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SALT DILUTION FLOW MEASUREMENT: AUTOMATION AND UNCERTAINTY

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ABSTRACT

The tracer method of flow measurement is a relatively convenient and accurate method to measure discharge in turbulent streams and rivers where conventional current metering flow measurement is not suitable or safe. However, it can be difficult to obtain a full range of flow measurements for a hydrometric rating curve, especially at remote locations. Resources are often wasted visiting sites at similar flow conditions, and it can be difficult and dangerous to attempt flow measurements during peak flow events in active water courses. This paper describes and presents results from our Automated Salt Dilution system, AutoSalt. We also present the derivation of the uncertainty associated with the measurements. We have developed a system that can achieve acceptable results (<7% uncertainty) using as little as 100 g per m³/s of flow by increasing the Signal to Noise Ratio (SNR). We present results from installations in New Zealand, British Columbia, and Alberta and discuss how this work is aiding in the ongoing effort to establish a Standard Operating Protocol (SOP) for Salt Dilution in British Columbia, Canada.

Keywords: *Flow Measurement, Salt Dilution. Hydrometry, Tracer method, Uncertainty.*

1. INTRODUCTION

Salt Dilution is a method of flow measurement that has been in use for at least 54 years (Østrem, 1964), and is experiencing a renaissance in popularity in the last 15 years as people discover its accuracy, relative ease, and convenience (Hudson and Fraser 2002, Moore 2005, Richardson et al 2017). We have developed an automated salt injection system capable of measuring a wide range of flows, unattended. This paper discusses three sites where the AutoSalt system was recently installed and the challenges, complications, and success of each system. The sites are Rollergate near Dunedin, New Zealand, Peyto Glacier near Canmore, Alberta Canada, and Nordic Glacier near Golden, B.C. Canada. Each site discussed in this paper presented unique challenges. We also discuss the uncertainty associated with each measurement as it pertains to the AutoSalt System but is equally applicable to any salt dilution measurement using the Slug injection method.

2. METHODS

2.1 Theory

The dry salt (a.k.a. slug) method is based on the following expression:

$$Q = \frac{M}{CF_T \cdot A_{BC}} \tag{1}$$

where Q is stream discharge (m^3s^{-1}), M is the mass of salt injected (kg), CF_T is a calibration factor for converting temperature-compensated electrical conductivity to salt concentration, and A_{BC} is the area under the "Breakthrough Curve" commonly calculated as

$$A_{BC} = \Delta t \sum [EC(t) - EC_{BG}] \tag{2}$$

where Δt is the recording interval (s), EC(t) is the electrical conductivity as a function of time recorded downstream of the point of salt injection (µS cm^{-1}), EC_{BG} is the background electrical conductivity of the stream water, and the summation is carried out over the duration of the salt wave passage (i.e., the period with $EC(t) > EC_{BG}$). As recommended in Richardson et al (2017), we use temperature compensated EC, or EC_T[1].

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[1] A.k.a Specific Conductance. Richardson et al.(2017) goes on to recommend Non-Linear Function (nlf) compensation based on European standard (ÖNORM EN 27888 1993) to 25°C. Above 10°C, this is essentially 2.0%/°C and below 10°C it is reduced to 1.9%/°C. The CF.T of 0.486 mg·cm·µS-1·L-1 ± 2.8% can only be applied to properly calibrated meters using temperature compensation to 25°C.

Equation (1) is based on two key assumptions: (1) there is no loss of salt between the injection and monitoring points, and (2) the salt or solution is completely mixed across the stream width at the monitoring location. Complete mixing is the state of a watercourse where the water on the left bank has travelled to the right bank at least once. It coincides with the area under a salt tracer EC_T Breakthrough Curve (BC) where the area under the [NaCl]-time integral is equal at any point in the transect**.** A typical breakthrough curve is shown in Figure 1A.

2.2 AutoSalt System Description

The AutoSalt system is comprised of two parts, the upstream injection system and two downstream conductivity-temperature monitoring sites. A typical AutoSalt Injection System installation is shown in Figure 2.

The injection system consists of a brine reservoir with conveyance method to deliver a measured amount of brine to the creek as required. Brine is delivered to the creek via pump through rigid piping with a mechanical flow meter providing feedback on the rate and total amount of brine delivered. Brine volume in the reservoir is measured with a pressure transducer, providing a redundant measure of delivered volumes as well as remaining capacity. The pump time provides a 3^{rd} independent measure of volume injected. A second pump is utilized prior to each injection to mix the brine within the reservoir and ensure a known concentration of salt.

