Techniques for measurement of discharge by dye dilution

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Abstract. Dye-dilution type discharge measurements have been made by the United States Geological Survey for a wide variety of conditions to ascertain the suitability of the method for flow conditions where the current meter is not entirely adequate. The development of a reliable pneumatically-powered constant-rate injection apparatus and of stable fluorescent dyes measurable by fluorometers at concentrations of less than 0.1 μg/l enhances the constant-injection plateau method of dilution gauging. This method has been used extensively in gauging turbulent mountain streams, flow beneath ice, flow in shifting sand-channel streams, and in numerous canals and man-made structures.

TECHNIQUES DE MESURE DU DEBIT PAR LA DILUTION DE COLORANTS

Résumé. Cet article décrit les procédés pratiques, les colorants et les instruments utilisés par l'United States Geological Survey pour mesurer les débits par la méthode de dilution des colorants dans un grand nombre de cas où les méthodes habituelles ne sont pas tout à fait appropriées.

Le développement de colorants fluorescents stables et de fluoromètres capables de mesurer avec précision les faibles concentrations a ravivé l'intérêt pour les méthodes utilisant la dilution pour la mesure du débit.

Les injections à vitesse constante ont fait que les méthodes d'injection continue de concentrations sont devenues préférables aux méthodes dites d'injection lente et de récupération totale. Les systèmes d'injection multiples et les techniques d'échantillonnage ont rendu possible la mesure des écoulements par les méthodes de dilution.

Cette technique est particulièrement appropriée pour la mesure de l'écoulement turbulent et de faible profondeur dans les ruisseaux de montagne, sous une couche de glace, dans des chenaux de sable, dans de nombreux canaux et dans d'autres ouvrages réalisés par l'homme.

TÉCNICAS PARA LA MEDICIÓN DE CAUDAL POR DILUCIÓN DE COLORANTES

Resumen. El U.S. Geological Survey ha realizado mediciones de caudal por dilución de colorantes dentro de una amplia variedad de condiciones, a fin de averiguar la adaptación del método para corrientes en las cuales el medidor de corriente no es enteramente adecuado. El desarrollo de un aparato accionado neumáticamente para inyección a velocidad constante, de garantía y apto para colorantes fluorescentes estables medibles por fluorómetros con concentraciones de menos de 0,1 μg/l, favorece el método de inyección constante para aforo por dilución. Este método se ha utilizado ampliamente para medidas en cursos de agua turbulentos de montaña, corrientes bajo hielo, corrientes en cursos arenosos, y en numerosos canales y estructuras artificiales.

ОБОРУДОВАНИЕ ДЛЯ ИЗМЕРЕНИЯ РАСХОДА МЕТОДОМ РАЗБАВЛЕНИЯ КРАСКИ

Резюме. Измерения расхода с помощью разбавления краски выполнено Геологической Службой США для широкоменяющихся условий с целью выяснения пригодности этого метода для условий, где вертушка совсем неприменима. Разработка надежного прибора, обеспечивающего выпуск в лоток краситела с постоянной интенсивностью (с применением пневмати-

ческого устройства), и устойчивых флюоресцентных красок, измеряемых флюориметрами при концентрациях менее 0,1 мг/л, повышает надежность этого метода. Он был широко использован при измерении турбулентных горных потоков, потоков под ледяным покровом, потоков с деформируемыми (песчаными) руслами и на многих каналах и искусственных сооружениях.

INTRODUCTION

In recent years the United States Geological Survey has been active in the development of dye-dilution gauging techniques. The availability of stable fluorescent dyes and fluoromoters which can accurately measure concentrations of the order of 0.1 μg/l has enhanced the use of dilution methods. In general,dye-dilution gauging of natural streams is not economically competitive with the current meter. However, for extremely turbulent flow or where flow geometry is undefinable or constantly changing, dilution methods have considerable merit.

