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STREAMFLOW MEASUREMENT USING SALT DILUTION IN TUNDRA STREAMS, NORTHWEST TERRITORIES, CANADA[1]

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ABSTRACT: With the recent increased exploration and mining activity in the Northwest Territories, there has been growing interest in streamflows. However, streamflow monitoring in Canada's north is limited, especially in the central Northwest Territories where the exploration activity is concentrated. To complicate matters, the standard approach of measuring discharge with current meters or weirs is often inadequate or prohibitively expensive, as many streams in the region are shallow, braided and rocky. In response, alternative techniques such as salt dilution can be used. A salt tracer's competence in turbulent and rocky channels makes it ideal for discharge measurements in these situations. This paper summarizes the work performed by Indian and Northern Affairs Canada and Canamera Geological Ltd. staff in determining the stream discharge of a lake outlet using a potassium chloride (KCl) tracer. A variety of streamflow measurement methods were performed and compared to determine the viability and rigor of the dilution method. Results suggest the dilution method compares favorably to other measurement techniques both in accuracy and operational ease.
(KEY TERMS: Northwest Territories; streamflow measurement; salt dilution; instrumentation.)

INTRODUCTION

With the recent increased exploration and mining activity in the Northwest Territories, there has been growing interest in regional streamflows. However, streamflow monitoring in Canada's north is limited, especially in the central Northwest Territories' Slave Geological Province where the exploration activity is concentrated. The standard approach of measuring discharge with current meters or weirs is often impracticable or prohibitively expensive as many streams in the region are shallow, braided and rocky. Alternative techniques such as tracers, including electrolytic solutions, fluorescent dyes and radioisotopes, may prove more suitable due to their competence in turbulent and rocky channels.

The recent intensive exploration activity for diamonds in the Slave Geological Province has led to the discovery of a number of diamond-bearing kimberlite "pipes". One of these pipes underlies Ranch Lake, located two kilometers southwest of the study area. Pre-development plans for Ranch Lake have resulted in the study area lake, Nisha, being designated as a potential mine tailings deposit area. This paper summarizes the work performed by Indian and Northern Affairs Canada and Canamera Geological Ltd. staff in determining the stream discharge of the Nisha Lake outlet. The purpose of such work was twofold. To assist with the design of runoff controls and tailings management for Nisha Lake, lake discharge data must be collected and an open water rating curve established. The second goal was to determine if salt dilution is a viable and rigorous method for measuring discharge for the purposes of constructing a rating curve for tundra streams in the Northwest Territories.

STUDY AREA

The study stream is located at a remote site in the Slave Geological Province, in the central portion of the Northwest Territories at 65° 16.11′N and 111° 30.05′W (Figure 1). The stream originates from Nisha Lake, and constitutes the only outlet from this regionally above average sized lake. The Nisha Lake subbasin is part of the much larger Coppermine River

