# Streamline
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Introduction to Salt Dilution Gauging for Streamflow Measurement Part III:

# Slug Injection Using Salt in Solution

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## Introduction

Previous Streamline articles introduced the general principles of stream gauging by salt dilution (Moore 2004a) and the procedure for constant-rate injection (Moore 2004b). While constant-rate injection is best suited for use in small streams at low flows (discharges less than about 100 L/s or 0.1 m³/s), slug injection can be used to gauge flows up to 10 m³/s or greater, depending upon channel characteristics. Slug injection works well in steep, highly turbulent streams, such as the bouldery mountain channel shown in Figure 1. This article introduces the conceptual basis and field procedures for slug injection using salt in solution.

*Slug injection works well in steep, highly turbulent streams.*

## Conceptual Basis

In this approach, a volume of salt solution, *V* (m³), is injected as a near-instantaneous slug or gulp at one location in the stream. Following injection, the salt solution mixes rapidly throughout the depth of the stream and less rapidly across the stream width as it travels downstream with the general flow of water. Because some portions of a stream flow faster than others (e.g., flow tends to be faster in the centre than near the banks), the cloud of salty water "stretches" downstream in a process called *longitudinal dispersion*. This dispersion results in the cloud having a leading edge with relatively low concentrations of salt solution, a central zone of high concentrations, followed by a trailing edge of decreasing concentration.

If the electrical conductivity (EC) is recorded at some point downstream, where the tracer has been completely mixed across the stream width, the passage of the salt cloud will cause EC to increase from its background value to a peak value, corresponding to the passage of the core of the cloud, followed by a decline to background EC as the trailing edge of the cloud passes, resulting in a characteristic *salt wave* (Figure 2). Longitudinal dispersion reduces the peak EC of the salt wave as it travels downstream. The time required for the peak of the wave to move past an observation point will depend inversely on the mean velocity of the streamflow, while the duration of the salt wave will depend

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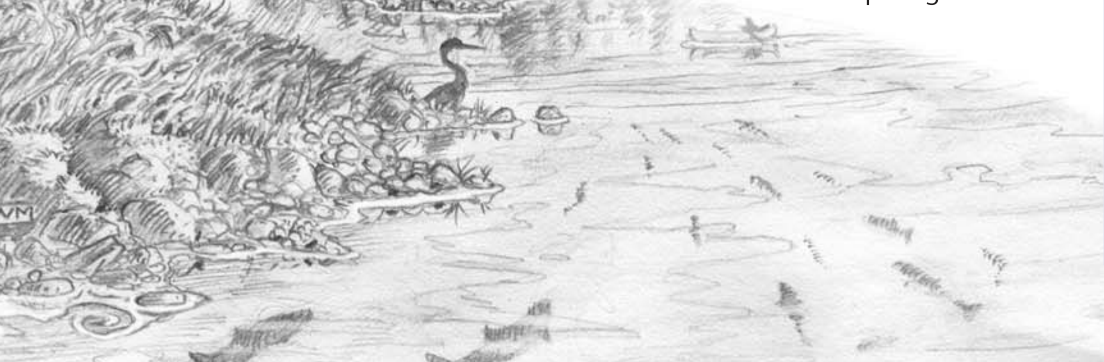

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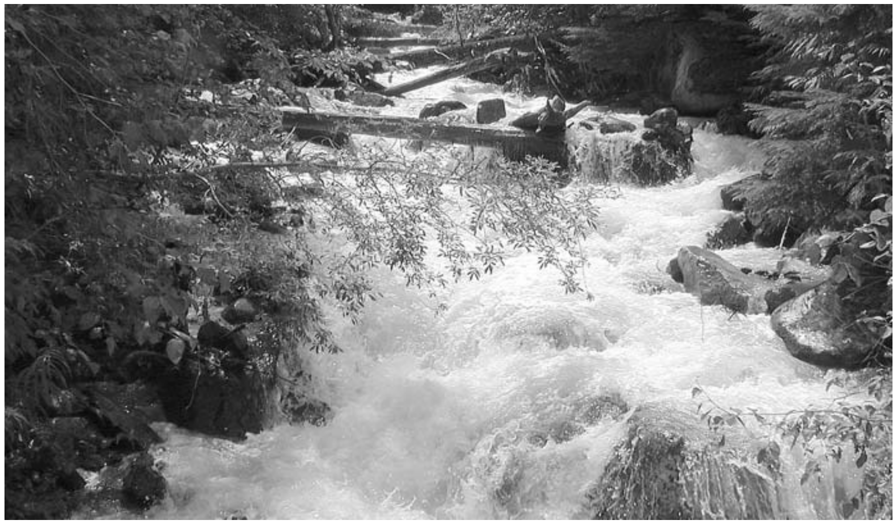