Creek stage is monitored with an instream mounted pressure transducer. This sensor is used to track rising and falling stage conditions. During a flow event, the system will wait until peak stage has been reached and begins receding. This reserves brine for the highest flow measurements and allows measurements to be made on the falling limb when stage changes are more gradual. The creek stage sensor also provides an estimate of creek flow to determine the required volume of brine for each measurement.

All logic is programmed into the system controller. User inputs include targeted stage ranges for measurements, increments in stage between measurements, required time delays between successive measurements, a nominal rating curve for the injection location to determine creek flow, the amount of brine to inject per flow volume, as well as a regular time interval for routine injections. The system controller also logs all parameters to an SD card. It is also possible to request injections over a cellular or satellite telemetry network, as well as monitor all system levels remotely.

Electrical conductivity is recorded continuously by independent data loggers and Fathom Scientific T-HRECS (Temperature-High Resolution EC Serial) sensors. These sensors have been specifically designed for Salt Dilution measurements:

- High sensitivity with 0.001 μS/cm and 0.001°C resolution and nlf temperature compensation.
- High stability within 0.01% of reading for both EC and Temperature. For example, a 100 μS/cm reading will have a standard deviation of 0.01 uS/cm.
- No autoranging to avoid non-linearities in the full range of interest (0-1000 uS/cm)
- SDI-12, 4-20 mA, serial, or self-logging units available.

The high sensitivity, resolution, and stability of the T-HRECS allows us to “see” into the noise floor and achieve a much higher SNR, thereby requiring less salt, than conventional sensors, as demonstrated in Figure 1 and Figure 3. Future installations will include telemetry between EC loggers downstream and the injection system controller.

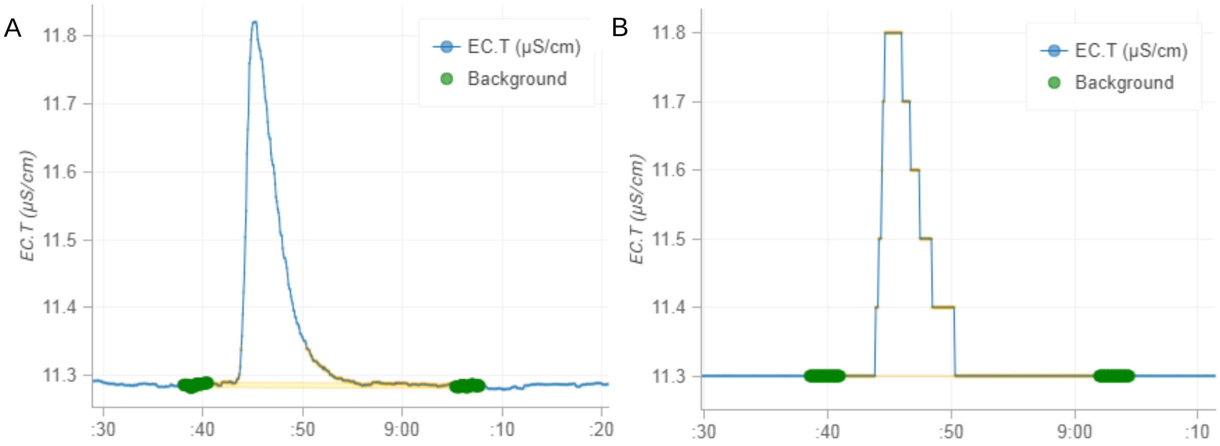

Figure 1: A) A typical low amplitude, high SNR Breakthrough Curve showing some noise in the EC_{BG} that is averaged out with 30 samples Pre- and Post-BC. This measurement used 5.042 kg to measure 91 m^3/s with a resulting uncertainty of ±4.5%. It is from a manual injection using the T-HRECS probe, which has a resolution of 0.001 μS/cm. This curve is an example of good mixing but noisy background from some slight aeration. B) Shows the same curve but rounded to 0.1 μS/cm, a conventional EC Probe resolution. This same sample results in a Q of 100 m^3/s±54% due to the quantification error of ±0.05 μS/cm. (Screenshots from salt.fathomscientific.com SDIQ web portal)

Figure 2: A typical AutoSalt installation showing Control Box, 300L Brine Tank, custom stand, and injection pipe.

