Introduction to Salt Dilution Gauging for Streamflow Measurement Part 2: Constant-rate Injection

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Introduction

Stream gauging by salt injection is a technique that will work in many streams in which current-meter measurements are unreliable. This extension note builds upon a previous Streamline article (Moore 2004b) and describes field and computational procedures for stream gauging by constant-rate salt injection. The emphasis is on small streams (less than about 2 m in wetted width) under low flow conditions (discharge less than about 100 L/s). A future article will introduce slug injection, which is better suited to gauging higher flows. Users are encouraged to experiment with the following procedure to suit individual circumstances.

The Concept

A tracer solution injected into a stream at a defined rate, q (L/s), will become uniformly mixed across the stream at some distance below the injection point as a result of turbulent flow. After enough time has elapsed, a steady state (equilibrium) will develop, where the relative concentration of the tracer in the stream is

$$RC_{ss} = \frac{q}{q+Q} \approx \frac{q}{Q} (q << Q) \quad (1)$$

where Q is the stream discharge (L/s) and RC_{ss} is the relative concentration at steady state (L/L). From Equation (1), the discharge can be computed as:

$$Q = \frac{q}{RC_{ss}} \quad (2)$$

Because electrical conductivity (*EC*) is linearly related to *RC* for dilute solutions, RC_{ss} can be determined from *EC* measurements as follows:

$$RC_{ss} = k(EC_{ss} - EC_{bg}) \quad (3)$$

where k is the slope of the relation between *RC* and *EC*, and EC_{bg} and EC_{ss} are the electrical conductivities of streamwater at background (i.e., prior to injection) and at steady state (i.e., *EC* remains constant in time).

Combining Equations (2) and (3), discharge can be computed as:

$$Q = \frac{q}{k(EC_{ss} - EC_{bg})} \quad (4)$$

To apply Equation (4), we need to measure the injection rate of salt solution, q, and the background and steady state values of *EC*, and to construct a calibration curve of *RC* versus *EC* to derive k. Table 1 lists the equipment required.

> *An ideal reach begins upstream of a flow constriction and contains no pools or backwater areas below.*

Choice of a Measurement Reach

To apply the technique successfully, find a stream reach that features complete lateral mixing in a short distance (Moore 2004b). Longer reaches require a longer injection duration (and thus volume of salt solution) to achieve steady state. Selected reaches should have as little pool volume as possible, because the slow exchange of tracer within the pool volume will greatly increase the time to achieve steady state. An ideal reach begins upstream of a flow constriction (e.g., where the flow narrows around a boulder, promoting rapid lateral mixing) and contains no pools or backwater areas below. A rough guideline is that the mixing length should be at least 25 stream widths, but complete mixing may require much longer or shorter distances, depending on stream morphology. Culverts can be convenient measurement locations if large cobbles are positioned in the flow just below the upstream (input) end to promote lateral mixing within the culvert.

Methods of Injection

Several methods are available for injecting solution at a constant rate, including siphons (Johnstone 1988), battery-powered pumps (Elder *et al.* 1990), and Mariotte bottles (Mellina *et al.* 2002; Story *et al.* 2003). For small streams, a Mariotte bottle constructed from a 10-L carboy with spigot works well for injecting the tracer (Figure 1). The 10-L carboy holds an adequate volume of solution appropriate for small streams, and fits into a large backpack for hiking to remote sites. Also, it does not require batteries and has no mechanical parts. A companion article (Moore 2004a, this publication) describes the

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construction and application of a Mariotte bottle.

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Figure 1. Mariotte bottle injecting into culvert.

Mixing the Injection Solution

We use NaCl (table salt) because it is inexpensive, readily available, and environmentally benign for the concentrations and durations normally involved in discharge measurement. The salt concentration in the injection solution should be high enough to produce a measurable increase in electrical conductivity while remaining less than the solubility. It should also be low enough to avoid raising the salt concentration in the streamwater above any thresholds associated with negative ecological impacts (Moore 2004b).