***Figure 1. Place Creek at high flow during summer glacier melt.***

on the amount of longitudinal dispersion, which, in turn, depends on how variable the stream velocities are across the stream. The author has found that the time required for the salt wave to pass typically varies from a couple of minutes (e.g., Figure 2) to over 20 minutes. Under low-flow conditions with low velocities, the duration can be longer than desired for accurate measurements (e.g., well over 30 minutes).

At any time *(t)* during the salt wave passage, the discharge of tracer solution *q(t)* (L/s or m³/s) past the point will be approximated by:

$$q(t) = Q \cdot RC(t) \qquad [1]$$

where *Q* is the stream discharge (L/s or m³/s) and *RC(t)* is the relative concentration of tracer solution (L/L) in the flow at time *(t)*. Equation [1] assumes that *q(t)* is much smaller than *Q*, which should be true in virtually all cases. If the tracer discharge is integrated over the duration of the salt wave, and if the stream discharge is constant over that time, then the following equation should hold for a conservative tracer (i.e., one that does not react with other chemicals in the water, bind to sediment, or otherwise change as it flows downstream):

$$V = \int_T q(t)dt = Q\int_T RC(t)dt \quad [2]$$

where *T* represents the salt wave duration (s). Equation [2] can be rearranged to solve for *Q*:

$$Q = \frac{V}{\int_T RC(t)dt} \qquad [3]$$

In practice, *RC(t)* is determined at the downstream measurement point at a discrete time interval $\Delta t$ (e.g., 1 or 5 s), and the integral is usually approximated as a summation:

$$\int_T RC(t)dt \cong \sum_n RC(t)\Delta t \quad [4]$$

where *n* is the number of measurements during the passage of the salt wave. The relative concentration can be determined from EC:

$$RC(t) = k[EC(t) - EC_{bg}] \quad [5]$$

where *EC(t)* is the electrical conductivity measured at time *t*, $EC_{bg}$ is the background electrical conductivity of the stream, and *k* is a calibration constant. The calibration constant, *k*, depends primarily on the salt concentration in the injection solution and secondarily on the chemical characteristics of the streamwater. Combining Equations [3], [4], and [5], the following practical equation can be derived for computing discharge:

$$Q = \frac{V}{k\Delta t \sum_{n} [EC(t) - EC_{bg}]} \quad [6]$$

To apply Equation [6], we need to know *V*, the volume of salt solution injected; measure the resulting changes in *EC* at intervals of $\Delta t$ until *EC* returns to background levels; and determine the calibration constant, *k*.

## Field Procedures

### Choice of a Measurement Reach

Successful application of the slug injection technique requires a stream reach that generates complete lateral mixing in a short distance. Selected reaches should have as little pool volume as possible because the slow exchange of tracer between the pool volume and the flowing portion of the stream will greatly increase the time required for the salt wave to pass. An ideal reach begins with an injection site 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 the constriction. 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 (Day 1976).

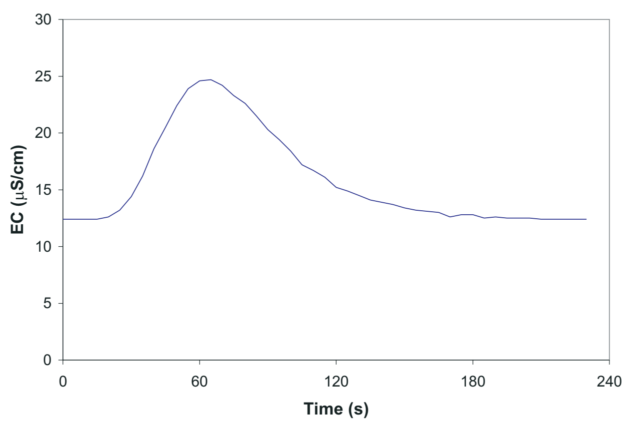


*Figure 2. Example of salt wave in Place Creek.*

### Mixing the Injection Solution

We use NaCl (table salt) as a tracer because it is inexpensive and readily available. In addition, the salt concentrations and durations of exposure normally involved in discharge measurement are less than thresholds associated with deleterious effects on organisms (Moore 2004a). Wood and Dykes (2002) observed transient increases in invertebrate drift during slug injection, but concluded that salt injection had a relatively short-term effect and is unlikely to have any long-term deleterious impacts on invertebrate communities at most locations.

