may require considerable distance before they are homogeneously mixed. The flow containing the dye at the junction point of a tributary inflow is analogous to a side injection, and the distance to mixing with the tributary flow may be approximated by equation 2. A sampling section below a major tributary should be located a distance at least equal to L_m below the junction. In such cases, several points across the section should be sampled to define the dye distribution. If lateral mixing is not complete, it may be necessary to weigh dye concentrations on the basis of lateral discharge distribution.

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

Dye requirements

Rhodamine WT dye is recommended for time-of-travel measurements. Rhodamine B and BA dyes should be used only with a full understanding of their deficiencies.

Several empirical equations have been derived for estimating the quantity of dye necessary for a time-of-travel study. These equations provide an estimate of the dye quantity required to produce a desired peak concentration at a selected sampling site and take the general form:

$$V = k \left[\frac{Q_m L}{v} \right]^x C_p , \qquad (3)$$

where

V is the volume of dye, in liters,

Q_m is the maximum discharge in the reach, in cubic meters per second,

L is the distance from injection to sampling point, in kilometers,

v is the mean velocity, in meters per second, and

C_p is the peak concentration desired, in micrograms per liter.

The constant, k, and the exponent, x, depend somewhat on the characteristics of the dye and are determined from field experience.

For rhodamine WT 20-percent dye, the dosage formula (Kilpatrick, 1970) is

$$V = 2.0 \times 10^{-3} \left[\frac{Q_m L}{v} \right]^{0.93} C_p . \qquad (4)$$

The volume of rhodamine WT 20-percent dye required to produce a peak concentration of 1 μg/L can be determined from figure 11 for a range of flow-reach conditions.

The following example illustrates the method of computing the dye quantity and peak concentrations of intermediate points on a stream having significant tributary flow into the test reach.
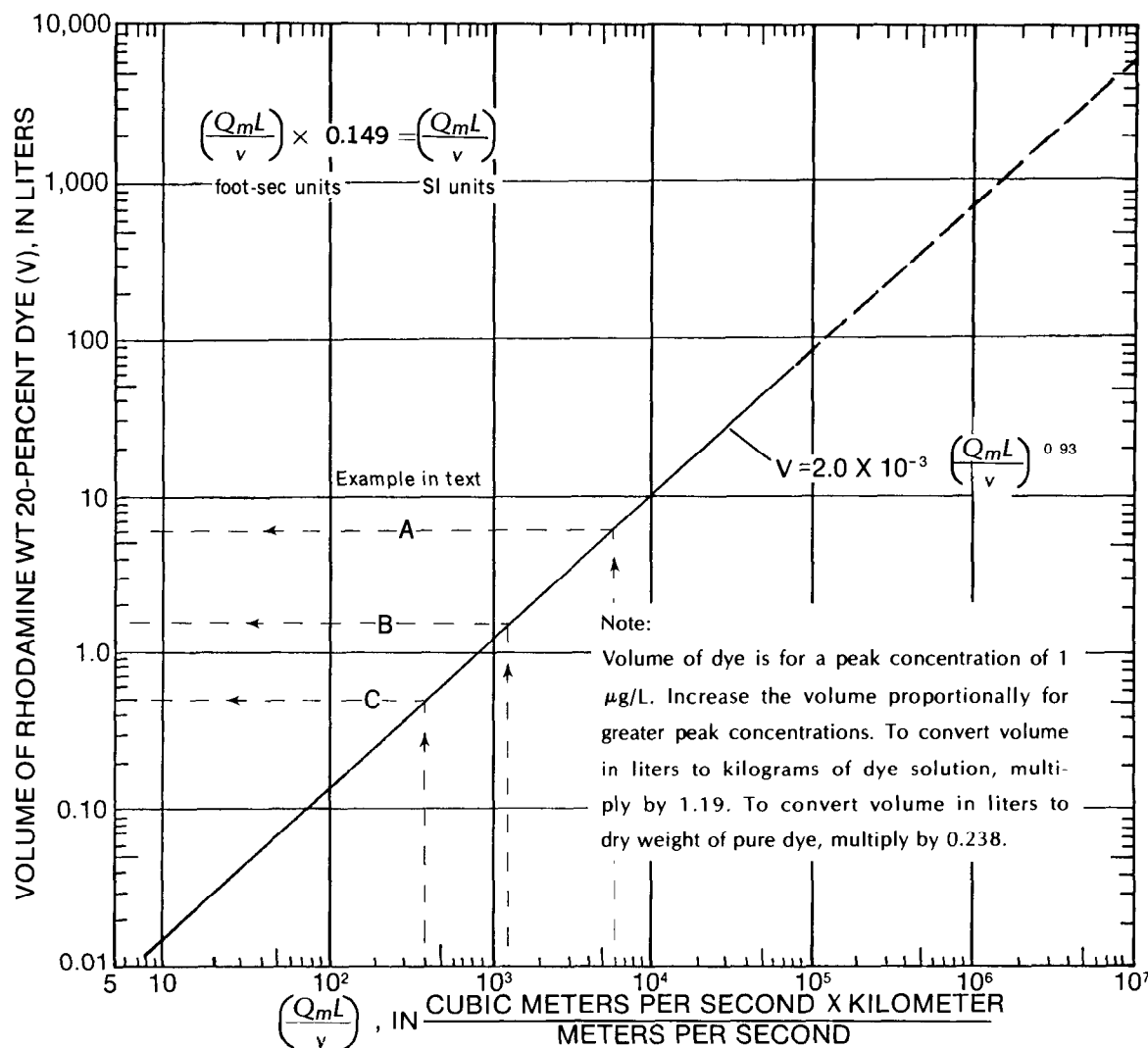
Figure 11.—Quantity of rhodamine WT 20-percent dye required for slug injection to produce a peak concentration of 1 μg/L at a distance, L, downstream, at a mean velocity, v, and with a maximum discharge Q_m in the reach.

Example. – For the stream reach and flow conditions shown in figure 12, determine the following: (A) Volume of rhodamine WT 20-percent dye to be injected at kilometer 0 necessary to produce a peak concentration of 2 μg/L at kilometer 50 and (B) peak concentration to be expected at the water plant at kilometer 20:

A.

$$\frac{Q_m L}{v} = \frac{12 \text{ m}^3/\text{s} \times 50 \text{ km}}{0.1 \text{ m/s}} = 6 \times 10^3.$$

From figure 11, $V = 6.5$ L for a peak concentration of 1 μg/L, and, for $C_p = 2$ μg/L, $V = 2 \times 6.5 = 13$ L.

B.

$$\frac{Q_m L}{v} = \frac{6 \text{ m}^3/\text{s} \times 20 \text{ km}}{0.1 \text{ m/s}} = 1.2 \times 10^3.$$

From figure 11, $V = 1.5$ L for 1 μg/L; hence,

$$C_p \text{ at the waterplant} = \frac{13}{1.5} = 8.7 \ \mu\text{g/L}.$$

While this is less than 10 μg/L, it is sufficiently large that reducing the injected volume to about 10 L might be advisable.
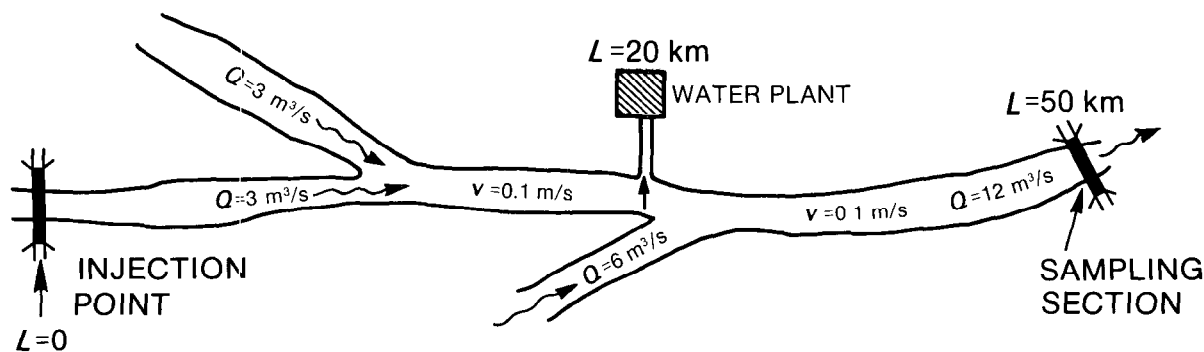
Figure 12.—Stream where a water user is involved and discharge is increasing in the downstream direction.

In some cases there may be significant diversions of flow in the test reach that also serve to divert a part of the injected dye. Example C illustrates the procedure for determining the dye quantity needed where a major diversion of flow takes place in the reach.

Example. – For the stream reach and flow conditions shown in figure 13, determine the volume of rhodamine WT dye to be injected at kilometer 0 necessary to produce a peak concentration of 2 μg/L at kilometer 4.0.

C.

$$\frac{Q_m L}{v} = \frac{10 \text{ m}^3/\text{s} \times 4 \text{ km}}{0.1 \text{ m/s}} = 4 \times 10^2.$$

From figure 11, V = 0.5 L for a peak concentration of 1 μg/L, or 1.0 L for a peak of 2 μg/L.

Only a part of the dye injected will reach kilometer 50, and therefore in order to obtain a peak concentration of 2 μg/L at kilometer 4, the volume of dye must be increased by the ratio of the discharge above the diversion to that in the stream immediately below it. Therefore, the volume of dye required, with the diversion, is

$$V = \frac{1.0 \times 9 \text{ m}^3/\text{s}}{6 \text{ m}^3/\text{s}}$$

= 1.5 L, with 0.5 L being diverted.

Sampling schedule

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

The relationships shown in figure 14 were derived from time-of-travel data as a guide for preparing a tentative sampling schedule. Estimates of the mean velocity, width, and depth of flow in the reach are required to use figure 14. The time to peak dye concentration, T_p, is computed using the estimated mean velocity:

$$T_p = \frac{L}{v}. \tag{5}$$

Enter figure 14 with T_p and the average width-mean depth ratio, W/d, and determine the estimated passage time for the dye cloud, t_d. Sampling should start at the arrival time of the leading edge of the dye cloud. Assume a dye cloud is symmetrical in shape; then the elapsed time to the leading edge, T_e, is computed as

$$T_e = T_p - (T_d/2). \tag{6}$$

Initially, sample-time requirements will be estimated for all sites. However, as data become available, these estimates should be updated and sampling plans altered accordingly.

The use of figure 14 to estimate a sampling schedule may be illustrated for the case shown in figure 12 where L = 50 km and W/d = 100.

$$T_p = \frac{L}{v} = \frac{50 \text{ km}}{0.1 \text{ m/s}} = 500 \times 10^3 \text{s} = 139 \text{ hours.}$$
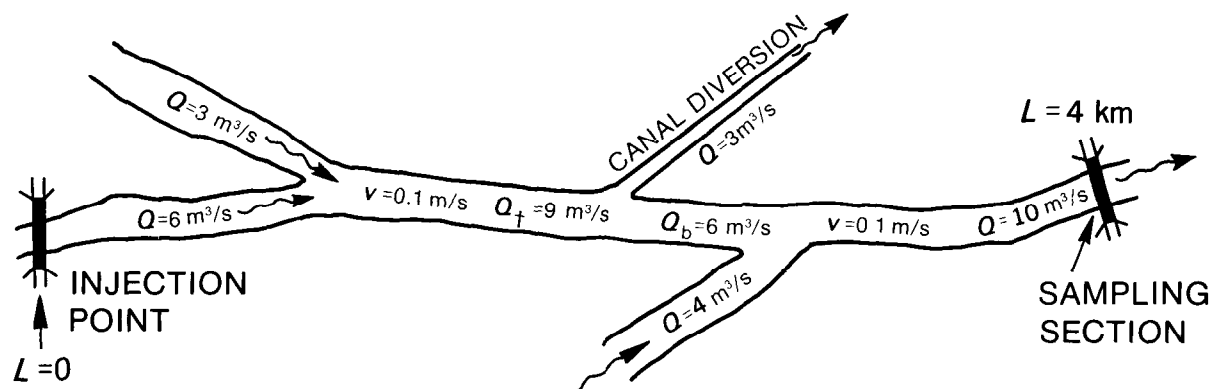
Figure 13.—Stream where flow is increasing in the downstream direction and a major diversion of flow occurs.

Enter figure 14 with $T_p = 139$ hours and $W/d = 100$; $t_d = 56$ hours, and a sampling interval of 1 to 2 hours is suggested. The leading edge of the dye cloud will arrive at approximately

$$T_e = T_p - (t_d/2) = 139 - 56/2 = 111 \text{ hours.}$$

The measurement plan

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

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

Personnel assignments

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

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

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

The plan should include the name, location, and telephone number of lodging accommodations for all personnel.

Equipment

The plan should show the assignment of equipment to the various individuals and party chiefs.

