Electrical Conductivity as an Indicator of Water Chemistry and Hydrologic Process

R.D. (Dan) Moore, G. Richards, and A. Story

Introduction

Electrical conductivity (EC) is a measure of the ease with which electrical current can pass through water. It can be measured accurately in the field using a portable conductivity probe and meter, and can also be recorded electronically with a data logger. Therefore, both the spatial and temporal variability of EC can be measured with as high a resolution as desired. The objective of this article is to discuss the factors that govern the spatial and temporal variability of electrical conductivity and to illustrate how these variations can be used as indicators of water chemistry and hydrologic process.

Definition and Quantitative Expression of EC

Ohm's law defines the resistance of a substance to the passage of an electrical current as

$$R = V/I \tag{1}$$

where R is the electrical resistance (ohms), V is electrical potential (volts), and I is current (amperes). The resistivity of a substance is defined by the resistance to electrical current passing between the faces of a unit cube of the substance. The SI units of resistivity are ohm/m. For fluids, the inverse of resistivity, or conductivity, is conventionally used to characterize their ability to transmit electrical currents. The SI units of EC are thus 1/(ohm·m). The units for the inverse of ohms were, in the past, often designated as "mho," but the preferred unit is siemen (abbreviated "S"). Given the low conductivities of most freshwater sources, the commonly used units of EC are µS/cm (i.e., 10^{-6} S/cm).

The term specific conductance (SC) has sometimes been used to refer to electrical conductivity measured at a specified reference temperature. However, SC is considered synonymous with electrical conductivity by the International Union of Pure and Applied Chemistry (Mills *et al.* 1993), and the latter term (EC) will be used throughout this article.

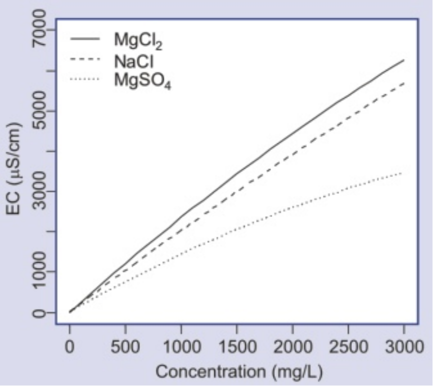

Figure 1. Relations between electrical conductivity (EC) and concentration for different salts (after Hem 1982, Figure 6).

Factors Influencing EC

Pure water is a weak electrolyte, and the EC of aqueous solutions will thus depend on the presence of charged ions. Electrical conductivity increases with the number of ions in solution. However, the relation is inherently nonlinear because, at higher concentrations, interactions among ions can impede their mobility. These effects are shown in Figure 1. Despite the overall nonlinearity, the relation is close to linear for concentrations less than about 1000 mg/L. Because the mobility of a charged ion depends on ionic size and charge, the overall EC of a fluid will depend on which chemical species are present and not just their concentration. For example, magnesium chloride ($MgCl_2$) has a higher EC for a given ionic concentration than the other two salts.

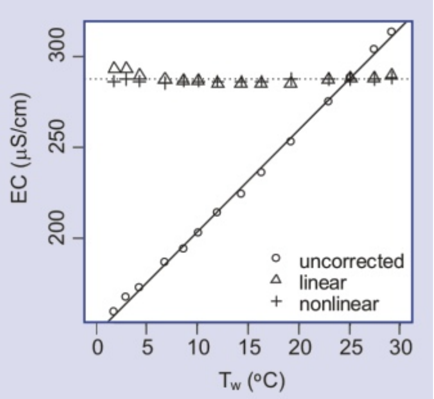

Figure 2. Relations between electrical conductivity (EC) and temperature (Tw) for a water sample from Fishtrap Creek, British Columbia. Measurements were taken with a WTW LF 340 conductivity probe. Uncorrected values are shown (circles), with a fitted linear regression line. Two sets of values corrected to 25°C are shown: one uses a linear correction of 2%/°C (triangles), the other uses a nonlinear correction (crosses). The horizontal line shows the "true" value at 25°C, based on the regression line.