If C_s represents the maximum desired salt concentration in the stream (g/L), the corresponding concentration in the injection solution (C_{is}; g/L) can be estimated as

$$C_{is} = (Q_{est} / q) C_s \tag{5}$$

where Q_{est} is an estimate of stream discharge based on the product of estimated width, depth, and velocity. The change in electrical conductivity from background to steady state (ΔEC; S/cm) will be, to a close approximation, proportional to the concentration of added salt:

$$\Delta EC = \beta C_s \tag{6}$$

where β is a proportionality factor, approximately equal to 2100 (µS/cm)/(g/L) at 25°C; the precise value depends on background electrical conductivity (Hongve 1987). For example, a steady-state concentration of $C_s = 20$ mg/L (= 2×10^{-2} g/L) should produce a change in EC of about 42 µS/cm. Combining Equations (5) and (6), we can estimate the salt concentration in the injection solution that would be required to generate a desired change in EC:

$$C_{is} = (Q_{est} / q) \Delta EC / \beta \tag{7}$$

The injection solution does not need to be made with local streamwater. If site access is easy, it is often useful to premix the solution to allow generous time for dissolution. The accuracy of the method critically depends on the *complete* dissolution of the salt. For strong solutions, decanting is advised to minimize the presence of undissolved salt.

When mixing the injection solution in the field, we use pre-weighed bags of salt (typically 10 to 100 g per bag, depending on the flows to be gauged) to allow for flexibility in the volumes and concentrations. The concentration of salt need not be precisely controlled, since calibration is expressed as the volumetric concentration of tracer solution in streamwater, not the mass concentration of salt in the streamwater.

Determining *k* by Calibration

Steps:

1. Create a secondary solution by mixing X mL (typically 5 or 10 mL) of injection solution with a measured volume V_0 of streamwater (typically 1000 mL, but different volumes can be used). Use of streamwater for mixing the calibration solution is necessary. This solution will have a relative concentration, RC_{sec}, given by

$$RC_{\mathrm{sec}} = \frac{X}{V_o + X} \tag{8}$$

for $X = 10$ mL, $V_0 = 1000$ mL, $RC_{sec} = 9.90 \times 10^3$.

2. Measure a volume V_c of streamwater (typically 1000 mL, but greater volumes allow for greater dilution) into a "calibration tank," a beaker or pail dedicated for this use. The calibration tank must be clean, and have never carried a strong salt solution because residual salt will bias the calibration. Even though most electrical conductivity probes will adjust EC to a standard value of 25°C, the calibration tank should be immersed in streamwater (e.g., in a shallow pool at the stream's edge), to minimize temperature changes during the calibration. A "corral" constructed from cobbles helps to hold the calibration tank in place.

3. Measure the initial conductivity, EC_0, in the calibration tank. This EC will correspond to $RC = 0$.

4. Use a pipette to add a known amount of the secondary solution to the calibration tank (e.g., 2 mL). Separate pipettes for the injection and secondary solutions must be used to avoid contamination. Mix thoroughly and record the EC and water temperature.

5. Repeat step 4 until the mixed EC in the calibration tank exceeds EC_{ss}. At each step, compute the relative concentration as

$$RC = \frac{RC_{\mathrm{sec}} \, \Sigma y}{(V_c + \Sigma y)} \tag{9}$$

where Σy = the cumulative amount of secondary solution added to the calibration tank (mL).

Use at least three additions of secondary solution, even if EC_{ss} is exceeded on the first or second addition, to allow a check on the linearity of the calibration and to protect against errors that could occur undetected if only one addition were used (as in the calibration procedure described by Elder *et al.* 1990).

Start out using additions of 2 mL of secondary solution. If the resulting change in *EC* is small relative to the difference $EC_{ss} - EC_{bg}$ (i.e., it would take many additions to cover the range), then the volume of additions can be increased to 5 or 10 mL.

6. Using the *RC* – *EC* data from steps 3 to 5, fit a straight line to the points and find its slope, *k*. Alternatively, for field computation, the slope can be estimated as

$$k = \frac{RC_f}{EC_f - EC_o} \qquad (10)$$

where RC_f is the relative concentration for the final calibration mixture, and EC_f is the corresponding electrical conductivity.

Summary of Field Procedures

Table 1 lists the equipment required. Steps in conducting a measurement are as follows.

