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MEASUREMENT OF DISCHARGE USING TRACERS

Book 3

CHAPTER A16

in tables 5 and 6 provides the total dilution factors, D_T, for whatever concentration is used. Following the diagram in figure 20, it can be seen that the standard, C_3, is equal to S_GCD_T. Thus, $C=C_3/S_GD_T$ and the discharge equation, substituting net dial readings for concentrations, is

$$Q=5.89\times10^{-7}\,q\left[\frac{R}{\bar{r}}\times\frac{1}{S_GD_T}\right] . \qquad (11)$$

As an example, the same test conditions as those previously used and presented in figure 17 are assumed, except that now a three-step serial dilution of C must be performed. Referring to table 5, a convenient serial dilution combination for the case where $C=2.38\times10^7$ µg/L is found on line 3c (for $C_3=10.34$), since the injection rate for the estimated stream discharge was chosen to produce a plateau concentration of about 10 µg/L (fig. 9). A standard, C_3, is analyzed on the fluorometer on scale III at the same time the field samples are analyzed. This sample gives a dial reading of 47.2 for a net of 47.0 (the stream background was 0.2). Thus for the stream samples taken at 25 minutes after the start of injection and having an average dial reading, $\bar{r}$, of 48.6, the discharge may be computed as

$$Q=5.89\times10^{-7}\times31.2\left[\frac{47.0}{48.6}\times\frac{1}{(1.02)4.34\times10^{-7}}\right]$$
$$=40.1\ \text{ft}^3/\text{s} .$$

The dilution factor, D_T, was picked from column 9, line 3c of table 5 for the standard chosen. Note that in tables 5 and 6, the first two dilutions for any one concentration, C, are the same. Thus the second dilution may be treated as a working solution. If the 10.34-µg/L standard was not close to that experienced in the stream (R did not approximately equal $\bar{r}$), another standard could be prepared quickly, starting with the second dilution.

This method must be considered the most accurate of those presented, because only a three-step serial dilution of C is involved. Any error in preparing the injection solution is eliminated, and fluorometer dial readings are used directly without recourse to calibration curves.

Appendix B contains a form for recording field sampling, fluorometer analysis, and calculation of discharge using the constant-injection method. It incorporates the use of relative concentrations, dilution factors, and discharge weighting. Provision is made for sampling as many as five locations laterally across a flow section; however, on narrow well-confined flows, three sampling locations are usually sufficient unless the adequacy of mixing is suspect. Appendix B also contains a completed form using the data for the example measurements illustrated in figures 17 and 19 where relative concentrations are used.

Mixing Length

The mixing length equation, equation 4, can be rewritten as

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

where the variables are as previously defined, except that K is a variable with a value dependent on the degree of mixing, the location of injection and the number of injections. The degree of mixing is a measure of the degree to which a tracer is mixed in the flow; the higher the percentage, the more nearly are the concentrations the same laterally. Appendix A shows the recommended method of computing percentage of mixing.

The value of K of 0.1 given in equation 4 is for 95-percent mixing with a single-center injection at midstream. Coefficients, K, for other conditions are given in table 7.

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

Injection at the side of a channel is equivalent to an injection into a stream with a width of 2B. Because B is squared, the coefficient K must be increased by a factor of 4.

Table 7.—Values for coefficient, K, for different degrees of mixing and numbers and location of injection

Number and location of injection points	Coefficient, K		
	Percentage mixing		
	90	95	98
One center injection	0.070	0.100	0.140
Two injection points [a]	0.018	0.025	0.035
Three injection points [b]	0.008	0.011	0.016
One side injection point	0.280	0.400	0.560

[a] For an injection made at the center of each half of flow.

[b] For an injection made at the center of each third of flow.

Where the mixing length must be shortened, it is best to inject at two or three points in the cross section. A line injection is not recommended, with the possible exception of canals where very uniform flow exists across the section (see fig. 21). If the injection rate from a line source is not proportional to the flow at each point across the section, the use of a line source may actually increase the mixing distance.

Equation 12 is for an injection in the center of each flow segment and for a fairly uniform channel. If the injection is not in the center of flow, the theoretical mixing distance will be increased. The equation for mixing provides only an estimate of mixing length. Experience at a site may indicate a very different mixing distance. From a practical and theoretical standpoint, the narrower and deeper the flow, the shorter the channel length required for mixing. Thus, mixing length may change with stage; a flood flow that fills the channel may require a significantly greater channel length than a lower flow because of higher velocity and greater width. However, the effect of increased depth partly offsets this difference.

A common fallacy is that shallow, turbulent whitewater streams produce rapid mixing. Turbulence is effective in yielding rapid vertical mixing, but unless there is substantial depth, lateral dispersion occurs gradually and the mixing length may be quite long.

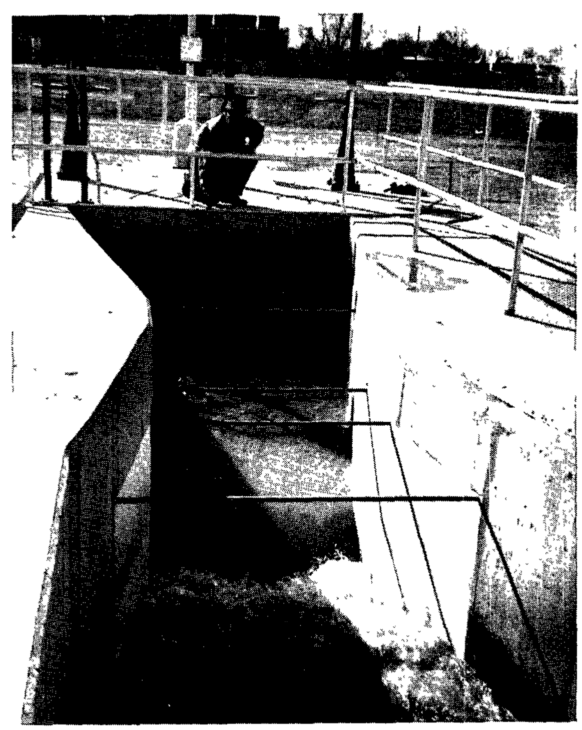


Figure 21.—Multiple dye injection in the approach to a Parshall flume; not visible is dye-injection pump, which preinjects dye into a hose line from a domestic water supply. Eight samples taken across the channel about 10 ft below the hydraulic jump in the bottom of the picture yielded good results.

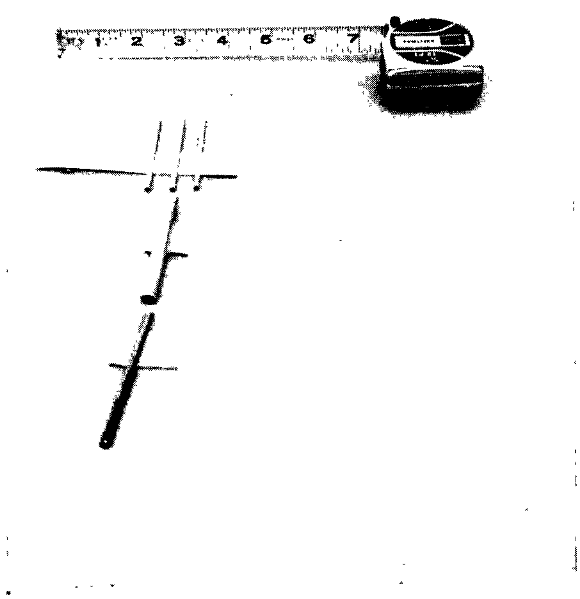


Figure 22.—Tubing used in the fabrication of a one-to-three manifold for multiple injection of dye.