Ionic mobility and EC vary with temperature, mainly due to the effect of temperature on the viscosity of water (Robinson and Stokes 1965). One approach to address this temperature dependence is to bring samples into a laboratory where they can be brought to 25°C before measurement. Alternatively, measurements of EC made in the field can be adjusted to equivalent values at 25°C using an assumed relation between EC and temperature.

The relation between EC and temperature is approximately linear over the typical range of stream temperatures (Figure 2), but some nonlinearity has been reported below about 3°C (Østrem 1964; Collins 1977). Most EC meters can adjust EC measurements to 25°C using a specified linear correction, typically 2%/°C. Some conductivity meters can also apply a

Continued on page 26

Continued from page 25

nonlinear correction. Figure 2 illustrates corrected and uncorrected EC for a water sample from Fishtrap Creek, located northwest of Kamloops, BC. If the corrections were accurate for all temperatures, the corrected values would lie along the horizontal line that intersects the uncorrected relation at 25°C. For Fishtrap Creek, the linear and nonlinear corrections are similar, but the nonlinear correction is more accurate for the low-temperature readings. While the temperature corrections perform well for the sample from Fishtrap Creek, it is prudent to verify that this is the case for other streams because corrections can vary. For example, Hayashi (2004) found slightly lower correction factors, ranging from 1.75 to 1.98%/°C with a mean value of 1.87%/°C, while Smart (1992) derived factors ranging from 2.73 to 3.01%/°C.

Electrical conductivity can also be influenced by the presence of fine sediment (Fenn 1987). For example, EC has been observed to increase after filtering for suspended sediment, possibly due to desorption of ions held on sediment surfaces (Collins 1977; Smart 1992).

Electrical Conductivity as an Indicator of Water Chemistry

Because EC depends on the overall ionic concentration in water, it has often been used as an index of the total dissolved solids (TDS) carried by a stream. As shown in Figure 1, the ratio of TDS to electrical conductivity for solutions of pure salts ranges from 0.4 to 0.7 for EC up to about 500 µS/cm, depending on the salt. For natural streamwaters, the ratio generally ranges from about 0.55 to 0.75, but may be near unity for high-sulfate water or less than 0.5 for strongly basic or acidic waters (Hem 1982). One limitation to the use of EC as an indicator of TDS is that EC does not respond to the presence of uncharged dissolved substances, such as silica, a common weathering product from igneous rock.

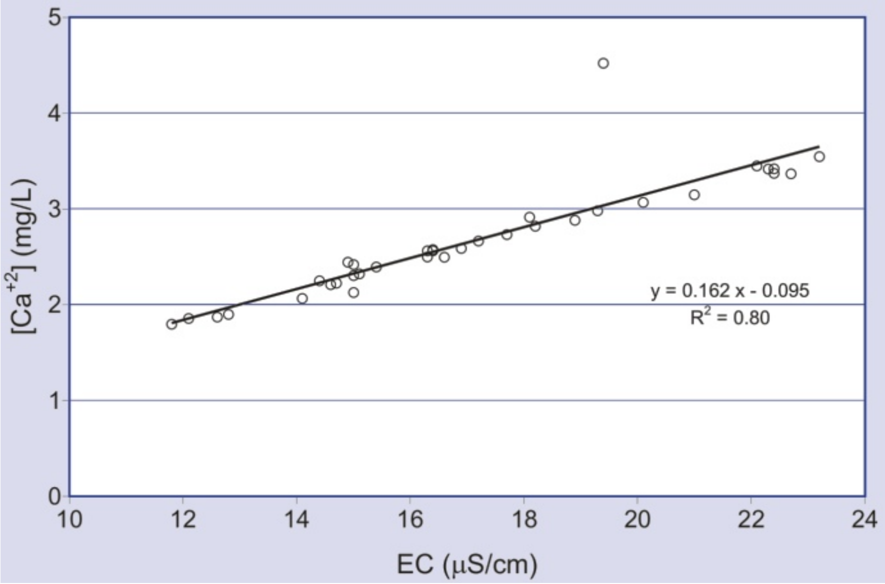

Figure 3. Relation between calcium concentration [Ca^{+2}] and electrical conductivity (EC) for Place Creek, a glacier-fed stream in the southern Coast Mountains.