Tracer gauging may be divided into two categories: (1) the tracer-velocitymethod, and (2) the tracer-dilution method. The former is most commonly thought of as the salt-velocity method, although any tracer may be employed. It has the advantage of simple injection, requires a relatively small amount of tracer, and is not critically dependent on the conservativeness of the tracer. Its chief disadvantages are the requirement that the channel-flow geometry be defined exactly, sampling is extensive, and cloud-to-cloud measurements are required.

Two tracer-dilution methods are available, both based on the fact that mixing a known amount of soluble tracer with the total flow of a stream yields concentrations inversely proportional to the discharge. The chief advantage of dilution gauging is that precise knowledge of the flow geometry is not required.

TRACER-DILUTION METHODS

Slug-injection total-recovery method. This method employs the slug injection of a measured quantity of tracer into the flow and subsequent sampling of the entire time-concentration curve downstream where mixing is adequate. The discharge may then be computed as

$$Q = \frac{V_I \; C_I}{\int_0^\infty c \, dt} \qquad (1)$$

where V_I and C_I are the volume and concentration, respectively, of the dye injected, and the denominator is the area of the time-concentraton curve. The advantages of the method are ease of injection and minimum dye requirements. However, as indicated in Figure 1 top, the total mass of dye must be accounted for and unless complete mixing is known to exist, the entire dye cloud must be sampled at 3 to 5 points in the cross-section. Although the slug-injection method is simple and economical, the sampling and analysis are rigorous.

Constant-injection plateau method. In this method a tracer of concentration C_I is injected at a constant rate, q, until an equilibrium or plateau concentration, C_p , is reached at the sampling point downstream where mixing is adequate. The discharge is then determined as

$$Q = q\,\frac{C_\mathrm{I}}{C_p}. \tag{2}$$

The constant-injection plateau method can be visualized (Fig. 1 bottom) as the integration of the time-concentration curves for a series of closely spaced slug-type injections. The required period of constant injection must equal or exceed the passage time for a slug-injected dye cloud, ΔT_c, at the sampling section to achieve the plateau concentration. The advantages of the constant-injection method are:

1. Only a few samples are necessary to determine the plateau concentration, C_p.
2. Samples may be collected any time during the steady state-plateau concentration period.
3. From a practical sense, generally one man can make a measurement, operating the injection apparatus and collecting samples down-stream.
4. Sampling the entire flow section provides a measure of the adequacy of mixing, hence improving the accuracy and reliability of the measurement.

The chief disadvantages are the requirement of a constant flow-rate apparatus, and the greater quantity of tracer required to measure a given discharge.

MEASUREMENT REACH

The channel reach between the points of injection and sampling must be such that the tracer is adequately mixed with the flow. The dye-cloud passage characteristics of slug and constant-rate injections with sampling reach length are illustrated in Figure 2, using concentration-time curves. The optimum reach is the shortest length of channel that produces adequate mixing. Practical experience indicates the optimum mixing length, L_m, may be estimated by the formula

$$L_\mathrm{m} \approx KV\cdot\frac{W^2}{D} \tag{3}$$

where V is the mean velocity in metres or feet per second; W is the mean width of the stream in metres or feet; D is the mean depth of the stream in metres or feet; and K is a coefficient depending on the method of injection and type of channel and flow conditions as suggested in Table 1.

Table 1. *Mixing length coefficients*

Type of injection	Channel and flow conditions	Coefficient, k	
		(sec/m)	(sec/ft)
Single, bankside	Straight and uniform	8.5	2.6
Single, midchannel	Straight and uniform	4.9	1.5
Single, midchannel	Pool and riffle	3.3	1.0
Multiple, 3 to 5 points	Straight and uniform	1.6 to 1.0	0.5 to 0.3