Mixing in pool-and-riffle streams sometimes occurs in relatively short distances, although the time to reach an equilibrium plateau (in the case of a constant-rate injection) should not be underestimated. Streams with deadwater areas or shallow side flows should be avoided; such conditions produce the long, attenuated tracer clouds requiring long injection times.

For further information on mixing, see Yotsukura and Cobb (1972).

Injection Schemes

In most cases, a single-point injection of dye is used. The injection line may ordinarily be placed over the flow with no difficulty, as shown in figure 16. In somes instances, however, excessive stream width or depth and flow velocities or the lack of bridges may make proper placing of the injection line difficult. If the station is one where dye-dilution measurements are to be made repeatedly, it may be worthwhile to install a permanent apparatus. Figure 13 shows a 5-gal can mariotte vessel positioned over a stream by use of a light cable and trolley. In this instance, the injection rate is measured volumetrically several times with a 100-mL graduated cylinder and stopwatch

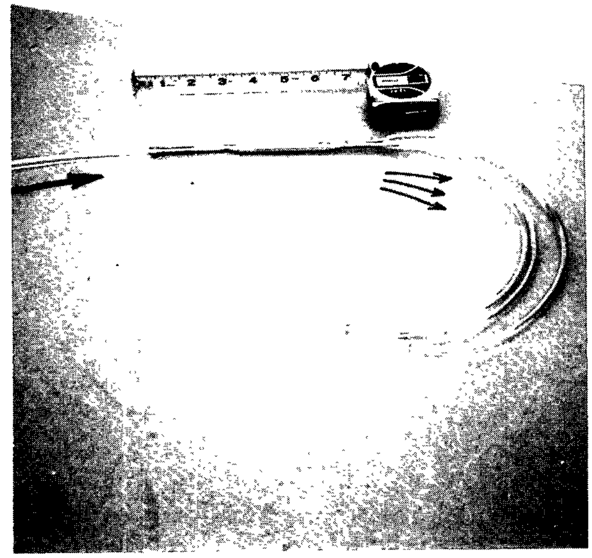


Figure 23.—Fabricated manifold for three-point multiple dye injection; the three lengths of tubing should be equal to produce three equal injection rates.

before allowing the mariotte vessel to roll out over the stream. A light rope is secured to the vessel for recovery.

Where a pump is used, the injection line may be permanently secured over the stream by attaching it to a cableway, running it through a pipe, or attaching it to the underside of walkways and bridges. In each case, the pump is attached to the line for injection and, upon completion of the measurement, a solution of alcohol and water is flushed through both the pump and line.

Multiple injection may be desirable in wide channels with shallow flow or where rapidly varying flow is to be measured and mixing lengths are to be minimized. If a multiple-injection scheme is needed, multiple lines may be permanently located to distribute the dye injection in approximate proportion to the flow. Figures 22 and 23 show the fabrication of a one-to-three tube manifold device to permit a three-point injection from a single injection source. The manifold consists of three equal lengths of 1/16-in-diameter thin brass tubing nested and soldered inside a 3/8-in section of brass tubing. A 1/8-in piece of copper tubing is soldered into the other end of the 3/8-in tubing to receive the discharge tube from a pump. Three plastic lines of equal length are led to the stream for positioning over the flow.

Another approach involves the preinjection of the dye into a larger line leading to a sprinkler line. In figure 21, a sprinkler line consisting of a perforated rigid pipe is placed over the approach of a Parshall flume. Unchlorinated tap water from a domestic hose line is fed to the pipe; dye has been preinjected into the hose, permitting it to mix with the larger flow of tap water before discharging through the sprinkler. An injection pump or chemical-feed device capable of injecting under pressure is necessary. The injection rate is calculated by measuring volume or weight change with time, as discussed previously.

A sprinkler-type system across the flow should not be used to shorten the mixing distance unless the flow is fairly evenly distributed across the channel. If the flow is not evenly distributed, use of a sprinkler system may actually increase the mixing distance.

Dye Losses

The section on theory discusses the principles involved in performing slug and constant-rate dye-dilution discharge measurements. Experience shows that measurement errors are often falsely attributed to dye losses. As can be seen from equation 9, a dye loss would produce a low value for $\bar{c}$, and the computed discharge would be high. In many instances, failure to inject long enough or sampling too soon results in low values of c, particularly along the stream banks (see fig. 3). Using a sufficiently long injection and waiting long enough to sample will permit the slowly developing plateaus along the banks to stabilize. Dye losses do occur, but the above cautions need to be emphasized.

Real dye losses occur where excessively long stream reaches are involved; where there is finely suspended sediment, particularly clay or flocculent organic particles; and where chemicals like chlorine oxidize or quench the dye. To avoid quenching, measurements should not normally be made on streams having a pH less than five (Smart and Laidlaw, 1977). Where a low pH does exist, the use of pontacyl pink dye is advisable. Dye losses have also been noted on very turbulent streams. The high oxygen levels may oxidize the dye in the same way that chlorine does.

If the stream to be measured may contain substances that can cause a dye loss, a gallon of the stream water should be obtained for laboratory use in preparing a standard to be compared with a duplicate one prepared from distilled water. The laboratory work must be done promptly, because the chemistry of the river water may change if it is stored too long. A stream-water standard may be prepared in the field at the time of the dye test if a 100-μg/L working solution for the dye lot is available.

The preparation of a complete set of standards from stream water with the objective of cancelling any reactions that may be taking place in the stream is to be discouraged. Normally, it is difficult to replicate reactions between dye and stream water in a bottle. Standards should provide absolute values without the uncertainty inherent in using water that may produce unpredictable results.

Adhesion of the dye to particle surfaces does not appear to take place immediately. In special situations, dye losses from adhesion on fine sediment have been avoided by immediate filtration of the samples to minimize the exposure of the dye to particles.

Tests by Rathbun (USGS, written communication, 1983) indicate that significant losses of rhodamine WT may occur where diluted concentrations are exposed to direct sunlight for several hours. Thus, excessive reach lengths, like those used in time-of-travel studies, may result in significant photochemical decay of rhodamine WT dye. Most exposure times for dye-dilution discharge measurements are short enough that photochemical decay losses are not a problem.

Special Measurements

Beneath ice

The measurement of discharge in ice-covered streams by conventional current-meter methods is laborious and often of questionable accuracy. On small streams, the dye-dilution method of measuring discharge is particularly useful under such conditions because it does not depend on measurement of either the flow area or velocity.

Site preparations

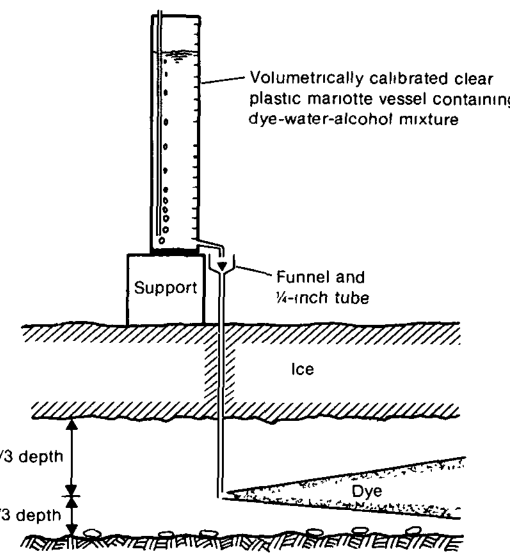
For most small streams, a single, midchannel dye injection is sufficient. Preparations, including selection of the reach length, are the same as the criteria discussed in the earlier section for the slug-injection test. Equation 4 can be used to estimate the mixing length; the deeper and narrower the channel, the better.