2.3 AutoSalt Uncertainty Analysis

This is the same uncertainty analysis undertaken for all Salt Dilution flow measurements. Based on standard formulae for error propagation, the relative uncertainty in discharge computed from injection of dry salt can be expressed as

$$\frac{\delta Q}{Q} = \frac{\delta M}{M} + \frac{\delta[\sum(EC(t) - EC_{BG})]}{\sum(EC(t) - EC_{BG})} + \frac{\delta\Delta t}{\Delta t} + \frac{\delta CF_T}{CF_T} \tag{3}$$

where δX represents the uncertainty in the term X and in units of X.

The uncertainty in time should essentially zero and ignored.

For slug injections of salt, the uncertainty associated with the mass of injected salt, δM, can be estimated as either one-half the scale resolution, or the stated accuracy of the scale. This term can generally be reduced to a very small contribution (~0.1%) of the total error budget by using a scale with appropriate resolution. However, it's important to note that salt can absorb upwards of 5% of its weight in moisture and still be granular. Typically, the moisture content is <1% by weight when purchased at a grocery store, but the practitioner must be aware of the moisture content before injection. This can be done by weighing the salt before and after heating in a microwave oven to evaporate the moisture. For the case of AutoSalt, a brine is made with up to ~20% salt by weight. The mass of salt injected then has two components: 1. the salt content of the brine and 2. the volume of brine. Each of these has their own error terms based on 1. the accuracy of the [NaCl] concentration measurement and 2. the accuracy of the flow meter. We measure the [NaCl] using an optical refractometer at every site visit on the brine pumped out of the injection pipe. We also mix the brine before every injection to eliminate stratification in the brine. We also calibrate the flow meters in situ. Typically, we aim to reduce the error associated with the salt mass to <4%. The error in pump volume is ~1-2% at 95% confidence after Insitu calibration. The error in [NaCl] is approximately 1-2%. We assign a mass error of 4% to these measurements. We believe with upcoming improvements to the system we can achieve <2% error in salt mass. One advantage of the brine is that the moisture uncertainty is no longer an issue. As a corollary benefit, 20% brine remains liquid down to -20°C.

The term $\delta[\Sigma(EC(t) - EC_{BG})]$ is an indicator of the noise in the measurement signal, represented by the standard error of the mean of EC_{BG}, as shown in equation 4.

$$\delta(EC - EC_{BG}) = \frac{s}{\sqrt{n}} \tag{4}$$

where s is the standard deviation of all EC_{BG} measurements (pre- and post-trace) and n is the total sample size. Ten samples pre- and post- wave should reduce the estimate of the mean (EC_{BG}) to 0.22% of the sample s; 30 should reduce the noise to 0.13%. It is clear that the larger n is, the lower the uncertainty in the derived discharge until the streams natural drifting begins to increase s. When the noise is smaller than the sensor resolution (i.e. no fluctuations in measured EC), **then half the sensor resolution should be used for $\delta(EC - EC_{BG})$** as demonstrated in Figure 1B. The denominator of this term is simply the time-averaged EC(t)-EC_{BG}, or the area under the curve divided by time (in seconds). An example of two measurements with a difference of approximately 10x the salt mass for the same flow is shown in Figure 3.

The uncertainty associated with CF_T is explored fully in Richardson et al (2017). This paper has several important findings with respect to AutoSalt, the most important being "if calibration is not performed, CF_T can be estimated from the relation between CF_T and background temperature-corrected electrical conductivity (EC_{BG}) with an uncertainty of about ± 2%, or estimated as a set value of 0.486 mg·cm·µS-1·L-1 with an uncertainty of about ± 2.8% for a properly calibrated probe." All AutoSalt probes are properly calibrated and so uncertainty associated with the CF_T is limited to 2.8%.

Uncertainty associated with incomplete mixing is not represented in equation 3. Instead, we treat each injection as a single measurement and the associated uncertainty as:

$$\frac{\delta\bar{Q}}{\bar{Q}} = \max\left[QUnc_{LB}, QUnc_{RB}, \frac{abs(Q_{LB}-Q_{RB})}{\bar{Q}}\right] \tag{5}$$

where $\bar{Q}$ is the average of the Left Bank and Right Bank derived Q, Q_{LB} and Q_{RB} respectively. $QUnc_{LB}$ and $QUnc_{RB}$ are the independent estimates of uncertainty for each bank derived from equation 3. If the difference in the derived discharges is greater than the sum of the independent estimates of uncertainty for each bank, then incomplete mixing is assumed, and the measurement reach length should be adjusted.