It may be possible, depending on the hydrology and geochemistry of a stream, to correlate concentrations of individual ions with EC. This approach can be used to predict ionic concentrations for times when water samples were not analyzed. For example, Figure 3 shows the relation between the concentration of calcium ion and EC for Place Creek, a glacier-fed stream in the southern Coast Mountains. Plots such as Figure 3 can also be used to help identify gross analytical errors, which would show up as outliers — points that lie anomalously far from the best-fit line (e.g., the point corresponding to [Ca^{+2}] ≈4.5 mg/L).

Electrical Conductivity as an Indicator of Hydrologic Process

Temporal variability of EC as an indicator of changing runoff sources

Figure 4 shows the relation between EC and discharge for Place Creek (Richards and Moore 2003). The EC values were determined for water samples collected several times per day by an auto-sampler for suspended sediment analysis. The EC-discharge relation can be characterized as a family of concave-up curves that shifted down through the melt season. During the nival period, which was dominated by snowmelt, and during the transition from snowmelt to glacier melt, these concave-up patterns likely reflect short-term dilution cycles associated with diurnal snowmelt and/or storm rainfall inputs, possibly associated with shifts in flow paths (e.g., shallow vs. deep) with changing discharge. The downward shift of the EC-Q curves through time reflects the progressively upwards shift of runoff source areas associated with the rising snowline. This rise in elevation of the source areas for snowmelt runoff would be expected to progressively decrease the EC of water reaching the stream channel because weathering rates decrease at higher elevations (Drever and Zobrist 1992) and water would flow through thinner, less mature soils (Sueker *et al.* 2000). Both of these factors would tend to generate more dilute soil water and hence more dilute streamflow.

As the flow contribution from seasonal snowmelt decreased and the glacial contributions to streamflow increased, the points in the EC-Q plot dropped further and the curves became flatter because water from proglacial Place Lake, the dominant contributor to streamflow in late summer, had an EC

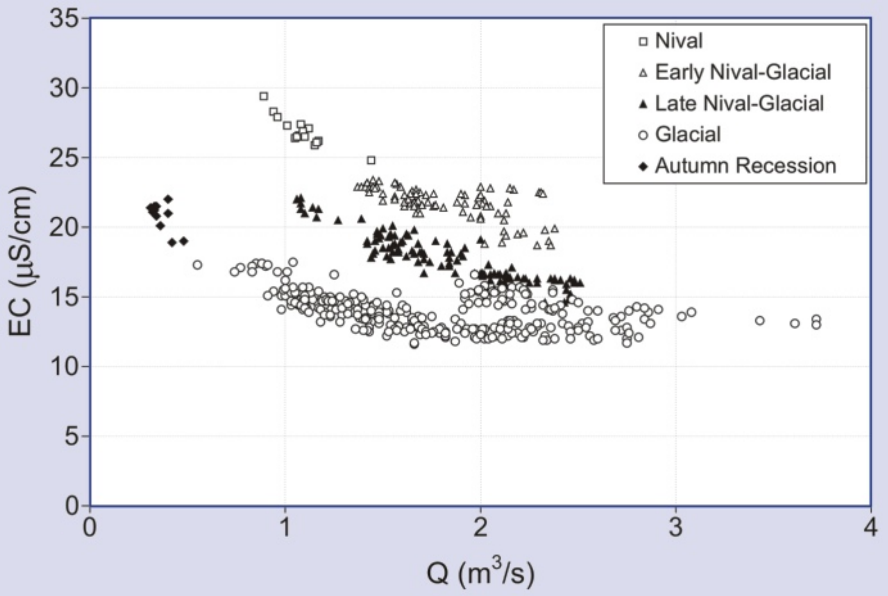

Figure 4. Relation between electrical conductivity (EC) and stream discharge (Q) at Place Creek for the 2000 melt season. After Richards and Moore (2003).