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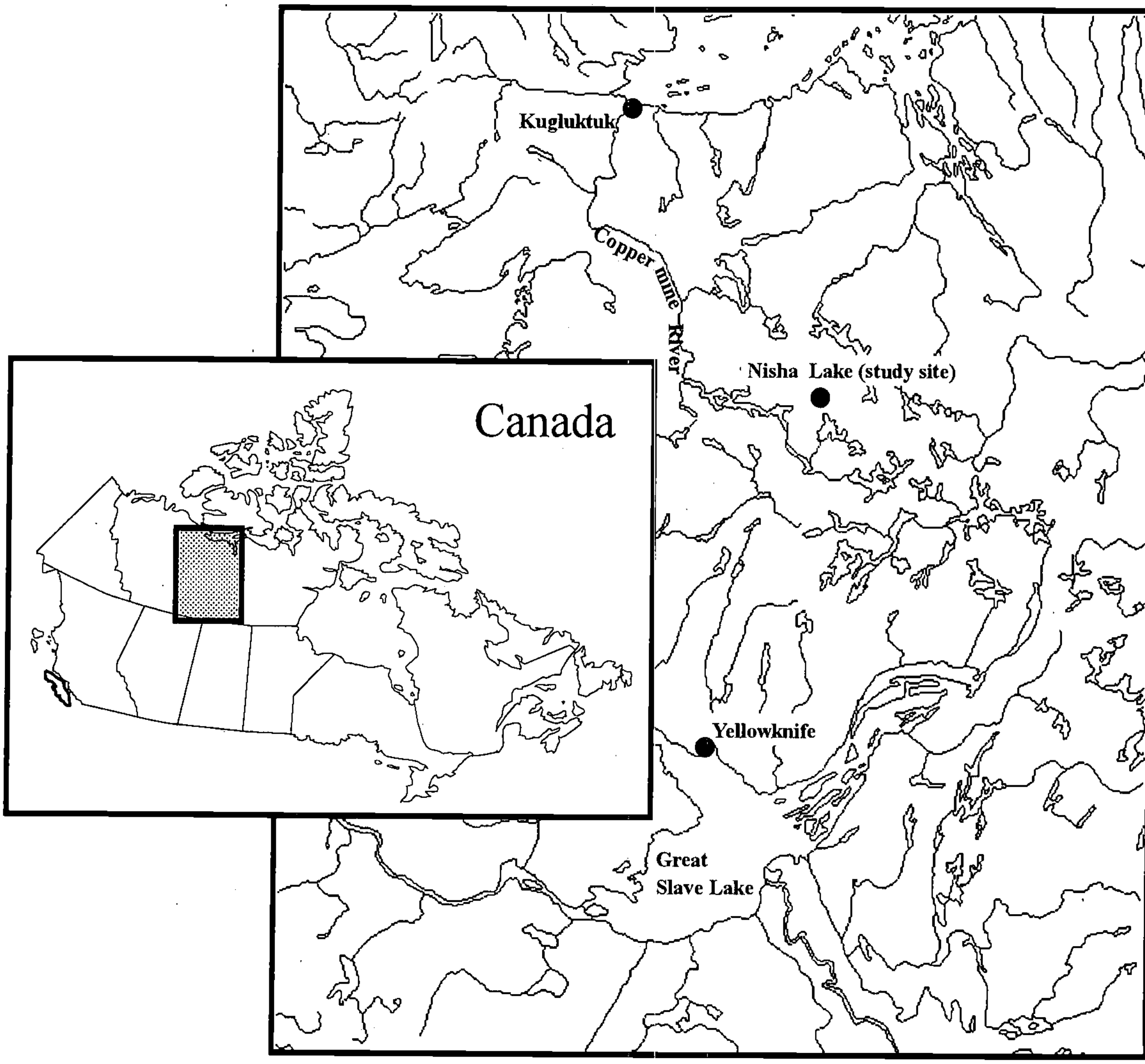

Figure 1. Study Site Location.

drainage basin that drains approximately 330 kilometers to the northwest at the hamlet of Kugluktuk, on the shores of the Coronation Gulf.

Nisha Lake has one outlet stream that flows in a north-westerly direction. Typical of many streams in the region, the waterway that constitutes the Nisha Lake outlet is a complex set of small streams that form a diffuse drainage pattern through an area of low relief (Figure 2). These characteristics make conventional means of measuring streamflow difficult. However, at one point these small streams do converge to form a steep channel (Figure 3), where it is possible to gauge stream discharge with a current metre. As the objective of the project was to determine if salt dilution is a viable and rigorous method for measuring stream discharge in these diffuse streams, salt dilution measurements were made along a reach which began in the diffuse channels and ended in the steep channel.

Figure 2. The Diffuse Drainage Pattern of the Nisha Lake Outlet.