Unlike open-channel, current-meter flow measurements, selection of the channel reach is not limited by availability of bridges; a firm ice cover will permit ready access to the stream for placing equipment and selecting the injection and sampling sites. Unlike current-meter measurements beneath ice, only very small holes need be drilled through the ice for injection and sampling. A single 1/2-in-diameter hole through the ice in the centroid of the flow is used for the injection. It may be necessary to drill several exploratory holes to find the main flow. It is well to select a measurement reach before freezeup. The injection line may be supported beneath the ice by inserting it inside a 3/8-in-diameter metal or plastic tube. This tube will usually vibrate when projected into the main flow and this can be used as a guide in selecting the centroid of flow. As shown in figure 24, the dye-injection line should be positioned well beneath the ice but clear of the streambed. Slush ice conditions immediately downstream from the injection should be avoided.

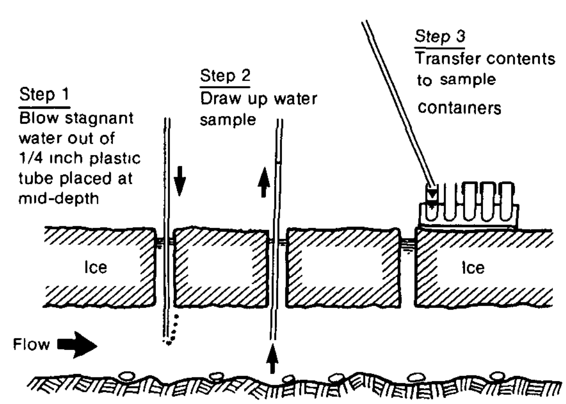
Three to five small holes should be drilled across the channel at the section chosen for sampling. An ordinary carpenter's brace and long auger wood bit may be used to cut the small holes through the ice. The spiral helps to remove ice cuttings (see figs. 25 and 26). Grinding off the small starting tip of the wood bit makes it more suitable as an ice auger. Because of the smallness of the holes, they may have to be marked with rocks or sticks to be readily located when needed. Too small a hole may cause drill freezeup, and the hole itself is apt to freeze back before it can be used.

Tracer preparation and injection

For a constant-injection test, the amount of tracer needed should be calculated from the estimated discharge and the graph in figure 9. The constant-injection type of test is recommended for measurements beneath ice. Rhodamine WT dye 20-percent solution as received from the manufacturer has a specific gravity of approximately 1.19. Normally, this solution is mixed with water in amounts such as shown in tables 3 and 4. When performing dye-dilution measurements under freezing conditions, the addition of antifreezing agents such as methanol alcohol or glycol is mandatory if the



(A) Injection system for measurement beneath ice



(B) Method of "pipetting" water samples from under the ice

Figure 24.—Dye-dilution discharge measurement under ice cover.

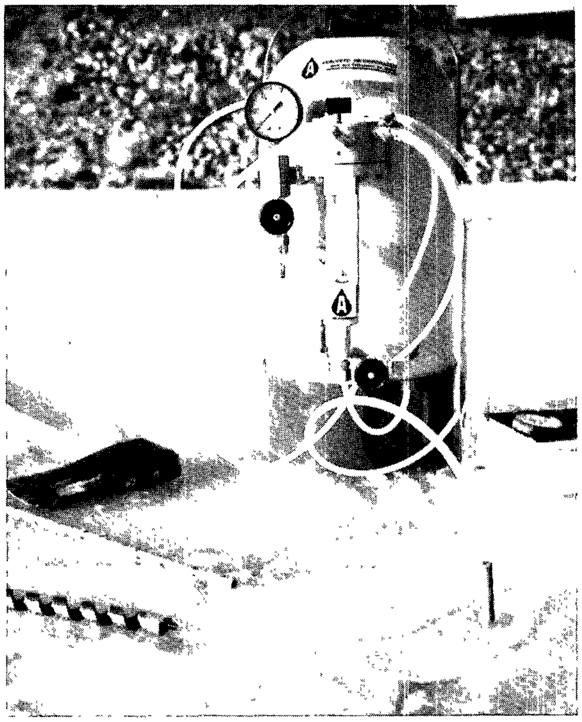


Figure 25.—Dye injection under ice cover, using a chemical-feed tank. An auger is used to drill holes through the ice and a tube is used to draw background samples from under the ice before injection.

Figure 26.—Sampling under ice cover as part of a dye-dilution discharge measurement; an auger is used to drill three to five holes through the ice across the channel at a suitable distance downstream from the injection, and a tube is used to draw samples.

small injection rates used are not to be interrupted or altered by solution freezeup. Automobile-type antifreeze should not be used because it frequently contains sealers and rust inhibitors that may clog the injection apparatus. Methanol alcohol is recommended for addition to dye-water solutions because it has a specific gravity of 0.80 and, if added in equal proportions to the dye, will yield essentially a neutrally buoyant mixture. Figure 27 shows the amount of alcohol to be used for a given temperature. The sum of the water and alcohol should equal the volumes of water shown in column 2 of table 3 or the total volume of water-dye mixture in column 3, table 4. Unless a neutrally buoyant solution is used or the injection solution is below 2 percent concentration, the injection rate should not be determined by weighing; volumetric-displacement methods should be used, if possible.

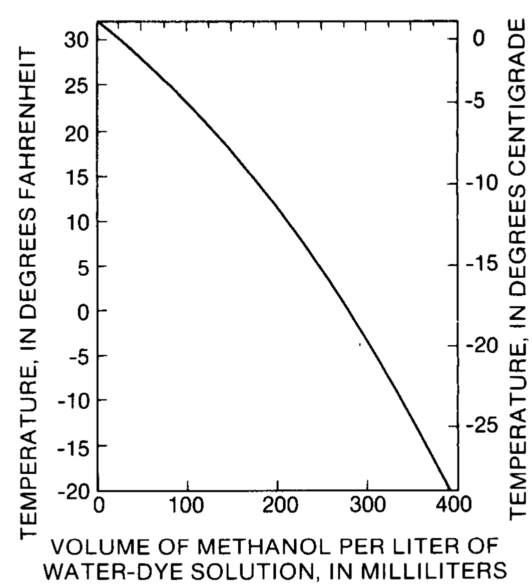


Figure 27.—Proportions of methanol alcohol and water-dye solution needed to prevent freezing of mixtures at selected temperatures.

Dye injection using the constant-rate pump for withdrawing the dye solution from a graduated cylinder is recommended. The backpack enclosure shown in figures 11 and 12 is suggested, for it protects the equipment from freezing winds. As shown in figure 24A, a mariotte vessel may be substituted for the constant-rate pump by using a funnel and tube arrangement. All equipment should be thoroughly flushed with an alcohol-water solution upon completion of the measurement.

Sampling

It is important that the water sample be taken below the ice in flowing water. To obtain a representative sample, a rigid plastic tube with a 1/4-in inside diameter is inserted through the ice hole until the tube is below the ice but not hitting the streambed. If the flow is swift, the plastic tube will vibrate in the flow. This and the depth at each sampling hole can be a guide in estimating the proportion of flow to be allotted each sample. Draw freshwater up into the tube, taking care not to swallow any, and immediately blow it back out. That washes out previous samplings and removes any stagnant water that may enter the tube as it is first lowered through the hole. Next, draw or pipet in a freshwater sample, hold it in the tube by placing a finger over the top, and withdraw the tube from the hole, transferring the contents to suitable containers. Samples of about 15 to 20 mL are needed for laboratory analysis. In addition to the river samples taken during the actual dye tests, water samples for background analyses should be taken before the injection.

Analysis

The samples should be protected from freezing and returned to the laboratory for the usual anlaysis. Analyses and computations are the same as those described for other dye-dilution, constant-injection discharge measurements.