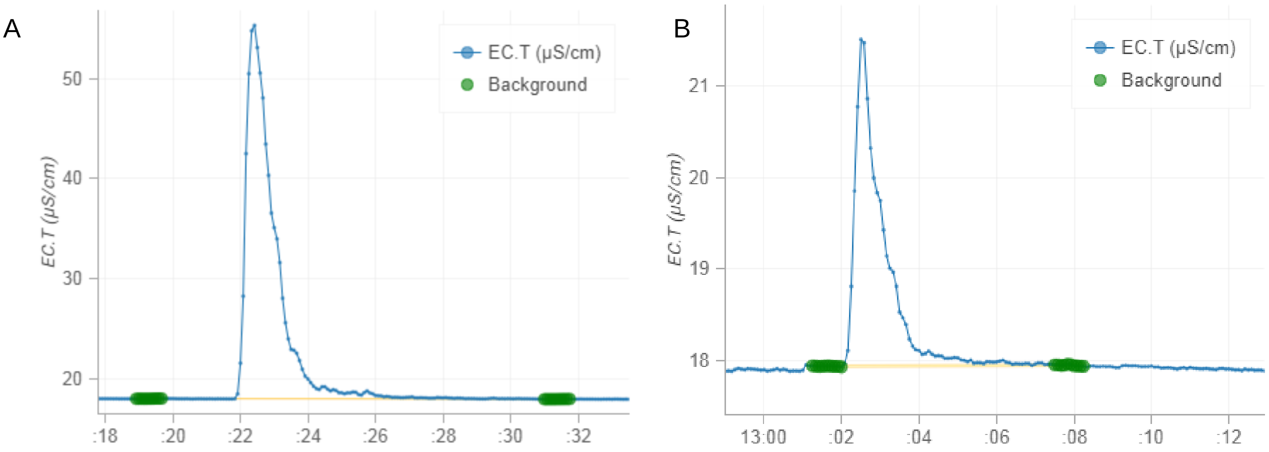

Figure 3: A) A high amplitude measurement using the conventional dosing of ~1 kg/cms at Rollergate AutoSalt DS-RB Station on Oct 30, 2018 resulting in a Q of 4.31 m³/s ±3.5% with 4.42 kg of salt injected manually. B) Immediately after, an AutoSalt injection was made using only 0.35 kg of salt in brine resulting in 4.29 m³/s ±8.4%. The difference in uncertainty is the additional 3.5% from mass uncertainty and 1.5% from EC_{BG} uncertainty. These pulses are a bit sharp due to a short mixing reach for this flow but are not significantly different from the Sommer TracerQ measurement for the manual injection of 4.36 m³s ±3% (a difference of only 1%) at a much further downstream site. Note the sensitivity to EC_{BG} in **B**, however. A small step can be seen to the left of the pulse, where the Pre-EC_{BG} is set in **B**, but if the Pre-EC_{BG} is set before the step the resulting Q is 4.1 m³/s, a difference of 5%, which is still within the stated uncertainty.

2.4 Sites

The Rollergate station is operated by the National Institute of Water and Atmosphere (NIWA) of New Zealand. This is a manmade channel shown in Figure 4A. It is approximately 2m wide with steep channel banks. The probes were mounted in the channel approximately 40m downstream of the injection system.

The Peyto Glacier station, Shown in Figure 4B, is currently maintained by the Center for Hydrology, a project of Dr. John Pomeroy's Global Water Futures. At 2300 meters, it's a 3-5 hour hike from the Bow Summit parking lot in Banff National Park, Alberta, Canada. While not an ideal site for Salt Dilution, we were able to find a site far enough downstream to achieve "complete mixing."

Just over the ridge from Peyto is the Nordic Glacier and the WSC site NORDIC GLACIER NEAR THE TONGUE (08NB020) shown in Figure 4C. Although installed in a bedrock "chute", this site is subject to frequent hydraulic control changes as mobile sediment bed degrades and aggrades constantly.