that ranged between 9 and 11 µS/cm (based on measurements from 2000 and 2001). Following the decline in glacial contribution to streamflow during the autumn recession period, EC increased as streamflow decreased and groundwater became the dominant source of streamflow in Place Creek.

Between-Stream Variability In EC As An Indicator Of Differing Hydrologic Behaviour

Given relatively homogeneous geological conditions (and negligible surface water storage in lakes or wetlands), differences in EC between nearby streams can provide clues as to the likely hydrologic behaviour of different catchments. Table 1 illustrates this point using data from two headwater streams studied as part of the Stuart-Takla Fish-Forestry Interaction project (Story *et al.* 2003). Stream B3 consistently had higher EC than stream B5.

The greater streamwater EC at B3 (>400 µS/cm vs. <200µS/cm at B5) suggests that the hydrology of that catchment is dominated by deeper, slower flowpaths than those active in the B5 catchment. This notion is supported by two independent pieces of evidence. First, visual observations at road cuts indicated shallower till in the B5 catchment than in the B3 catchment. Second, compared with the B5 reach examined in detail in summer 2000, groundwater levels in the B3 study reach varied little through time, suggesting the influence of an intermediate to thick aquifer (Hill 2000).

Streamflow at B5 varied more rapidly and with greater amplitude than at B3 (Table 1). The smaller B3 catchment produced peak flows about half as large as those at B5, on a unit-area basis. However, following a 2-week drought in August 2000, unit-area streamflow at B3 was 5 times higher than at B5 (Table 1), reflecting differences in baseflow generation. Thus, the contrasting hydrologic behaviour suggested by the EC data was confirmed by the different streamflow responses of the B3 and B5 catchments to snowmelt and summer drought. Multi-year monitoring of peak discharges (Table 1) and EC data from summer 1999 (Moore *et al.* 2003) indicate that these patterns are persistent and represent fundamental differences in the hydrologic behaviour of the two catchments.

Along-Stream Variability In EC For Identification Of Groundwater Discharge Zones

Changes in EC along a short (i.e., hundreds of metres) stream reach indicate the inflow of chemically dissimilar water. Measurements of EC can therefore be used as a tool for identifying groundwater discharge zones. Figure 5 illustrates changes in EC, discharge, water temperature, and hydraulic gradient across the streambed along stream B5 (Story *et al.* 2003). The upper 150 m of the study reach lost flow by infiltration into the bed, as indicated by the dominantly negative hydraulic gradients (measured with piezometers inserted into the bed of the stream to 20- to 30-cm depths). Groundwater discharge entered the stream at about 160 m, coinciding with a zone of mixed positive and negative hydraulic gradients.

The upper, losing portion of the reach exhibited nearly uniform EC, suggesting little or no groundwater discharge. Below about 150 m, EC decreased downstream, suggesting the inflow of chemically more dilute water via groundwater discharge. Streamwater temperature showed contrasting

Table 1.
Electrical conductivity (EC) and streamflow (Q) data for two small streams studied as part of the Stuart-Takla Fish-Forestry Interaction Project. Drainage areas are 0.42 km^2 (B3) and 1.5 km^2 (B5). Data for calculation of the mean peak discharge values (i.e., for years 1996–1999) were taken from Beaudry (2001).