The salt concentration in the injection solution should be high enough to increase EC reasonably when using volumes of solution that can be easily handled, but it also needs to remain less than the solubility. Given the low temperatures often associated with field conditions, the maximum concentration that will dissolve readily is about 20%, or about 1 kg of salt in 5 L of water (Østrem 1964; Kite 1993). We have found that a mixture of 1 kg of salt with 6 L of water (roughly a 17% solution) provides a suitable compromise between strength and ease of dilution.

The injection solution does not need to be mixed from local streamwater. Where access to the stream does not involve a long hike, it is often convenient to pre-mix the injection solution to allow generous time for dissolution and to minimize time spent at the field site.

Note that the volume of the injection solution will be greater than the volume of water used to mix it. We have found that when a 1-kg box of salt is mixed with 6 L of water, the resulting solution has a volume of 6.36 L (±0.01 L). Commonly, the salt solution is mixed in one container then decanted into a second, pre-calibrated container (e.g., Østrem 1964). This procedure ensures that the salt in the injection solution is completely dissolved, and allows accurate measurement of the injection volume.

### Required Volumes of Injection Solution

The accuracy of a measurement depends on how much EC increases above background during the salt wave passage, relative to the accuracy of the conductivity probe. The change in EC during the salt wave passage depends, in turn, on the volume of salt solution and its concentration, as well as the mixing characteristics of the stream. Those streams with less longitudinal dispersion will exhibit a more peaked salt wave with higher concentrations, and will require lower injection volumes.

Kite (1993) suggested that peak EC should be 50% higher than background, while Hudson and Fraser (2002) suggested that peak EC should be at least 5 times higher than background. Background EC in B.C. streams typically ranges from about 10 µS/cm for stormflow conditions in streams draining catchments underlain by granitic bedrock, to over 400 µS/cm for low-flow conditions in streams sustained by groundwater discharge. The author suggests that increasing EC by 100–200% of background should be adequate for streams with low background EC (less than about 50 µS/cm), while Kite's (1993) guideline should be reasonable for streams with background EC greater than about 100 µS/cm.

Table 1 summarizes the masses/volumes of injected salt/salt solution used by various authors. The range reflects the diversity of channel morphologies and discharges encountered in the different studies. The author recommends starting with 1 L of 15–20% solution per $m^3/s$. Greater volumes of injected salt

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solution may be appropriate for wider streams that require longer mixing reaches, while lower volumes may work for narrower streams. To avoid excessive salt concentrations in the stream, one or more trial injections should be conducted with low volumes, working up to larger volumes as required.

**Table 1. Volumes/masses of injected salt used in different studies**

| Author | Mass of salt injected per $m^3/s$ streamflow (kg) | Equivalent volume (L) of 20% salt solution (1 kg salt in 5 L water) |
|---|---|---|
| Østrem (1964) | 0.5 | 2.5 |
| Church and Kellerhals (1970) | 0.2 | 1 |
| Day (1976) | 0.3 | 1.5 |
| Elder *et al.* (1990) | 5 | 25 |
| Hudson and Fraser (2002) | 2 | 10 |

Figure 2 illustrates a salt wave for Place Creek, where the author has found the salt waves to be highly reproducible. Injecting 6.35 L of a roughly 17% solution into a flow of 2.66 $m^3/s$ produced a peak EC about 100% higher than background.

### Recording Electrical Conductivity

Ideally, a data logger should be used to record the passage of the salt wave. Some conductivity meters have built-in data logging, while others can output a signal that can be recorded using a separate data logger. If you do not have data logging capacity, record EC manually at 5-s intervals. Although this approach may not be as accurate as using a data logger and a 1-s recording interval, it can produce satisfactory results. In most cases, two people are required to conduct a salt dilution measurement with manual recording, while the use of a data logger allows a single person to make the measurement.

The conductivity probe should be placed within the main part of the flow, not in a backwater. Avoid locations with substantial aeration, as air bubbles passing through the probe cause spurious drops in conductivity. The probe should be firmly emplaced (e.g., by wedging it between carefully placed cobbles) so that it will not move during the measurement. To position the probe in a strong current, it may be useful to attach the probe to a rod weighted at the end that is placed in the water.