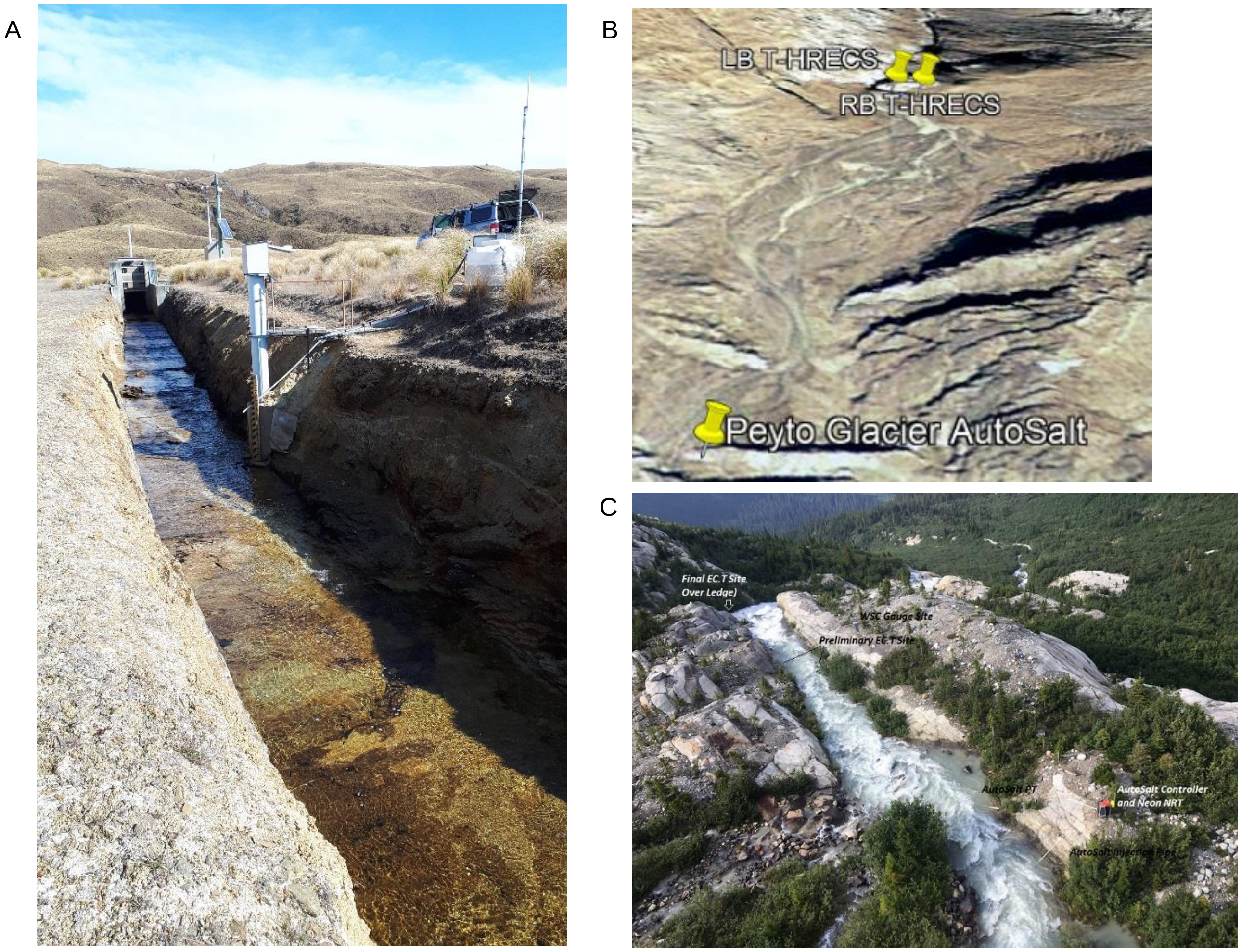

Figure 4. A) Rollergate station showing NIWA hydrometric station and AutoSalt station. B) The Peyto Glacier showing the AutoSalt sites, from Google Earth. C) The Nordic AutoSalt station in the lower right showing the mixing reach. Incomplete mixing occurred at the “Preliminary EC-T Probe” site and had to be relocated to the Final EC-T Site for complete mixing at this flow (~2.5 m³/s).

2.5 Site Setup

The Rollergate station is well suited for salt dilution and there were very few challenges. The NIWA staff, Evan Baddock and Eric Stevens were very efficient at installing the pipes in the soft earth by pounding metal stakes in and fastening the pipe using metal strapping. The 500L tank was leveled with fence posts laid vertically and the entire tank held fast with spikes and strapping. A UniData Neon Cellular NRT was used for telemetry and a UniData LoRaWAN network employed to retrieve the Left Bank EC_T probe’s data. The RB was left as a standalone T-HRECS Datalogger unit, available from Fathom Scientific. This ensured that we would capture any injections made if there were any issues with the NRT site. Initial mixing tests confirmed complete mixing at the flow during installation, however future comparisons at higher flow levels indicated that the LB probe was not experiencing complete mixing when compared to results from EC_T probes placed much further downstream.

At the Peyto Glacier site, the channel is constricted to a bedrock chute directly below the injection site, followed by a low gradient riffle-glide with braiding and significant storage at low flows, shown in Figure 4B. This is not an ideal site for salt dilution. However, we found that if we placed the probes about 450m downstream where all the flow is constricted as it enters another bedrock canyon, we could get results that agreed with wading flow measurements. To complicate matters further, small tributary inflows entered the channel above the canyon. Although very small, they had the effect of diluting the well-mixed water and adding noise to the measurement.