1. Select the reach to be measured.
2. Record the background *EC* and water temperature at the downstream end of the mixing reach, as well as upstream of the injection point.
3. Measure a volume V_0 of water using the volumetric flask and pour into the secondary solution bottle.
4. Measure a volume V_c of water using the volumetric flask and pour into the calibration tank.
5. Immerse the calibration tank in a shallow pool at the stream's edge, downstream of the measurement point.
6. If using a Mariotte bottle set up on a tripod within the stream to inject the salt solution, set up the tripod at the injection point, then remeasure *EC* at the downstream end of the reach to ensure that setting up the tripod has not altered the background conductivity.
7. Begin constant-rate injection, and observe *EC* at the downstream end of the mixing reach. When *EC* appears to level out, measure it across the section to check for lateral mixing. If *EC* varies across the stream, try moving farther downstream. If there are large pools downstream, and it appears unlikely that complete lateral mixing will occur, note the highest and lowest *EC* values across the stream. You can use these values to estimate a "most likely" value for EC_{ss}, as well as to estimate error bounds.
8. After you have recorded EC_{ss} and the water temperature, measure the injection rate using a graduated cylinder and stopwatch.
9. Retain some of the injection solution in a 60-mL Nalgene bottle, then turn off the Mariotte bottle.
10. Determine *k* using the procedure described previously, then compute the discharge by Equation (4).

Table 1. Equipment list

Item	Purpose
Siphon, pump, or Mariotte bottle	injecting at a constant rate
1-L volumetric flask	measuring streamwater
1-L plastic graduated cylinder	providing backup in case volumetric flask breaks
Plastic measuring cup with handle	pouring streamwater into volumetric flask
Squirt bottle	topping up streamwater in volumetric flask
60-mL Nalgene bottle	taking a sample of injection solution for pipetting
5- and 10-mL pipettes[1,2]	measuring injection solution to mix secondary solution
Pipette filler (rubber squeeze bulb)	drawing water into pipettes
2-L wide-mouth plastic water bottle	mixing the secondary solution
2-L plastic beaker or pail	calibrating tank
2-, 5-, and 10-mL pipette[1,2]	measuring secondary solution
Plexiglas rod or tubing, 30 cm long	stirring in calibration tank
100-mL graduated cylinder	measuring injection rate
Stopwatch	measuring injection rate

[1] Separate sets of pipettes need to be used for measuring the injection and secondary solutions.

[2] Spare pipettes should be carried in case of breakage in the field. Alternatively, 10-mL plastic graduated cylinders or graduated pipettes could be carried as a backup.

Example

The following example is from measurements made on a stream near Takla Lake, B.C. The injection solution was mixed using approximately 300 g of NaCl in 6 L of water. The secondary solution was mixed from 10 mL of injection solution and 1 L of streamwater. The injection rate was q = 1.53 mL/*s.*

The calibration data are summarized in Table 2. The volumes V_0 and V_c were both 1000 mL. From a regression of *RC* against *EC*, the slope of the *RC* – *EC* relation was $k = 1.23 \times 10^{-5}$cm/µ*S*.

$$Q = \frac{q}{k(EC_{ss} - EC_{bg})} = \frac{1.53 \cdot 10^{-3} L/s}{(1.23 \cdot 10^{-5}\, cm/\mu S)(221 \mu S/cm - 206 \mu S/cm)} = 8.3\ L/s$$

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Table 2. Calibration data for example

Vol. of secondary added (mL)	Cumulative vol. of secondary added (Σγ) (mL)	Electrical conductivity (*EC*) (µS/cm)	Relative concentration (*RC*) (L/L)	T (°C)
0	0	206	0.0	14.7
5	5	210	4.93×10^{-5}	14.6
5	10	214	9.80×10^{-5}	14.6
5	15	218	1.46×10^{-4}	14.6
5	20	222	1.94×10^{-4}	14.6
5	25	226	2.41×10^{-4}	14.6
5	30	229	2.88×10^{-4}	14.5

Errors and Limitations

Two key requirements for accurate measurements are that (1) the salt in the injection solution be completely dissolved, and (2) the injection solution be fully mixed across the channel. In addition, discharge should not change appreciably during the injection trial.

Errors may arise through inaccuracies in measuring the volumes of streamwater, injection solution, and secondary solution. These errors can be effectively minimized if a volumetric flask is used to measure streamwater and if glass pipettes are used to measure the injection and secondary solutions. However, take plastic ware into the field as a backup in case of breakage. The accuracy of the calculated discharge is directly related to the accuracy of the injection rate. To reduce the magnitude of this source of uncertainty, conduct several measurements and average them.