In some cases, the background EC may vary. One possible cause is an overly sensitive conductivity meter. Another cause of varying background EC is incomplete mixing of streamwater and groundwater (which typically has higher EC than the streamwater) within and immediately downstream of groundwater discharge zones. Similar problems with incomplete mixing can occur downstream of tributaries. In these latter cases, find an observation point where background EC is uniform across the channel and constant in time.

### Determining *k* by Calibration

To determine *k*, a known volume of injection solution (typically 5 or 10 mL) is added to a known volume of streamwater (typically 1 L) to produce a secondary solution. Known increments of this secondary solution are then added to a second known volume of streamwater (typically 1 L), to generate a set of EC values corresponding to different values of relative concentration. The slope of the relation between relative concentration and EC provides the required value for *k*. This two-step procedure dilutes the injection solution to the relative concentrations observed during the salt wave without using large volumes of streamwater. See Moore (2004b) for a more detailed description of the procedure and the calculation of *k*.

Although ideally the calibration is performed in the field, particularly to maintain water temperature as close to stream temperature as possible, it can also be conducted in the laboratory. To perform the calibration off site, two 1-L samples of streamwater should be measured accurately into sample bottles using a volumetric flask. A sample of the injection solution should also be taken in a small glass (not plastic) bottle to avoid potential problems with salt sorbing onto the walls of a plastic bottle. The calibration can then be conducted following the procedure described by Moore (2004b).

## Summary of Field Procedures

Table 2 lists the equipment required. Suggested steps for conducting field measurements are as follows:

**1.** Mix injection solution (either at office or on site).

**2.** Select measurement reach.

**3.** Use a pipette to extract a known volume of injection solution (e.g., 10 mL) and add to the secondary solution bottle. Cap the bottle and store upright.

**4.** Record background EC and water temperature at the downstream end of the measurement reach, and upstream of the injection point.

**5.** Set up the conductivity probe at the downstream end of the mixing reach. Record the background EC and water temperature. If you have a data logger, start recording EC.

**6.** Inject a known volume of salt solution at the upstream end of the mixing reach.

**7.** Record the passage of the salt wave, continuing until EC returns to background. If EC does not return to background, measure EC upstream of the injection point again to determine whether the background changed.

**8.** Measure a volume $V_0$ (e.g., 1 L) of streamwater using the volumetric flask and pour into the secondary solution bottle, which already contains the sample of injection solution. Cap the bottle and shake vigorously to mix the streamwater and injection solution. This mixture is the secondary solution.

**9.** Measure a volume $V_c$ (e.g., 1 L) of streamwater using the volumetric flask and pour into the calibration tank. Immerse the calibration tank in a shallow pool at the stream's edge. Keep the temperature in the tank as close to stream temperature as possible (Moore 2004b). To help hold the calibration tank in place, position a "corral" of cobbles around it.

**10.** Perform the calibration and determine *k* using the procedure described by Moore (2004b), then compute the discharge using Equation [6].

## Worked Example

Figure 2 shows a salt wave recorded during a slug-injection measurement at Place Creek, located about 30 km northeast of Pemberton, B.C. Place Creek, a steep, bouldery mountain stream, would be impossible to gauge accurately using a current meter (Figure 1). The volume of injection solution was 6.35 L. This volume resulted from mixing 1 kg of salt with 6 L of water (to produce 6.36 L of solution), followed by extracting 10 mL (0.01 L) of injection solution for use in the calibration procedure. The stream EC data were logged at 1-s intervals, and the calibration constant was $2.99 \cdot 10^{-6}$ cm/µS.

$$Q = \frac{V}{k\, \Delta t\, \Sigma[EC(t) - EC_{bg}]} = \frac{6.35 \cdot 10^{-3} m^3}{(2.99 \cdot 10^{-6}\, cm/\mu S)(1\, s)(797 \mu S/cm)} = 2.66 m^3/s$$

## Errors and Limitations

*Under suitable conditions, streamflow measurements made by slug injection can be precise to within about ±5%.*

Under suitable conditions, streamflow measurements made by slug injection can be precise to within about ±5% (Day 1976). Accurate measurements require that (1) the salt in the injection solution be completely dissolved, and (2) the injection solution be fully mixed across the channel at the location where the salt wave is recorded. 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 glass pipettes used to measure the injection and secondary solutions. However, take plasticware into the field as a backup in case of breakage.

