

SOME RECENT DEVELOPMENTS OF CONSTANT-INJECTION SALT DILUTION GAUGING IN RIVERS

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ABSTRACT

A recent Water Resources Survey method for constant-injection salt-dilution gauging is summarised. An assessment of errors associated with flow gaugings $\leq 100\text{m}^3/\text{s}$ using the method indicates a tolerance of $\leq \pm 5\%$ with 95% confidence limits for constant injection salt gaugings, where the ratio of the tracer injection rate to the river flow is $\geq 10^{-5}$. Comparison of the accuracy and precision of the salt gauging method with current gauging shows no significant systematic error, and a salt-gauging random error less than that for current meter gaugings. An automatic salt-dilution gauging method is described, together with a precalibration method which significantly abbreviates determinations for a series of constant-injection salt gaugings. Methods are described for estimating the ratio of tributary flows at a confluence from conductivity measurements.

INTRODUCTION

Dilution gauging is a well-recognised method for estimating stream flows too turbulent or rough for the use of current meters.

Chemical tracers are used for measuring average velocity through a reach (John et al., 1978), and for measuring discharge. Discharge gauging can be carried out by injecting the tracer into the flow either at a constant rate (Bjerve and Groterud, 1980; Church and Kellerhals, 1970; ISO 555/1, 1973; Rantz et al, 1982) or all at once (sudden injection) (Kilpatrick and Cobb, 1984; ISO 555/II, 1974; Ostrem, 1964; Day, 1977). Mixing reach and sampling point selection are more critical for sudden-injection gauging. Constant-injection gauging is generally the more accurate and widely applicable method.

Salt is especially convenient for dilution gauging because it is cheap and non-toxic, and its concentration is readily monitored using a relatively inexpensive and easily portable conductivity meter. Complete mixing of the tracer is essential for accurate dilution gauging. Use of salt and a conductivity meter allows ready confirmation of mixing at the time of gauging.

Constant-injection salt dilution gauging was formerly considered as suitable for gauging relatively small flows only (Rantz et al, 1982). Development of more accurate equipment and procedures which reduce errors have enabled the method to be extended to accurate measurement of moderate flows. A standard Water Resources Survey (WRS) constant-injection salt gauging procedure (Johnstone, 1985) has been used in recent years to estimate accurately flows up to $100\text{m}^3/\text{s}$. The measurement of greater flows is limited only by the practicality of handling the large tracer volumes necessary.

Following a brief outline of the basic method, an assessment of the errors associated with salt-dilution gaugings carried out using this standard procedure

is presented here. Three specialised developments of the method are also described; automation, a precalibration procedure, and methods for estimating the ratio of tributary flows at a confluence.

SUMMARY OF METHOD

The standard constant-injection salt gauging procedure outlined in Johnstone (1985) details the equipment and practice required for reliable results, including mixing reach selection, optimum tracer concentrations and injection rates, and plateau assessment and sampling technique. The injection device used is a floating siphon capable of delivering tracer at rates constant to within $\pm 1\%$.

The discharge equation is:

$$Q = \frac{q}{R_p} \quad (1)$$

where Q is the river discharge (l/s), q is the injection rate (l/s) and R_p is the relative concentration of the plateau sample (dimensionless).

The relative concentration, R , of a solution made by diluting the tracer solution with river water is the concentration of that solution expressed as a fraction of the undiluted tracer concentration.

The contribution of the injection rate to the river flow below the injection point is normally negligible and is ignored in this equation.

The injection rate, q , can be measured by timing the delivery of measured volumes from the floating siphon. A calibration curve representing the relationship between relative concentration and conductivity can be defined by preparing a set of standard solutions of known R from the tracer and background samples and measuring their conductivities. Conductivity measurements must be precisely corrected for temperature. With the exception of salt gaugings of very small flows, the conductivity range represented by the standard solutions is less than $500 \mu S/cm$ and the calibration curve is straight (Fig. 1).

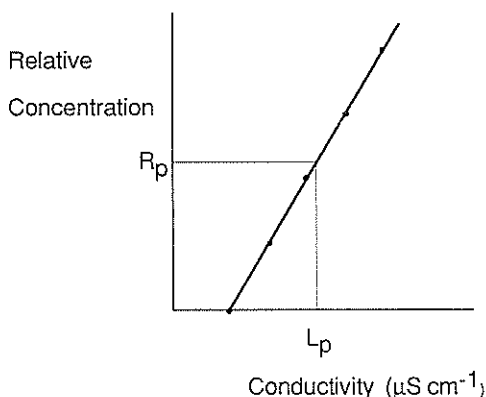


FIG. 1—Calibration line for relative concentration and conductivity.

R_p is determined by entering the plateau conductivity, L_p , into either the graph or the equation of the calibration line.

ERRORS IN CONSTANT INJECTION SALT GAUGING

Sources of Error

Indeterminate and possibly large errors in dilution gauging may result from faulty procedures. These errors are easily avoided by adhering to correct methods.

Loss of tracer along the mixing reach will lead to a reduced plateau conductivity, causing the calculated discharge to be erroneously high. Mixing reaches where unmixed tracer could be lost with river flow, either to the ground or by abstraction, should be avoided. Loss of tracer by absorption onto bed or plant material is not usually a problem but could be significant where long mixing reaches are required. Gains to channel flow from ground water will cause dilution of the tracer which could be misinterpreted as loss by absorption onto bed material.

In sediment-laden rivers, some injected salt, usually less than 5%, is lost from solution because of absorption onto suspended sediment. Absorption has been found to very quickly reach its full extent. Salt is lost to the same extent both in the passage through the mixing reach and in the R_p determination, and so does not contribute to an error in the discharge measurement. The sediment concentration of the background samples must not be altered and the samples should be thoroughly mixed before portions are taken for rinsing or for preparing standard solutions.

Fluctuations in injection rate of up to $\pm 50\%$ can occur due to air bubbles lodging in the siphon arch. This can be eliminated by adhering to the minimum operating heads and tubing types specified for floating siphons.

Errors in the estimated discharge of up to $\pm 40\%$ will occur if the plateau samples are taken at a location where mixing is incomplete, or before the plateau has stabilised. The plateau conductivity reaches a stable maximum value once the passage of tracer through slack water along the mixing reach has equilibrated. These sources of error can be avoided by using a conductivity meter to confirm the completion of mixing and plateau development at the sampling site.

Contamination of the background or plateau samples by salt crystals or tracer residue will cause an error. The conductivities of these samples should be checked against the river values at the time of sampling.

Conversion of Conductivity Readings to a Common Temperature Base

For accurate salt gauging, in the course of the R_p determination conductivity readings must be precisely corrected to a common temperature base. The method used by Church and Kellerhals (1970) to achieve this requires the construction of a temperature correction graph. Total proportional corrections are read from the graph and applied to conductivity readings to bring them to the desired temperature base.

The WRS salt-gauging procedure (Johnstone, 1985) uses an empirical equation to transpose conductivity readings to a common temperature. Derivation of the equation is based on conductivity and temperature readings taken over a temperature range of 0.5–25°C for a set of eight water samples collected from North Canterbury rivers. The samples ranged in total solute concentration from 30–277 mg/l. The data for each sample plot as straight lines (Fig. 2), with high correlation coefficients and with a common intercept at a temperature of -27.7°C.