At first glance, the Nordic site is well suited to Salt Dilution with several constrictions, boiling and churning flow, and bedrock channels throughout. However, upon closer inspection there are several complications. Upstream of the “chute". We installed the AutoSalt injection system downstream of the braids on solid bedrock near the channel. Downstream of this site above the dropoff/falls, the flow is so turbulent in the section after complete mixing, there are no sites that are not fully aerated. There is a steep dropoff/falls below the chute; access below this on the left bank is a bit of a scramble but not unachievable. Access on the right bank would require at least a 30 min detour to a safer route. We were therefore forced to put both probes on the left bank below the chute and were unable to determine complete mixing objectively. However, from Figure 4C, we can see that complete mixing is highly probable below the chute at all flow levels.

3. RESULTS

We do not yet have a controlled objective trial of the AutoSalt system. This section describes the measured flows in comparison to a few manual measurements and site expectations. In each case, we processed the measurements using our online salt dilution web processing portal (salt.fathomscientific.com), which is freely available.

3.1 Rollergate

We achieved the best results at Rollergate station. Over 2 months, over 250 measurements were made from the same 500 litre brine tank. We aim for 200 g NaCl per m^3/s of flow (approximately 1 L per m^3/s of 20% brine), however this is based on a nominal rating curve at the site. For many of the measurements at Rollergate as little as 50 g NaCl per m^3/s were used with <7% calculated uncertainty. An example of one is shown in Figure 3B. The rating curve derived on the Salt portal is shown in Figure 5A and the comparison with the NIWA measurements in Figure 6. The Sommer Salt Dilution system was used to measure concurrent points as high as 4.36 m^3/s with no significant difference found. NIWA undertook steps to automate the realtime flow measurements, linking the downstream site into their online Neon web portal and calculating the Q based on the reported volume of brine pumped.

3.2 Peyto Glacier

Results were mixed at Peyto Glacier. Although we did get measurements over a range of flows, in order to get a good measurement (high SNR) we had to inject 5 L per m^3/s (about 1 kg/ m^3/s) and so we didn't get as many measurements as at Rollergate. Also, we used a smaller tank of only 200 L, which fit inside the helicopter and can be carried on one's back. In addition, there appears to have been a hydraulic control change between May 29, 2018 and Jun 12, 2018, shown in Figure 5C

3.3 Nordic Glacier

Nordic Glacier site results are also mixed. 53 measurements were made between Aug 8, 2018 and Sep 9, 2018. Shown in Figure 5B, these points generally agree with each other using concurrent stage from the WSC station. However, there are a few outliers, and not complete agreement with WSC wading measurements. Wading measurements were made upstream using a Flow Tracker current meter. Measurements going back to Jun 9, 2015 were provided. Transition dates of Jul 18, 2018 and Aug 10, 2018 were used to distinguish measurements. In this figure we can see that WSC measurements after Jul 18, 2018 fall below pre-Jul 18, 2018 measurements except for the Aug 23, 2018 measurement. Although this rating curve is inconclusive, we can say that:

1. AutoSalt points agree with one another over this time period, with perhaps a break after large flows on Aug 10, 2018.
2. AutoSalt points agree with 3 of the 4 concurrent WSC measurements, and also with historical high flow measurements at this site.
3. AutoSalt points either add confusion to this rating curve and site or provide a high enough temporal and Q resolution to start to understand the amount of hydraulic control movement at this site, as evident in the historical WSC measurements that manifests as scatter.

4. DISCUSSION

In general, the AutoSalt systems have been successful. How we measure success, however, has been called into question. In the case of Rollergate, there's no question that the system provided a higher temporal and Q resolution not possible with manual measurements. It is part luck, and part geomorphology, that the site did not undergo any significant hydraulic control changes over the course of the study. In the case of both Peyto and Nordic, however, the AutoSalt system captured enough points to determine a likely hydraulic control change, or two, over the course of the study. The same system is installed at all three sites, and the consistency of the Rollergate site helps to validate the measurements at the other two sites, assuming we have complete mixing.

Some may argue that a hydrometric site does not need 250 measurements over the course of 2 months, however the AutoSalt system serves several purposes:

- Capture extreme high and low flow events. The former presents logistical and safety issues for manual measurements.
- Track the hydraulic control over time.
- Define inflection points in the rating curve.