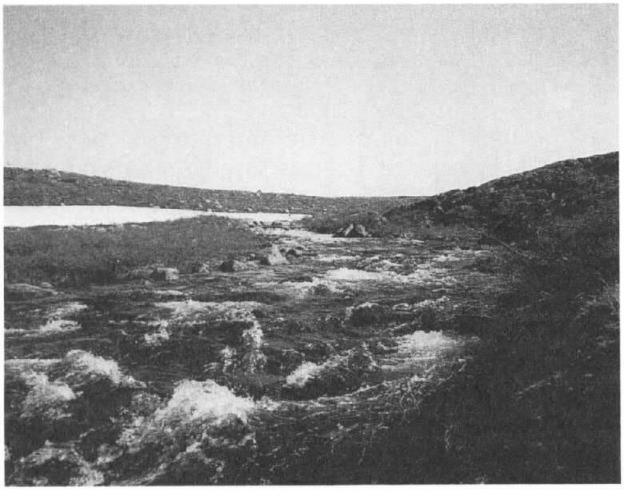

Figure 3. Steep Channel Reach of the Nisha Lake Outlet Stream.

MEASUREMENT TECHNIQUES

Current Meter Measurements

Current meter measurements were made on three occasions from late June to early July. An cross-section for current metre measurement was chosen across the steep reach of the Nisha Lake outlet. The cross-section was divided into ten cells, each 1 meter in length, within which velocity, depth and discharge were measured. Velocity measurements were obtained at sixth-tenths depth in each cell. Stream discharge was calculated as the sum of discharge in each cell. During each measurement two other cross-sections were also measured within the steep reach to confirm initial stream discharge results.

Slope Area Calculation

The slope-area calculation method of estimating flow is an application of hydraulic principles. This approach is most frequently used to estimate the peak discharge of a stream (Church and Kellerhals, 1970; Linsley, Jr. *et al.*, 1982). The slope, S, and cross-sectional area, A, of the steep reach (Figure 3) were measured and an estimate of channel roughness, n, determined. The hydraulic radius, R, was calculated from a mean of several sections of the stream (Church and Kellerhals, 1970), and the area of these sections was computed. Discharge was calculated, in m^3/s, using the Chezy-Manning formula:

$$Q = \frac{A \cdot R^{2/3} \cdot S^{1/2}}{n} \tag{1}$$

The Manning roughness coefficient, n, in this study is assumed to be equal to 0.05. The average value for n for natural streams is about 0.035 (Linsley, Jr. *et al.*, 1982). A value of 0.05 represents the high end of the scale for a steep stream with rocky beds similar to the steep reach shown in Figure 3 (Church and Kellerhals, 1970).

Salt Dilution Applications

The basic principle of salt dilution is the conservation of mass of some form of tracer (Kite, 1994). If a salt solution is instantaneously added to a stream of unknown discharge, Q, at some point downstream, the observed salt concentration, c(t), will rise from zero to some peak value and then fall back to zero as the "solution wave" passes. At each instant of time, t, during the passage of the wave, the stream water will contain a quantity, S, of the original solution. The mean concentration of the solution will be:

$$c(t) = S/Q\,. \tag{2}$$

When the entire wave, uniformly mixed across the channel, passes the point downstream so that:

$$S = Q\int_0^T c(t)dt \tag{3}$$

stream discharge can be approximated by:

$$Q = S \cdot \left(\int_0^T c(t)dt\right)^{-1} \tag{4}$$

where the concentration values are measured by electrical conductivity readings which are then transformed to concentration via a calibration (Church and Kellerhals, 1970).

Conductivity and salt concentration were calibrated by first mixing an initial 100 milliliter 20 percent solution. This 100 milliliters is the primary solution and has a relative concentration of 1.0. The primary solution was then diluted by placing 10 milliliters into a 1 liter flask and filling the remainder volume with stream water. This new, secondary solution has a relative strength of 0.01. Next, 20 liters of stream water was placed in a calibration tank partially submerged into the stream to minimize temperature changes in which background temperature and electrical conductivity was measured. Secondary solutions of 2, 5, 10, 25, 50 and 100 milliliters were then added to the calibration water, noting concentration and measuring conductivity and temperature each time. The conductivity-concentration relationship was determined by plotting measured conductivity against relative concentration and performing a regression analysis (Church and Kellerhals, 1970). As electrical conductivity can vary with temperature, a temperature-correction factor was also determined by simultaneously measuring temperature and conductivity in a large (30 liter) sample of stream water with a constant conductivity. This temperature correction factor was applied to the final conductivity readings.