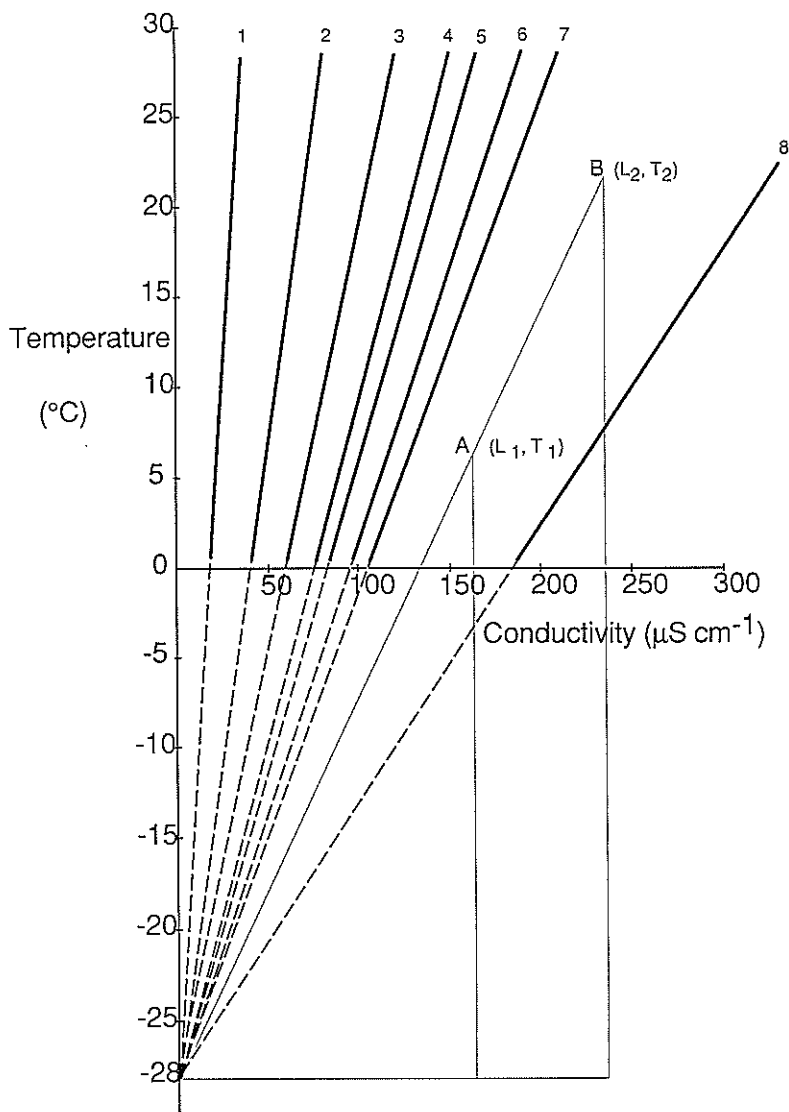


FIG. 2—The common intercept for temperature/conductivity plots.

Point A in Figure 2 corresponds to a solution of ions whose conductivity is L_1 when measured at temperature T_1 . The relationship between temperature and conductivity for this solution is represented by a straight line passing through point A and the common intercept -27.7 . Point B corresponds to the conductivity, L_2 , for the solution at another temperature, T_2 .

TABLE I—Uncertainty Data for a Range of Salt Gaugings

Gauging No.	Site	Q (m ³ /s)	q (l/s)	R _p (×10 ⁻⁶)	ΔL ₂₅ (μs/cm)	Correlation Coeff., r.	Standard Deviations		Coefficients of Variation		Percentage Error in Q with 95% Confidence Limits
							q (l/s)	R _p (×10 ⁻⁶)	q (%)	R _p (%)	
1	68529	0.252	0.048	190	46.3	0.999994	0.0004	1.33	0.75	0.7	2.05
2*	68529	0.425	0.048	113	67.3	0.999993	0.0005	0.85	1.04	0.75	2.56
3*	62103	5.88	0.591	100	29.1	0.999982	0.0060	1.2	1.004	1.2	3.13
4*	62103	16.85	0.513	30.2	15.3	0.999991	0.0053	0.32	1.038	1.05	2.95
5*	62103	23.6	0.529	22.6	11.5	0.999996	0.0054	0.23	1.03	1.0	2.87
6	62103	62.3	0.650	10.4	5.3	0.999967	0.0089	0.16	1.36	1.6	4.20
7	62103	102.7	1.078	10.5	5.2	0.999987	0.022	0.16	2.04	1.5	5.06
8	62103	101.5	0.711	7.0	2.9	0.999851	0.0077	0.21	1.08	2.95	6.28

Q is the river discharge

q is the injection rate

R_p is the relative concentration of the plateau sample

ΔL₂₅ is the conductivity increment from the background level to the plateau level at 25° C

The correlation coefficient, r, is for the data pairs (R,L) defining the calibration line.

* automatic gaugings

The equation

$$L_2 = L_1 \left(\frac{T_2 + 27.7}{T_1 + 27.7} \right) \quad (2)$$

may be used to transpose conductivity values from one temperature to another within the temperature range 0.5–25°C.

Standard Methods for the Examination of Water and Wastewater (1981) gives the following equation for converting conductivity readings to 25°C values:

$$L_{25} = \frac{L_T}{1 + 0.0191(T - 25)} \quad (3)$$

This equation is equivalent (within 0.5%) to equation (2), but is specific to conversion to a 25°C base and more cumbersome.

Total Error Estimates for a Set of Salt Gaugings of Flows up to 100m³/s

Dilution gauging methods used by the US Geological Survey are described in detail by Rantz et al (1982), and Kilpatrick and Cobb (1984), but these publications do not discuss the computation of errors. Kilpatrick (1968) reports laboratory comparisons of constant-injection dye dilution gaugings with volumetric and current meter gaugings, for flows up to 10 m³/s, where excellent agreement was achieved.

A sophisticated statistical method for computing error in constant-injection dilution gauging is described by Smith (1977). ISO 555/1 (1973) describes a method for estimating the 95% confidence limits on discharges determined using constant-injection dilution gauging methods.

The assessment of total error presented here was carried out for a set of eight salt gaugings of flows ranging from 0.25 to 100 m³/s. Four of the gaugings were carried out automatically using the method described below. Systematic and random errors arising in the measurements necessary for the estimation of the injection rate, q , and the relative concentration of the plateau sample, R_p , contribute to the total error for a calculated discharge. Overall tolerances with 95% confidence limits for the computed discharges are presented with other uncertainty data in Table 1.

The injection rates were determined at the start of the manned salt gaugings by timing the delivery of 5 or more volumes of tracer from the injection device, and averaging the results. The volumes of calibrated bottles used to measure injection rates were 2.08 litres for gauging # 1 and 5.22 l for gaugings # 6 and 7. Bottle volumes were determined as the average of five separate volume measurements. Coefficients of variation, representing the random and systematic errors in volume measurements for the two bottles, were 0.74% and 0.78% respectively. The corresponding time periods measured were approximately 43 seconds for gauging # 1, 8 seconds for gauging # 6, and 5 seconds for gauging # 7. Coefficients of variation for the total error in the time measurements were estimated to be 0.102, 1.25 and 2.0% for gaugings # 1, 6 and 7, respectively.

During an automatic gauging a timer was used to measure the period required for the floating siphon to descend through a fixed height range in the tracer tank, corresponding to a previously measured volume (31.86 l for gauging # 2 at site 68529, and 263.7l for the automatic gaugings at site 62103). The injection-

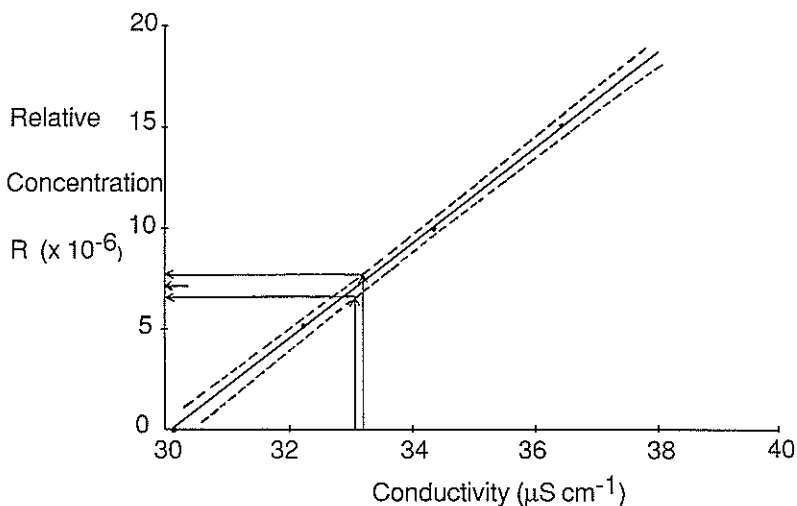


FIG. 3—Calibration line for gauging #8 with 95% confidence limits plotted.

rate data for the manned gauging # 8 were also obtained in this way. The corresponding time periods measured were 664 seconds and 499–726 seconds. Coefficients of variation corresponding to the total error associated with these volume measurements were estimated to be $\leq 1.0\%$. Coefficients of variations for the total error associated with the automatic timer measurements were estimated to be $\leq 0.5\%$.