Maps and tables are very useful for briefing personnel and for reference. In fact, the measurement plan–including injection and sampling instructions, personnel assignments, and equipment disposition–may be put on a map. It should show sampling sites, injection points, the road and bridge system, lodging, towns, and landmarks. The map should be supplemented with sketches of hard-to-find sites.
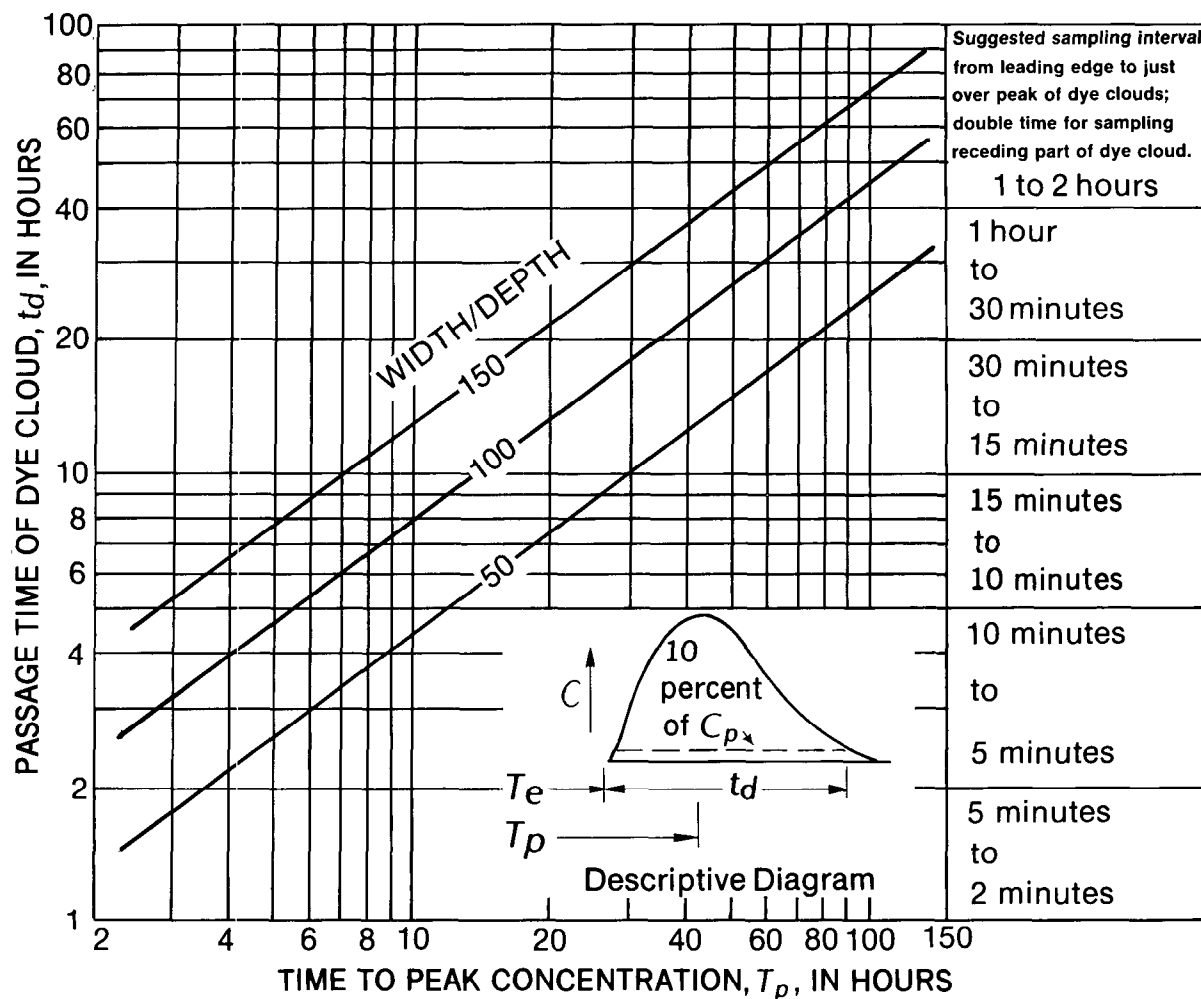
Figure 14.—Passage time of dye cloud as a function of traveltime to peak and average channel width-depth ratio. Relationship is approximate and should be used only for planning initial sampling schedules subject to field revisions.

Collection of Field Data

Injection of dye

A single-slug injection of dye is usually made in the center or in the main thread of flow. As mentioned previously, this should be L_m upstream from the head of the reach unless L_m is insignificant compared with the test-reach length. Similarly, multiple-point injections or line injections across the stream may be used where the channel is wide or the flow is shallow. The line injection should be made in the middle half to two-thirds of the flow and not too near the banks. The time required to cross the stream is usually insignificant, and injection may be considered instantaneous. For each injection the type and amount of dye, time and location of injection, and the stream stage and discharge should be noted.

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

Collection of water samples

At least one sample is needed for a fluorometer reading of background fluorescence

at each site before the dye arrives. If the site is also to be used as an injection site, the background samples should be collected before injecting the dye or should be taken upstream from the point of injection. Sampling should begin early enough to insure not missing the leading edge of the dye cloud. Usually, it is not necessary to sample more than 10–20 cm below the water surface. If initial mixing has occurred, the concentration will be nearly the same in a vertical direction.

The availability of a fluorometer at the first sampling section permits on-the-spot detection of dye. The preliminary fluorometer results can be used as a basis for altering the schedule to provide 20 to 30 samples at proper time intervals to define the time-concentration curve at a sampling point. Field plots of dial readings against time and of distance against time of leading edge and peak, as illustrated in figure 15, can be extrapolated to check or adjust the downstream sampling schedules.

Ideally, sampling should continue until the concentrations are down to the background level. This procedure is unwarranted from a practical standpoint. It is recommended that samples be collected until concentrations (or dial readings) have reached either 10 percent of the peak or 0.2 µg/L, whichever is lower.

Unless unusually good conditions exist, accurate fluorometric analysis in the field is not practical using any but the most modern fluorometers.

The need to move the fluorometer from site to site with the movement of the dye cloud precludes adequate instrument warmup and sample-temperature control. Thus, after the field analysis, the bottled samples should be stored out of sunlight, such as in the chest shown in figure 5, and returned to the laboratory or office for future analysis. A number of investigators have established field laboratories in a motel, or elsewhere, and have achieved accurate results with less delay than would be involved in transporting the samples from the field.

Measurement of discharge

The stream discharge should be measured or otherwise determined at each sampling site at the time the dye is present. Establishment of stage reference marks at each sampling site can be used in conjunction with current-meter discharge measurements to rate each site; this is helpful if several time-of-travel tests at different discharges are contemplated.
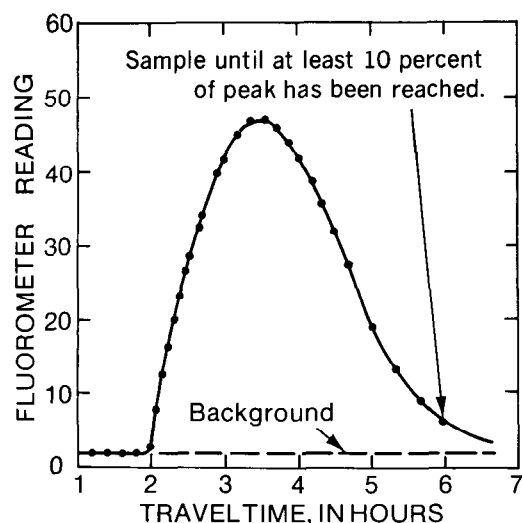
A. Time-concentration curve as measured in field at first sample site, kilometer 5.
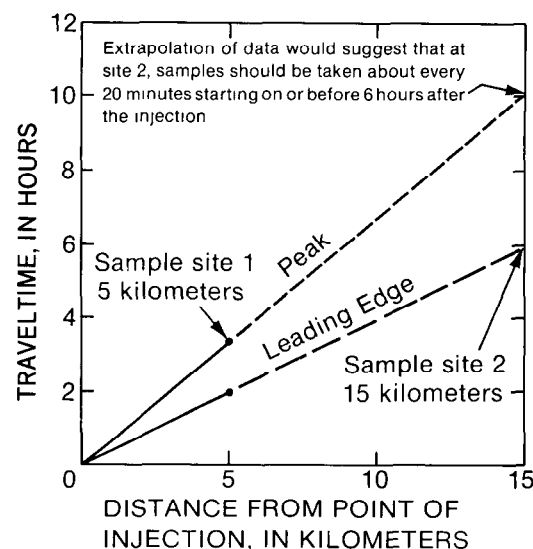
B. Time-distance plot extrapolation

Figure 15.—Use of data collected at the first sampling site to schedule sampling at succeeding downstream sites.

Use of fluorometers

The fluorometric testing of samples in the field is recommended to guide subsequent sampling. Basic time-of-travel information can be derived from field tests, but accurate measurement of sample concentration should be done in the office or laboratory under controlled conditions. Fluorometer readings for samples tested in the field should be recorded, and the notes should be retained on the data sheet, as shown in figure 6, even though retesting is contemplated.

Most fluorometers require shielding from the sun while in use because sunlight may leak into the instrument and cause erroneous responses. Under field conditions, usually neither complete fluorometer warmup nor measurement of sample temperatures is practical.

Some newer fluorometer models are light tight, require short warmup, and do not increase the temperature of the sample. If standard solutions are on hand and have the same temperature as the stream samples, fluorometer readings obtained in the field on these instruments may be considered satisfactory and sufficient.

When a battery-inverter-fluorometer setup is used, it should be turned on only when a group of samples has been accumulated. In situations where approximate data are acceptable and drain on the battery must be minimized, a minimum warmup period of five minutes may be employed.

Analysis and Presentation of Time-of-Travel Data

Laboratory analysis of samples

The samples collected in the field should be reanalyzed carefully as outlined by Wilson (1968). The form shown in figure 6 provides for recording both the field and laboratory data. The laboratory work can be expedited if the analysis can be made using only one fluorometer

scale. By inspection of the field data or by trial, select the scale that will yield the maximum reading for the sample representing the peak concentration for the sampling site. All samples for this site can then be analyzed on this one scale, minimizing the number of fluorometer scales that will need calibrating. For this reason, it is convenient to calibrate the fluorometer after the samples for each day have been tested and the scales actually used are known. This is contingent upon a sufficient warmup for the fluorometer model being used before any samples are analyzed.

Interpretation and presentation of results

The concentration for each sample should be plotted against elapsed time, and a smooth curve fitted to the points. The typical curve, shown in figure 2, is bell shaped but always slightly steeper on the rising limb than on the falling limb. The tail part is much longer and flatter than the leading edge and approaches the zero-concentration level asymptotically. The shapes of those parts of the curve not defined by sampling, such as a missed leading edge or the tail beyond the last sample, should be estimated (figure 16).

To illustrate data presentation, part of a study that Taylor (1970) conducted on the Monocacy River in Maryland during 1967 and 1968 is used throughout this manual. The data necessary to make the analyses appear in table 1 and are typical of a well-executed higher-level dye study. The part of Taylor's study that is included is for the subreaches A and B as shown on the map, figure 17.

Many users of the data can find what they need directly in a table such as table 1 without requiring any further analysis. Table 1 is a little more extensive than is necessary for just a time-of-travel study but will be used subsequently in explaining dispersion analyses. More information is also included to illustrate alternative methods of data analysis, in addition to typical methods.
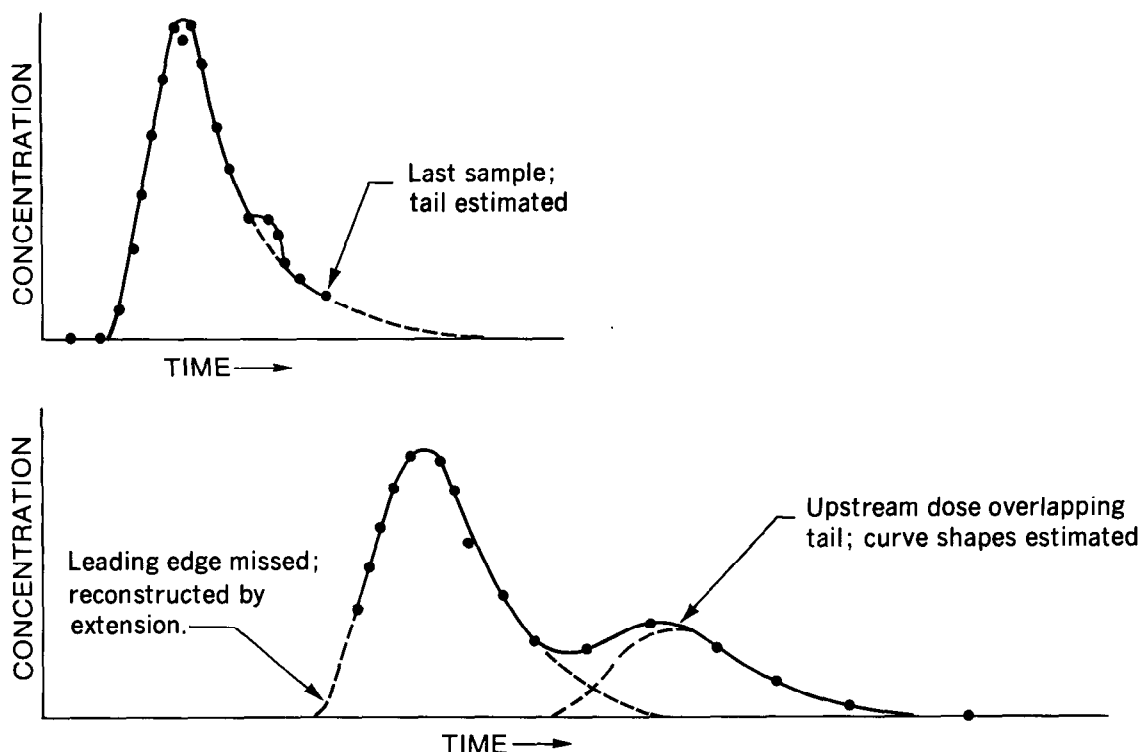
Figure 16.—Time-concentration curves; sketching techniques are illustrated.

