Measuring Stream Temperature

Ed Quilty and R.D. Moore

Stream temperature controls many aspects of stream ecology. It influences rates of biological and chemical processes, limits dissolved oxygen concentrations, and affects the life history and behavioural ecology of aquatic organisms. Summer stream temperature typically increases following the removal of riparian forest canopy, as a result of forest harvesting, wildfire, and (or) other disturbances (Nitschke 2005; Moore *et al.* 2005a). Urban development, agricultural land use, water withdrawals (e.g., for irrigation), and impoundments can also influence stream temperature, primarily through changes to shading and streamflow (Klein 1979; Hockey *et al.* 1982; Quinn *et al.* 1997; Webb and Walling 1997). Because these changes can potentially harm aquatic ecosystems, particularly cold-water species such as salmonids (Beschta *et al.* 1987; Nelitz *et al.* 2007), substantial attention has focused on the effects of land use on stream temperature.

This article is the first in a series focused on stream temperature and its implications for watershed management. The current article introduces methods for stream temperature measurement and data processing. It begins with a discussion of the ranges of stream temperature variability typically found in British Columbia, then introduces the technologies available for measurement, data processing, and field installation of sensors. Follow-up articles will focus on monitoring and analytical approaches for characterizing stream temperature regimes and the effects of forest harvesting and other human activities.

Stream Temperature Variability

Stream temperature varies diurnally and seasonally in response to changes in the energy available for heating. The absolute rates and relative importance of various heat transfer mechanisms depend on a range of time-varying climatic factors, such as solar radiation, air temperature, humidity and wind speed, as well as site characteristics, such as the amount of shading by riparian vegetation (Teti 2004) and rate of groundwater discharge (Brown 1969; Webb and Zhang 1997; Story *et al.* 2003; Moore *et al.* 2005b). The change in temperature associated with a given heat input depends on stream depth: shallower streams are more sensitive to heat inputs than deeper streams. Because stream depth is correlated with streamflow, variations in stream discharge play a secondary, though still important, role in controlling stream temperature variability (Webb *et al.* 2003; Moore *et al.* 2005b).

Most streams in British Columbia follow an annual stream temperature cycle, which varies somewhat depend-

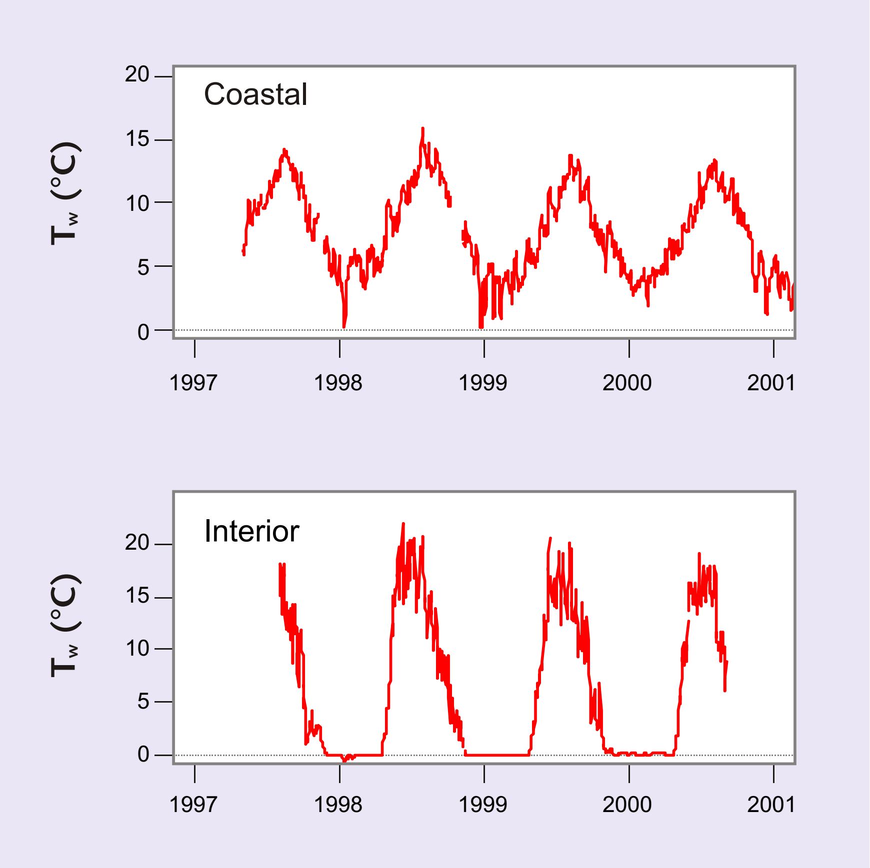

Figure 1. Mean daily water temperatures for a coastal (upper panel) and an interior stream (lower panel). In the lower panel, the sub-freezing temperatures in early 1998 reflect ice formation around the temperature sensor.