Total standard deviations on the computed injection rates were calculated from assessments of the errors in each of the component measurements in the manner described by ISO 555/1 (1973). Where the value of a quantity was based on a single measurement, the standard deviation was taken as half the estimated maximum error. The standard deviations for the respective quantities were converted to coefficients of variation, and the total coefficient of variation was calculated as the square root of the sum of the squares of the individual coefficients of variation.

Coefficients of variation on the injection rates for the eight gaugings indicate that the total error for computed injection rates is generally $< 1.4\%$ and is independent of the magnitude of q . The high injection rate, 1.078 l/s, for gauging # 7 was measured by sampling the injection rate for relatively short periods (~ 5 seconds). Less uncertainty would have been incurred by sampling for longer, and sampling for periods > 10 seconds is desirable.

Error in Plateau Relative Concentration, R_p

To determine the plateau relative concentration, R_p , a calibration curve relating relative concentration, R , and conductivity, L , for a set of standard solutions is defined (Fig. 1).

To assess the standard deviation on R_p , 95% confidence limits were plotted as a band about the calibration line (SAS Institute Inc., 1982) (Fig. 3). The maximum error in L_p was projected onto this band and corresponding 95%

confidence limits on R_p projected on to the R axis. The standard deviation on R_p was taken to be half the 95% confidence range.

Factors contributing to error in an R_p determination are uncertainties associated with the goodness of fit of the calibration line, error in the plateau conductivity measurement, the magnitude of R_p , and the slope of the calibration line.

Goodness of fit of the calibration line. The standard solutions required to define the calibration line were prepared by diluting the tracer solution (by a factor $\leq 150,000$) with water from the background sample. For gaugings # 1-4, 4 volume measurements are necessary to prepare the most dilute standard solution of each set. One additional pipette measurement is required to prepare each of a further three standard solutions. The resulting maximum error in R values for the standard solutions is estimated to be $\leq 1.5\%$. Preparation of standard solutions for gaugings # 5-8 requires two extra volume measurements. The maximum error in standard solution R values for these gaugings is estimated to be $\leq 1.8\%$.

The conductivities of the standard solutions were measured using a Triac CM-100 meter switched to the 0-199 $\mu\text{S}/\text{cm}$ range, which can be read to $\pm 0.1 \mu\text{S}/\text{cm}$. One meter was used to measure both standard solution and plateau sample conductivities, so possible bias in the instrument was unimportant. Readings were stable within the period required to complete a determination (<15 minutes). The maximum error in conductivity measurements was therefore $\pm 0.1 \mu\text{S}/\text{cm}$. Samples for the set of eight gaugings ranged in conductivity from 20-150 $\mu\text{S}/\text{cm}$. The corresponding conductivity error range is from $\pm 0.5\%$ to $\pm 0.07\%$.

The total error associated with determination of the data pairs (R,L), and the quality of the calibration line derived, is reflected in the dispersion of the data pairs about the best fit calibration line, as indicated by the correlation coefficient, r , (Blank, 1968), and the 95% confidence limits about the line (Fig. 3). Consistently high correlation coefficients (Table 1) and narrow 95% confidence band widths were obtained for salt gaugings # 1-5. A gradual decline in the value of r , and increase in the 95% confidence band width occurs for the gaugings # 6-8 of flows $> 20 \text{ m}^3/\text{s}$.

This is attributed primarily to the error in conductivity measurement becoming more significant as the conductivity range of the calibration lines becomes smaller. The R_p values for gaugings of large flows are relatively small, and preparation of the standard solutions for gaugings of large flows requires large dilutions, involving an extra dilution step which will incorporate a small additional error ($\leq \pm 0.3\%$) in the relative concentrations of the standard solutions.

Measurement of Plateau Conductivity. Plateau sample conductivity, L_p , was measured immediately after the conductivities of the standard solutions for each gauging. L_p values for the eight gaugings ranged from 33-110 $\mu\text{S}/\text{cm}$ with corresponding maximum errors ranging from $\pm 0.3\%$ to $\pm 0.1\%$.

Magnitude of R_p . The uncertainty with which R_p is estimated increases as the size of the river flow increases, resulting in an increase in the total error of the computed discharge (Table 1). For a given injection rate, the magnitude of R_p decreases as the discharge, Q, increases (See eq. (1)).

The 95% confidence limits on estimated R_p represent a greater percentage of a smaller value of R_p (Fig. 4).

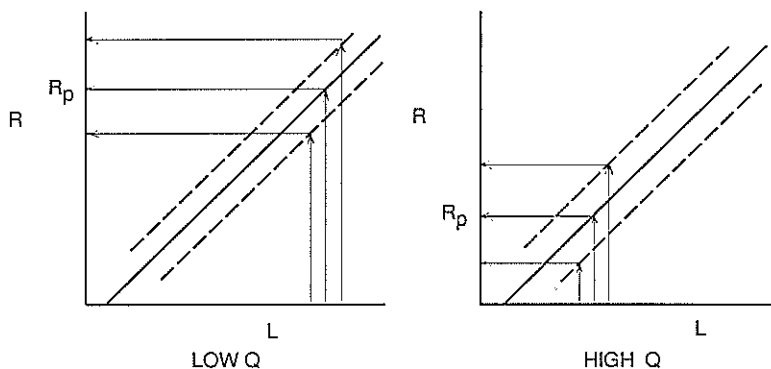


FIG 4.—Percentage error in R_p increases where q is fixed and Q increases.

Conversely, for a given discharge, increasing the injection rate results in a larger R_p value and greater accuracy. Gaugings #7 and 8 are both of flows of approximately 100 m³/s. Despite greater uncertainty in the injection rate determination, the R_p and overall Q uncertainties are smaller for gauging #7 because of the higher injection rate. Similarly, the flow increase from gauging #6 (62 m³/s) to gauging #7 (102 m³/s) was not accompanied by an increase in R_p uncertainty because the injection rate was increased proportionately (ie, R_p was constant). Salt-gauging error is minimised by using the maximum practicable injection rate.

The slope of the calibration line is a function of the tracer concentration and decreases as tracer concentration increases. For a given plateau conductivity error, the magnitude of the R_p error reduces as the tracer concentration increases (Fig. 5). With the exception of small flow gaugings (< 500 l/s), a maximum salt concentration of 250 mg/l is normally recommended. For gaugings of small flows, the advantage of reduced calibration-line slope may be offset where high plateau-conductivity levels necessitate the use of a lower-resolution conductivity meter range.

A Comparative Current Meter—Salt Gauging Study

The current meter and constant-injection salt gauging methods are completely independent, and relative systematic error can be assessed, along with random error, by plotting salt gaugings on a current-meter-defined rating curve.

At the Acheron at Clarence (Site No. 62103) in North Canterbury, good sites are available for both current meter and salt gauging. A stage-discharge rating for the site was defined by a series of current meter gaugings. Constant-rate injection salt gaugings were carried out for flows ranging from 12 to 100 cumecs. The rating curve with current meter and salt gaugings plotted is shown in Figure 6. Figure 7 shows the stage hydrograph for the period and bed plots for the two sets of gaugings.

No significant systematic error is indicated and the salt gaugings all plot within 5% of the rating curve determined by the current meter.