Canals and pipes

The data shown in figures 8 and 17 for a small, moderately sloping stream with a depth-to-width ratio of 1 to 20 and a mixing length of 700 ft are typical of a natural stream. Using those data and referring to figure 2, the total time of passage of a slug-response curve, T_D, was 7 minutes, and a stable plateau concentration was achieved 12 minutes after the start of injection. Had greater mixing distances been employed or had the natural channel contained more slack-water zones, a longer period of injection would have been necessary before a plateau was reached.

When a tracer is slug injected into manmade canals or pipes, the resulting response curves are much less elongated than those depicted in figures 1, 2, and 3 because of the lack of slack-water areas. Consequently, the plateau in response to a constant-rate tracer injection will also be reached rapidly in lined canals and pipes. Figure 28 shows time-concentration data obtained from a 4-minute-duration, constant-rate injection in a large irrigation canal in Colorado. Note that, although the distance was more than a mile, a plateau was reached within 3 minutes, 16 minutes after the start of injection. The mean velocity in this canal during the measurement was more than 7 ft/s; as seen in equation 4, the mixing length required is directly proportional to the mean velocity. Thus, in such structures, the time for mixing may be brief but the distance large.

Similar results may be expected in pipes and other manmade conduits where velocities are high and pools and riffles nonexistent. If adequate mixing lengths are physically available, excellent dye-dilution measurements can be made in such structures.

Measurement During Unsteady Flow

Concepts

According to the constant-rate injection formula for discharge, equation 2, if tracer is injected continuously at a constant rate into a flow varying as shown by the solid line in fig-

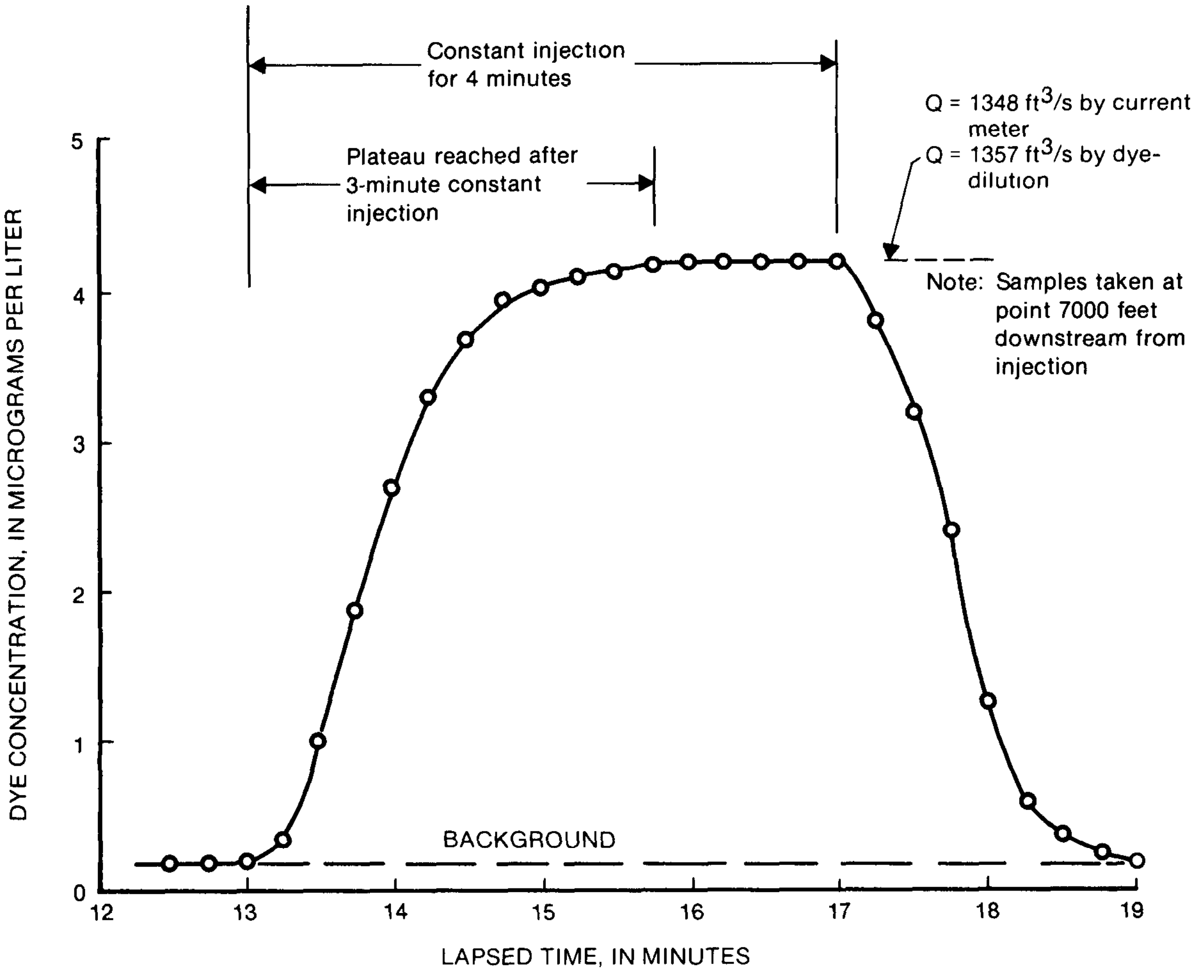
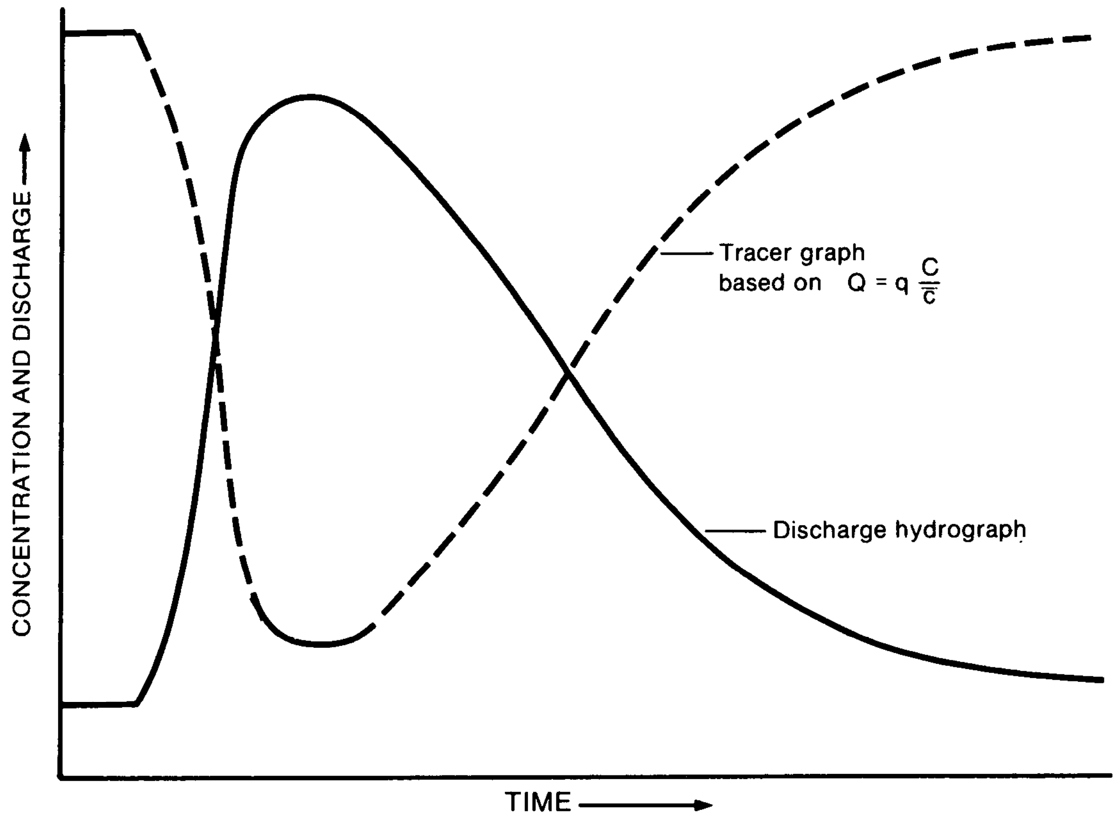


Figure 28.—Rapid measurement of discharge in a lined canal by dye dilution, Charles Hanson Canal, Colorado.