Time-concentration curves

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

Figure 18 shows the time-concentration curves from the injection of September 25, 1968, for subreach A of the Monocacy River. Notice that, if desired, the graph could have been started at an elapsed time of zero, which would allow labeling of site 1 directly on the illustration.

Stewart (1967) illustrated the nonuniform lateral distribution of dye by presenting the curves resulting from sampling at three points on a cross section of a wide river.

Many authors use a limited number of time-concentration curves sufficient to illustrate the procedures used in their study and the concepts important to their report. Other kinds of illustrations are utilized in presenting their time-of-travel and dispersion data. Depending on the objectives of the study, however, one or all time-concentration curves may be presented.

Traveltime-distance curves

Traveltime-distance data can be effectively presented in tables such as table 1. These data can also be presented graphically. Figure 19 is a typical traveltime-distance curve, showing traveltime of the leading edge, centroid, peak, and trailing edge. Generally, traveltime-distance curves for each subreach are shown, but since it is useful to combine the traveltime-distance data for adjacent subreaches and plot cumulative traveltime against total distance in the study reach, the individual traveltime-distance curves do not appear in every report. Traveltime-distance curves should have such im-
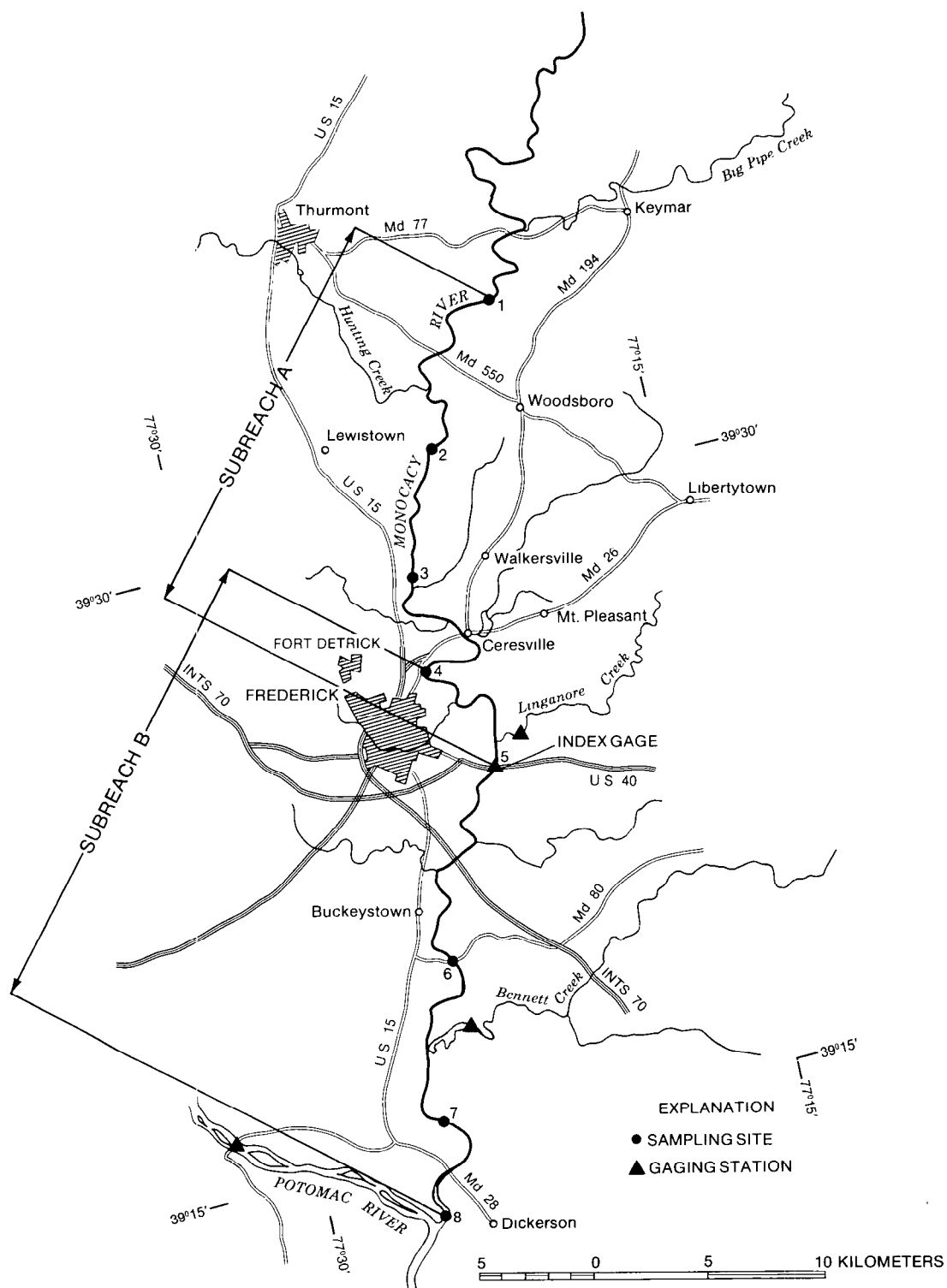
Figure 17.—Location of the study reach, Monocacy River, Md.

Table 1.—Traveltime, dispersion, and related data from the dye studies of November 1967, June 1968, and September 1968 on subreaches A and B of the Monacacy River, Md.

Subreach A — [Injected 0.714 kg, w_d, of rhodamine WT dye at 0600 Nov 14, 1967 Discharge at index gage 7.65 m³/s]

Site No.	Distance from point of injection (km)	Distance from mouth (km)	Leading edge Travel-time (hours)	Leading edge Cumulative travel time (hours)	Peak Travel-time (hours)	Peak Cumulative travel time (hours)	Centroid Travel-time (hours)	Centroid Cumulative travel time (hours)	Trailing edge Travel-time (hours)	Trailing edge Cumulative travel time (hours)	Discharge at sampling site, Q (m³/s)	Conservative peak concentration, C_p (µg/L)	Peak concentration produced by 1 kg of dye [1]	Unit peak concentration, C_{up} [2]	Time of passage of dye cloud (hours)
1	0	60.90	—	—	—	—	—	—	—	—	—	—	—	—	—
2	10.30	50.60	11.5	11.5	12.5	12.5	13.6	13.6	16.4	16.4	5.38	12.4	17.3	93.2	4.9
3	18.34	42.56	20.5	20.5	23.0	23.0	24.8	24.8	30.9	30.9	5.66	6.82	9.55	54.1	10.4
4	26.79	34.11	29.0	29.0	34.0	34.0	35.2	35.2	42.9	42.9	6.37	4.19	5.87	37.4	13.9
5	34.27	26.63	38.0	38.0	43.5	43.5	45.6	45.6	54.2	54.2	7.65	2.91	4.08	31.2	16.2

Subreach B — [Injected 1.545 kg, w_d, of rhodamine BA dye at 0510 Nov. 14, 1967 Discharge at index gage 8.10 m³/s]

Site No.	Distance from point of injection (km)	Distance from mouth (km)	Leading edge Travel-time (hours)	Leading edge Cumulative travel time (hours)	Peak Travel-time (hours)	Peak Cumulative travel time (hours)	Centroid Travel-time (hours)	Centroid Cumulative travel time (hours)	Trailing edge Travel-time (hours)	Trailing edge Cumulative travel time (hours)	Discharge at sampling site, Q (m³/s)	Conservative peak concentration, C_p (µg/L)	Peak concentration produced by 1 kg of dye [1]	Unit peak concentration, C_{up} [2]	Time of passage of dye cloud (hours)
4	0	33.95	—	—	—	—	—	—	—	—	—	—	—	—	—
5	7.32	26.62	7.5	38.0	8.5	43.5	9.9	45.6	13.4	54.2	8.10	18.0	11.6	94.2	5.9
6	18.83	15.12	26.0	56.5	29.0	64.0	31.6	67.3	38.7	79.5	8.35	7.35	4.76	39.7	12.7
7	27.59	6.36	36.0	66.5	41.0	76.0	43.3	79.0	53.6	94.4	9.35	5.03	3.26	30.4	17.6
8	33.79	.16	43.0	73.5	48.0	83.0	51.5	87.2	62.4	103.2	9.49	4.55	2.94	27.9	19.4

Subreach A — [Injected 1.904 kg, w_d, of rhodamine WT dye at 1626 June 7, 1968 Discharge at index gage 18.6 m³/s]

| Site No.	Distance from point of injection (km)	Distance from mouth (km)	Leading edge Travel-time (hours)	Leading edge Cumulative travel time (hours)	Peak Travel-time (hours)	Peak Cumulative travel time (hours)	Centroid Travel-time (hours)	Centroid Cumulative travel time (hours)	Trailing edge Travel-time (hours)	Trailing edge Cumulative travel time (hours)	Discharge at sampling site, Q (m³/s)	Conservative peak concentration, C_p (µg/L)	Peak concentration produced by 1 kg of dye [1]	Unit peak concentration, C_{up} [2]	Time of passage of dye cloud (hours)
1	0	60.90	—	—	—	—	—	—	—	—	—	—	—	—	—
2	10.30	50.60	6.4	6.4	7.1	7.1	7.9	7.9	9.9	9.9	14.3	18.4	9.67	138	3.5
3	18.34	42.56	11.8	11.8	13.6	13.6	14.2	14.2	17.4	17.4	15.2	11.9	6.23	94.8	5.6
4	26.79	34.11	17.0	17.0	19.6	19.6	20.4	20.4	24.2	24.2	15.9	9.01	4.73	75.2	7.2
5	34.27	26.63	22.2	22.2	25.8	25.8	26.6	26.6	31.3	31.3	18.5	6.06	3.18	58.9	9.1

Subreach B — [Injected 3.708 kg, w_d, of rhodamine BA dye at 1455 June 7, 1968. Discharge at index gage: 20.4 m³/s]

Site No.	Distance from point of injection (km)	Distance from mouth (km)	Leading edge Travel-time (hours)	Leading edge Cumulative travel time (hours)	Peak Travel-time (hours)	Peak Cumulative travel time (hours)	Centroid Travel-time (hours)	Centroid Cumulative travel time (hours)	Trailing edge Travel-time (hours)	Trailing edge Cumulative travel time (hours)	Discharge at sampling site, Q (m³/s)	Conservative peak concentration, C_p (µg/L)	Peak concentration produced by 1 kg of dye [1]	Unit peak concentration, C_{up} [2]	Time of passage of dye cloud (hours)
4	0	33.95	—	—	—	—	—	—	—	—	—	—	—	—	—
5	7.32	26.63	4.0	22.2	5.2	25.8	5.6	26.6	7.3	31.3	20.4	26.6	7.18	147	3.3
6	18.83	15.12	13.0	31.2	15.5	36.1	16.4	37.4	19.4	43.4	20.4	15.6	4.20	85.6	6.4
7	27.59	6.36	19.0	37.2	22.0	42.6	23.4	44.4	27.8	51.8	22.1	10.1	2.72	60.1	8.8
8	33.79	.16	24.0	42.2	27.5	48.1	29.0	50.0	33.2	57.2	22.1	9.88	2.66	58.9	9.2

Subreach A — [Injected 1.236 kg, w_d, of rhodamine BA dye at 1200 Sept. 25, 1968 Discharge at index gage: 3.06 m³/s]

Site No.	Distance from point of injection (km)	Distance from mouth (km)	Leading edge Travel-time (hours)	Leading edge Cumulative travel time (hours)	Peak Travel-time (hours)	Peak Cumulative travel time (hours)	Centroid Travel-time (hours)	Centroid Cumulative travel time (hours)	Trailing edge Travel-time (hours)	Trailing edge Cumulative travel time (hours)	Discharge at sampling site, Q (m³/s)	Conservative peak concentration, C_p (µg/L)	Peak concentration produced by 1 kg of dye [1]	Unit peak concentration, C_{up} [2]	Time of passage of dye cloud (hours)
1	0	60.90	—	—	—	—	—	—	—	—	—	—	—	—	—
2	10.30	50.60	22.0	22.0	27.0	27.0	—	—	37.2	37.2	2.01	21.7	17.6	35.3	15.4
3	18.34	42.56	45.5	45.5	54.0	54.0	—	—	72.3	72.3	2.01	12.6	10.2	20.5	26.8
4	26.79	34.11	64.5	64.5	76.0	76.0	—	—	104.6	104.6	2.27	8.0	6.47	14.7	40.1
5	34.27	26.63	83.5	83.5	100.0	100.0	—	—	131.7	131.7	2.55	6.4	5.18	13.2	48.2

Subreach B — [Injected 1.854 kg, w_d, of rhodamine BA dye at 1035 Sept. 25, 1968. Discharge at index gage: 3.06 m³/s]

Site No.	Distance from point of injection (km)	Distance from mouth (km)	Leading edge Travel-time (hours)	Leading edge Cumulative travel time (hours)	Peak Travel-time (hours)	Peak Cumulative travel time (hours)	Centroid Travel-time (hours)	Centroid Cumulative travel time (hours)	Trailing edge Travel-time (hours)	Trailing edge Cumulative travel time (hours)	Discharge at sampling site, Q (m³/s)	Conservative peak concentration, C_p (µg/L)	Peak concentration produced by 1 kg of dye [1]	Unit peak concentration, C_{up} [2]	Time of passage of dye cloud (hours)
4	0	33.95	—	—	—	—	—	—	—	—	—	—	—	—	—
5	7.32	26.63	14.0	83.5	17.5	100.0	21.0	—	26.8	131.7	3.06	24.8	13.4	40.9	12.8
6	18.83	15.12	54.0	123.5	64.0	146.5	69.5	—	96.2	201.1	3.20	7.90	4.26	13.6	42.2
7	27.59	6.36	70.0	139.5	86.0	168.5	93.2	—	125.3	230.2	3.46	5.54	2.99	10.3	55.3
8	33.79	.16	85.0	154.5	99.0	181.5	110.7	—	152.1	257.0	3.51	4.78	2.58	9.05	67.1

[1] C_p/w_d, in micrograms per liter per kilogram.