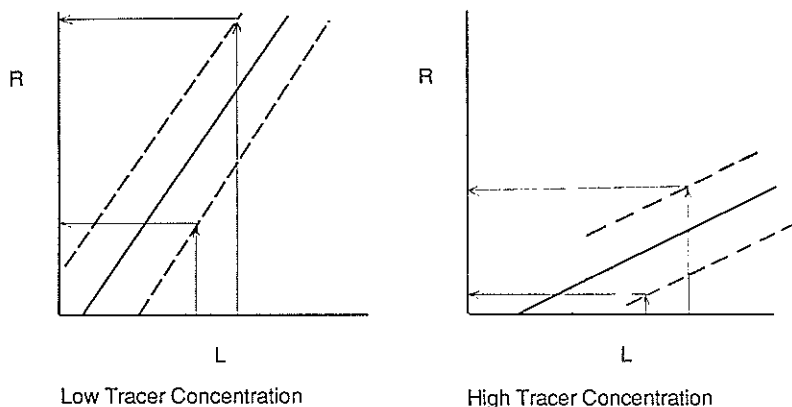


FIG 5.— R_p uncertainty decreases as tracer concentration increases.

Conclusions

The results of the current meter/salt gauging comparison are consistent with the estimates of total error for the constant-injection salt gauging method.

Uncertainties in the quantities q and R_p contribute to the error associated with the computation of discharge for the constant-injection salt gauging.

The injection rate can be measured with good accuracy and precision where sampling volumes are selected so that sampling periods exceed 10 seconds. Error incurred in measuring q is independent of the magnitude of q .

Uncertainty in the estimation of R_p tends to increase as the magnitude of R_p decreases. Precise R_p estimation requires precise definition of the calibration curve and a high-resolution conductivity meter range should be used. The repeatability and consistency of the conductivity meter used are important. The calibration of the meter is not important, as any systematic error will be nullified provided the same meter is used to measure conductivities for the standard solutions and the plateau sample. For gaugings involving very low R_p values, definition of the calibration curve may be improved by preparing additional standard solutions.

Total error for the salt gauging method is reduced by using the maximum possible injection rate and tracer concentration. An overall tolerance $\leq \pm 5\%$ with 95% confidence limits can be expected for salt gaugings where $R_p \geq 10^{-5}$.

AUTOMATION OF CONSTANT-INJECTION SALT GAUGING

Practical difficulties often prevent flood gaugings from being carried out. Warning may be inadequate, the flood may occur overnight, access may be lost, there may be insufficient staff to cover all sites of interest, debris may preclude the use of current meters, or the area may become unsafe in extreme events. A means of automatic flow measurement is therefore desirable.

Duerk (1983) and Marsalek (1974) described automation of constant-injection dye dilution gauging, for measuring relatively small flows in sewer channels,

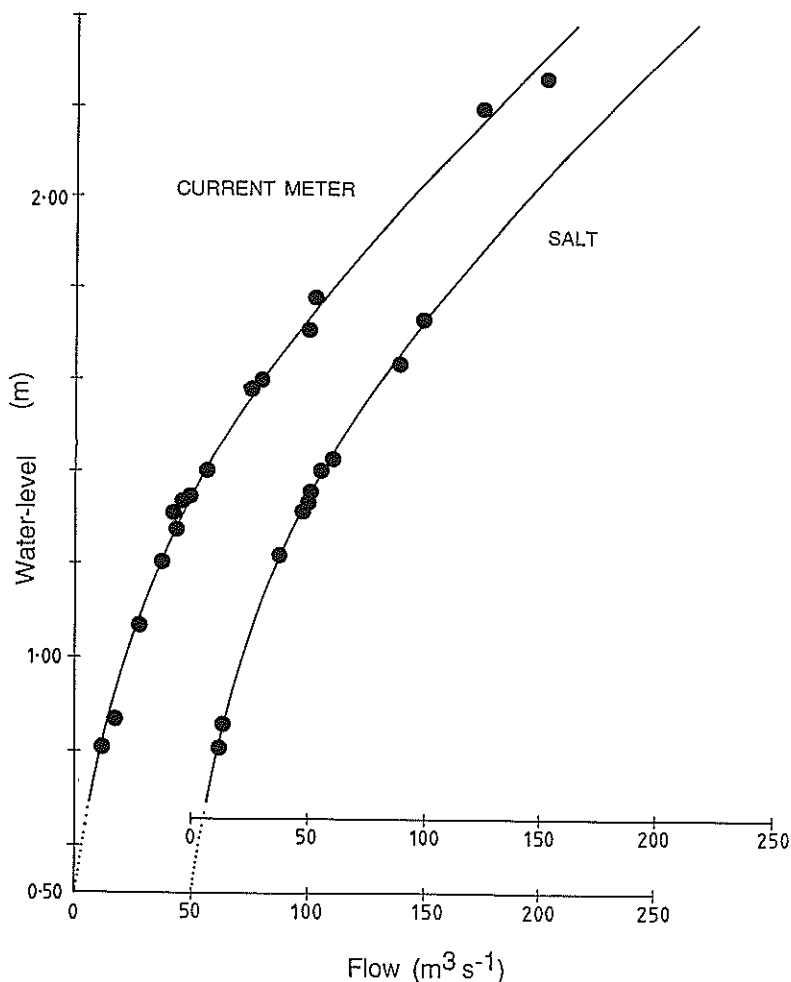


FIG 6.—Current meter and salt gaugings at Acheron River plotted about the current-meter determined rating curve.

but their methods have limited application to river gauging. We have developed equipment to carry out peak stage or selected-stage river gaugings automatically using the constant-injection salt dilution method (Johnstone, 1985). It has been used for flows up to 40 m³/s, and has similar accuracy to the standard manned method already described.

General Description

The injection rate, q , and the relative concentration of the plateau sample, R_p , must be estimated in order to compute the discharge for a constant-injection salt gauging (equation 1). q can be estimated from a record of the time required

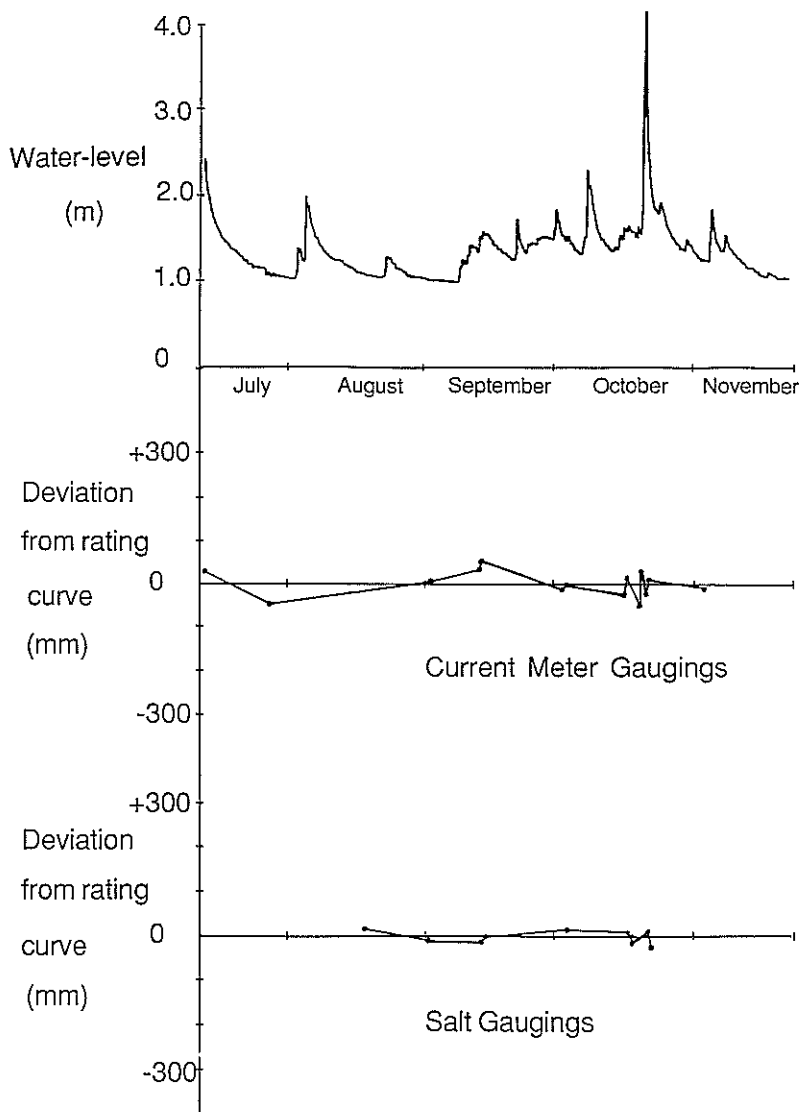


FIG 7.—The Acheron hydrograph for the period of the comparative study, with current meter and salt gauging bed plots.

to inject a known volume of tracer. An R_p determination requires the availability of tracer, background and plateau samples.