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ing on hydroclimatic regime (Figure 1). Streams draining low-elevation coastal catchments tend to remain above freezing through winter, except during occasional periods dominated by cold air masses. Interior streams, on the other hand, tend to stay at or near 0°C through winter, and below-freezing temperatures can be recorded if the temperature sensor becomes encased in ice (e.g., Figure 1, lower panel). Summer temperatures typically range from 10 to 25°C, depending on riparian shading and influences of groundwater and glacier runoff (Figure 2), but can reach more than 30°C for poorly shaded streams during extreme summer drought conditions (Quilty *et al.* 2004). Overlying the annual cycle are variations associated with the passage of frontal weather systems (lasting days to weeks), diurnal (daily) oscillations in daytime versus night-time air temperatures, storms (hours to days), and microclimatic variation (hours to seconds).

Diurnal variations in BC tend to be relatively small (°C) during winter, especially for interior streams that become filled with snow and ice and remain at or near freezing. In coastal streams, diurnal variation is suppressed in winter by low incident solar radiation and generally higher flows compared with summer. Diurnal variations in summer can range from 2 to 5°C, or even greater (Figure 2).

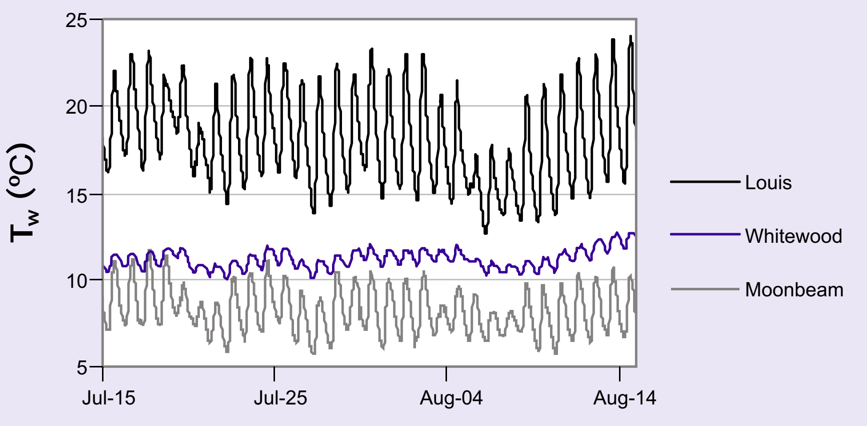

Figure 2. Temperature patterns for three streams in the North Thompson drainage during summer 2004. The McLure Fire in 2003 heavily disturbed Louis Creek's riparian zone, leaving it poorly shaded. Whitewood Creek is heavily shaded. Moonbeam Creek has significant summer flow contributions from glacier runoff.

Over large regions, stream temperature broadly follows spatial variations in air temperature, as both variables respond to variations in solar radiation and air mass characteristics, but is also modified by catchment and channel characteristics, such as mean catchment elevation, percent glacier cover, and percent lake cover (Moore 2006). Stream temperature tends to increase with distance from the channel head, with headwater streams being generally cooler than larger, downstream reaches. For streams with undisturbed riparian vegetation, diurnal and seasonal variability tends to be low for headwater streams, increase for intermediate streams, then decrease for large rivers (Vannote *et al.* 1980). Local deviations from a dominant downstream warming trend may occur as a result of groundwater inflow, hyporheic exchange, or thermal contrasts between isolated pools and the flowing portion of a stream (Mosley 1983; Bilby 1984; Ebersole *et al.* 2003a; Story *et al.* 2003). Localized cool zones, which can offer thermal refugia for cold-water species during high temperatures, are an important aspect of stream habitat (Neilsen *et al.* 1994; Ebersole 2003b). In addition, lakes, ponds, and wetlands can produce elevated water temperatures at their outlets, resulting in downstream cooling below them over hundreds of metres, even through cutblocks (Mellina *et al.* 2002).

