Refinements in dilution gauging for mountain streams

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ABSTRACT Dilution gauging has become a common technique for measuring stream discharge in high gradient channels with boulder beds. During a three-year study of the hydrology of an alpine basin in the Sierra Nevada of California, USA, a few hundred measurements were made with the slug injection method. This work led to a few refinements in the general techniques and identified some problems. A lightweight, compact kit and simple operating procedure were developed to permit dependable measurements by one or two hydrographers. Although the replicate measurements were nearly identical in most cases, measurements made at the same stage several days apart were different in several cases. An alternative technique that calculates discharge from a mass balance after injecting salt in solid form was used and found to closely match results from slug injections of brine. This method is very simple in its field application. A continuous injection method suitable for remote use was also developed.

INTRODUCTION

Accurate determinations of discharge in mountain streams are needed for a growing number of purposes. In the past, mountain streams were gaged primarily as part of short-term research projects in such fields as snow hydrology, runoff generation mechanisms, glaciology, geomorphology, fisheries, and biogeochemistry. Increasing use and development of mountain areas have expanded the need for knowledge about mountain runoff quantities into such areas as water supply development for rural communities and recreational areas, micro-hydroelectric generating facilities, water rights disputes, instream flow requirements, environmental impact assessment, and monitoring effects of land use change.

The turbulent flow regime and irregular channel geometry of mountain streams make traditional velocity-area gauging difficult or impossible. Velocity varies dramatically with depth and distance from the rough channel boundary. The velocity at any point can fluctuate wildly over time in the turbulent conditions. Current meters have also been found to over-register velocity in high-gradient streams (Jarrett, 1988). Therefore, sampling the velocity distribution over a cross-section will produce an average with a high degree of uncertainty. Adequate surveying of the cross-sectional area of a boulder-bed channel is also problematic. A substantial part of the active flow area may lie underneath the uppermost surface of rocks along the bed. Although the profile and geometry of step-pool and riffle-pool channels change markedly along any given reach, ideal cross-sections for velocity gauging are rare in most mountain streams. Streams
below glaciers involve further measurement difficulties such as high sediment load, rapidly fluctuating discharge, and shifting channels (Bergmann and Reinwarth, 1977).

These same characteristics of high-gradient, boulder-bed streams that make traditional river gauging ineffective enhance the suitability of dilution gauging. "In rock-strewn shallow streams, the dilution method may provide the only effective means of measuring flow" (Herschy, 1985:363). "... a high degree of turbulence in the river makes the results [of dilution gauging] more accurate than those of most other methods of discharge measurement" (Østrem, 1964:21). Stream discharge measurement employing the dilution of a chemical tracer has become a common hydrographic procedure. It was developed more than 80 years ago (Stromeyer, 1905) and has been thoroughly described in the literature (e.g., Aastad and Søgnen, 1954; Østrem, 1964; Church and Kellerhals, 1970; Browne and Foster, 1978; Bjerve and Grøterud, 1980; Kite, 1989). During a detailed study of the hydrology of an alpine basin in the Sierra Nevada of California, we further adapted the general techniques for greater ease-of-use and portability in remote areas.

The basic principle behind dilution gauging is mass conservation of a chemical tracer before and after dilution by a flowing stream. Measurement of the concentration of a tracer after it has become dispersed uniformly downstream of an injection point allows calculation of the discharge required to achieve the measured dilution. In practice electrical conductivity is substituted for mass conductivity. There are two primary alternatives in dilution gauging: the tracer can be injected in a single dose, or it can be introduced at a constant rate over several minutes.