The essential components of an automatic salt gauging installation are:

- a device capable of sensing a peak water level or other level of interest, and initiating a gauging;

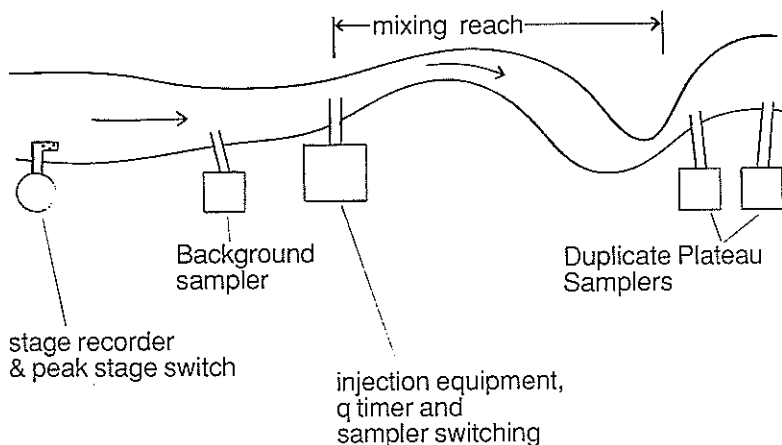


FIG 8.—Deployment of automatic equipment at a flow station.

- a constant-rate injection device;
- a timer capable of recording the duration of injection of a known tracer volume;
- a device to control the switching of the injection-rate timer and the samplers;
- suitable samplers for collecting and storing background and plateau samples (a sample of the tracer solution can be taken from the injection tank before or after the gauging);
- landline or radio links between the components to transmit switching of the sequence of operations.

Deployment of automatic salt-gauging equipment at a flow station is depicted in Figure 8.

The Trigger Device

Automatic gaugings are initiated by a peak water-level detector designed by the Water and Soil Instrument Service Centre of the Ministry of Works and Development. The sensor for the device is a segmented rod which is suspended in the stilling well of a water-level recorder at a known level. The lengths of the rod and the component segments may be selected to suit a particular gauging programme. An electronic latching occurs for each segment as it is covered by a rising water level, and again when it is uncovered as the river level falls. A gauging is triggered when the highest segment covered double latches (just after the peak water level), or, if required, when a lower pre-selected segment double latches. The time of triggering and the activating segment number are stored by the device and can be retrieved later.

The Injection Device

The constant-injection device is a floating siphon fitted with a tube selected to give an adequate injection rate for the largest flow anticipated. Prior to each gauging, the injection tank is recharged and the siphon primed. The siphon

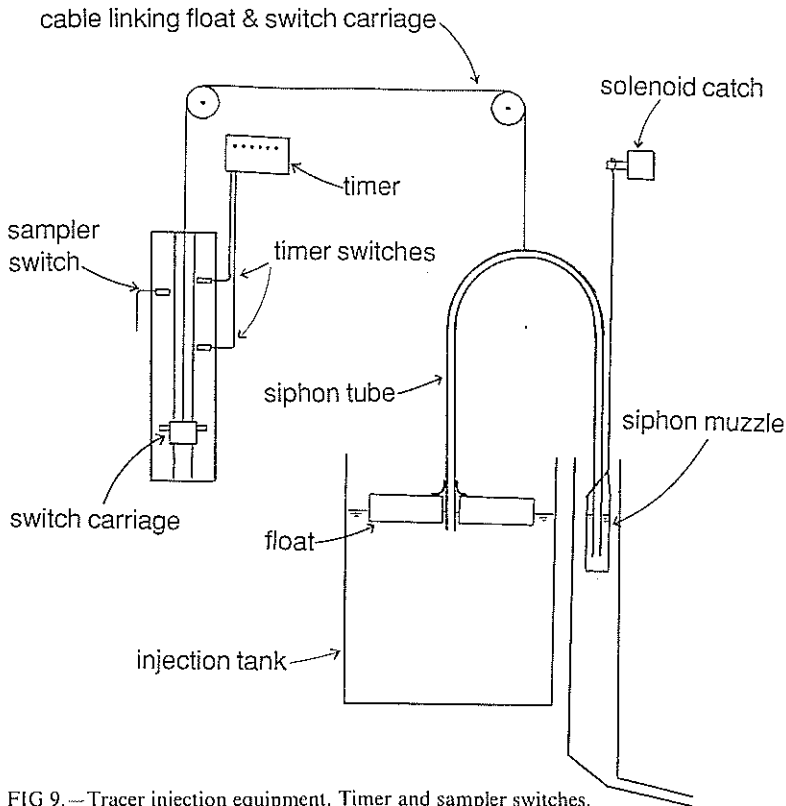


FIG 9.—Tracer injection equipment. Timer and sampler switches.

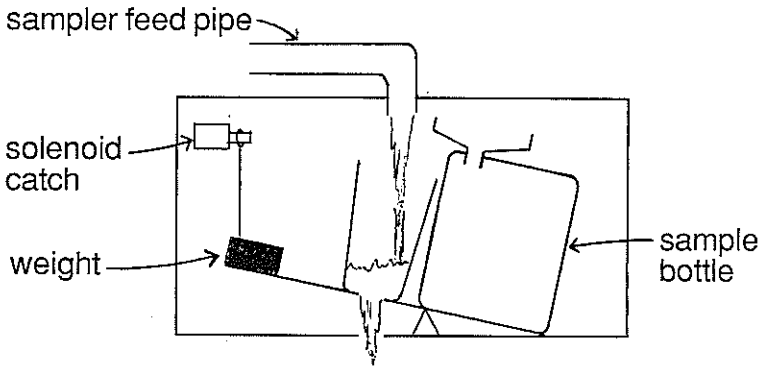
prime is retained by enclosing the siphon outlet in a 'muzzle' (Fig. 9). A solenoid catch allows the muzzle to fall clear when a gauging is triggered and tracer injection commences. Concentrated salt solutions left standing at ambient temperatures ranging from -5 to 20°C have been found to remain homogeneous for periods of at least six weeks, so no additional stirring of the tracer solution prior to a gauging is necessary.

The Injection Rate Timer

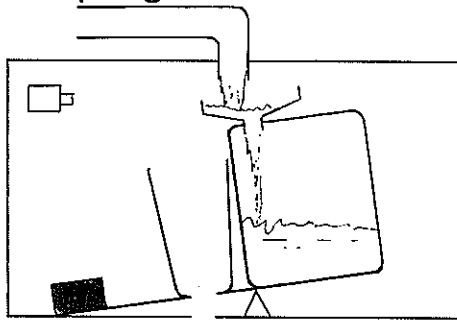
As the siphon float descends in the tank, the switch carriage (Fig. 9) is drawn upwards by a cable connecting it to the float. A magnet fixed to the switch carriage passes across two reed switches. The interval between the respective closing of these switches is electronically timed and corresponds to the injection of a precalibrated volume of tracer. The measured period is stored by the timer for later retrieval.