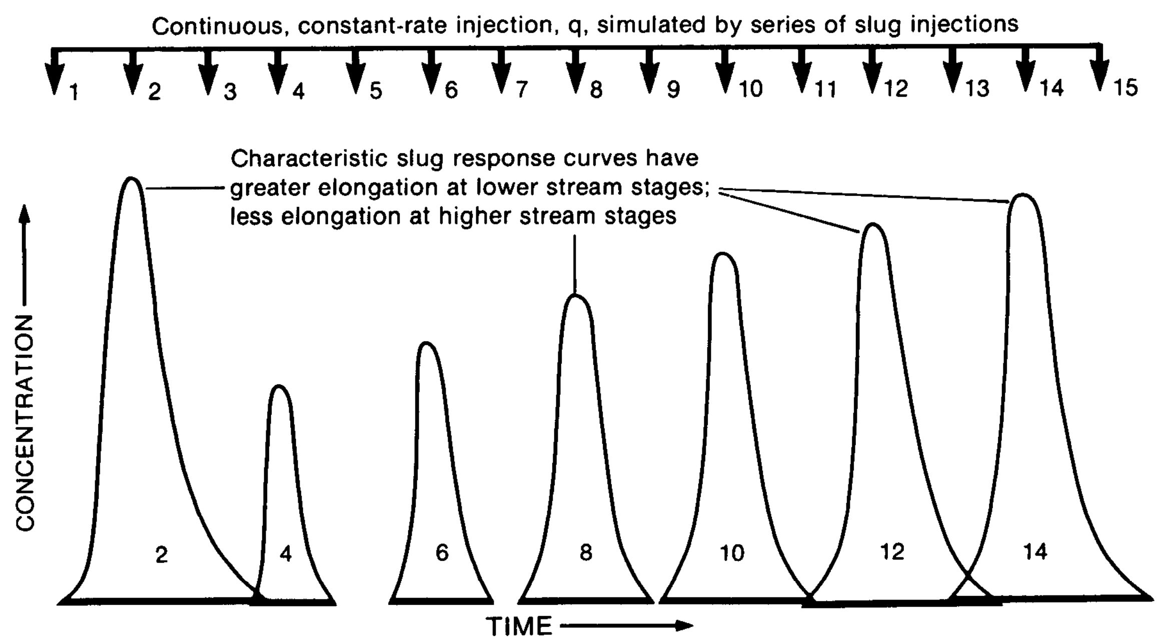
ure 29A, the inverse tracer concentration graph shown as a dashed line results. Theoretically, any sample taken (assuming adequate mixing) during such an unsteady flow would be a measure of the discharge at that instant. Thus, interesting possibilities exist for the accurate measurement of unsteady or rapidly varying flow.

Unfortunately, certain factors limit the degree of unsteadiness that can be measured practically by dilution techniques. Fortunately, field tests show that the method can be used and equation 9 applied for rather high degrees of unsteady flow. Additional laboratory and field tests are in progress to attempt to define the conditions and limits of use of the constant-rate injection method for the measurement of unsteady flow.

For the theoretically correct measurement of unsteady flow using a continuous injection, a given element of tracer would have to mix instantaneously in the flow element into which it was injected. That is, the longitudinal dispersion that produced the ever-elongating tracer response curves shown in figure 1 could not exist. But of course it does exist; and, in steady flow, the plateau is produced by the summation of the superposed slug-response curves, as shown in figure 2, which are shaped by longitudinal dispersion. The greater the elongation of



A. Tracer hydrographs produced by constant-rate injection into unsteady discharge



B. Conceptualized slug responses that occur at different discharges; every other response curve is shown.

Figure 29.—Constant-rate injection into unsteady flow.

the characteristic slug-response curves, the greater the probable error in a constant-injection dye-dilution measurement in unsteady flow.

A precise theoretical analysis of a continuous, constant-rate tracer injection into unsteady flow has not yet been accomplished. Some idea of the factors involved can be ascertained, conceptually at least, by using the superposition principle discussed in the section on Theory, in which the plateau resulting from a constant injection of tracer into steady flow is simulated by superposing the characteristic slug-response curves (fig. 2). In figure 29B, the characteristic slug-response curves are superposed but increased or decreased in concentration to reflect the dilution that would occur if each slug mass were mixed into its respective element of flow. Furthermore, as flow depth and velocities increase at the higher stages, longitudinal dispersion typically decreases; that is, slug-response curves become shorter in time of passage and, thus, favorable to an accurate dilution measurement of unsteady flow. At the same time, it is probable that the mixing length required to measure the discharge hydrograph shown in figure 29A would be the longest (mixing length would change primarily due to change in depth and velocity) at the higher discharges until bankfull stage was reached. Thus, the reach length chosen would have to be greater than necessary for the lower discharges and the characteristic response curve for the lower stages elongated excessively over that needed for an accurate dilution measurement. This occurs particularly when pool-and-riffle rather than channel-control flow conditions exist. The characteristic response curves shown in figure 29B have, therefore, been altered from the steady-state shape to reflect dilution and change in longitudinal dispersion with stage and discharge. Figure 29 provides conceptually the following insights into what is apt to happen with the continuous constant-rate injection into an unsteady flow and where the best accuracy for discharge measurements is likely.

1. Greatest errors are apt to occur on the rapidly changing rising limb of the discharge hydrograph.
2. Lesser longitudinal dispersion at higher stages just past the peak and on the recession will result in the most accurate results during this part of the hydrograph.

Results

Constant-rate, dye-dilution measurement tests of unsteady flow have been successfully performed by F. A. Kilpatrick, by Katz and Fischer (1983), and by M. D. Duerk (U.S. Geological Survey, 1983). Duerk was successful in accurately measuring discharge by the constant-injection method for rates of change in stage of as much as 5 ft/hr (550 ft^3/s/hr) on a recession. While limited, his data showed greater errors for measurements on the rising-stage portion of hydrographs. Constant-injection dilution measurements by the senior author in a lined canal in Colorado indicated good accuracy on a recession having a rate of change of stage of 1.6 ft/hr (360 ft^3/s/hr) but with poor results on a rising hydrograph: −10 percent on the average for a 5.5 ft/hr rate of change (940 ft^3/s/hr).

Automatic dilution gaging

There has always been a need to measure flows and develop ratings for small streams. The need has increased as interest has increased in land-use impact resulting, for example, from urban development and coal mining. Flows from small basins are characteristically unsteady with rapidly changing stage hydrographs of 1 to 6 hours duration and turbulent, high-velocity debris and sediment-laden flows. Such conditions make conventional measurement by current meter virtually impossible. Remoteness of the small basins and the unpredictability of flow events further complicate conventional measuring techniques, even if measuring such streams were physically possible.

The application of dilution gaging to the automatic measurement of runoff hydrographs involves the marriage of any one of the types of injection apparatus previously discussed with some sort of water-sampling system located at the gage site. The system is activated by a stage or discharge indicative of storm runoff. Such a system could be installed at a station until rated and then moved to other stations as needed.