> *Errors may arise through inaccuracies in measuring the volumes of streamwater, injection solution, and secondary solution.*

Another source of uncertainty is in measuring the difference in *EC* between background and steady state. In the previous example, the uncertainty in the difference will be ±1 µS/cm relative to a difference of 15 µS/cm, or about ±7%. This error could be reduced by injecting at a higher rate or using a more concentrated injection solution to effect a greater *EC* at steady state. Equation (7) could be used to estimate the desired concentration (assuming a fixed injection rate).

We have used constant-rate salt injection to measure flows from 1 to 100 L/s. For higher flows, the main limitation is the ability to inject tracer at a sufficient rate and duration to achieve steady state with a measurable change in *EC*. Higher flows may be gauged by using a larger carboy, floating siphon, or pump equipment, or alternative methods such as slug injection. For example, Johnstone (1988) measured flows up to 100 m^3/s using a floating siphon. However, that approach is not feasible for remote sites accessed by foot.

At low flows, hyporheic exchange may complicate measurements through the infiltration of streamwater into the bed or banks and re-emergence some distance downstream. Consequently, streamflow gauged by salt injection would measure not only flow within the channel, but also an additional component flowing in the subsurface. Thus, salt dilution measurements may not be comparable to methods that gauge surface flow in the channel such as a current meter or other volumetric method.

Rainfall can influence the measurements in two ways. First, unless the calibration tank is sheltered, rain falling into it may dilute the concentrations below the calculated values, producing biased calibrations. Second, rain may generate stormflow, resulting in altered discharge and background *EC*. Subsequently, *EC* may not achieve a clear plateau, resulting in uncertainty. The hydrologic response, however, will depend greatly on characteristics such as soil depths, textures, and moisture content, so generalizations cannot be made.

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Construction of a Mariotte Bottle for Constant-rate Tracer Injection into Small Streams

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Liquid tracers are commonly injected into streams to measure streamflow, hydraulic characteristics, and rates of nutrient uptake (e.g., Webster and Ehrman 1996; Story *et al.* 2003). A Mariotte bottle, based on a device developed by the French physicist Edme Mariotte in the 17th century, provides a simple method for injecting tracer at a constant rate. This article describes the construction and application of a Mariotte bottle appropriate for injecting tracer into small streams.

Construction

A simple Mariotte bottle can be constructed from a carboy fitted with a spigot (Figures 1 and 2; Table 1). A 10-L carboy holds a sufficient volume of tracer for gauging small streams at low flow, and fits into a large backpack for transport to remote field sites. We have measured flows as low as 1 L/s and as high as 100 L/s using a Mariotte bottle (e.g., Mellina *et al.* 2002; Story *et al.* 2003).


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Figure 1. Materials required to construct Mariotte bottle. From left to right: 10-L carboy, pipette tip, Quick Disconnect Connector, rubber stopper with Plexiglas tube inserted.

To construct the Mariotte bottle, the screw-on cap is replaced by a size 13½ one-hole rubber stopper with a length of Plexiglas tube inserted to a level about 10 cm higher than the spigot level. The tube should be inserted such that it remains below the surface of the tracer fluid (as shown in Figure 2) throughout the measurement period; otherwise, tracer solution will not discharge at a constant rate. The tube allows air to enter as water drains, thereby maintaining a constant water pressure at the spigot, resulting in a constant outflow rate. The lower end of the tubing should be cut on a bevel, to facilitate bubbling.

The spigot is fitted with a tubing connector and pipette tip with the end cut off. The non-tapered end of the tubing connector fits snugly into the spout of the carboy, and the pipette tip is slid over the tapered end of the connector. This set-up "steps down" the outflow rate, and allows the spigot to be opened fully for delivery of tracer while controlling the injection rate. Several pipette tips with a range of hole diameters allow for a range of injection rates. It is important that the outflow be a continuous stream rather than discrete drips. If the water drips out, air will enter and create an inconsistent outflow rate.

Application

The Mariotte bottle can be set up on a square of plywood fixed to the top of a tripod, to provide a stable base for the bottle. If the stream is narrow, it may be possible to have the tripod legs span the stream.

After setting up the Mariotte bottle, open the spigot to begin injection. When the spigot is first opened, the

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