The Samplers

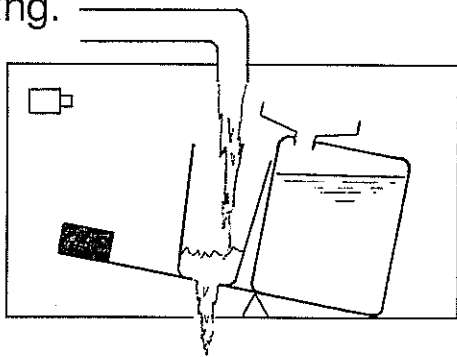
Background river conductivity changes with discharge and is likely to increase significantly as the river falls during the period required to establish the plateau



(a) Before sampling.



(b) Sampling.



(c) After sampling.

FIG 10.—Sampler for automatic gauging.

(normally 10–20 minutes). It is, therefore, necessary to site a background sampler upstream of the injection point and to take the background and plateau samples simultaneously.

To confirm mixing, two plateau samples are collected from distinct points below the mixing reach.

Fifteen litre samples allow sufficient water for liberal washing of glassware, a second R_p determination if required and retention of a sample for suspended sediment analysis.

The operation of the samplers used for automatic salt gauging is depicted in Figure 10. Samplers must be positioned above maximum flood level. For some steep streams, gravity-fed water supplies to samplers are possible. Alternatively, submersible pumps can be used to lift water to the samplers. Water supply intakes are mounted above low flow level since they are normally required only during floods. Water fed to samplers passes to waste prior to sampling. Where a pump is used to supply a sampler, the pump is operated for a short period prior to sampling to flush the line. Sampling is triggered by the switch carriage (Fig. 9) passing the sampler switch. The length of the injection period prior to sampling is regulated by adjusting the starting position of the switch carriage relative to the sampler switch.

The polypropylene containers used in the samplers can store samples for more than four weeks without affecting their conductivity.

The river gauging occurs at the time the samplers operate. This time must be determined so that the corresponding stage can be obtained from the stage record. The time at which the injection commenced is recorded by the peak stage detector. The further interval to sampling corresponds to the ratio of the distance travelled by the switch carriage to reach the sampler switch (d_1 , Fig. 9) to the timed distance between the two timer switches (d_2 , Fig. 9).

Communication Links between the Components

It is necessary to transmit switching from the stilling-well site to the injection housing and from the injection housing to the samplers. Where animal interference is not a problem, electrical cables can be laid over short distances along the ground or strung through trees. Where the ground is suitable, a mole plough can be used to bury moderate lengths of cable. Alternatively, remote-control radio can be used to link the components.

Discussion

Automatic salt-gauging installations have been tested at two flow stations in Canterbury, the Dry Acheron (68529), and the Acheron (62103). Gaugings have been carried out at flows up to 40 m³/s. The equipment has proved to be very reliable and the quality of discharge results is comparable with manually-performed constant-injection salt gaugings. Four automatic gaugings are included in the evaluation of total error for the constant-injection salt gauging method presented above.

At the time of writing, automatic salt-gauging equipment is being assembled for a Southern Alps installation designed to gauge flows in excess of 300 m³/s.

Future development of the method could include the use of existing radio telemetry systems to initiate automatic salt gaugings, and the telemetered retrieval

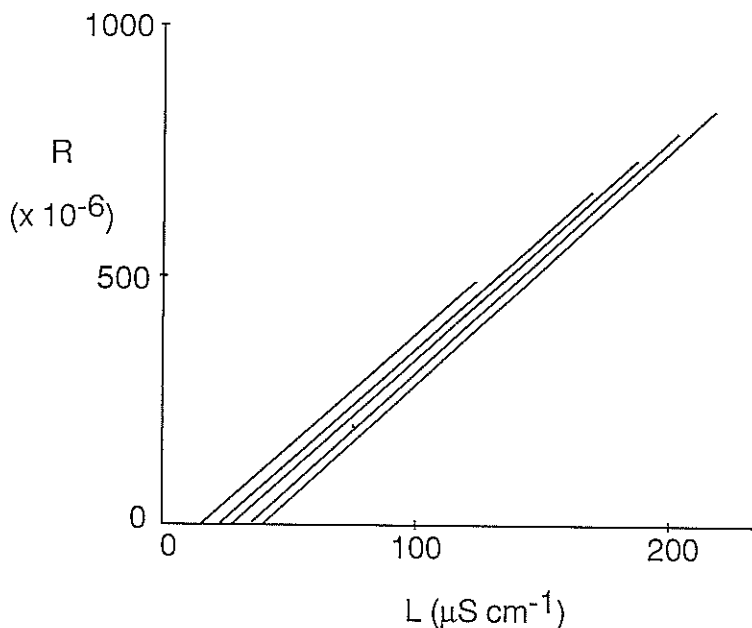


FIG 11.—Family of calibration lines for tracer stock prepared at Camp Stream 12 February 1985.

of conductivity data enabling discharge to be calculated at a base station at the time of a flood.

A PRECALIBRATION METHOD FOR CONSTANT-INJECTION SALT GAUGING

To compute the discharge for a constant-injection salt gauging, an R_p determination is normally carried out following the gauging, by defining a calibration line (Fig. 1) which relates R , and conductivity, L , for a set of standard solutions. These are prepared by diluting samples of the tracer solution with water from the background sample collected at the time of the gauging.

Precalibration can be of value where it is convenient to prepare a large stock of tracer for a series of salt gaugings. Discharges can be calculated for successive gaugings upon measurement of the background and plateau conductivities, without the need for retaining samples for the time-consuming (approximately 30 minutes) definition of the calibration line.

Method

The background conductivity of a stream normally declines with discharge and varies from one stream to another. For a given tracer solution the calibration line varies from one gauging to another as the background conductivity changes.

For a stock of tracer solution, a family of calibration lines can be defined for a range of background conductivities, by preparing several sets of standard

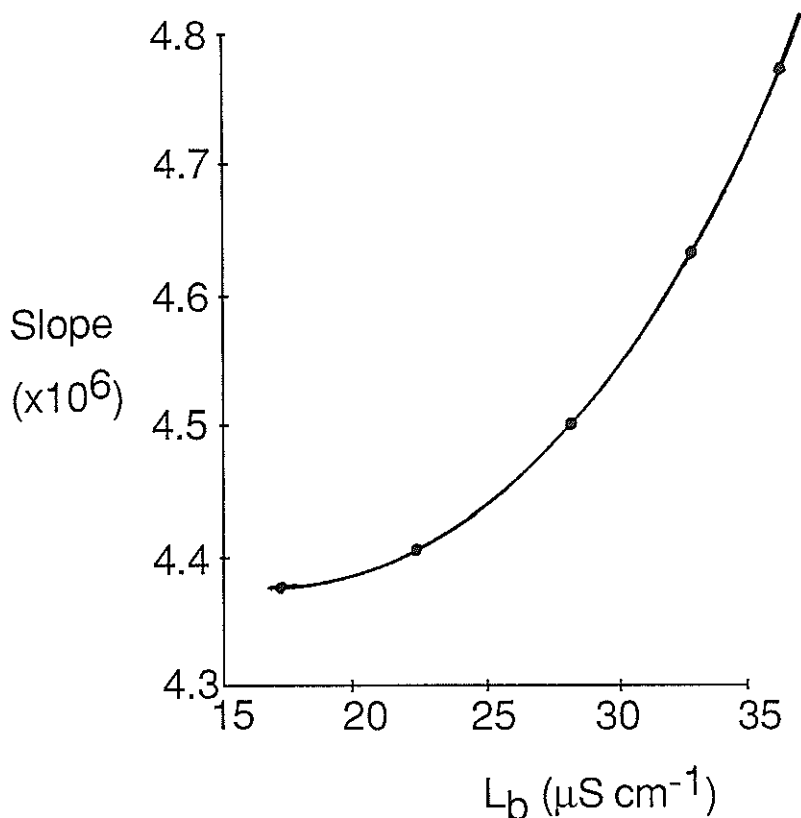


FIG 12.—Slope/Background Conductivity relationship for Camp Stream tracer stock calibration lines.

solutions from the tracer solution and selected synthetic 'background solutions' (Fig. 11).