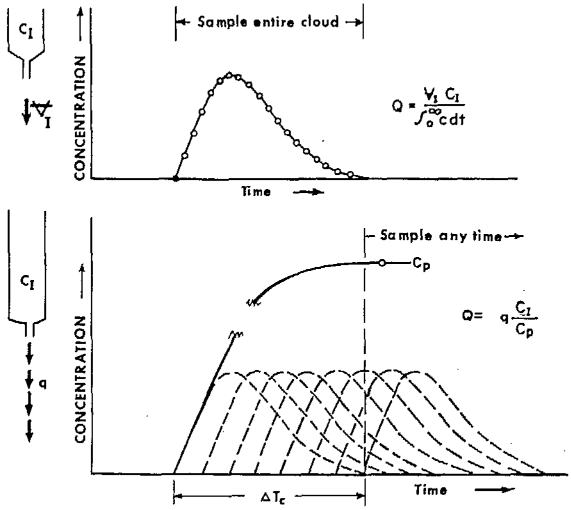
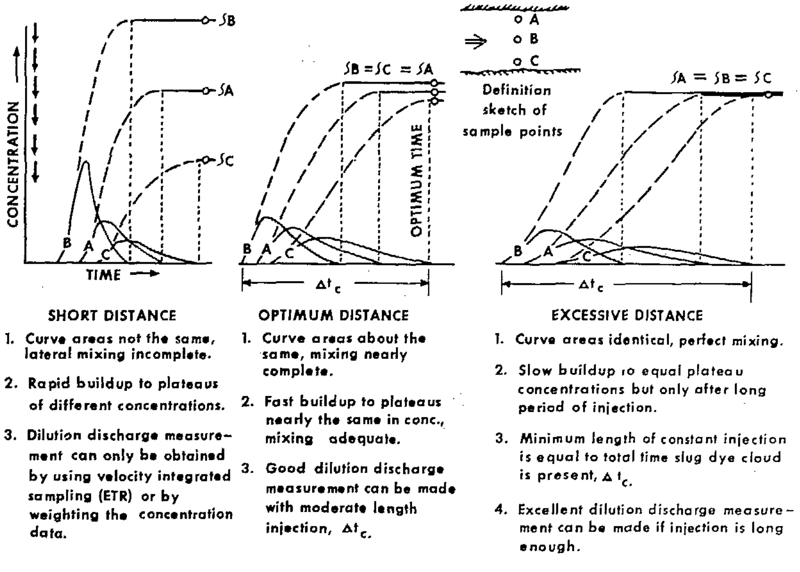


Figure 1. *Dye-dilution discharge measurements by slug and constant rate injection methods*



SHORT DISTANCE

1. Curve areas not the same, lateral mixing incomplete.
2. Rapid buildup to plateaus of different concentrations.
3. Dilution discharge measurement can only be obtained by using velocity integrated sampling (ETR) or by weighting the concentration data.

OPTIMUM DISTANCE

1. Curve areas about the same, mixing nearly complete.
2. Fast buildup to plateaus nearly the same in conc., mixing adequate.
3. Good dilution discharge measurement can be made with moderate length injection, Δt_c.

EXCESSIVE DISTANCE

1. Curve areas identical, perfect mixing.
2. Slow buildup to equal plateau concentrations but only after long period of injection.
3. Minimum length of constant injection is equal to total time slug dye cloud is present, Δt_c.
4. Excellent dilution discharge measurement can be made if injection is long enough.

Figure 2. *Slug and constant injections, time-concentration curves to be observed at three points laterally across channel at three different distances below the injection point*

The shortest mixing lengths are usually found on pool and riffle streams because the pools serve as mixing basins.

Generally, the excessive mixing length becomes a practical limitation of dilution gauging rather than discharge and dye quantities. The use of multiple injections greatly reduces the optimum mixing length, as can be seen in Table 1. A simple manifold attachment to the injection line from the dye tank makes multiple injections possible.

A site where routine constant-rate dye-dilution measurements are to be made should be calibrated for optimum mixing lengths, injection periods, and sampling times for a range in discharges. Perfect mixing generally is not necessary and usually requires excessive channel lengths.