Injection system

Figure 30A shows a recommended injection system with these features:

1. A constant-head mariotte tank has been coupled with a 12-volt constant-rate injection pump, thus sealing the dye reservoir from dirt and evaporation and improving pump performance by ensuring constancy of injection rate.
2. A small graduated section (see mariotte vessel on the right in fig. 14) has been incorporated into the top of the larger mariotte reservoir to permit checking the flow rate each time the station is visited.[4] It is important that an accurate measurement of the injection rate be obtained and that it reflect the resistance from the plumbing of the injection apparatus. This is especially true of a multiple-injection scheme. A dye solution of the same concentration should be added to the tank after each rate check, keeping the tank full.
3. A valve and flushing-tank arrangement is incorporated into the system to allow cleansing of the pump and injection lines each time the system is visited. An alcohol solution should be used as a flushing agent to cleanse, prevent freezing, and discourage insects from entering the injection lines.
4. The injection may be initiated by a stage sensor at the injection site or by hard-wire relay from the sampling station. Stage sensors should be set to initiate and stop injection above and below a given stage.
5. The dye reservoir should be adequate for a continuous injection throughout the expected duration of the hydrograph.
6. The dye solution should contain alcohol if freezing conditions are expected. The concentration of the solution and the pump rate should be sufficient to yield concentrations of about 5 μg/L using rhodamine WT 20 percent (see fig. 9) at the maximum expected discharge.
7. Unless the channel reach above the gaging station where sampling is to take place is narrow and the flow likely to be highly turbulent, a two-point injection is recommended to minimize the necessary mixing length. As can be seen from the section on Mixing Length, a two-point injection shortens mixing length by a factor of four, compared to single-point injection.

Sample recovery system

Several commercial, bottle-type water samplers are available and may be incorporated into a recovery system. The recommended sampling system is shown in figure 30B and should have these features (Duerk, 1983):

1. It must be capable of obtaining a sample when flow velocities are high, preferably from an intake located well within the main flow.
2. The sampler must take discrete samples and not allow cross-contamination between samples. For highly responsive streams, the shortest pumping time necessary to obtain a sample should be used so that each sample more closely represents an exact stage and discharge.
3. Individual samples must be coordinated with stage and time.
4. As with all dilution-discharge measurements, background samples are needed. This may be done by having the sampler turn on simultaneously with the dye-injection system so that a sample is obtained before the dye arrives.

The technique suggested in (4) above would not allow evaluation of background during the dye-injection period, and the assumption would have to be made that once the samples had been permitted to set in the laboratory, background was constant. If rhodamine WT dyes or

[4] If there is sufficient flow at the time of a routine visit, the flow-rate check might also be made a routine dye-dilution discharge measurement, thus lending confidence to future automatic measurements.

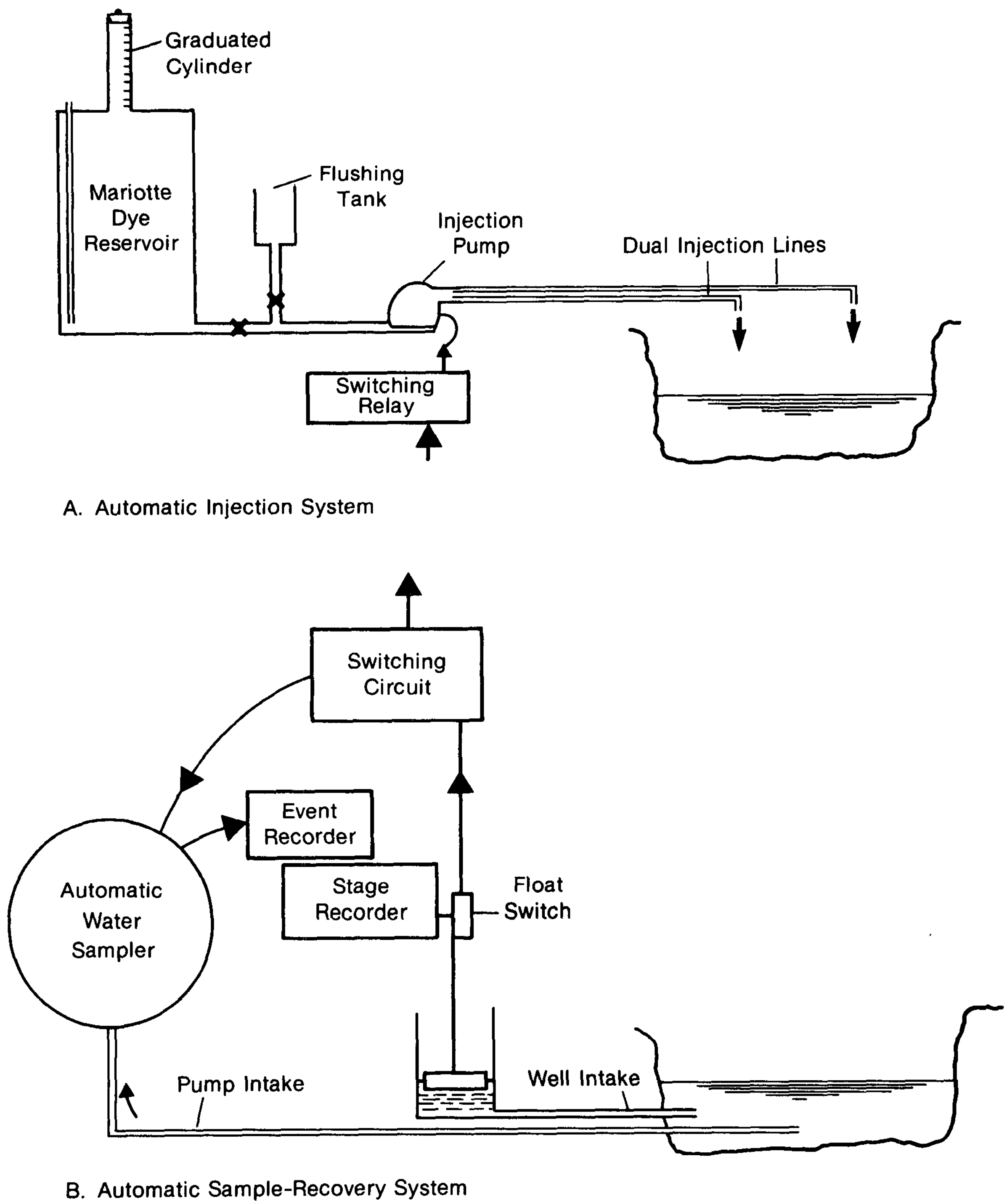


Figure 30.—Automatic injection and sampling systems for dye-dilution measurement of unsteady flow.

pontacyl pink are used, that is probably a safe assumption. If other tracers are used, variation in background with flow may be a problem. The collection of samples upstream from the injection system at selected stages during the flow event would provide evidence of any background variation.

The biggest deterrent to the accurate dye-dilution measurement of storm-produced runoff flows is possible error due to dye losses in flows transporting large sediment loads, particularly fine clay sediments. That source of error can be partly countered by using high dye concentrations where permissible and possibly by developing a means of filtering the samples immediately upon collection.

Velocity Area Measurements

One of the earliest forms of discharge measurement was the "salt-velocity" method (Allen, 1927). It consists of measuring the time of passage of a pulse of sodium chloride in a full-flowing conduit of uniform and known cross-sectional area and length. Using that technique, the discharge may be computed as

$$Q=\frac{\forall}{t_c} \tag{13}$$

where $\forall$ is the volume of the conduit through which the lapsed time of travel of the tracer, t_c, is measured.