CONTINUOUS INJECTION METHOD

The continuous injection method is the conceptually and computationally simpler of the two versions of dilution gauging, but it traditionally requires more elaborate equipment to introduce the tracer into the stream. With this method, the tracer is added to the stream at a constant rate until an equilibrium concentration is reached downstream. A simple mass balance provides the basis for calculating discharge:

\[
Q \cdot C_B + R_T \cdot C_S = C_E \cdot (Q + R_T)
\]

where \( Q \) = discharge, \( R_T \) = injection rate of the tracer solution, \( C_B \) = background concentration of the stream, \( C_S \) = concentration of the tracer solution, \( C_E \) = equilibrium concentration of the tracer downstream. Solving for \( Q \) yields

\[
Q = \frac{R_T (C_E - C_S)}{C_B - C_E}
\]

The measurement can be stopped as soon as the observer is satisfied that the concentration of the tracer in the stream is constant both along the reach and over time. In steep, swift mountain streams, equilibrium is usually achieved within a couple of minutes. Measurement accuracy tends to increase as the difference between the background and equilibrium concentrations increases. Bjerve and Grøterud (1980:125) provide a table of conductivity differences needed at various ranges of background conductivity to minimize error.

This technique has been extended to larger rivers by taking advantage of natural differences in specific electrical conductance ("conductivity") between a tributary and the main river (Kite, 1989). If a river's conductivity is significantly different above and below the confluence with some tributary and the flow in the tributary is small enough to measure by dilution or other means, then the above equations can be applied. In this case, \( Q \) = discharge of main stream above confluence, \( R_T \) = discharge of tributary, \( C_B \) = conductivity of main stream above confluence, \( C_S \) = conductivity of the tributary, \( C_E \) = equilibrium concentration of main stream below confluence. Where conditions are favorable, this method has the potential of measuring discharges of several tens of m\(^3\) s\(^{-1}\),
which would otherwise require radioisotopes and/or elaborate equipment (e.g., Raja, et al., 1982; Herschy, 1985).

SLUG INJECTION METHOD

The slug injection method involves the injection of a slug of tracer in solution of known volume and conductivity into the stream. From measurement of the conductivity wave as it passes downstream, and the background conductivity, discharge can be calculated from

\[ Q = C_s \frac{V_s}{\int (C_C - C_B) \, dt} \]  

where \( V_s \) = volume of salt solution slug, \( C_C \) = channel conductivity, \( t \) = time, and \( T \) = final time of conductivity wave passage.

Since conductivity is a ratio in this equation the result is independent of the units used to measure conductivity, and discharge is given in \( m^3 \, s^{-1} \). The dilution method requires that complete mixing has occurred. This requires that the measurement site is downstream from the slug injection site at a point greater the mixing length. The measurement-time resolution must be fine enough to capture variations in the conductivity wave as it passes.

Although this method has high precision when applied carefully, it has certain disadvantages compared with the method described below. Each gauging, even at the same site on the same day, requires an individual calibration, which is time consuming. Accurate volumetric measurements must be made, both of \( V_s \) and of the small quantities during the calibration procedure; this measurement is more difficult in the field than in lab conditions. Two large containers are needed, plus fragile volumetric glassware for the calibration. The set-aside sample for calibration must be representative of \( V_s \); this requirement is difficult to achieve if the solution is almost saturated so that precipitation and stratification are occurring (this problem is more acute at lower temperatures since the saturation concentration is lower).

MASS BALANCE METHOD

The alternative approach uses a mass balance, rather than a volumetric balance. A measured mass \( M \) of salt is injected and its mass concentration \( M_C \) in the stream is monitored as the tracer wave passes, using a calibrated relationship between \( M_C \) and the conductivity \( y \). If \( M \), \( M_C \), \( Q \), and the wave duration \( T \) are in commensurate units, the mass balance is

\[ M = \int_0^T Q \, M_C \, dt \]  

so that, for steady flow

\[ Q = \frac{M}{\int_0^T M_C \, dt} = \frac{M}{T \langle M_C(t) \rangle} \]  

where \( \langle \rangle \) denotes the arithmetic mean over time. This method has been used by Ferguson since 1984, and has been discovered independently by other workers (e.g., Hongve, 1987; C.R. Fenn, personal communication, 1988). It has the immediate
advantage that \( M \) can be measured in the lab in advance, e.g. by preparing preweighed packages of salt labeled with the mass \( M \). It is also possible to inject dry salt without preparing a primary solution. Comparative studies by Ferguson (1988, unpublished) and Hongve (1987) found no systematic difference between the salt waves or discharges calculated using dry salt or using a solution. Dissolution on the stream bed need not be instantaneous, so long as the tracer salt does not remain solid long enough to be washed past the conductivity measurement point in suspension or as bedload rather than in solution.