CONSTANT-RATE INJECTION APPARATUS

The application of the constant-injection method requires a reliable apparatus capable of injecting a dye solution at a constant rate. Figures 3 and 4 show an

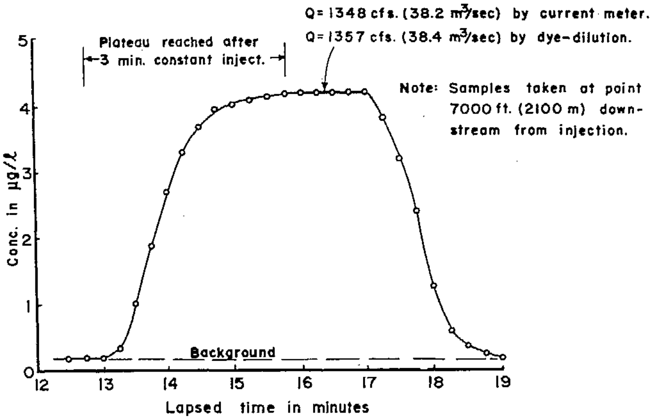


Figure 3. *Rapid measurement of discharge in a lined canal by dye-dilution, Charles Hansen Canal, Colorado*

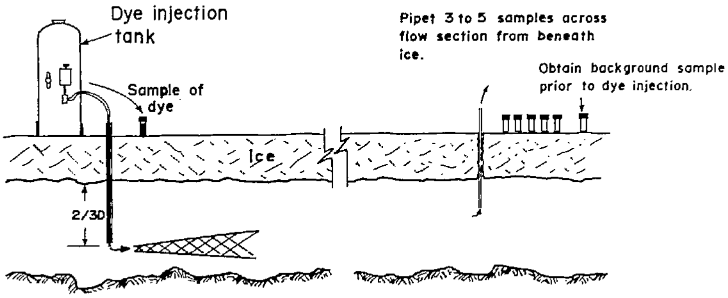


Figure 4. *Dye-dilution discharge measurement beneath ice cover*

adaptation of a pneumatically-powered chlorine-feed tank manufactured by Aerofeed, Inc., Chalfont, Pa. A slight alteration of the orifice control unit provides a range of constant-flow-rate settings from 0.5 to 4 ml/sec, accurate within 1 per cent. Flow is regulated by means of a spring-diaphragm mechanism which maintains a constant differential pressure across an adjustable orifice regardless of changes in tank or external pressures. The unit is loaded with 8 litres of dye solution, sealed, and pressurized with an air pump. It weighs approximately 25 pounds (11 kg) when full, and is readily portable. This unit, with a dye solution concentration of 2×10^7 μg/l (2 per cent), can be used to measure discharges up to 700 cubic feet per second (cfs; equivalent to 20 m^3/sec). With greater dye-solution concentrations, proportionally larger discharges may be measured.

LABORATORY ANALYSIS

These dye dilution techniques are capable of accuracies equal to current-meter measurements under favourable conditions. This is due in part to the quality of fluorescent dyes and fluorometers now available. Rhodamine WT is the dye most commonly used because it is a more conservative tracer than most other dyes presently available. The Turner 111 filter-type fluorometer, with suitable accessories and proper laboratory techniques, is capable of measuring dye concentrations within 1 per cent.

In practice, a supply solution of dye is prepared of such concentration as to measure the anticipated range of discharges. For calibration of the fluorometer, a sample of this supply solution is reduced by a serial dilution process to concentrations covering the range that will be obtained in the field measurements. Once calibration standards have been prepared from the supply solution, the fluorometer analysis of these and the half-dozen field samples comprising a dilution-type discharge measurement, requires only minutes.

APPLICATIONS

Turbulent mountain-streams. The constant-rate dye-dilution method is particularly useful in measuring turbulent mountain streams at flows either too small and shallow, or too large and turbulent for reliable current-meter measurements. A measurement in a reach of Owl Creek, a mountain stream in Wyoming, consisted of five samples collected across the channel at a point 800 ft (244 m) downstream from a midchannel injection of about 15 minutes' duration. The injection rate of about 1.5 ml/sec was determined volumetrically using a 100-ml graduated cylinder and stopwatch.

Conduits canals, and man-made structures. The method is suitable for measuring in closed conduits, canals, and at man-made structures. Seven measurements, ranging from 0.5 to 45 cfs (0.014 to 1.27 m^3/sec) were made with one tank of dye. The injection rate is measured using a laboratory balance and stopwatch. Weighing is frequently used to measure the injection rate for field measurements, especially for multiple injections since only the total rate is desired.