That method is still entirely feasible and very accurate for discharge measurement using a variety of tracers. Tracer losses no longer become a factor, the only essential requirements being a single uniform-flow cross section throughout the test reach and a steady flow. Fluorescent dyes are well suited to such measurements (Harris and Sanderson, 1968).

The following precautions should be taken:

1. Lapsed time, T_c, should be based on measurements of the centroids of upstream and downstream time-concentration curves. Lapsed time should not be based on time from slug injection to downstream time-concentration curves unless unavoidable or the distance between observation points in very large.
2. Careful synchronization of the time between observation points is essential.
3. Physical dimensions of the conduit need to be checked if feasible; as-built dimensions may be slightly different from blueprint dimensions. A slug-injection type dye-dilution discharge computation may also be made, using the same data as for the velocity test. Then condiut geometry would not be a factor in the accuracy of the measurement. Assuming that mixing length is adequate and care is exercised in performing the test, as discussed previously, the discharge by dilution should confirm the results of the velocity test (using the same data) if the volume of the conduit is correct.

Selected Bibliography

Aastad, J., and Reinhardt, S., 1954, Discharge measurements by means of a salt solution, the relative dilution method: International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, General Assembly of Rome, v. 3, no. 38, p. 289-292.

Allen, C. M., 1927, Hydraulic-turbine tests by the Allen method: Power Plant Engineering, 31, no. 10, p. 549-551.

Duerk, M. D., 1983, Automatic dilution gaging of rapidly varying flow, U.S. Geological Survey Water-Resources Investigations 83-4088.

Dunn, B., and Vaupel, D. E., 1965, Effects of sample and fluorometer-compartment temperatures on fluorometer readings, *in* Geological Survey Research 1965: U.S. Geological Survey Professional Paper 525-D, p. D225-227.

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

Frederick, B. J., 1964, Measurement of turbine discharge with radioisotopes: U.S. Geological Survey Report TEI-855, 32 p.

Guy, H. P., and Norman, V. W., 1970, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter C2, 59 p.

Harris, D. D., and Sanderson, R. B., 1968, Use of dye tracers to collect hydrologic data in Oregon: American Water Resources Association Bulletin, v. 4, no. 2, p. 51-68.

Holley, E. R., Dilution method of discharge measurement in pipes: Flow Measurement Symposium, National Bureau of Standards, Gaithersburg, Maryland, October 1977, Special Publication 484, Proceedings p. 395-421.

Katz, B. G., and Fisher, G. T., 1983, A comparison of selected methods for measuring flow rate in a circular storm sewer: 1983 International Symposium on Urban Hydrology, Hydraulics, and Sediment Control, University of Kentucky, Lexington, Kentucky, July 25-28, p. 359-369.

Kilpatrick, F. A., 1968, Flow calibration by dye-dilution measurement: Civil Engineering, February, p. 74-76.

——— 1969, A comprehensive evaluation of dye-dilution discharge measurement applications: ASCE Hydraulics Division 17th Annual Specialty Conference, Utah State University, Logan, Utah, August 20, 1969.

——— 1970, Dosage requirements for slug injection of rhodamine BA and WT dyes, *in* Geological Survey Research: U.S. Geological Survey Professional Paper 700-B, p. B250-253.

Morgan, W. H., Kempf, D., and Phillips, R. E., 1977, Validation of use of dye dilution method for flow measurement in large open and closed channel flows: Flow Measurement Symposium, National Bureau of Standards, Gaithersburg, Maryland, February 23-25, 1977, 34 p.

Ostrem, G., 1964, A method of measuring water discharge in turbulent streams: Geographical Bulletin, no. 21, May 1964 (Publication of the Geographical Branch, Ottawa, Canada).

Schuster, J. C., and Hansen, R. L., 1968, Discharge measurements using radioisotopes in high-head turbines and pumps at flatiron power and pumping plant: Colorado-Big Thompson Project, TID-25177, Bureau of Reclamation Report no. 40, Hydraulic Branch, Chemical Engineering Branch, November 1968, Bureau of Reclamation, Denver, Colorado, 116 p.

Smart, P. L., and Laidlaw, I. M. S., 1977, An evaluation of some fluorescent dyes for water tracing: Water Resources Research, February, v. 13, no. 1, p. 15-33.

Spencer, E. A., and Tudhope, J. R., 1958, A literature survey of the salt-dilution method of flow measurement: Institute of Water Engineers Journal, v. 12, p. 127-138.

Wilson, J. F., Jr., Cobb, E. D., and Kilpatrick, F. A., 1984, Fluorometric procedures for dye tracing: U. S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A12 (in press).

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

Yotsukura, N., and Kilpatrick, F. A., 1973, Tracer simulation of soluble waste concentration: American Society of Civil Engineers, Journal of Environmental Engineering Division, v. 99, no. EE4, p. 499-515.

APPENDIX A
COMPUTATION OF PERCENTAGE MIXING

Computation of Percentage Mixing

The degree of mixing of a tracer is a measure of the extent to which mixing has occurred laterally in a channel cross section. Thus, when a tracer is uniformly mixed across a channel, the degree of mixing is 100 percent. From a theoretical standpoint, 100-percent mixing requires an infinite channel length, but for practical purposes, mixing on the order of 95 percent is ordinarily sufficient to yield an accurate discharge measurement. When greater accuracy is required, mixing on the order of 98 percent may be desirable.

Ordinarily, the computation of percentage mixing is not necessary, because inspection of the concentration data will indicate the adequacy of mixing. Furthermore, if those data are discharge weighted, less than ideal mixing is acceptable. Several mixing equations exist; the one by Yotsukura and Cobb (1972, p. C5) is recommended. This may be expressed as

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

where c_i are the concentrations at points i across the section or, if the slug injection is used, the areas under the concentration-time curves as measured at those same points. Fluorometer dial readings adjusted for background may be used in lieu of concentrations if all are on the same scale;

$\bar{c}$ is the average of the plateau concentrations, c_i, as determined by discharge weighting or by arithmetic averaging; dial readings adjusted for background may also be substituted if all are on one scale;

Q_i are the discharges applicable to the points, i; and

Q is the total stream discharge and must equal the sum of the Q_i's.

The term $\left|c_i-\bar{c}\right|$ results in absolute values.

An example computation of percent mixing follows, using the data from the example described in figure 18.

$$P_m=100-[|32.0-44.4|3+|42.0-44.4|5+|58.4-44.4|11+|40.0-44.4|17+|37.2-44.4|4]\frac{50}{44.4\times 40}$$

$$=P_m=100-[|12.4|3+|2.4|5+|14.0|11+|4.4|17+|7.2|4]0.0282$$

$$=91.3 \text{ percent.}$$

APPENDIX B

FORMS AND SAMPLE COMPUTATIONS

Constant-rate dye-dilution discharge measurement on ____________ Date ___/___/___
G.H. = ________ @ ________; Est. Q = ________; Required injection rate ________ mL/min
C = ________;
Est. mixing length required, ______ ft. Injection started @ ______ stopped @ ______; measured q = ___ mL/min

FIELD DATA					FLUOROMETRIC ANALYSIS				DATA ANALYSIS AND COMPUTATIONS			
Sampling Locations		Bottle no.	Lapsed time, min	Estimated portion of total discharge, Q_n (ft^3/s)	Fluorometer scale				Conc. in µg/L	Weighted conc., columns 10 x 5	Weighted (a) avg. conc. reading $\bar{c}=\frac{\sum \text{Col } 11}{Q_{est}}$	Computed discharge $Q=5.89\times10^{-7}\ q\ \frac{C}{\bar{c}}$
Distance	Pt				1X	3X	10X	30X				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Stream backgr.												
Stream @ ___ ft downstr.	a											
	b											
	c											
	d											
	e											
										Σ		
Stream @ ___ ft downstr.	a											
	b											
	c											
	d											
	e											
										Σ		
Stream @ ___ ft downstr.	a											
	b											
	c											
	d											
	e											
										Σ		

FLUOROMETER CALIBRATION							
		Concentration in ug/L	1X	3X	10X	30X	Net dial reading, R[b]
Standard							
Standard							
Dist. Water							

(a) Enter arithmetic average if weighting is not used.
(b) Use to define fluorometer calibration for scale used with stream samples.