If a quantity of solution is added to a stream, the amount of this solution which passes through a given section downstream can be determined as a relative probability of the water which passed through the injection point, subsequently passing through the point downstream. For an accurate measurement of flow, the discharge-weighted probabilities must be equal everywhere at the measurement point, so the measurement is a true reflection of the total amount of water flowing downstream (Church and Kellerhals, 1970). For dilution discharge measurements, this means the injected solution must flow a distance before it becomes completely mixed into the streamflow and a measurement of the solution is made. There have been a number of methods derived for determining this mixing length, L_m, using channel properties. Hull (1962) recommended:

$$L_m = B \cdot Q^{1/3} \tag{5}$$

where B is equal to mean river width and Q is an estimate of discharge. Kite (1993), using data from Patra and Bhunia (1984), found the equation:

$$L_m = 260 \cdot \sqrt{A} \tag{6}$$

where A is the cross sectional area of the stream, to best fit a data set of calculated and measured mixing lengths. However, neither of these approaches account for turbulent dispersion. Church and Kellerhals (1970) summarize the development of:

$$L_m = \frac{\left(v \cdot w^2\right)}{\left(4 \cdot d_y\right)} \tag{7}$$

where v is the mean velocity of the stream, w is the mean width and d_y is lateral dispersion. An estimate of dy can be determined by injecting a quantity of fluorescent dye into a stream and timing the period it takes for the dye to cover the entire width of the stream. For midstream injection:

$$d_y = \frac{(w/4)^2}{2t} \quad . \tag{8}$$

Mixing length was determined using Equations (7) and (8). A survey of the stream was conducted in order to determine w and v. A fluorescent dye solution was injected at a midpoint across the stream. The period it took for the dye to reach both banks (t) was timed with a stopwatch. Once the mixing length was determined, suitable sites for the injection point and measurement site were selected.

The reach within which dilution measurements were made began at an injection point in the diffuse channels and ended at a measurement point in the steep channel. To create a well-defined solution wave, the required increase in conductivity should be approximately 50 percent of background conductivity of the stream (Kite, 1993). This required roughly 1 liter of 20 percent potassium chloride (KCl) solution per cubic meter of expected discharge (Church and Kellerhals, 1970). KCl was chosen as it is considered a standard in salt dilution work as well as being inexpensive. This solution was then injected into the stream as close to the center of flow as possible. As the two sites were at least the mixing length apart, placement of a conductivity probe at the measurement site in a specific part of the stream cross-section was not important, but it was placed in a strong-flowing section of the stream in order to allow proper sampling by the probe. The solution wave was then recorded at one-second intervals and averages logged every three minutes by a Campbell Scientific data logger. Once the solution wave had passed, conductivity measurements were downloaded and converted to concentration values, plotted against time and discharge calculated (Figure 4). In total, six measurements were made over the open water season. To define preliminary rating curves, stage was measured using a pressure transducer in a pool immediately below the measurement site (bottom center of Figure 5) where water levels were deeper and much more constant than those in the stream proper.

RESULTS AND COMPARISON

Discharge measurement results are summarized in Table 1. A peak discharge value of 4.57 m^3/s was obtained from the Manning formula. This result is similar to the 4.83 m^3/s from the salt dilution method and 4.2 m^3/s from the current meter. It is expected that the peak flow of the spring freshet occurred very close to June 23. If this is the case, the salt dilution measurement appears to be compare favorably with