Figure 3 shows the time-concentration curve and results of a 5-minute injection, 7,000 ft (21 m) upstream from the sampling point.

Ice-covered streams. The measurement of flow beneath ice-covered channels (Fig. 4) is greatly simplified by using the constant-rate injection technique. Dye is injected through a small hole in the ice. The injection line outlet is supported clear of the underside of the ice to avoid "painting". Samples are obtained by pipetting through several small holes in the ice. Methanol alcohol or glycol added to the dye solution eliminates freezing problems.

Sand-channel streams. Many sand-channel streams in the western United States are characterized by a constantly changing bed configuration and fluctuating flow conditions. These conditions can have an adverse effect on the accuracy of current-meter measurements, but have little effect on the accuracy of dye-dilution measurements. Figure 5 A and 5B show the variations in depth and discharge for three current-meter measurements made during and 8-hour period on the Middle Loup River at Dunning, Nebr.

Sand-channel streams are usually wide relative to depth, and require very long mixing lengths for single-point injections. The effect of multi-point injection in

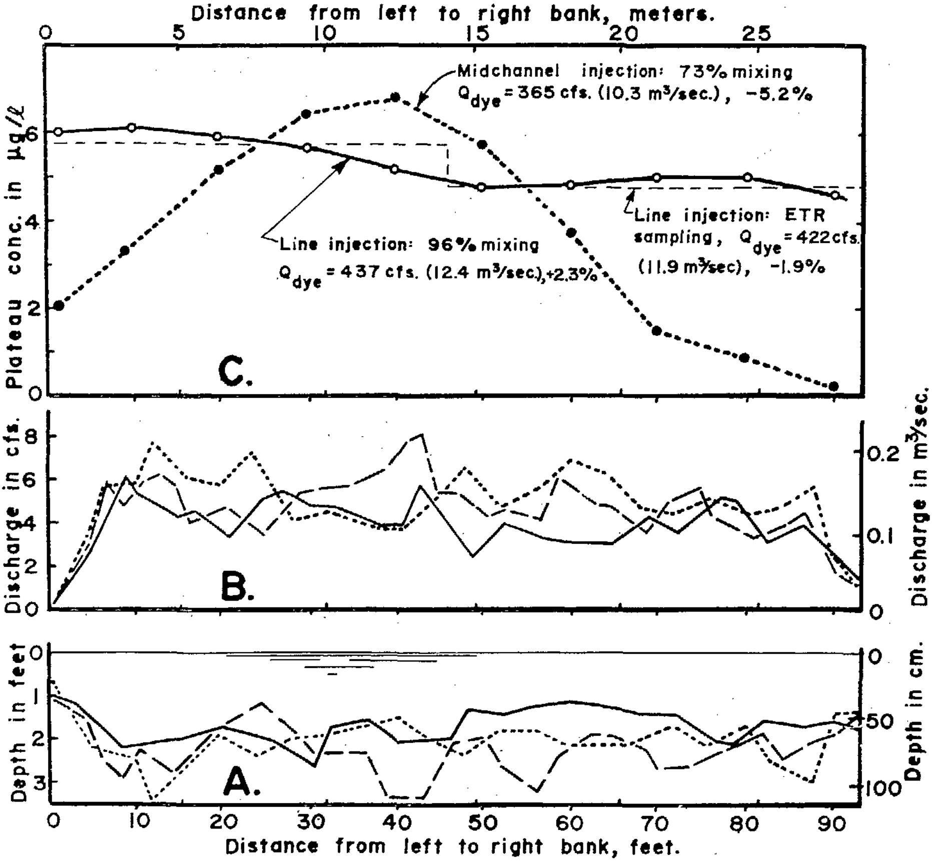


Figure 5. *Variation of depth, discharge and dye concentration for single-and multi-point injections with width during an 8-hour period on the Middle Loup River, a sand-channel stream in Nebraska*

reducing the optimum mixing length is illustrated in Figure 5C. The lateral distribution of the plateau dye-concentration for single and multi-point injections is compared at a relatively short mixing length of 100 ft (33.5 mètres). The optimum mixing length for a single-point injection would be about 12,000 ft (3,660 m).