[2] $C_{up} = \dfrac{C_p Q}{w_d}$, in (micrograms per liter times cubic meters per second) per kilogram.
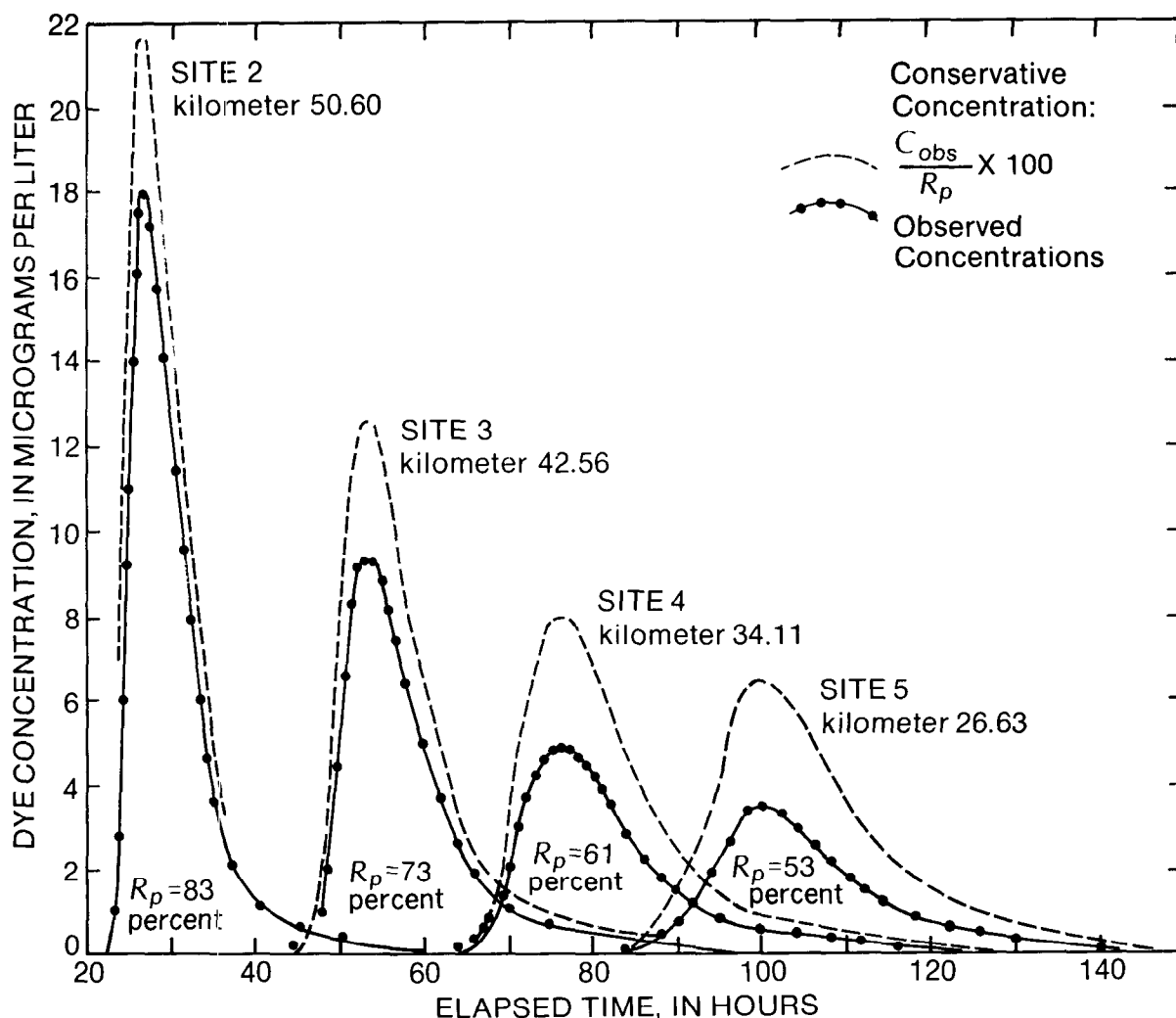
Figure 18.—Observed and conservative time-concentration curves for subreach A, Monocacy River, Md. Injection of 4 L of rhodamine BA, 30-percent solution, made at site 1, kilometer 60.90, at 1200 hours, September 25, 1968.

portant features as water-supply intakes, major tributaries, or landmarks, for example, highway crossings, located on them.

When summing the traveltime for individual subreaches only the data for the traveltime of the centroid are truly additive. Initial dispersion affects the traveltime of the leading edge, peak, and trailing edge. However, the time interval between passage of the peak concentration at two successive sites is virtually the same as the time interval between the centroids of the time-concentration curves, hence these traveltimes may be added and plotted to approximate the pattern to be expected for a single injection.

Figure 20 shows the cumulative times of travel for subreaches A and B of the Monocacy for the injection of November 14, 1967. Note that the reaches were overlapped, to avoid the errors that would exist if the initial dispersive data had to be used as indicated by the dashed lines for the leading edge and peak curves in figure 20. The cloud moved more quickly through the beginning of the study reach since initial dispersion was not complete. The traveltime of the trailing edge was also affected by the initial dispersive effects, and the technique employed of truncating the trailing edge at a concentration of 10 percent of the peak concentration introduced further error.
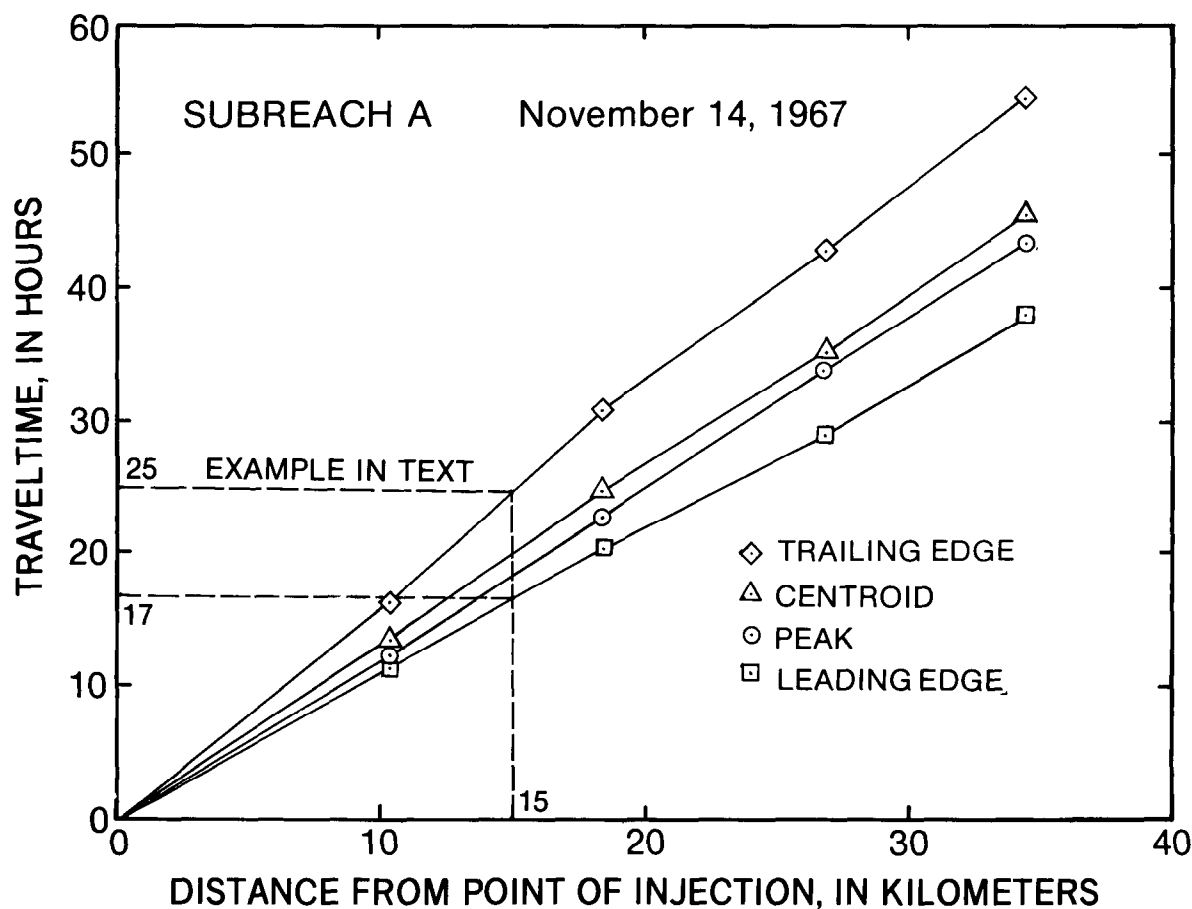
Figure 19.—Traveltime-distance relations for subreach A, Monocacy River, Md. Discharge at index gage was 7.65 m³/s.

This same error exists between the injection point for subreach A, kilometer 60.90, the first sampling site, and, perhaps, even farther downstream, but since there are no overlapping data, the error cannot be corrected.

Note that the slope of the curve is inversely proportional to the velocity of the dye cloud. For convenience, a small diagram depicting several slopes and labeled with velocities can be provided to enable the user to quickly estimate velocities.

While traveltime-distance curves are useful primarily in presenting time-of-travel data, they also illustrate longitudinal dispersion by showing the ever increasing passage time of the solute cloud. In the example shown in figure 19, at 15 km from the point of injection, the leading edge passed after an elapsed time of 17 hours, and the trailing edge, after 25 hours, giving a passage time of 8 hours. Similarly, the passage time of the dye cloud can be determined for other elapsed times (Taylor, 1970).

Traveltime-discharge curves

Many investigators have used traveltime-distance relations of the peak concentration—and in some instances, the centroid—to show the variation with discharge of mean time of travel through a reach. Figure 21 shows these relations for subreaches A and B of the Monocacy River. These curves were interpolated or extrapolated from traveltime data for three studies conducted at different discharges. At least two dye studies at different discharges are necessary to make this analysis. Martens and others (1974) used three separate graphs—one each for the leading edge, the peak,
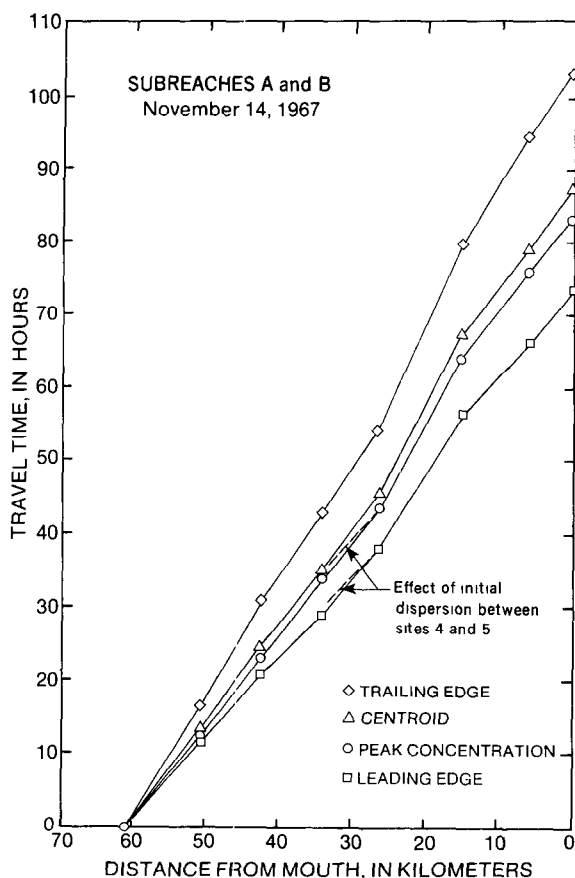
Figure 20.—Traveltime-distance relations for Monocacy River, Md. Discharge at the index gage averaged 7.88 m³/s.
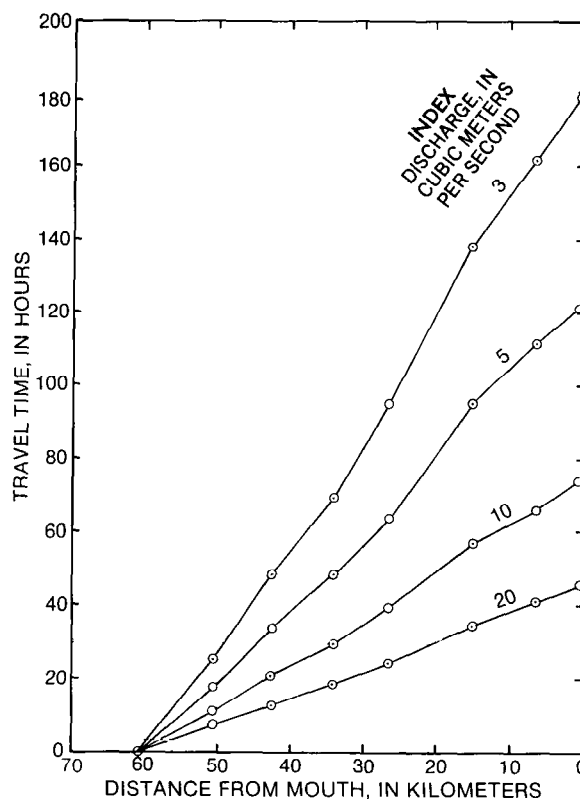