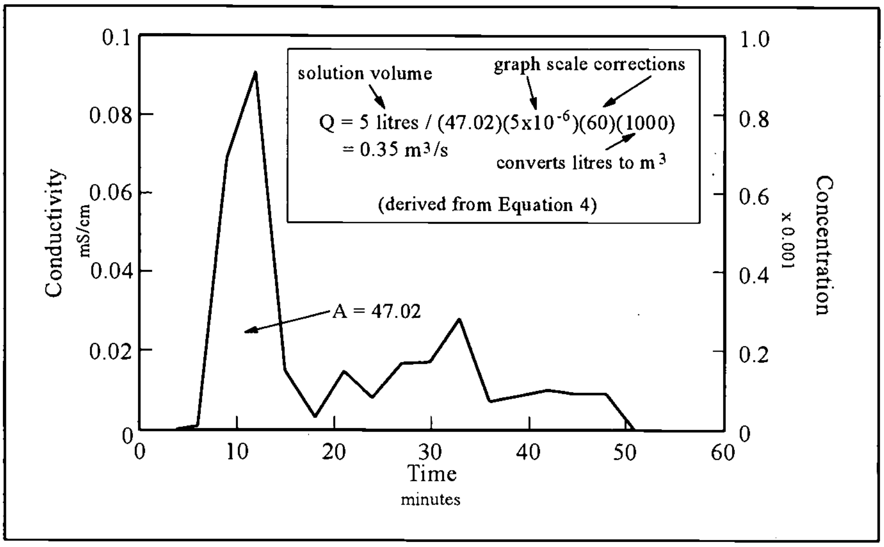

Figure 4. Graph Illustrating July 27 Conductivity Measurements, the Solution Wave Plotted Against Time and Discharge Calculations.

both the current meter and Manning's formula. Except for the July 26 measurement, the current meter produced results consistently lower than the salt dilution method or slope area calculation. These lower measurements may be due to the shallow depth of the stream. Conventional current meters can underestimate streamflows in depths of less than about 15 centimeters of water (Church and Kellerhals, 1970). Thirty percent of depth measurements along the cross-sections were below this 15 centimeter criterion.

TABLE 1. Summary of Discharge Measurements.

Date	Q (slope-area) (m^3/s)	Q (dilution) (m^3/s)	Q (metered) (m^3/s)	Depth (m)
June 23	4.57	4.83	4.2	0.437
July 11		1.36	.89	0.426
July 13		1.45		.422
July 20		1.00		.417
July 26		0.47	0.50	0.42
July 27		0.35		0.414

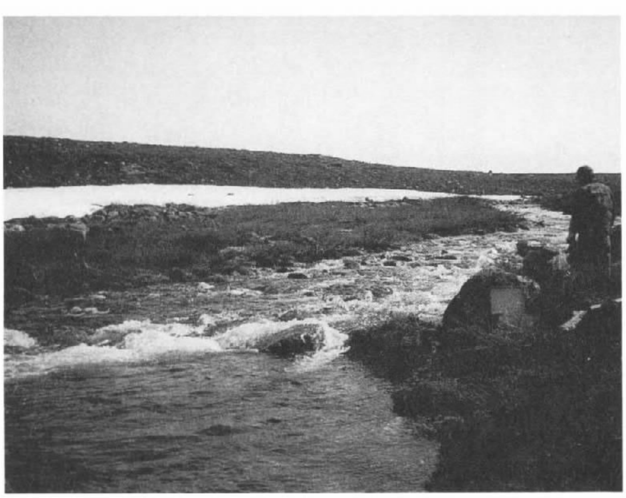

Figure 5. Lower Reach of Nisha Lake Outlet Showing Pool Below Measurement Site Within Which a Pressure Transducer Was Placed for the Measurement of Stage.

Rating curves were derived for both the metered and salt dilution measurements (Figure 6). The number of measurements taken, especially with the current metre, suggests these curves should be considered rudimentary and subject to further measurement. It would have been ideal for more measurements to be included to improve these curves. However, budgetary limitations and a short open water season did not allow for more than three site visits. Nonetheless, the curves presented in Figure 6 provide preliminary estimates of the rating curve for the Nisha Lake outlet.