A further advantage is that the calibration can be done in advance in the lab, or just once in the field, for any number of gaugings using the same combination of conductivity meter and batch of salt. The relationship between measured conductivity \( C_C \) at time \( t \) and water temperature \( W_T \) is

\[
C_C(t, W_T) = C_B(W_T) + K C(t) f(W_T)
\]  

where \( C_B = \) natural background conductivity, \( K = \) proportionality constant, and \( f(W_T) = \) temperature correction factor that allows for the increase in \( C_C \) with \( W_T \) for a given \( C \). To a close approximation

\[
f(W_T) = 0.50 + 0.02 W_T
\]  

(Östrem, 1964; Hongve, 1987). The constant \( K \) depends on the type of tracer used, the accuracy and cell constant of the conductivity meter, and to a small extent the ionic activity of the streamwater to which the tracer is introduced. The constant \( K \) is equal to 0.214 for pure NaCl in otherwise ion-free water, and an accurate meter of cell constant equal to unity measuring conductivity in units of mS m\(^{-1}\) (1 mS m\(^{-1}\) = 10 mS cm\(^{-1}\)) (Hongve, 1987). Hongve recommends using this value with an empirical correction of -0.0003 per mS m\(^{-1}\) of background conductivity. Ideally \( K \) should be estimated from lab calibration, rather than relyng on the purity of the salt and the accuracy of the conductivity meter and cell constant. This calibration involves preparing standard solutions of different concentration, measuring their temperature and conductivity, and regressing \( C_C(W_T) \) on \( C(W_T) \) (cf Eq. 6). An alternative is to take the standard solutions into the field, immerse them in the edge of the stream to eliminate any temperature difference, measure their conductivity, and regress \( C_C(W_T) \) on \( C \) to obtain an estimate of \( Kf(W_T) \) (A. Jenkins, U.K. Institute of Hydrology, personal communication, 1988).

Once \( K \) or \( Kf(W_T) \) has been estimated by one of these calibration procedures, the same value holds for all gaugings using this particular combination of salt and conductivity meter. Discharge is calculated by combining Eqs. 5 and 6:

\[
Q = \frac{MKf(W_T)}{T[<C_C(t, W_T)> - C_B]}
\]  

The only field measurements required are of the background conductivity, temperature and salt wave. The mass balance approach therefore minimizes the time required for a gauging and maximizes the accuracy.

TRACERS

A variety of tracers are available and the choice depends on factors such as cost, accessibility, contamination of natural waters, worker safety and availability. Tracers should be soluble in water at the ambient temperature of application, have density and viscosity properties similar to water, be nonreactive with the chemistry of the natural water, exhibit stability in light, organic materials and suspended sediments, and be conservative regarding sorption losses. Further, a tracer should not be found in the natural streamwater except at low concentrations that will not affect its use, and should be
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detectable at very low concentrations, e.g., less than one part per million. Lastly, the tracer must not be detrimental to the stream biota or unacceptable to water users, and must not have lasting effects (Church, 1975).

Major classes of tracers include chemicals, electrolytes, fluorescent dyes, radioactive substances, and the natural waters themselves (Church, 1975). Many chemicals are available for almost any application and usually can be applied at acceptable dilution levels if careful laboratory calibration is carried out. Electrolytes use electrical properties (conductance) as a surrogate for concentration. A variety of common salts are popular and work well in field situations. Fluorescent dyes are also good for field applications because the fluorometry is carried out in the lab and they have the added advantage of providing a visual verification of mixing. Sorption losses must be considered for some dyes. Rhodamine WT dye was found to be inadequate in a mountain stream because of sorption of the dye onto natural stream features and observed concentrations were as low as 45% of the expected measurements (Bencala, et al., 1983). Radioactive tracers have been widely studied and are detectable at low concentrations, but have some noteworthy disadvantages. Safety of researchers, acquisition and transport of material, and regulations governing their use make them prohibitive in many cases. Although some are available with short half-lives, their effect on the biota in streams is cumulative and must be considered. Short half-lives also mean rapid transport and use are necessary and limits their application in remote field areas. The natural physical properties of water may be used as well. Temperature and natural background chemistry have been used as tracers.