Figure 21.—Traveltime-distance relations of peak concentrations for selected discharges at the index gage, subreaches A and B of the Monocacy River, Md.

and the trailing edge—to show the effect of discharge on traveltime in a reach of the Mississippi River. For many streams in Illinois, Stall and Hiestand (1969) plotted traveltime-distance curves for high, medium, and low flow, corresponding to 10-, 50-, and 90-percent flow durations, respectively. This technique has considerable merit where real-time discharge data are not readily available. Since a major purpose of time-of-travel data is to predict the effects of an accidental spill of some noxious material, decisions to protect public well being and safety may have to be made by managers and regulators before people who are knowledgeable about discharge at index gaging stations can be contacted. If the user could make an initial estimate of flow conditions based on weather conditions, appearance of nearby streams, and the time of year, a conservative evaluation of

the rate of movement of a contaminant could be made from such curves.

These same data may be plotted as the family of curves shown in figure 22—one for each of the sampling sites of the Monocacy River study. For a range of in-bank discharges these relations typically plot as straight lines on logarithmic graph paper. If the entire reach is fairly uniform with regard to geometry and roughness, the lines for each subreach will be approximately parallel.

Using a variation of the traveltime-discharge curve, Harris (1968) plotted travel rate, or velocity, against discharge of the solute cloud for streams in the Willamette River basin.

For the traveltime-discharge curves, or other relations that use the discharge at an index gage, it is necessary to select a gaging station that is reasonably representative of the study reach. If the discharge varies considerably upstream to downstream in the reach during the
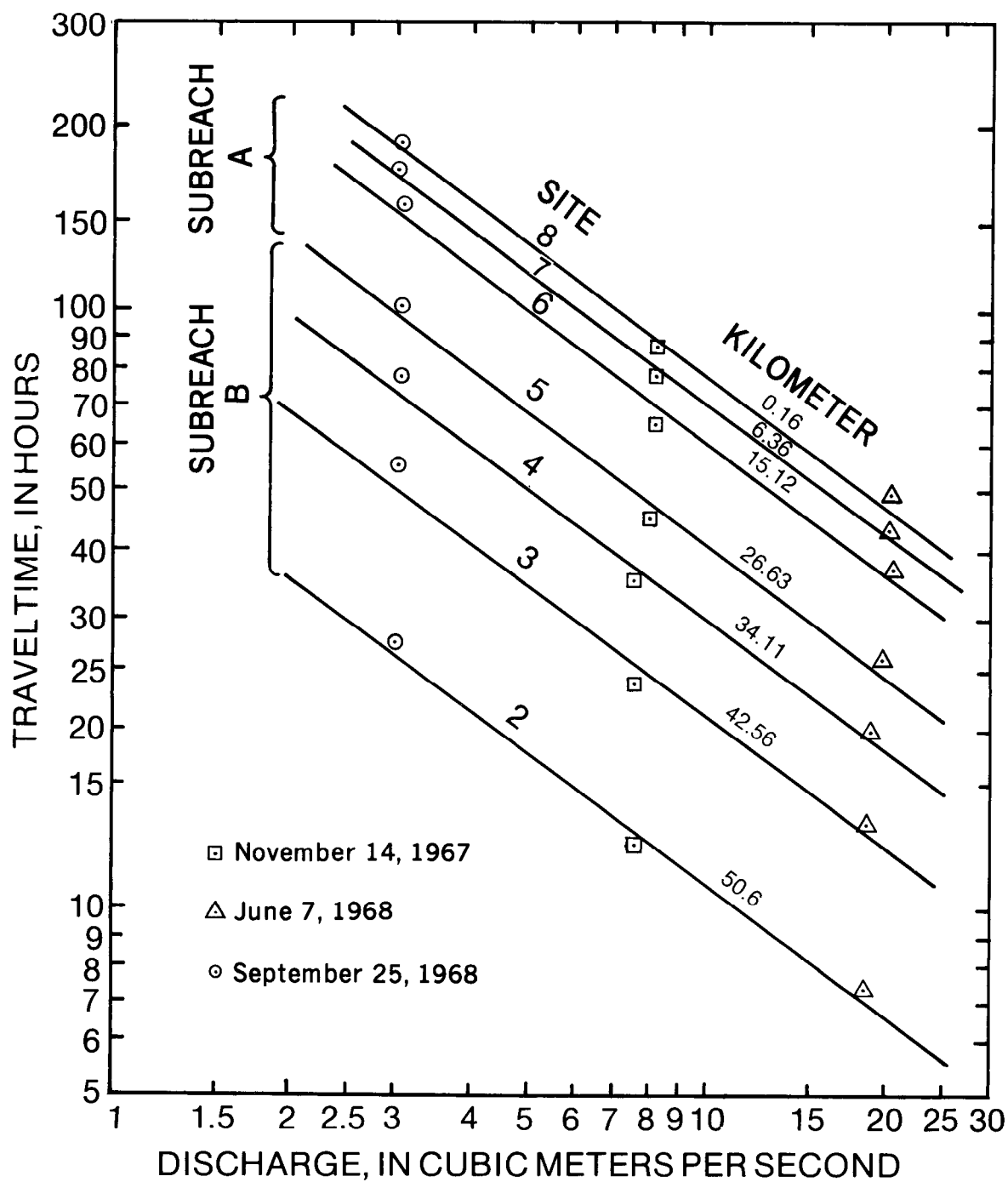
Figure 22.—Traveltime of peak concentration plotted against discharge at the index gage, Monocacy River, Md.

study, the use of more than one index gaging station may be advisable. For example, Lindskov (1974) related some of his traveltime-discharge curves to a gaging station on a small stream near the start of the study reach and the rest of the curves to a station on the Yadkin River, where the downstream subreaches were located.

Analysis and Presentation of Dispersion Data

The major objective of dye studies in the past has been the acquisition and presentation of time-of-travel data, probably still the most important information to be acquired. Nevertheless, there is increased interest and need to predict not just rates of movement but also the duration and magnitude of pollutant concentrations to be expected. Dispersion data are useful in predicting the results of an accidental spill of some objectionable material or the deliberate release, as a slug, of the contents of a holding pond or other containment to take advantage of, for example, the increased dilution brought about by larger stream discharges.

After an initial period during which lateral and vertical mixing occurs, dispersion data represent, practically, the rate at which the stream dilutes a soluble substance by mixing it into an ever increasing volume of water as the solute cloud lengthens. Data indicating the capacity of a stream to disperse a solute is usually presented in two ways—the decrease in peak concentration as a function of time as the solute cloud moves downstream and the time required for the solute cloud to pass a point of interest. The relations derived from these data should be used with considerable caution in predicting the concentration of an insoluble or immiscible substance, such as oil or other floating materials, as the peak concentrations of such substances tend to be greater because the substances may not be undergoing dilution throughout the entire flow.

Similarly, unless the substances' decay characteristics are known, the relations will not predict the concentration of nonconservative substances, such as nutrients, dissolved gases, and other materials that are biologically or chemically degradable. In this instance, the predicted concentrations would be greater than the actual, and, thus, estimates would be "safe" to use. Dispersion relations cannot predict with any accuracy the concentration or the passage time of a solute when flow conditions are unstable.

Time-concentration and traveltime-distance relations are useful in depicting the dispersion process, but they have certain limitations. Time-concentration curves show the peak concentration that would result from the injection of a certain weight of pure dye. If the peak concentrations determined from the time-concentration curves are multiplied by the ratio of the weight of a contaminant spilled to the weight of dye injected, both being injected at the same point, then the computed concentrations will be a prediction of the peak concentrations that will result from the spilled substance as it moves past the sites sampled during the dye study. For example, if a solution containing 1 km of rhodamine dye resulted in a peak concentration of 50 μg/L at some point downstream, then the release at the same point of a brine-holding pond containing 100 km of elemental chloride in salt compounds would result in a chloride concentration 100 times more than the concentration of dye, or 5,000 μg/L.

Similarly, the passage time of the solute cloud can be determined from the time-concentration curves. Passage time is independent of the weight of the released substance, so the passage time of the dye cloud will be about the same as that for any other solute injected at the same point.

As has been previously described a set of traveltime-distance relations can be determined for a range of discharges, allowing the user to predict the passage time in any part of the reach of a solute cloud resulting from a spillage at any point and at a selected discharge. This is generally possible because stream-channel characteristics for a given flow are consistent over considerable lengths. It has been found that the same thing is true for dispersion (F. A. Kilpatrick, written commun., 1969); that is, for a given flow (or stage) longitudinal dispersion is fairly constant over a reach and data can be analyzed and presented for a range of stream

discharges to allow the prediction of dispersion characteristics at any point in a reach from an injection at any point.

Observed concentrations

The magnitude of dye concentrations defined by the observed time-concentration curve depends on the quantity of dye injected, the discharge, the longitudinal dispersion, and dye losses.

The concentration varies inversely and the passage time, directly, with the dispersion capability of a stream; that is, the greater the dispersion capability, the longer the passage time of the dye cloud and the lower the peak concentration.

Tests using the different types of dyes under identical flow conditions yield time-concentration curves similar in shape but having different concentration magnitudes. The differences in concentration are due to dye losses. All the dyes in use for water tracing are non-conservative. However, the smaller the losses or, conversely, the greater the percent of dye recovered, the more conservative is a particular dye.

Conservative concentrations

Pollutants also vary in their conservativeness. When the decay characteristics of a pollutant are unknown or are unpredictable it is best to err on the high side. Thus, it is safer to present conservative concentration data.

If a tracer is conservative, the total weight, w_d, injected upstream will be completely recovered downstream. The continuity equation defining this relationship, more commonly referred to as the total-recovery equation, is

$$w_d = Q \int_0^\infty C dt, \text{ or}$$

$$VC_s = QA_c, \qquad (7)$$

where the total amount injected is the product of the volume of dye solution injected, V, and the concentration, C_s; Q is the stream discharge; and A_c is the area of the time-concentration curve after complete mixing. It is important to

note that A_c must be measured after complete mixing and that good practice dictates sampling a dye cloud at several points laterally to ascertain if complete mixing has been reached. In practice, 100 percent mixing will not be realized, but A_c will be more reliable if a good average value can be obtained using several time-concentration curves. It should also be noted that Q is the discharge at the point of sampling; with increasing discharge downstream, A_c will become smaller.

In practice the recovery of a dye tracer will always be less than 100 percent. If computations produce otherwise results, usually Q or A_c are in error; commonly, A_c has not been adequately or accurately defined. For example, it is important that the fluorometer used be calibrated using a sample of the injected dye at a concentration C_s. Poor fluorometry techniques may yield erroneous recovery values. Errors can often be detected by computing recoveries and comparing the recoveries at upstream and (or) downstream sites.

If the dye injected is measured in kilograms of a manufacturer's stock solution, such as 20, 30, or 40 percent, the percentage recovery, R_p, is computed as

$$R_p = \frac{3.60 \times 10^8 QA_c}{w_s C_s}. \qquad (8)$$

When the dye is measured in liters of a manufacturer's stock solution, the specific gravities of the dye must be considered. For rhodamine WT having a specific gravity of 1.19,

$$R_p = 1.51 \frac{QA_c}{V}. \qquad (9)$$

For both equations,

Q is the discharge at the point of sampling;

A_c is the mean area of the time-concentration curve, in micrograms per liter hours;

C_s is the concentration of the manufacturer's stock solution, in micrograms per liter (20 percent = 20 × 10^7 μg/L);

V is the volume of dye, in liters; and w_s is the amount of dye solution injected, in kilograms, having a concentration C_s.

The observed dye concentrations, when adjusted for dye losses, are equivalent to the concentrations that would be produced by a conservative tracer. The concentration of a conservative solute, C_{cor}, can be computed approximately from observed dye concentrations, C_{obs}, by the equation

$$C_{con} = 100 \frac{C_{obs}}{R_p} . \qquad (10)$$

Figure 18 shows the observed and conservative-concentration time curves for subreach A of the Monocacy River in Maryland. At the most downstream sampling section, the conservative concentrations are approximately double the observed because only about 53 percent of the rhodamine BA dye injected was recovered. In subsequent tests on this reach using rhodamine WT dye, approximately 95 percent of the dye was recovered.