- Provide validation of a given stage-Q relationship with several measurements at the same stage-Q separated over time.

The other advantages of this system are:

- Fewer site visits required resulting in reduced costs for the customer to achieve the same or better results. The AutoSalt customer can still invoice their client for a complete rating curve and hydrograph within a given standard if they are consultants or reduce their hydrometric budget significantly if they are a data user.
- Take measurements remotely (from your workdesk, conference, or vacation) during peak or low flow events with on-demand measurements.
- Fully autonomous operation with many user definable options.
- Accuracy within 2-3% of a manual Salt Dilution measurement, which can be accurate to within 5% for good sites.

As hydrologists, we often wonder why there may be so much scatter around a rating curve and whether it's due to measurement error or hydraulic control movement. With AutoSalt, we can start to answer this question.

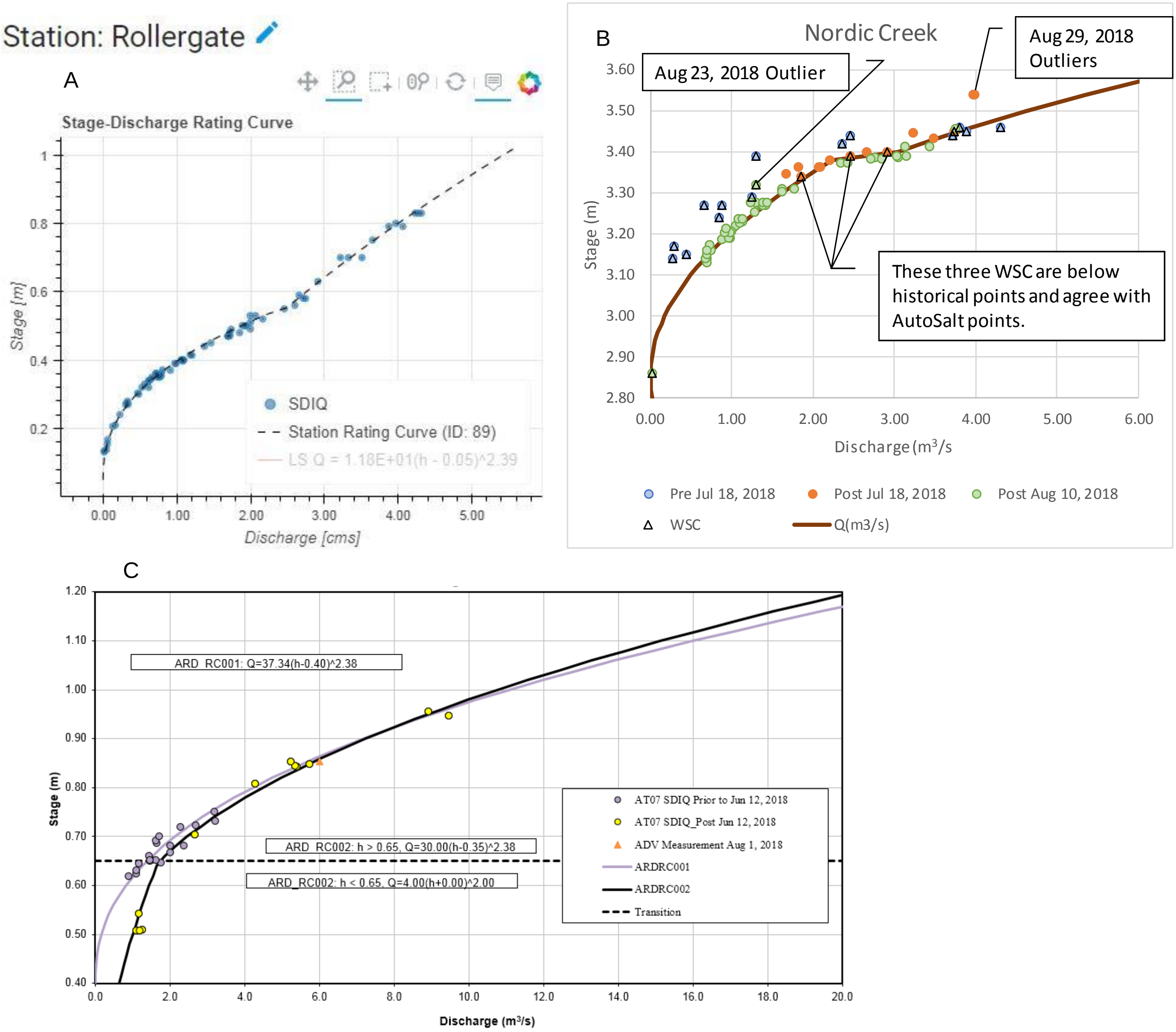

Figure 5. A) Rollergate Station RC as derived on the salt.fathomscientific.com site. B) Nordic Creek WSC Rating Curve. Orange points are Post Jul 18, 2018 points, including 53 measurements from AutoSalt. Triangles indicate WSC manual Flow Tracker measurements. C) Peyto Glacier site showing transition sometime between May 29 and Jun 12. The spread is more than desirable but this is a poor SD site.