It is important that the tracer selected be conservative in the environment it is being applied. A tracer that is conservative in one environment may be nonconservative in another where the chemical constituency is different. For example, salt was an effective tracer in the Sierra Nevada where background conductivities were low (5-10μS cm⁻¹), but other tracers are better in saline streams where it is difficult to introduce a tracer with conductivity above the background value. This example is simplistic and more subtle problems may arise with other tracers.

Researchers should be aware that introduction of tracers to natural waters may have effects on the biota of the aquatic ecosystem. The obvious disadvantages of radioactive tracers have been identified above. Salt is relatively harmless as a tracer, although its effect has not been well quantified. At Emerald Lake researchers found an increase in macroinvertebrate drift after an increase in solutes in the stream. The amount of drift is a function of the intensity and duration of the solute shock wave. The most sensitive organisms drift first but they also recolonize most rapidly. Recolonization is also a function of intensity and duration because a greater drift will result in slower recolonization. There is little doubt of an effect, the question is how much of an effect there is and what the implications are. The effect of changes in the solute chemistry on large organisms such as fish is not as drastic in this context because of the greater mobility of these organisms.

APPLICATION OF DILUTION METHODS AT EMERALD LAKE

Adaptation of the slug injection technique

During a three-year study of the hydrology of an alpine basin in the Sierra Nevada of California, a few hundred measurements were made with the slug injection method. A lightweight, compact kit and simple operating procedure were developed to permit dependable measurements by one or two hydrographers. The practical experience gained during this field program may be helpful in other studies. Listed below are details of the equipment used and the basic procedure.
Equipment

All the equipment listed is available from a variety of sources at a range of prices. Individual needs should be considered when selecting products. The following items are required:
1) A lightweight digital conductivity meter with a submersible probe.
2) A timing device.
3) Two plastic containers, with a volume of about 10L each.
4) Two plastic graduated cylinders, volumes 1000mL and 10mL
5) An adequate supply of common table salt.

The type of conductivity meter selected will depend on the natural background conductivity and the discharge being measured. At most of the flows we observed, a 0-200μS cm\(^{-1}\) meter scale was adequate. At moderate flows (0.05 m\(^3\) s\(^{-1}\)) 250 g of salt mixed with 8L of stream water produced a slug conductivity of 40,000 μS cm\(^{-1}\) and an effective conductivity wave. This mixture was varied depending on flow.

Procedure

Choose a channel reach for measurement. An adequate injection and measurement site should be located and should allow the slug to be dumped into the main channel flow and allow placement of the conductivity probe in the main current without movement after placement. The distance between the two sites should not be too close or the wave will pass too quickly as a sharp peak. If they are too far apart, attenuation from mixing will provide a poorly defined peak that is difficult to measure. Stream stage should be measured and recorded. Measure and record the background conductivity of the stream. Fill one plastic bucket with the appropriate amount of stream water. Record the volume of the water and the amount of salt added to make the slug mixture. After mixing thoroughly, measure 10mL slug solution and 1000mL of stream water and mix in the second bucket and measure and record the diluted slug conductivity and the dilution factor (e.g., 100/1). The conductivity of the undiluted salt slug (C\(_S\)) is computed by multiplying the diluted slug conductivity C\(_{dil}\) by the dilution factor (x) and removing the background conductivity (C\(_B\)):

\[
C_S = C_{dil}(x - 1) - C_B
\]

After placing the probe and meter at the measurement site, inject the slug and record the wave passage as conductivity. Conductivity should be recorded at 5 to 10 second intervals. The procedure takes 15 minutes or less to complete for experienced personnel. Two measurements should be taken for quality assurance and error estimation. Calculation of discharge can be done in the field with an inexpensive calculator capable of simple integration.