CONCLUSION

The results imply that the salt dilution method can work well and provides a viable choice in measuring

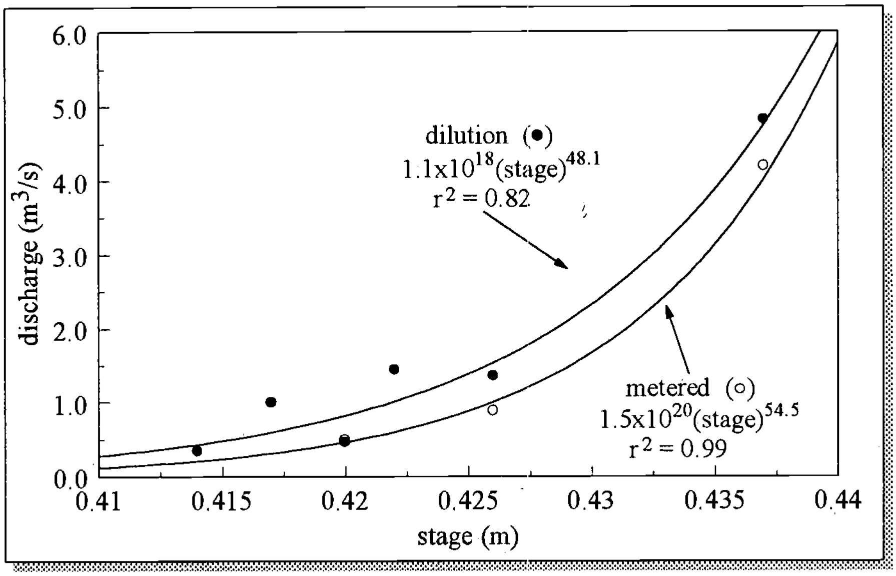

Figure 6. Nisha Lake Outlet Open Water Rating Curves Derived from Current Meter and Salt Dilution Measurement Methods.

streamflow in remote tundra streams. While the number of coincident observations does not permit a statistical comparison, the dilution method compares well visually against the current meter. The difference between the higher estimates of flow from the salt dilution method and the lower current metre measurements may account for the underestimation expected in the measurements from the current metre that occurred due to the shallow depths in the stream. The peak stream discharge as measured with the dilution method also agrees closely with the theoretical peak discharge as calculated with the Manning formula.

By the beginning of August, stream levels had dropped and exposed enough of the bed above the water level that the authors believed the current metre was no longer able to accurately measure discharge. While the results are not shown here due to a lack of comparative data, dilution methods were still used to measure streamflow into August. This is important because streamflow data for small streams are scarce in the Northwest Territories. To be able to measure flows in small isolated streams and collect data irrespective of stream cross-sectional characteristics provides decision makers with much needed information.

Due to a short open water season and the high cost of access, only three coincident measurements were made. The study stream is an arctic-nival stream (Church, 1974) and experiences high flows for two weeks of the year during the spring snowmelt, quickly declines to low flow and drops to zero flow by freeze up in late September. The authors intent was to measure each significant phase in annual flow - freshet, declining summer flows and low baseflow because access to the study stream was only possible by floatplane at a high cost. For the purposes of water management, three measurements well timed over the summer was the most efficient use of taxpayer and corporate dollars. The remaining salt dilution measurements were made by the probe and data logger left on site, as an exploration camp employee injected the salt solution.

The only drawback of the salt dilution method is the need for complete mixing of the salt solution into the stream. Average tundra streams likely require a mixing length of 150-400 meters. Many streams in this region are much shorter. If the required mixing length is not present, it is recommended a more traditional measurement approach be used.

This rigorous and cost-effective method to measure streamflow in tundra streams could be repeated by other agencies and industry. It could be used in assessing mineral exploration and development in the North and make environmental studies easier and more cost effective. Better and more accurate environmental reviews of proposed mining and exploration activities could, in turn, promote sustainable practices in the mining industry.

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