Equal Transit Rate (ETR) sampling, the conventional method of sediment sampling, can be used to collect integrated samples of the dye concentration, as well as sample-suspended sediment. This technique is possible only with the constant-injection method, as a steady plateau concentration must exist during the sampling. Because this method of sampling discharge weights the dye concentration, good results can be obtained with poorer mixing and hence shorter channel reaches.

Automatic and semi-automatic dye-dilution gauging stations. While accurate dilution-type discharge measurement can be made on the types of natural streams thus far discussed, it is frequently difficult to establish stable stage-discharge relationships. Thus, the continuous or periodic measurement of flow and computation of streamflow record independent of stage would be most desirable. While still in the experimental stage, the feasibility of operating automatic dye injection and sampling equipment is encouraging. Such gauging stations will probably take two forms: (1) the completely automated dye injection and sampling system, and (2) the semi-automatic station comprised of permanently installed, but manually operated, injection and sampling equipment.

DISCUSSION

André: 1. La rhodamine n'est-elle pas retenue dans les sables et les argiles ?

2. La formule $L_m \approx KVW^2$ donnerait pour le Betsiboka une longueur de bon mélange de plus de 1 000 km alors qu'il a suffi de 3 km ; ma formule donne également de très mauvais résultats et je pense que toutes ces formules ne peuvent pas être universelles et sont dangereuses.

3. Des essais effectués par nous-mêmes et par nos collègues du Royaume-Uni ont montré que pour un mélange à près de 10 % les injections multiples réduisent notablement la distance de bon mélange, alors que pour un mélange à près de 1 % il n'y a pas de différence notable, que l'injection se fasse en un ou en plusieurs points.

Barnes: 1. We are aware that it is dangerous to use the above formula and we do not recommend it except as a guide-line to establish the calibration. In other words, the formula is not used. We recommmend that the sampling points, time of injection, injection rate, and the time to collect samples be based on calibration measurements.

2. Suspended matter has not been a great problem with rhodamine WT. Successful measurements have been made with a concentration of the order of several 1,000 ppm.

3. Third question: we normally do not recommend more than a 5-point injection because this leaves a very small return for the extra injection.

Liu: I too feel that equation 3 can be correct only within a certain range of conditions. It appears to me that for a very large width to-depth ratio, the "mixing length", L_m, is mainly determined by the width of the flow rather than the width. From the form of equation 3, it seems that the equation could only be correct for wide-open channels, within a certain range of width-to-depth ratio. I should like to know whether the equation was actually derived from experimental data taken in wide-open channels, and whether the range of conditions under which equation 3 holds true could be specified.

Barnes: The coefficients have been developed on the basis of those experimental measurements. The values of width and depth are approximate, since we only measure one or two points in a reach. These coefficients reflect any errors and estimates on the estimated parameters. The range of applicability of the formula is related to the channels used. The greatest width applied was more than 100 feet (30 m) ; the greatest depth was of the order of 10 feet (3 m).

Sauzay: Dans le texte, les auteurs utilisent la même phrase "where mixing is adequate" pour la discussion des sections de mesure, en ce qui concerne les deux méthodes de dilution. Il est nécessaire de rappeler que ceci recouvre deux notions différentes en théorie :

1. Méthode de l'injection instantanée : le bon mélange nécessaire à l'application de la formule 1 n'est pas représenté par une concentration uniforme dans la section de mesure, mais par une valeur constante de l'intégrale *cdt*.
2. Méthode de l'injection continue : la concentration doit être uniforme sur toute la section de mesure.

Ces deux conditions de "bon mélange" sont différentes.

Barnes: I agree that the problem is to compare the two mixing conditions. The way of mixing determines the degree of accuracy of the measurement. When the mixing is of the order of 95 per cent, the comparisons with current-meter measurements are of the order of 1-1.5 per cent.