Continuous injection for backcountry use

Because of the heavy and bulky equipment traditionally used for the continuous injection technique, this option has rarely been used in the backcountry. In our study in Sequoia National Park, we experimented with two transportable injection systems: small constant-speed pump and siphon. The battery-powered pump allowed injection of up to 250 ml min\(^{-1}\) of brine. Because of low background conductivities (3-5 μS cm\(^{-1}\)) in the basin’s streams, this injection rate was sufficient to double the conductivity at discharges up to about 0.2 m\(^3\) s\(^{-1}\). Conductivities reached equilibrium within 5 minutes of the start of injection. This time is probably much shorter than the time to equilibrium in most other streams (Church and Kellerhals, 1970). The pump with 8 D-cell batteries weighed about 3 kg and was completely reliable. A few comparisons between this method and the slug injection method at discharges of 0.1 to 0.2 m\(^3\) s\(^{-1}\) resulted in equivalent values except for one discrepancy of 20 percent. Discharge determined from simultaneous current meter measurements were up to 60 percent greater than the dilution measurements.
A siphon tube attached to a float in a large container also provides a constant flow rate. A lightweight cylinder or tank with cross-sectional area of 0.1 to 0.2 m$^2$ can be easily carried in a rucksack and can hold up to 1001 of brine. A couple of siphon tubes of different diameter allow a range of injection rates. Two or more tanks can be used simultaneously in larger streams. A few observations of the water level at different times provide the injection rate. The tank should be shaded if the solution must stand for more than 10 minutes to minimize temperature change. A simply-designed Mariotte vessel (Browne and Foster, 1978; Herschy, 1985:382) constructed of lightweight material could also be suitable for backcountry use.

Problems and considerations

Almost every dilution measurement was replicated immediately. Although the replicates were nearly identical in almost all cases, measurements made at the same stage several days apart were different in several cases. This discrepancy may result from difficulty in defining the shape of the tails in the final decline of the conductivity wave, a problem that we encountered and others have reported (Day, 1976). The problem may result from sampling at too coarse of a resolution or from changes in the background conductivity during a measurement. Background conductivity should not change during a measurement under normal circumstances, but will often change with changes in discharge. The problem we encountered at Emerald Lake was a result of the low background conductivities that ranged between 3-6 μS. At this level a change of a few μS represented about 100% of the background conductivity. We observed long tails as the solution from all the eddies and entire channel reach finally washed through the system past the measurement point. In some cases, the area under these tails was a significant portion of the entire conductivity wave. In calculating the discharge with Eq. 3 there was a considerable difference in the resultant discharge depending on the final value of time $t_f$ used in the integral. Not all field measurements were continued until the measured conductivity returned to the background level. This leaves the data analyst with the problem of estimating the behavior of the tail and produces an unknown error. Some researchers have used exponential decay and linear least-squares models to extrapolate the tail to the background level. Model fitting involves subjective choices of model type and the portion of the data to which it is fit thus producing error. The error will be minimized when a the area under the tail is a small portion of the total integral therefore, using a strong solution that maximizes the peak and area under the bulk of the curve will produce the best results.

The stream reach should be as turbulent as possible to maximize mixing and be free of tributaries, bifurcations, vegetation, and back-water areas or dead zones (Herschy, 1985). The minimum length of stream required for thorough mixing depends on the hydraulics of the particular stream reach. A variety of empirical equations for estimating mixing length have been developed (e.g., Day, 1977; Herschy, 1985:376). A study of mountain streams in New Zealand showed that complete mixing is achieved in a reach 25 times as long as the average channel width (Day, 1977). Day found that mixing lengths in his study reaches tended to be considerably shorter than lengths predicted with the various equations. He attributed these discrepancies to the greater roughness of the beds of mountain streams. With the continuous injection method, the mixing length can be determined by successively measuring the specific electrical conductance downstream of the injection site until the values become constant with distance downstream. In the turbulent streams at our study site in the southern Sierra Nevada, we found that Day's criteria was conservative and that complete mixing appeared to occur in as little as 15 times the mean channel width.
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