If it is raining during the measurement, ensure that the calibration tank is sheltered. Otherwise, rain falling into the tank may dilute the concentrations below the calculated values, producing biased calibrations.

The slug injection method may not be appropriate when the channel contains ice and (or) snow. In such cases, low velocities may result in poor lateral mixing and excessively long salt wave durations, particularly if salt solution flows into slush zones within the measurement reach.

The method will be subject to substantial errors if the measurement

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**Table 2. Equipment list for field measurement of streamflow using slug injection of salt**

| Item | Purpose |
|---|---|
| 1-L volumetric flask | Measuring streamwater |
| 1-L plastic graduated cylinder | Backup in case volumetric flask breaks |
| Plastic measuring cup with handle | Pouring streamwater into volumetric flask |
| Squirt bottle | Topping up streamwater in volumetric flask |
| 5- and 10-mL pipettes[1,2] | Measuring injection solution to mix secondary solution |
| Pipette filler (rubber squeeze bulb) | Drawing water into pipettes |
| 1- or 2-L wide-mouth Nalgene water bottle | Mixing the secondary solution |
| 1- or 2-L Nalgene beaker or pail | Calibration tank |
| 2-, 5-, and 10-mL pipettes[1,2] | Measuring secondary solution |
| Plexiglas rod or tubing, 30 cm long | Stir stick for calibration tank |
| Conductivity probe and meter | Measuring EC during salt wave passage and for calibration |
| Data logger (desirable but optional) | Recording EC during salt wave passage |

[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. In addition, 10-mL plastic graduated cylinders or graduated pipettes could be carried as backups

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reach is not sufficiently long to ensure complete lateral mixing. Unlike constant-rate injection, where lateral mixing can be verified once steady-state conditions have been achieved, assessing mixing is more difficult with slug injection. If two probes are available, then the salt wave can be recorded at two downstream distances or on either side of the stream. If mixing is complete, discharge calculated from both probes should be in reasonable agreement. If this is not the case, a longer mixing reach is required. Alternatively, if only one probe is available, successive measurements can be made during periods of steady flow using different distances.

Problems can occur if the conductivity does not return to background. If the measurements taken upstream show that the background has truly changed, then an average of the original and final background values may be used in Equation [6]. It is more problematic if EC has not returned to background due to a slow release of stored salt solution within the mixing reach, as can occur in reaches with pools, particularly at lower flows. In such cases, one solution would be to extend the tail of the salt wave by fitting an exponential decline to the values, although the actual form of the decline will still be uncertain (Elder *et al.* 1990). Ideally, one should find a reach with minimal storage.

## Injection of Salt in Solution Versus Injection of Dry Salt: A Comparison

A number of authors have advocated the use of dry salt injection as an alternative to injection of salt in solution (Hongve 1987; Elder *et al.* 1990; Kite 1993; Hudson and Fraser 2002). A future *Streamline* article will focus on streamflow measurement by dry salt injection. The key advantage of the method is that, for gauging higher flows (e.g., >5–10 $m^3/s$), it is easier to inject dry salt than to mix and inject adequate volumes of solution. However, a disadvantage of the dry salt method is that an accurate scale to measure the mass of salt or an adequate supply of pre-weighed salt in a range of quantities is needed. Where an accurate scale and pre-weighed quantities of salt are unavailable (e.g., at a remote site over an extended field season), the slug injection method using salt solution would still be possible because the precise mass of salt in the injection solution does not need to be known, just the volume of the solution (Equation [6]).

## Summary

Streamflow measurement by slug injection of salt solution has been successfully applied in many locations around the world. It is particularly suitable for steep, bouldery mountain streams, which are unsuitable for gauging by conventional current metering techniques. This article has described procedures that the author has found useful at sites throughout British Columbia. However, there is great scope to vary the details to suit individual circumstances and users are encouraged to experiment with the outlined procedure.

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George Richards helped me experiment with variations on the slug injection method while working at Place Creek. Tim Giles, Dave Hutchinson, Scott Babakaiff, and John Heinonen helped refine the methods by asking valuable questions and bringing relevant articles to my attention. Comments on earlier versions of this article by John Heinonen, Russell White, Michael Church, Robin Pike, and four anonymous reviewers helped improve its clarity. However, any errors remain my sole responsibility.

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