Peak-attenuation curves

These relations commonly show conservative peak concentrations at each sampling site as a function of either distance along the reach or of traveltime. Stewart (1967), in a study on the Mississippi River, used a curve of peak-concentration plotted against traveltime to show the decrease in peak concentration. Although Stewart used observed concentrations plotted on arithmetic scales, Nobuhiro Yotsukura (written commun., 1976) has shown that, based on the Fickian theory of dispersion, once the initial mixing period is reached, the graph of conservative peak concentration plotted against traveltime tends to be a straight line on logarithmic paper.

The concept may be carried still further by dividing the values for peak concentration by those for the weight of dye injected. This adjustment in conjunction with the adjustment of observed concentrations to conservative concentrations is referred to as normalizing the data. Thus, for a given discharge, a user of the relation derived from these data would only have to multiply the weight of a spilled solute by the value of peak concentration per unit weight to predict the concentration at some point in the

reach downstream. Figure 23 is an example of this concept derived from the data collected in subreach A of the Monocacy River for three different dye studies.

If the channel and discharge are fairly uniform throughout the reach, such that the relations as shown in figure 23 are approximately straight lines, then it can be assumed that these relations are independent of the point of injection. That is, a solute may enter the reach at any point and the peak concentration can be estimated after any elapsed time. The traveltime of the cloud peak can be determined from curves such as those in figure 21.

Figure 23 can be refined for selected discharges by deriving a family of curves by interpolation or extrapolation, as in figure 24; caution should be exercised in extrapolating the relations beyond the range of the actual data.

A family of curves such as those in figure 24 could very well be a logical stopping point in the analysis of peak-concentration data. The relation is general to the extent that the user can predict the peak concentration at any time while the solute cloud is in the study reach, for a range of discharge conditions and for for any weight of solute injected anywhere in the reach. Another important aspect to consider is the relative ease with which the relation in figure 24 can be explained.

Unit-concentration curves

As has previously been discussed, the shape and magnitude of a time-concentration curve that is the response to a dye injection is determined by (1) the amount of dye injected, (2) losses undergone by the dye, (3) the discharge that serves to dilute the cloud in the reach, and (4) longitudinal dispersion. It has been observed in many instances that longitudinal dispersion does not vary greatly for a given reach when flows are in-bank and channel controlled. Thus, if time-concentration curves for different tests and flows were adjusted for the first three factors, the variation or lack of variation in longitudinal dispersion might become apparent. The concept of unit concentration was formulated by Kilpatrick, whereby time-concentration curves or peak concentrations are further adjusted to represent the response(s) in
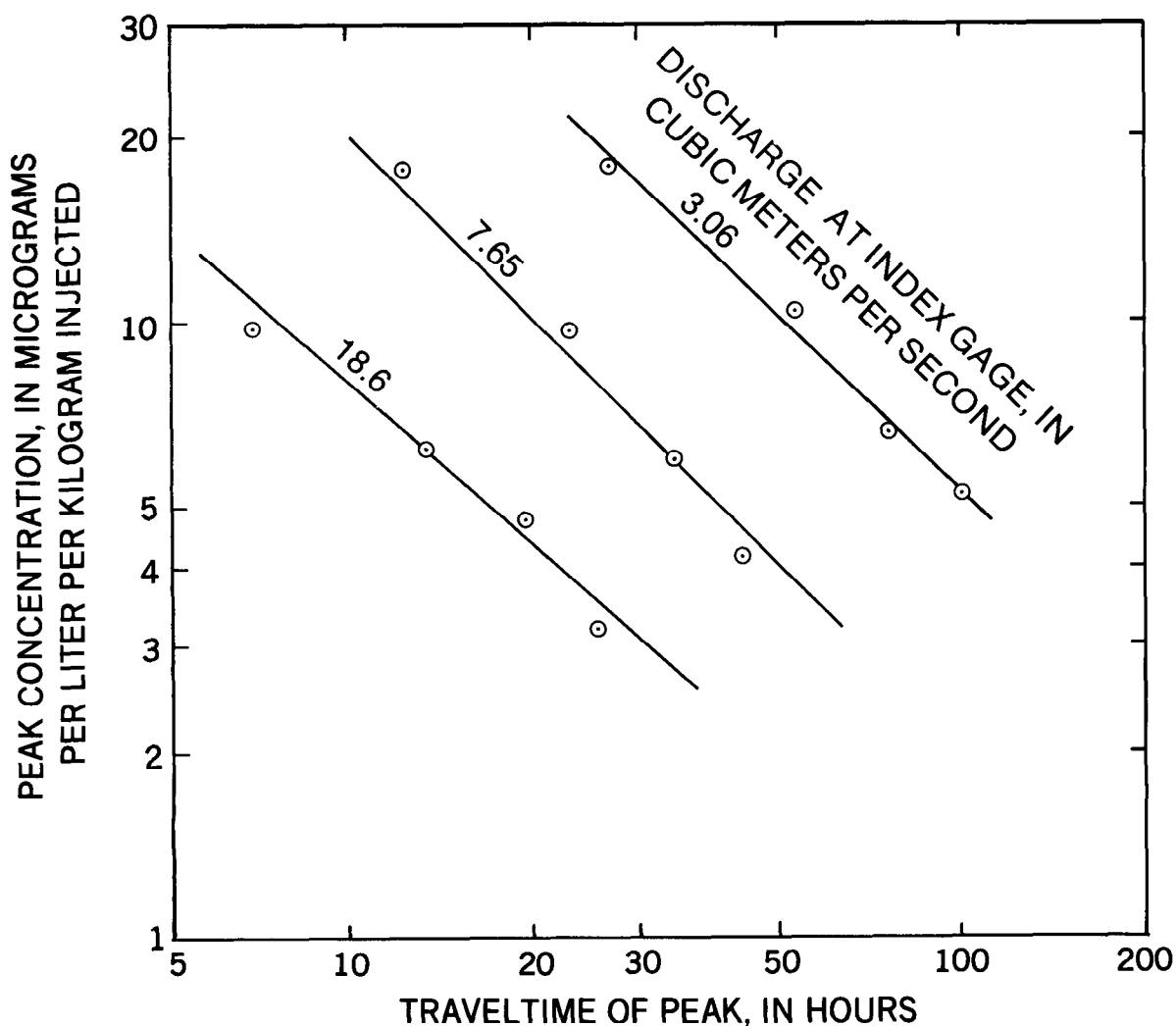
Figure 23.—Conservative peak concentrations that would result from injecting 1 kg of rhodamine dye into subreach A of the Monocacy River, Md. The peak concentrations derived from this relation may be multiplied by the number of kilograms of any conservative soluble material to predict its concentration at points downstream.

1 m³ of flow to 1 kg of conservative solute, or, more generally, the concentration produced in one unit of flow rate produced by one unit of weight of a conservative solute, since other unit systems may be used as well as the SI system. Unit concentrations may be computed by the equation

$$C_u = \frac{C_{con}Q}{w_d},$$ (11)

where w_d is the weight of pure dye injected.

Of particular interest is the prediction of maximum concentrations, so the unit peak concen-

tration, C_{up}, may be obtained by selecting the peak-concentration data for analysis. Figure 25 shows unit-peak-concentration curves derived from the data from three dye studies on subreach A of the Monocacy River. Notice that the only difference between figure 25 and figure 23 is that each unit peak concentration in figure 25 is obtained by multiplying the values given in figure 23 by the discharge at each sampling site. It should be emphasized that the values for discharges shown on the curves of figure 25 are those of index discharges and as such are not necessarily the same as those used in equation 11. Discharge may be replaced by river stage as
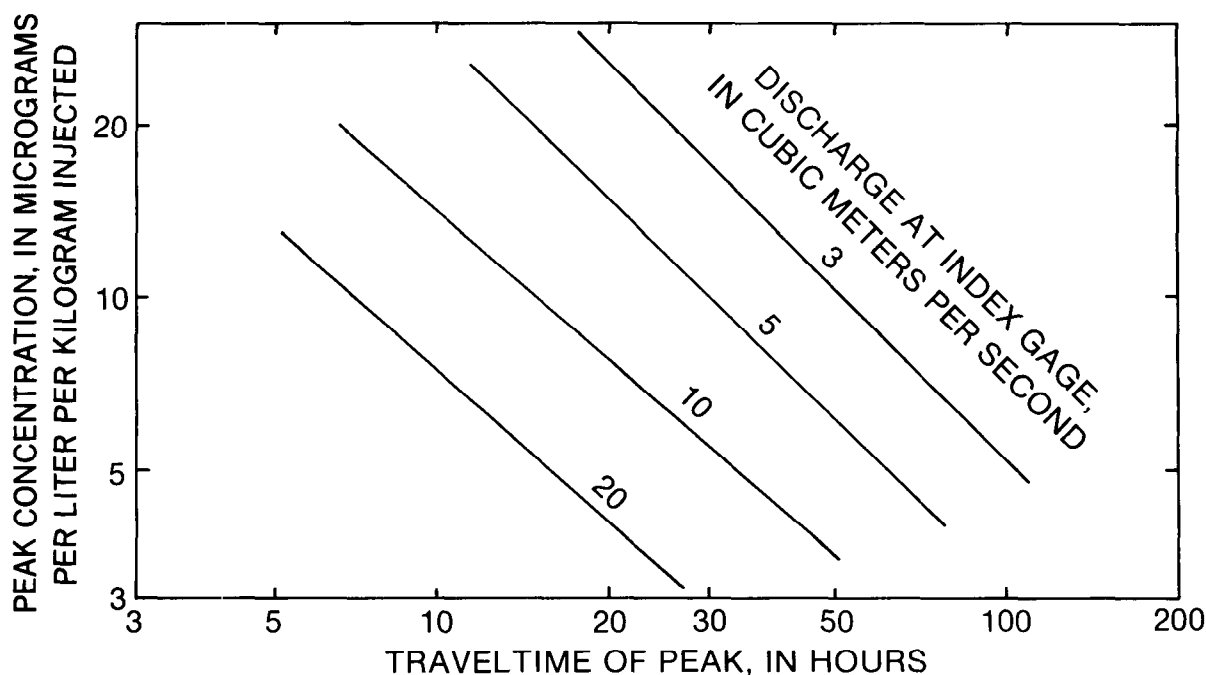
Figure 24.— Peak concentrations resulting from the injection of 1 kg of a conservative soluble material in subreach A of the Monocacy River, Md. The peak concentrations derived from this relation may be multiplied by the number of kilograms of material injected to predict concentration at points downstream.

an index and would probably have more utility to the lay user.

Conceptually, a peak concentration is directly proportional to the weight of solute injected and is inversely related, although not in simple proportion, to the discharge of the stream. If the weight of solute released is doubled, then the peak concentration of the solute cloud will be doubled, as will be all concentrations. If the discharge in the stream reach in which the solute cloud is moving is doubled, the peak concentration will decrease because of the increased dilution, but since the solute cloud will now move faster, reaching any given point sooner, time for dispersion to occur is less. Therefore, peak concentration does not respond in simple proportion to the diluting effect of increased discharge, but there is an inverse functional relation between the concentration of the solute and the discharge. If the data presented in figures 23 and 25 for subreach 4 are compared it can be seen that instead of a family of curves varying with discharge or stage, essentially one curve now exists. Thus the dilution effects of both increasing and different discharges have

been removed, and longitudinal dispersion is the only remaining variable. For subreach A, the longitudinal dispersion is essentially constant for the flows tested. To estimate the peak concentration of a solute released into the river multiply the value for C_{up} for the point of concern by the weight of solute released and divide by the value of the flow at that point.

Figure 26 shows the unit-peak-concentration curves for subreach B of the Monocacy River; there is some variation in longitudinal dispersion in this reach. The data for subreaches A and B can be shown on one graph as a family of curves using discharge or stage as an index to show that longitudinal dispersion is varying slightly. As is commonly the case, longitudinal dispersion increases at lower stages as pool-and-riffle conditions are reached.