	B3			B5		
	EC Aug. 16, 2000 (µS/cm)	Q Aug. 16, 2000 (L/(s • km^2))	Peak Q (L/(s • km^2))	EC Aug. 16, 2000 (µS/cm)	Q Aug. 16, 2000 (L/(s • km^2))	Peak Q (L/(s • km^2))
2000	424	2.6	54	186	0.5	100
1996–2000 mean	n.a.	n.a.	75	n.a.	n.a.	145

Continued on page 28

Continued from page 27

trends, tending to increase downstream in the losing reach (due to inputs of energy across the water surface by radiation and other processes) and decrease in the gaining reach (due to the cooling effect of groundwater) (Story *et al.* 2003).

That the groundwater discharging into the lower segment of stream B5 was more dilute than the streamwater appears unusual at first glance. However, the data were collected during an extended period of baseflow, and the streamwater chemistry at the upstream end of the study reach was dominated by groundwater discharge from higher up in the catchment rather than by more dilute sources such as lake water (e.g., as in the case of Place Lake). As a result, variations in groundwater chemistry along the reach controlled downstream changes in EC. Groundwater discharging higher in the catchment appeared to have higher ionic concentrations, possibly due to differences in catchment geology and/or flow paths (e.g., deeper and slower vs. shallower and faster).

> *Electrical conductivity can be used to estimate the relative contributions to streamflow from two distinct sources.*

EC As A Passive Tracer To Quantify Streamflow Sources

Electrical conductivity can be used to estimate the relative contributions to streamflow from two distinct sources. For example, suppose that Q represents the stream discharge at some location in a channel, and Q_1 and Q_2 represent the contributions from two distinct sources, so that

$$Q = Q_1 + Q_2 \tag{2}$$

As a first approximation, EC can be assumed to act as an inert tracer and obey the following mixing equation:

$$EC \cdot Q = EC_1 Q_1 + EC_2 Q_2 \tag{3}$$

where EC, EC_1, and EC_2 represent the electrical conductivities of the streamwater at the location of interest and the two sources, respectively. For example, the location of interest could be a point below the confluence of two tributaries, each of which would be one of the two sources. Equations (2) and (3) can be combined and solved to yield the following expressions:

$$Q_1/Q = (EC - EC_2)/(EC_1 - EC_2) \tag{4}$$

$$Q_2/Q = 1 - Q_1/Q \tag{5}$$

Therefore, if the electrical conductivities of the tributaries and the point of interest were known, then the relative contributions of the tributaries could be calculated using Equations (4) and (5). Further, if any of the three discharges were measured, the other two could be computed.

This approach has also been used to separate streamflow into time-varying components based on source. For example, Collins (1977) used Equations (2) to (5) to separate glacier runoff into the contributions from englacial flow (i.e., flow through conduits within the glacier ice) and subglacial flow. Kobayashi *et al.* (1999) used EC variations in streamwater to compute the contributions from surface and subsurface flow paths in a forested catchment.

Table 2 provides an example based on measurements on a headwater stream in the Baptiste study area of the Stuart-Takla Fish-Forestry Interaction Project. Discharges in the two tributaries were measured using constant-rate salt injection (Moore 2004). Although the relative contributions computed from EC do not agree perfectly with those computed from the measured discharges, the agreement is within the range of uncertainty of the measurements.

Summary

Electrical conductivity is relatively easy to measure either manually, using a handheld conductivity probe, or near-continuously using a probe connected to a data logger. EC measurements should be adjusted to a reference temperature, by convention 25°C, to account for the effect of temperature. The relation between EC and temperature can vary among water samples and not obey standard temperature corrections, especially for temperatures near 0°C. If the accuracy of temperature adjustments is important for a field study, it is recommended that the EC-temperature relation be determined directly for typical water samples (Figure 2).