The slope of the calibration lines increases as the background conductivity increases. A curve can be plotted relating calibration line slope to background conductivity (Fig. 12).

For a gauging using the pre-calibrated tracer solution, the calibration line slope corresponding to the background conductivity, L_b , measured at the time of gauging, can then be read from the graph of slope against L_b . The general equation for the calibration line is:

$$R = S.L + c \quad \text{where } R \text{ is relative concentration,}$$

$$S \text{ is the slope,}$$

$$L \text{ is conductivity} \quad \text{and}$$

$$c \text{ is a constant.}$$

$$\text{At } R = 0, \quad c = -S.L_b \quad \text{where } L_b \text{ is background conductivity.}$$

To compute R_p , the equation becomes:

$$R_p = S.(L_p - L_b) \text{ where } L_p \text{ is plateau conductivity.}$$

The only measurements necessary to determine R_p are then the background and plateau conductivities.

A Comparison of Salt Gauging Determinations using the Precalibration Method with Determinations by the usual Post-Gauging Calibration Method

A 900 l stock of tracer was prepared and stored at Camp Stream in Canterbury, in February 1985. A set of five calibration lines was defined for the tracer solution and a background conductivity range of 17–36 $\mu\text{s/cm}$, which was anticipated to cover the likely range occurring in the stream. A curve relating calibration-line slope to background conductivity was plotted (Fig. 12). During the following eight months a series of seven constant-rate injection salt gaugings was carried out, each using approximately 90 l of the tracer stock solution. Discharges were determined for each gauging using both the conventional post-gauging procedure and the precalibration method (Table 2).

Agreement between the methods is within the uncertainty that can be expected for the constant-injection salt gauging method. The pre-calibration method represents a considerable advantage for a gauging programme where it is possible to carry out several gaugings using tracer from one large stock solution.

TABLE 2—Calibration Method Comparison

Date	Post-gauging procedure Q (l/s)	Precalibration procedure Q (l/s)	Percent difference
12-2-85	15.0	15.0	0
26-2-85	11.5	11.5	0
25-3-85	8.7	8.7	0
31-5-85	9.9	10.0	1.0
13-8-85	20.5	20.1	2.0
5-9-85	227.1	222.2	2.2
24-9-85	24.1	24.1	0

TRIBUTARY DILUTION GAUGING AT A CONFLUENCE

A conductivity difference between two tributaries at a confluence can be used for estimating the ratio of the tributary flows. The tributary flows may have a significant natural difference in conductivity. Where required a moderate conductivity difference can be induced by injecting a strong salt solution into one of the tributaries at a constant rate.

A tributary flow ratio determination can be used in combination with a gauging of one of the flows at a confluence to compute the other two. A constant-rate injection salt gauging carried out on one of the tributaries may

have the added advantage of creating a useful conductivity difference between the tributaries.

A theoretical equation relating the ratio of tributary flows to the conductivities at a confluence can be derived, assuming that ionic species occur in the same proportions in each of the two tributaries. An alternative empirical method can also be used to accurately determine the tributary flow ratio irrespective of the ion mix contributed by the tributaries. The two methods are applicable where there is adequate natural or induced turbulence to ensure that the individual tributary flows above the confluence and the combined flow are completely mixed.

The techniques are useful in cases where confluent stream flows must be determined, because the conductivity measurements required can be obtained in less than one quarter the time required to carry out as second gauging.

They are also useful for gauging a tributary that cannot itself be measured directly because of poor access or the nature of the flow (e.g. a waterfall).

The method could be automated. For small flows the pre-calibration procedure could be used for rapid determination of a series of gaugings at a confluence.

Derivation of a Confluence Flows Equation

The total mass of ions in a solution formed by combining two dilute solutions of ion mixtures in fixed proportions, is equal to the sum of the mass of ions in the original solutions:

$$W_3 = W_1 + W_2 \quad (4)$$

where W_i is the mass (g) of ions in solution i .

The mass of ions in a solution is equal to the product of the concentration of ions and the volume of the solution:

$$V_3 C_3 = V_1 C_1 + V_2 C_2 \quad (5)$$

where C_i is the concentration (g/l) of ions in solution i .

V_i is the volume (l) of solution i .

Where flows of two solutions of ion mixtures in fixed proportions combine (Fig. 13):

$$Q_3 C_3 = Q_1 C_1 + Q_2 C_2 \quad (6)$$

Q_i (l/s) is flow i .

For dilute solutions conductivity is directly proportional to the concentration of ions:

$$C_i = a.L_i \quad (7)$$

where a is the slope of the concentration/conductivity relationship and L_i is the conductivity ($\mu\text{s}/\text{cm}$) of flow i .

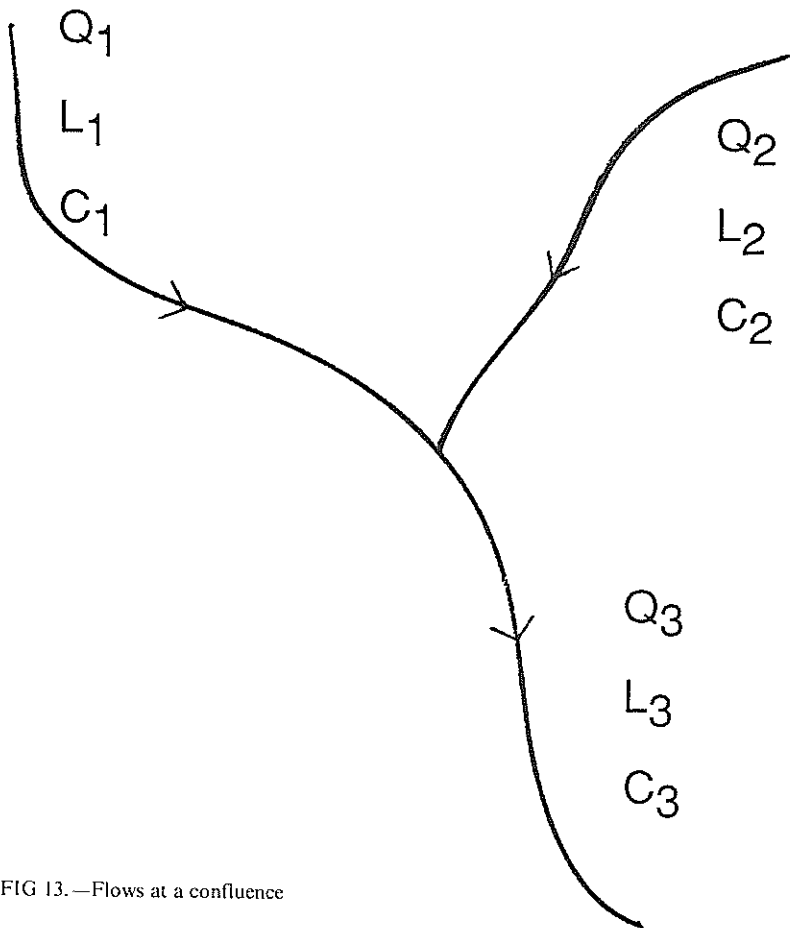


FIG 13.—Flows at a confluence

Substituting for concentration in equation (6) gives:

$$Q_3 \cdot a \cdot L_3 = Q_1 \cdot a \cdot L_1 + Q_2 \cdot a \cdot L_2 \quad (8)$$

Dividing by the coefficient, a , noting that $Q_3 = Q_1 + Q_2$, and substituting for Q_3 in equation (8) yields *the confluence flows equation*:

$$\frac{Q_1}{Q_2} = \frac{L_2 - L_3}{L_3 - L_1} \quad (9)$$

Where the difference in tributary conductivities is sufficient ($\geq 10 \mu\text{s/cm}$) an approximate tributary flow ratio can be computed using equation (9) directly upon measurement of the respective conductivities.