Note in figure 27 and to some extent in figures 25 and 26 that the relations are drawn somewhat to the right of the data points that have the shortest traveltimes. This interpretation is based on the alignment of subsequent points and the consideration that the initial data are still influenced to some extent by vertical
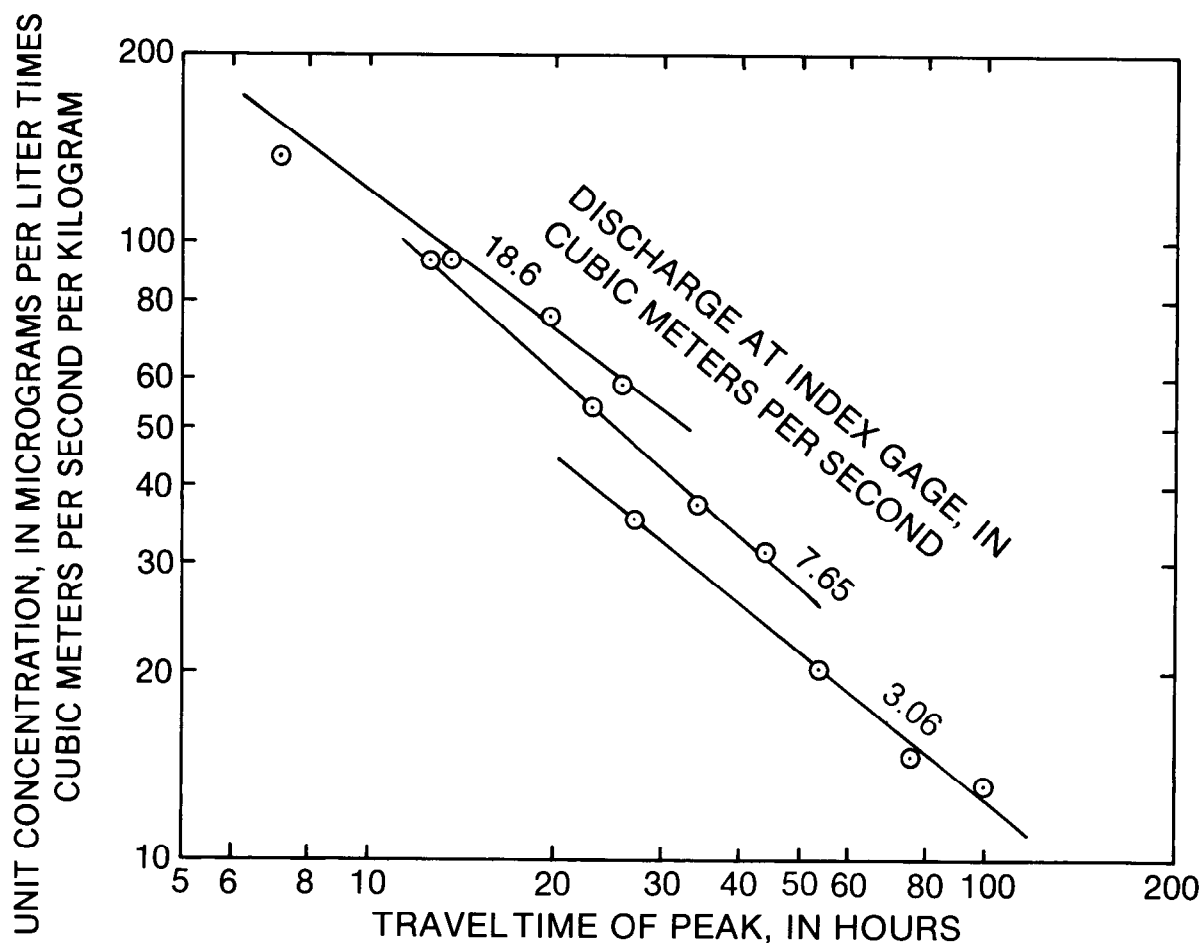
Figure 25.—Attenuation of unit peak concentration with traveltime for subreach A of the Monocacy River, Md.

and lateral dispersion mechanisms. While mixing is occurring in three dimensions, the unit peak concentration is decreasing relatively more rapidly with traveltime, hence the first data points plot low in comparison with the trend of subsequent points. As a final graph the data may be interpolated and extrapolated to represent a selected range of discharges or stages, as is shown in figure 28. These curves provide a means for predicting the peak concentration of contaminants, released or accidentally spilled, at selected points downstream.

As an example, assume 1,000 kg of a toxic substance was spilled into the Monocacy River (fig. 17) at the crossing of Maryland Highway 550; this could be an accidental spill or the con-

trolled but nearly instantaneous release of a holding pond. The problem is to predict the resulting magnitude and arrival time of the peak concentration at a hypothetical water-supply intake near Interstate Highway 70 when the discharge at the index gage is 20 m³/s and the estimated discharge at Interstate Highway 70 is 20.5 m³/s. The spill site is 56.2 km and Interstate 70 is 20.9 km upstream from the mouth. From figure 22 for a discharge at the index gage of 20 m³/s, the peak will arrive 27 hours after the spill (30 – 3 hours).

The curve in figure 28 for 20 m³/s at a traveltime of 27 hours indicates a unit peak concentration of 58 for the peak. For an assumed discharge of 20.5 m³/s at the hypothetical water
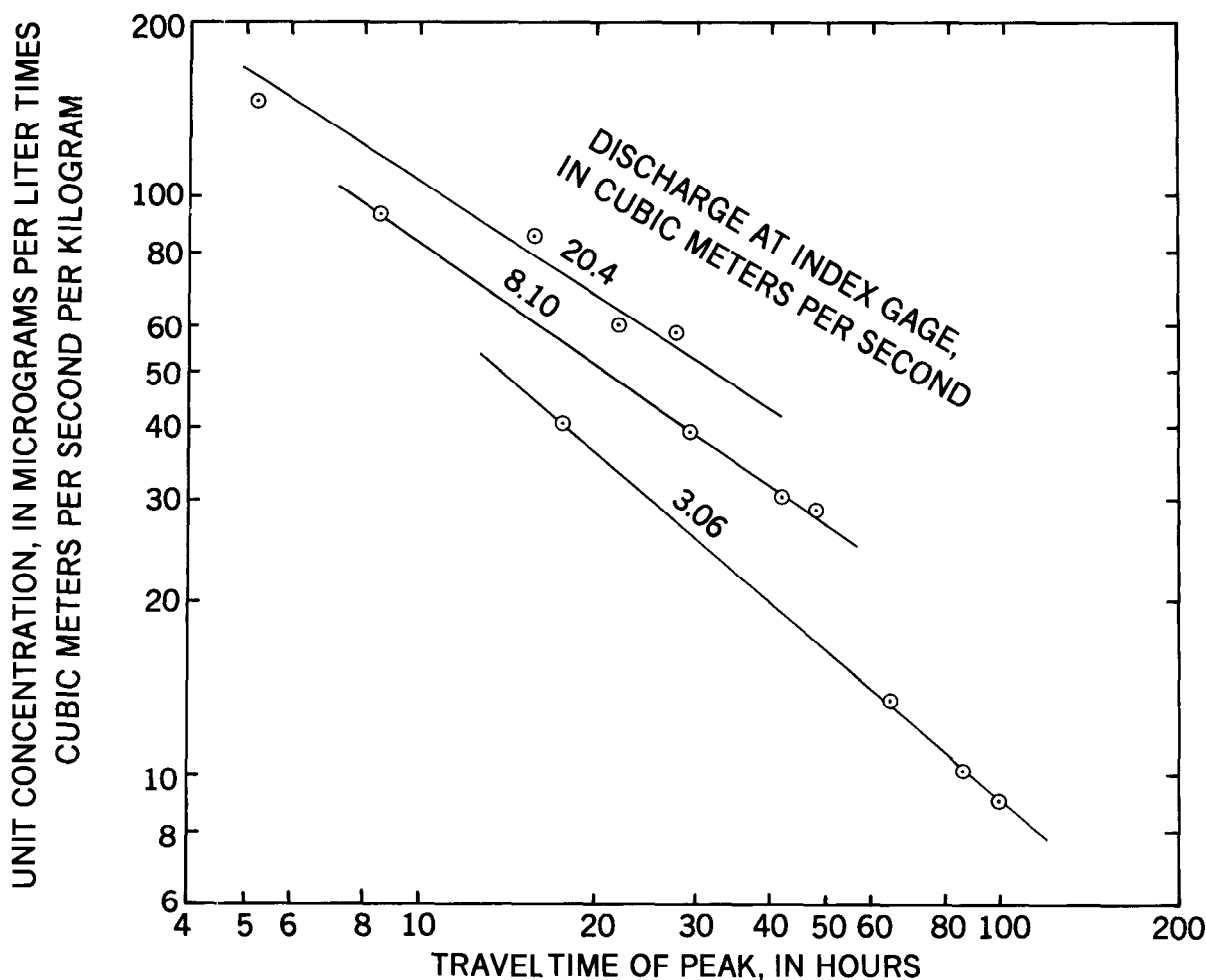
Figure 26.—Attenuation of unit peak concentration with traveltime for subreach B of Monocacy River, Md.

intake at Interstate Highway 70, the peak concentration would be

$$C_p = \frac{58\ \mu g/L \times m^3/s}{kg} \times \frac{1{,}000\ kg}{20.5\ m^3/s} = 2{,}800\ \mu g/L.$$

Health standards or other considerations for the particular contaminant would determine the hazard of such a concentration and whether water withdrawals would need to be suspended.

Instead of deriving a family of unit-peak-concentration curves for several discharges, Lindskov (1974) presented only one curve, which formed an upper envelope for the study for all the unit-peak-concentration data plotted against traveltime. Calling the relation an "ex-

treme unit-peak curve," Lindskov explained that the user can estimate the maximum-probable concentration from this curve. This idea can be a useful simplification of the unit-concentration concept, if it meets the objectives of an investigation.

Data for many dispersion studies have shown that the unit peak concentration is inversely proportional to traveltime raised to a power,

$$C_{up} \propto T_p^{\frac{1}{n}}, \qquad (12)$$

where n is a variable dependent on stream characteristics. Relation 12 can be logarithmically transformed to appear as

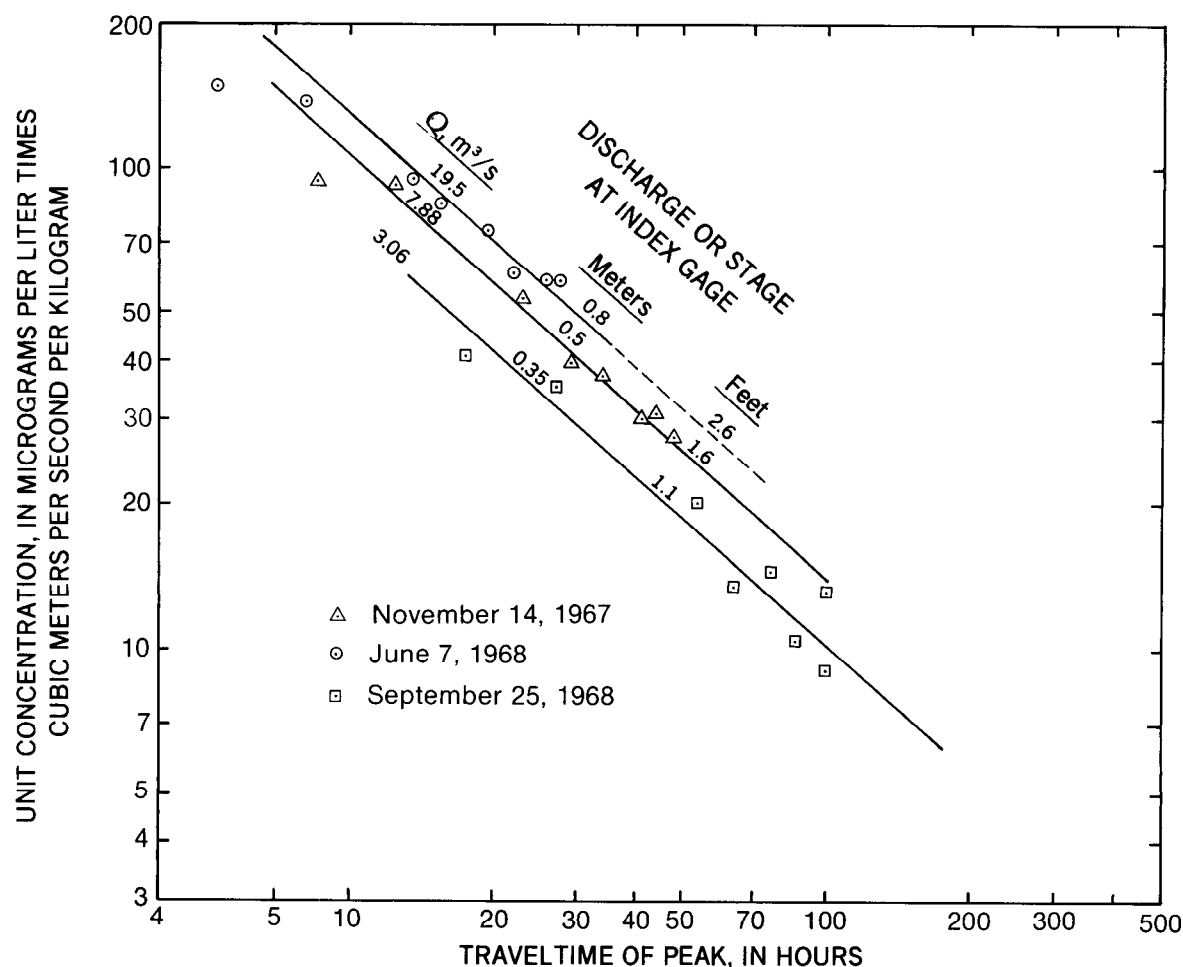$$\log C_{up} \propto -n\log T_p. \qquad (13)$$

Figure 27.—Attenuation of unit peak concentration with traveltime for subreaches A and B of the Monocacy River, Md.

Plotted on a logarithmic graph, $-n$ is, thus, the slope of the unit-peak-concentration curve.

Nobushiro Yotsukura (written commun., 1976) has shown, using Fickian theory, that $n = 0.5$ in a straight, uniform channel where mixing is complete in the vertical and lateral but not in the longitudinal direction. The Nordin and Sabol report (1974), concerning 50 time-of-travel and dispersion studies in streams for which they computed dispersion parameters, shows that n averaged 0.77 and ranged from 0.52 to 1.38.