Electrical conductivity can be used as an index of total dissolved solids and, in some cases, as a predictor of concentrations for individual ions. EC can also be used to interpret the changing sources of runoff on both diurnal/storm event and seasonal time scales, and to provide information about the contrasting hydrologic behaviour of specific catchments. Because groundwater commonly differs chemically from streamwater, groundwater discharge zones often coincide with relatively rapid changes in water chemistry along a stream, which can be detected by measuring along-stream variations in EC. Inferences regarding groundwater

Table 2.
Comparison of measured and calculated flow contributions from two tributaries to stream B3, Stuart-Takla Fish-Forestry Interaction Project

	Tributary 1	Tributary 2	Below confluence
EC (µS/cm)	411	377	388
% contribution[a]	35	65	100
Q (L/s)	1.12	2.79	3.91
% contribution[b]	29	71	100

[a] *Computed from EC using Equations (4) and (5).* [b] *Computed using measured discharge.*

discharge can be made more confidently by combining EC measurements with other observations, such as hydraulic gradients across the streambed, water temperature, and streamflow measurements (Figure 5). Furthermore, EC can be used to compute the relative contributions of two tributaries to flow below the confluence, or to separate quantitatively the contributions to streamflow from two distinct sources. As long as the limitations of EC are borne in mind, measurements of EC can provide useful and rapid insight into the chemical and hydrologic characteristics of aquatic systems.

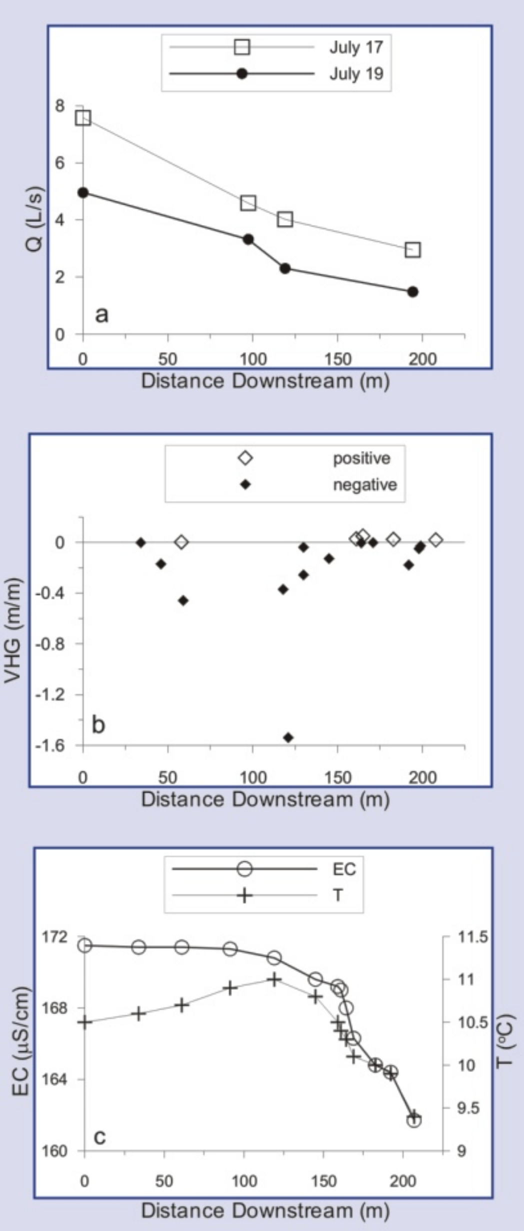

Figure 5. Along-stream profiles of discharge (Q), vertical hydraulic gradient (VHG), electrical conductivity (EC), and stream temperature at stream B5, Stuart-Takla Fish-Forestry Interaction Project. For vertical hydraulic gradient (VHG), the plotting symbol indicates the mean value observed over the summer of 2000. A negative value for VHG indicates infiltration of water into the streambed; a positive value indicates discharge upwelling into the stream.

Acknowledgements

This article benefited from thoughtful reviews by Masaki Hayashi and an anonymous referee. Data used as examples were drawn from projects funded by the Natural Sciences and Engineering Research Council and Forest Renewal BC.