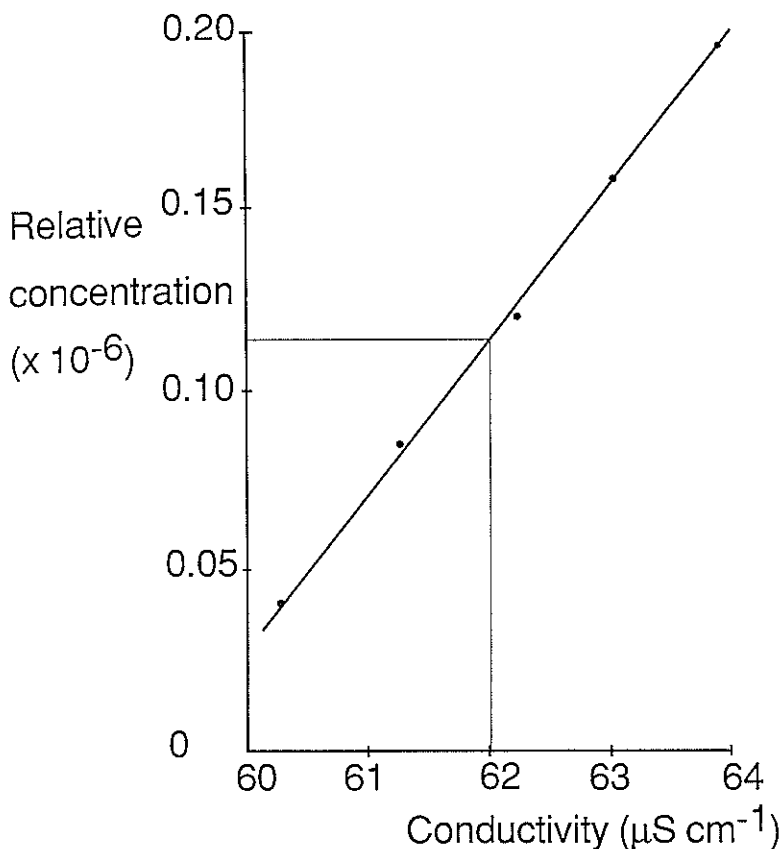


FIG 14.—Calibration lines for tributary flow ratio determination at Dry Acheron, 28 February 1986.

A Calibration Line Method for Determining Tributary Flow Ratios

The ratio of tributary flows can be determined by treating the minor tributary as a 'tracer' flow. If Q_1 is taken to be the 'tracer' flow, the dilution gauging discharge equation (equation (1)) becomes:

$$Q_1 + Q_2 = \frac{Q_1}{R_p} \quad (10)$$

$$\text{or } \frac{Q_1}{Q_2} = \frac{R_p}{1 - R_p} \quad (11)$$

R_p is the 'plateau' relative concentration of the 'tracer' after complete mixing below the confluence.

To compute the tributary flow ratio, Q_1/Q_2 , an R_p determination similar to that required for a conventional constant-injection dilution gauging is carried out. Samples are taken from the 'tracer' flow Q_1 , the 'background' flow Q_2 , and the combined ('plateau') flow Q_3 . Standard solutions representing a range of relative concentrations, R , are prepared by adding five successive volumes, V_1 , from the Q_1 sample to an initial volume, V_2 , from the Q_2 sample. A calibration line, (Fig. 14) relating the R and L values for the standard solutions is plotted and the R_p value, which corresponds to the conductivity reading for the Q_3 sample (" L_p "), is read from the graph. The slope of the calibration line will be negative where the conductivity of the major tributary is greater than that of the minor tributary.

The calibration-line method can be used to accurately determine the tributary flow ratio irrespective of the ion mix contributed by the two tributaries.

Preparation of the Standard Solutions

The R value for each standard solution is given by:

$$R = \frac{V_1}{V_1 + V_2} \quad (12)$$

The volumes V_1 and V_2 should be selected so that an estimate of R_p lies at the mid-point of the R range represented by the standard solutions, which corresponds to the R value of the standard solution prepared by adding the third aliquot of V_1 .

The estimate of R_p is calculated from equation (10) in the form:

$$R = \frac{Q_1/Q_2}{1 + Q_1/Q_2} \quad (13)$$

by substituting the approximate value of Q_1/Q_2 computed from equation (9). An appropriate V_2 value can be estimated by substituting the R_p estimate, and a volume, V_1 , that can be measured accurately, into equation (12) for the third standard solution:

$$V_2 = \frac{3V_1}{R_p} - 3V_1 \quad (14)$$

If necessary an alternative V_1 value could be selected, to allow a V_{23} value that can be measured with better accuracy.

An Example Determination of the Tributary Flow Ratio

Site: Dry Acheron. Confluence above site 68529

Date: 28 February 1986

Conductivities and temperatures were measured for the three flows and five samples were collected:

	L ($\mu\text{S/cm}$)	T ($^{\circ}\text{C}$)	L ₂₅ ($\mu\text{S/cm}$)
Q ₁	55.6	8.9	80.06
Q ₂	41.6	9.3	59.25
Q ₃	43.5	9.3	61.96

Using equation (9), the ratio of the tributary flows is:

$$\frac{Q_1}{Q_2} = \frac{L_2 - L_3}{L_3 - L_1}$$

$$= 0.150$$

Calibration Line Method:

Using equation (13), the approximate value of R_p is calculated:

$$R_p = \frac{Q_1/Q_2}{1 + Q_1/Q_2}$$

$$= 0.130$$

Standard solutions were prepared by adding by pipette 50 ml aliquots of the minor tributary to an initial volume of the major tributary, V₂. An approximate initial volume, V₂, was calculated using equation (14). For the third aliquot of V₁ (ie, the standard solution approximating R_p):

$$V_2 = \frac{3 \times 50}{0.130} - 3 \times 50$$

$$= 1003.8 \text{ ml}$$

An initial V₂ of 1000 ml was used.

Standard Solution Data:

V ₂ (ml)	ΔV_1 (ml)	ΣV_1 (ml)	R	L ($\mu\text{S/cm}$)	T $^{\circ}\text{C}$	L ₂₅ ($\mu\text{S/cm}$)
1000	0	0	0	41.9	9.6	59.2
1000	50	50	0.048	42.7	9.6	60.33
1000	50	100	0.091	43.4	9.6	61.32
1000	50	150	0.130	44.0	9.65	62.08
1000	50	200	0.167	44.6	9.7	62.85
1000	50	250	0.200	45.1	9.7	63.55
Q ₃ sample				43.8	9.5	62.05

From the plot of the calibration line (Fig. 14), the value of R_p is 0.129.

$$\begin{aligned} \text{The tributary flow ratio, } \frac{Q_1}{Q_2} &= \frac{R_p}{1 - R_p} \\ &= 0.148 \end{aligned}$$

For the Dry Acheron example the tributary flow ratio calculated using the confluence flow equation (equation (9)) agrees well with that determined using the time-consuming calibration-line method. The ion mix in natural streams depends on the geology, soil and land use patterns in the catchments. Error included in using the confluence flow equation, (9), will depend on the homogeneity of the respective catchments. Where the confluence flow equation agrees well with the calibration-line method for a low flow and a moderate flow at a given confluence, it would be reasonable to expect good accuracy from the confluence flow equation under other flow conditions.

SUMMARY AND CONCLUSIONS

Improved equipment and techniques have increased the scope and accuracy of constant-injection salt dilution gauging.

A WRS method has been used to measure flows up to 100 m³/s, with uncertainty $\leq + 5\%$. For large flows accuracy is optimised by using the maximum possible tracer injection rate and concentration.

Constant-injection salt gauging can be automated with potential to greatly expedite collection of flood flow data.

Where a series of salt gaugings is to be carried out and it is convenient to prepare a large stock of tracer solution, a precalibration method can be used which significantly reduces the time required for determination of the individual gaugings.

Natural or induced conductivity differences in tributaries can be used to estimate the ratio of the tributary flows, allowing the three flows at a confluence to be calculated from one flow gauging.

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