The slope of the unit-peak-concentration curve may be thought of as an indication of the dispersion efficiency of the channel. A less steep slope indicates a less efficient channel, where efficiency is the characteristic of dispersing a solute through the reach with greatest reduc-

tion of peak concentrations in a given time; such a channel is commonly one containing bends, dead water, eddies, or pools and riffles. This was apparently the case for the Monocacy River data, as the unit-concentration curves in figure 28 are slightly steeper for the smaller discharges than for the larger discharges. The slope of unit-concentration curves may be scaled directly from the logarithmic graph using an arithmetic scale. Slope is the ratio of the change along the vertical axis to a corresponding change along the horizontal axis between two points on the unit-concentration curve.

It can be shown (K. R. Taylor, written commun., 1974) that the unit peak concentration is

$$C_{up} = 3.6 \times 10^{-6} \frac{C_p(\text{obs})}{A_c(\text{obs})}, \qquad (14)$$
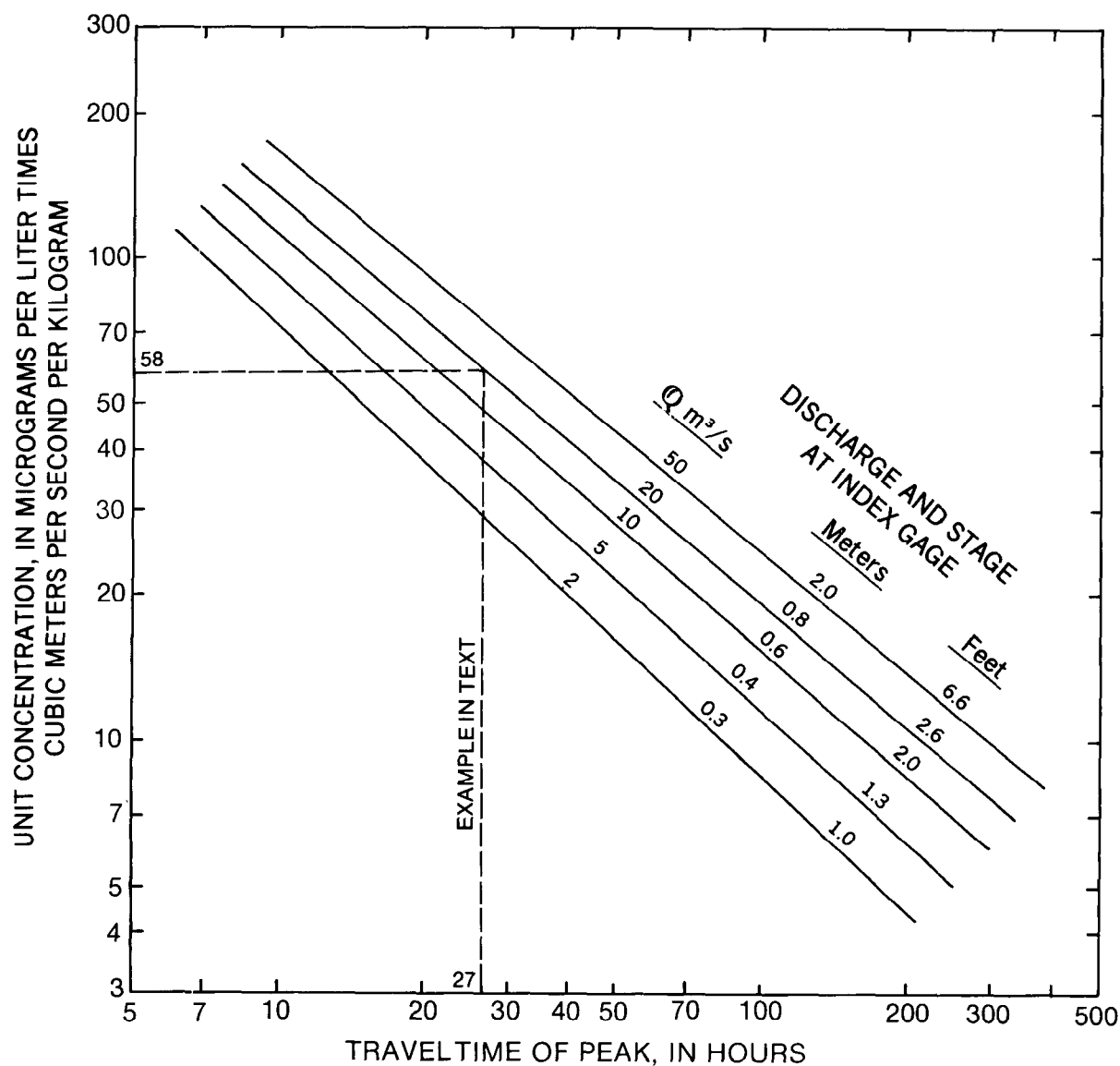
Figure 28.—Attenuation of unit peak concentration with traveltime for selected discharges in subreaches A and B of the Monocacy River, Md.

where C_p may have dimensions of concentration including just fluorometer dial readings and A_c is the area under the time-concentration curve, with dimensions of the same concentration units as C_p times hours. This results because in adjusting for dye losses, the weight of dye injected, and the discharge, the other units cancelled each other. Even though true concentrations do not have to be measured in arriving at unit concentrations or, for that matter, ordinary time-of-travel data, policy requires that absolute data be obtained.

Passage time-traveltime curves

It is apparent that the passage time of the solute cloud past a point is an inverse function of the peak concentration. As the solute cloud disperses into a longer length of channel taking more time to pass a point, the peak concentration will be less.

Since peak concentration and time of passage are strongly related, it follows that time of passage must also be related to traveltime, just as is peak concentration. Figure 29 shows the
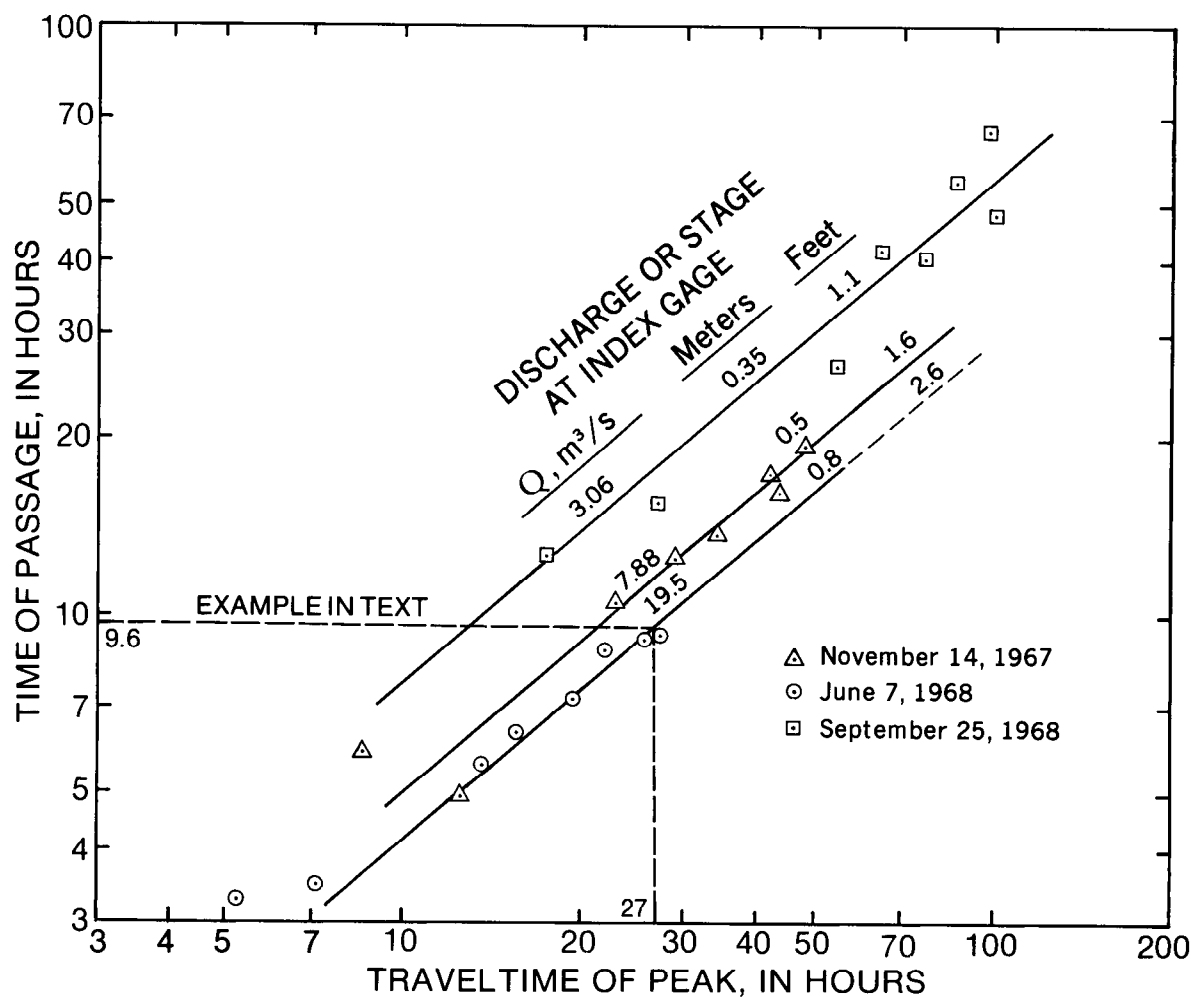
Figure 29.—Time of passage of a solute as related to traveltime for reaches A and B of the Monocacy River, Md.

time of passage, called "duration" in some literature, as related to traveltime for subreaches A and B of the Monocacy River. This might be presented in a user-oriented report as a family of curves for selected discharges or stages.

For an example, consider the previous problem of a spill into the Monocacy River at Highway 550. How much time would be required for the solute to pass the point of interest—a hypothetical water intake at Interstate Highway 70? Assume that the relation on figure 29 corresponding to 19.5 m³/s is close enough to the 20 m³/s used in the example to give a reliable estimate. Remember the traveltime of the solute from the point of the spill to the Interstate Highway was predicted to be 27 hours. From figure 29 the time of passage will be about 9.6 hours.

In computing time-of-passage data, it is necessary to subtract the traveltime of the leading edge from the traveltime of the trailing edge. For many studies the trailing edge is arbitrarily defined as some small percentage of the peak concentration, usually 10 percent. Thus passage time is, to a certain extent, arbitrary and should be carefully defined in a report.

Regionalization

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

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

The standard errors of estimate in the Boning study are not extremely large when the problem of application of the predictive relations and the noise inherent in the data are considered. Regionalization in a more limited area, such as a State or river basin, would probably reduce standard errors to even lower levels than those attained by Boning. For example, in an Indiana study, Eikenberry and Davis (1976) derived predictive equations to estimate traveltime of peak concentrations for selected discharge levels in streams having drainage areas of 210 km² or more. The standard error of these equations ranged from 16 to 18 percent for tributary streams and from only 11 to 15 percent for main stem streams.

Summary

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

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

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

Dye studies are usually conducted by injecting a known quantity of dye at the beginning of a stream reach and collecting samples for later measurement of dye concentration with a fluorometer. The collection of samples at a site during the passage of the dye may be done with hand-held samplers or by an automatic water sampler.

Depending on the objectives of the investigation, the data requirements for a dye study can range from the defining of the traveltime of the peak concentration at a single location to the collecting of an extensive set of data, including those on stream characteristics and dispersion, as well as on time of travel, at many points.

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

Dye is usually injected near the main thread of flow in a narrow stream or, on a wide stream, in a series of injections or continuous pouring across the width of the stream to achieve the

quickest possible lateral mixing. A sample of water should be taken at a sampling site prior to the arrival of the dye to obtain a background fluorometer reading, which is to be subtracted from recorded readings measured during the passage of the dye cloud. Having a fluorometer available at the sampling site enables the sampler to monitor the passage of the dye and to make an estimate of the arrival of the leading edge at the next sampling site downstream. However, final dye concentrations may have to be determined under more controlled conditions because ambient temperature, light, and other factors affect fluorescence and fluorometer performance. The sampling at a site should continue at least until the dye concentration is 10 percent or less of the peak concentration. To meet the objectives of most studies, it is necessary to determine the stream discharge during the passage of the dye.

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

The extent of analysis of the data depends on the objectives of the study. For best results, time-concentration curves are plotted for each sampling site and adjusted to concentrations that would be obtained for a conservative solute. Dye studies result in two principal kinds of information: those on time of travel and on dispersion.

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

Dispersion data take two forms: those on the attenuation of the peak concentration as a solute moves downstream and those on the time required for the solute cloud to pass a point of interest. Peak-attenuation data, when collected after initial mixing is complete, plot on a logarithmic graph as a linear function of traveltime. This feature allows the user of the graph to estimate the peak concentration that will occur at any point in the reach as a result of the injection of a solute at any other point independent of position in the reach.

Time of passage of a solute cloud also is a linear function of traveltime when plotted on a logarithmic graph and can be depicted in the same way as peak-attenuation data.

Both peak-attenuation data, including unit concentrations, and time-of-passage data are discharge dependent. If two or more studies are made at different discharges, it is possible to construct a family of curves for selected discharges or river stages.

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

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