For more information, contact:

R.D. (Dan) Moore
Department of Geography and
Department of Forest Resources
Management

University of British Columbia
Vancouver, BC
Email: rdmoore@geog.ubc.ca

G. Richards
KPMG, London, UK

A. Story
Story Environmental Services,
Haileybury, ON

References

Beaudry, P.G. 2001. Effects of riparian management strategies on the hydrology of small streams in the Takla region of British Columbia. Final report submitted to the Science Council of British Columbia by P. Beaudry and Associates Ltd., Prince George, B.C. 33 p.

Collins, D.N. 1977. Hydrology of an alpine glacier as indicated by the geochemical composition of meltwater. Zeitschrift fur Gletscherkunde und Glaziolgeologie 13(1/2):219–238.

Drever, J.I. and J. Zobrist. 1992. Chemical weathering of silicate rocks as a function of elevation in the southern Swiss Alps. Geochimica et Cosmochimica Acta 56:3209–3216.

Fenn, C.R. 1987. Electrical conductivity. In Glacio-fluvial Sediment Transfer: An Alpine Perspective. A.M. Gurnell and M.J. Clark (editors). John Wiley and Sons, Chichester, U.K., pp. 377–414.

Hayashi, M. 2004. Temperature-electrical conductivity relation of water for environmental monitoring and geophysical data inversion. Environmental Monitoring and Assessment 96:119–128.

Hem, J.D. 1982. Conductance: A collective measure of dissolved ions. In Water Analysis, Vol. 1. Inorganic Species. R.A. Minear and L.H. Keith (editors). Academic Press, New York, pp. 137–161.

Hill, A.R. 2000. Stream chemistry and riparian zones. Chapter 3 in Streams and Ground Waters. J.B. Jones and P.J. Mulholland (editors). Academic Press, San Diego, Calif.

Kobayashi, D., Y. Ishii, and Y. Kodama. 1999. Stream temperature, specific conductance and runoff process in mountain watersheds. Hydrological Processes 13(6):865–876.

Mills, I., T. Cvitas, K. Homann, N. Kallay, and K. Kuchitsu. 1993. Quantities, units and symbols in physical chemistry. International Union of Pure and Applied Chemistry. Blackwell Science.

Moore, R.D. 2004. Introduction to salt dilution gauging for streamflow measurement Part II: Constant-rate injection. Streamline Watershed Management Bulletin 8(1):11–15.

Moore, R.D., J.S. Macdonald, and H. Herunter. 2003. Downstream thermal recovery of headwater streams below cutblocks and logging roads. In Forestry Impacts on Fish Habitat in the Northern Interior of British Columbia: A Compendium of Research from the Stuart-Takla Fish-Forestry Interaction Study. E. MacIsaac (editor). Canadian Technical Report of Fisheries and Aquatic Sciences 2509:117–128.

Østrem, G. 1964. A method of measuring water discharge in turbulent streams. Geographical Bulletin 21:21–43.

Richards, G. and R.D. Moore. 2003. Suspended sediment dynamics in a steep, glacier fed mountain stream, Place Creek, Canada. Hydrological Processes 17:1733–1753.

Robinson, R.A. and R.H. Stokes. 1965. Electrolyte solutions. Butterworths, London.

Smart, C.C. 1992. Temperature compensation of electrical conductivity in glacial meltwaters. Journal of Glaciology 38(128):9–12.

Story, A.C., R.D. Moore, and J.S. Macdonald. 2003. Stream temperatures in two shaded reaches below cut blocks and logging roads: Downstream cooling linked to subsurface hydrology. Canadian Journal of Forest Research 33:1383–1396.

Sueker, J.K., J.N. Ryan, C. Kendall, and R.D. Jarrett. 2000. Determination of hydrologic pathways during snowmelt for alpine/subalpine basins, Rocky Mountain National Park, Colorado. Water Resources Research 36:63–75.