4.1 Uncertainty

We have not yet conducted a full uncertainty analysis on all of these rating curves and resulting flow time series. We have performed automated uncertainty analysis using the online salt.fathomscientific.com SDIQ calculator on individual measurements. These results indicate 95% confidence interval uncertainty values ranging between 5-10%. So long as there is not bias, which we work to ensure, then the sheer number of measurements should offset the higher uncertainty on individual measurements compared to manual measurements. Assuming that the uncertainty in measurements reflects the uncertainty in resulting hydrograph, we can expect a resulting hydrograph uncertainty of <7%, which would be considered Grade A in British Columbia RISC standards. More work is needed to full automate the uncertainty analysis and grade rating curves in the salt.fathomscientific portal.

E. Baddock has been tracking the accuracy of the AutoSalt system compared to manual Sommer SD measurements and found no significant bias or difference, except when one AutoSalt probe was too close to the point of injection. After moving this probe further downstream, no significant difference was found, shown in Figure 6.

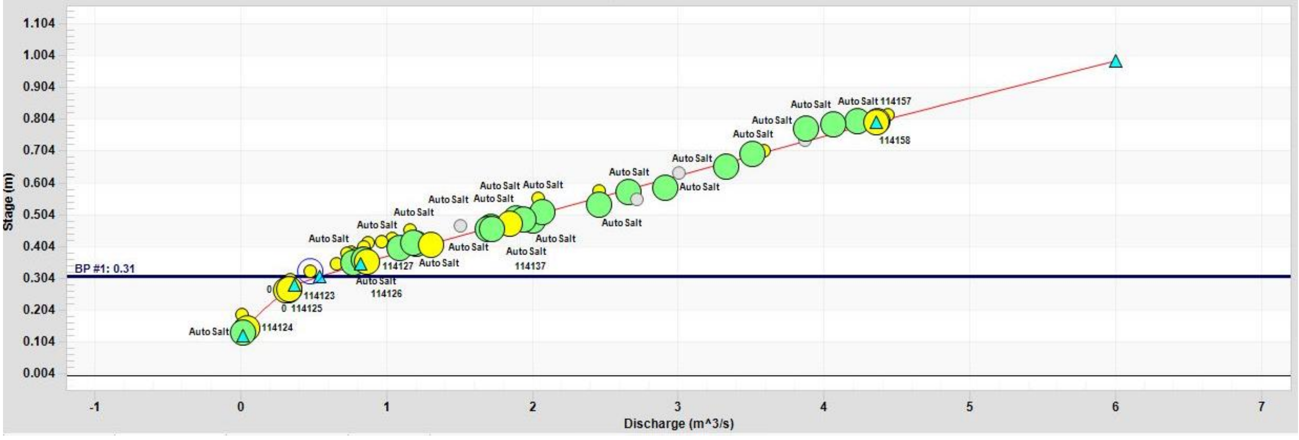

Figure 6. The Rollergate RC in NIWA's Aquarius software showing historical points as well (smaller dots) recent circles are larger. Large green are the AS measurements vs large yellow Sommer checks and small yellow historical ADCP. Blue triangles are transition points in the RC definition

5. CONCLUSIONS.

An approach to estimating the uncertainty associated with Salt Dilution and Automated Salt Dilution measurements is presented. Three recent AutoSalt sites were described and challenges and solutions were discussed. The most convincing results were achieved at the Rollergate site in New Zealand, which is the smallest and most stable of the 3 sites. The other 2 sites, Peyto and Nordic in the Canadian Rockies, presented some challenges and also appear to have more mobile hydraulic controls over the study period. However, the success of the Rollergate system lends credibility to the measurements in the other two projects, thereby identifying real issues with their hydraulic controls.

While manual salt dilution measurement can have less than 5% Uncertainty, AutoSalt measurements should have less than 10% uncertainty and with a properly calibrated system less than 7% uncertainty. All uncertainty estimates are at the 95% confidence interval.

ACKNOWLEDGMENTS

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