Figure 31.—Form for recording, analyzing, and computing constant-rate dye-dilution discharge measurement using actual concentrations.

Constant-rate dye-dilution discharge measurement on *Cane Creek near Hampton, Virginia* **Date** *7 / 7 / 77*
G.H. = *1.12* **@** *9:45 a.m.* **; Est. Q =** *40 ft3/s* **; Required injection rate** *30.0* **mL/min**
C = *2.38 x 10⁷ µg/L* **;**
Est. mixing length required, *700* **ft. Injection started @** *10:00 am* **stopped @** *10:30 am* **measured q =** *31.2* **mL/min**

FIELD DATA					FLUOROMETRIC ANALYSIS				DATA ANALYSIS AND COMPUTATIONS			
Sampling Locations		Bottle no.	Lapsed time, min	Estimated portion of total discharge, Q_n (ft³/s)	Fluorometer scale				Conc. in µg/L	Weighted conc., columns 10 x 5	Weighted (a) avg. conc. reading $\bar{c}=\frac{\sum \text{Col } 11}{Q_{est}}$	Computed discharge $Q=5.89\times10^{-7}\, q\, \frac{C}{\bar{c}}$
Distance	Pt				1X	3X	10X	30X				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Stream backgr.		302	0			0.2						
Stream @ ___ ft downstr.	a	303	20	10		48.7			10.65	106.5		
	b	304	20	18		49.0			10.67	192.1		$5.89x10^{-7}x31.2x$
	c	305	20	12		48.5			10.62	127.4	10.65	$\frac{2.38x10^{7}}{10.65} = 41.1\frac{ft^3}{s}$
	d											
	e											
									Σ	426.0		
Stream @ ___ ft downstr.	a	306	25	10		48.6			10.61	106.1		
	b	307	25	18		49.1			10.69	192.4		$5.89x10^{-7}x31.2x$
	c	308	25	12		48.6			10.60	127.2	10.64	$\frac{2.38x10^{7}}{10.64} = 41.1\frac{ft^3}{s}$
	d											
	e											
									Σ			
Stream @ ___ ft downstr.	a											
	b											
	c											
	d											
	e											
									Σ			

FLUOROMETER CALIBRATION							
		Concentration in ug/L	1X	3X	10X	30X	Net dial reading, R[b]
Standard	309	8.0		36.7			36.5
Standard	310	10.0		45.6			45.5
Dist. Water	311			0.1			

(a) Enter arithmetic average if weighting is not used.
(b) Use to define fluorometer calibration for scale used with stream samples.

Figure 32.—Completed form for recording, analyzing, and computing constant-rate dye-dilution discharge measurement using actual concentrations.

Constant-rate dye-dilution discharge measurement on ______________________ Date ___/___/___
G.H. = __________ @ __________; Estimated Q = __________; Required injection rate __________ mL/min
C = __________; Corresponding dilution factor, D_C relative to C_s = __________ *
Estimated mixing length required, ______ ft. Injection started @ __________ Injection stopped @ __________

FIELD DATA					FLUOROMETRIC ANALYSIS				DATA ANALYSIS AND COMPUTATIONS			
Sampling Locations		Bottle no.	Lapsed time, min	Estimated portion of total discharge, Q_n (ft^3/s)	Fluorometer scale				Net dial reading, $\bar{r}$	Weighted dial readings, columns 10 x 5	Weighted avg. dial reading $\bar{\bar{r}}=\frac{\Sigma \text{Col } 11}{Q_{est}}$	Computed discharge $Q=5.89\times10^{-7}\, q\frac{R}{\bar{\bar{r}}}\times\frac{D_C}{D_T}$ *
Distance	Pt				1X	3X	10X	30X				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Stream backgr.												
Stream @ ____ ft downstr.	a											
	b											
	c											
	d											
	e											
									Σ			
Stream @ ____ ft downstr.	a											
	b											
	c											
	d											
	e											
									Σ			
Stream @ ____ ft downstr.	a											
	b											
	c											
	d											
	e											
									Σ			

FLUOROMETER CALIBRATION

		Concentration in µg/L	1X	3X	10X	30X	Net dial reading, R	Total dil. factor, D_T
Standard								
Standard								
Dist. Water								

* D_C=1.0 if D_T is based on C rather than C_s.

Figure 33.—Form for recording, analyzing, and computing constant-rate dye-dilution discharge measurement using fluorometer dial readings and dilution factors.

Constant-rate dye-dilution discharge measurement on *Cane Creek near Hampton, Virginia* **Date** *7 / 7 / 77*
G.H. = *1.12* **@** *9:45 a.m.* **; Estimated Q =** *40 ft3/s* **; Required injection rate** *30.0* **mL/min**
C = *2.38 x 10^7* **; Corresponding dilution factor, D_C relative to C_s =** *10^-1* *****
Estimated mixing length required, *700* **ft. Injection started @** *10:00 a.m.* **Injection stopped @** *10:30 a.m.*

FIELD DATA					FLUOROMETRIC ANALYSIS				DATA ANALYSIS AND COMPUTATIONS			
Sampling Locations		Bottle no.	Lapsed time, min	Estimated portion of total discharge, Q_n (ft³/s)	Fluorometer scale				Net dial reading, $\bar{r}$	Weighted dial readings, columns 10 x 5	Weighted avg. dial reading $\bar{\bar{r}} = \frac{\Sigma \text{Col } 11}{Q_{est}}$	Computed discharge $Q = 5.89 \times 10^{-7}\, q \frac{R}{\bar{\bar{r}}} \times \frac{D_C}{D_T}$*
Distance	Pt				1X	3X	10X	30X				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Stream backgr.		302	0			0.2						
Stream @ ___ ft downstr.	a	303	20	10		48.7			48.5	485.0		$5.89 \times 10^{-7} \times 31.2 \left[\frac{45.5}{48.6} \times \frac{10^{-1}}{4.20 \times 10^{-8}}\right] = 41.0$ ft3/s
	b	304	20	18		49.0			48.8	878.4		
	c	305	20	12		48.5			48.3	579.6	48.6	
	d											
	e											
									Σ	1943		
Stream @ ___ ft downstr.	a	306	25	10		48.6			48.4	484.0		Same
	b	307	25	18		49.1			48.9	880.2		
	c	308	25	12		48.6			48.4	580.8	48.6	
	d											
	e											
									Σ	1945		
Stream @ ___ ft downstr.	a											
	b											
	c											
	d											
	e											
									Σ			

FLUOROMETER CALIBRATION

		Concentration in µg/L	1X	3X	10X	30X	Net dial reading, R	Total dil. factor, D_T
Standard	309	8.0		36.6			36.5	3.36 x 10^-8
Standard	310	10.0		45.6			45.5	4.20 x 10^-8
Dist. Water	311			0.1				

* D_C=1.0 if D_T is based on C rather than C_s.

Figure 34.—Completed form for recording, analyzing, and computing constant-rate dye-dilution discharge measurement using fluorometer dial readings and dilution factors.