Technologies for Measuring Stream Temperature

Most instruments for measuring stream temperature register the direct effects of the thermal agitation of the water molecules, and are often called "kinetic" measurements. Four main types of sensors measure kinetic measurements of stream temperature: thermometers, mechanical thermographs, thermocouples, and thermistors. An alternative technology for kinetic temperature sensing is based on "resistance temperature detectors" (RTDs), which are similar in some ways to thermistors. However, RTDs are less accurate than thermistors and, to the authors' knowledge, not commonly used for water temperature measurement. In addition, stream temperature can be measured using radiometric methods. These record the intensity of infra-red radiation emitted by the stream, which is a function of the water surface temperature. An emerging technology for measuring water temperature is based on fibre optics (Selker *et al.* 2006). At present, fibre-optic systems are best suited to research applications. Characteristics of kinetic and radiometric approaches are summarized below.

Thermometers use the volume changes of a fluid (usually mercury or alcohol) in relation to changing temperature to register the temperature. Field thermometers can be as accurate as ± 0.02°C, though they are more typically accurate to about ± 0.1°C.

Mechanical thermographs were commonly used for recording water temperature before the advances in electronic data acquisition over the last two decades, but the data are still used, especially where long data records are required. These devices record the effects of temperature changes via their effects on a bi-metallic strip. Because the two metals expand differently upon heating, temperature changes cause the curvature of the strip to vary. This displacement can be translated into the movement of a pen on a recording chart. Resolution is typically about 1°C. The charts must be digitized before analysis, commonly at relatively coarse time intervals, such as 3 hours (e.g., Hamel *et al.* 1997).

Thermocouples are based on the principle that temperature differences along a conductor (e.g., copper) will produce a difference in voltage that is proportional to the temperature difference. Thermocouples are constructed from a special two-conductor wire, with the conductors made from different metals. Various pairings of metals can be employed, but those made from copper and constantan (a copper/nickel alloy) are most appropriate for the typical range of stream temperatures. Thermocouple measurements are typically accurate to about ± 0.2°C. Handheld meters are commercially available for taking manual measurements, while most data loggers can make thermocouple-based temperature measurements using a built-in reference thermistor.

Thermistors employ a resistor whose resistance varies with temperature. If the relation between temperature and resistance is known, then the measured resistance can be converted into temperature. Handheld thermistor-based instruments are commercially available for taking manual measurements, while thermistors can also be connected to data loggers for near-continuous recording. In the last decade, integrated thermistor-logger units that can be submersed in water have become available at a reasonable cost. These can be pre-programmed to specify the logging interval, and have become popular for forest hydrology applications. They have a typical accuracy of about ± 0.2°C. A useful reference on measuring stream temperatures with thermistors is Dunham *et al.* (2005).

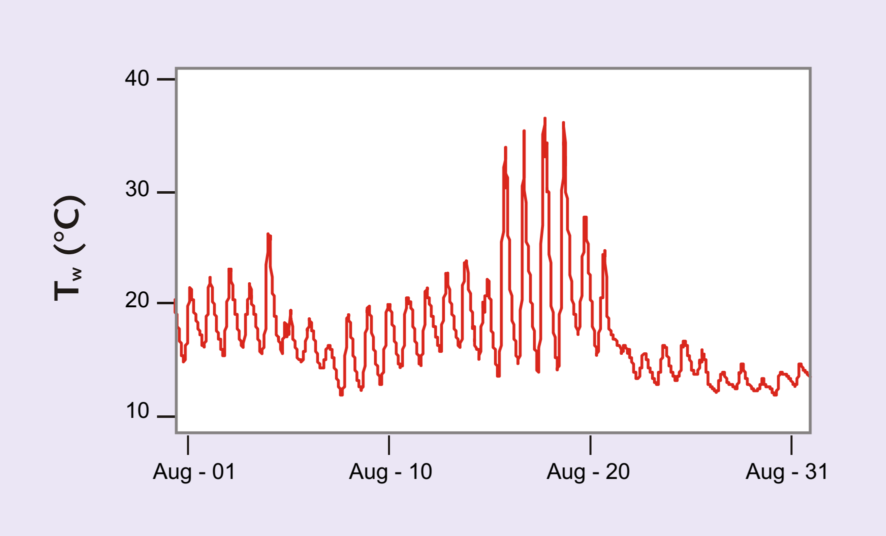

Figure 3. Stream temperatures before, during, and following a de-watering event, which began August 16 and ended August 22.

Radiometric measurements can be made using handheld infrared thermometers, airborne sensors, or even sensors on satellite platforms (Torgerson *et al.* 2001; Rayne and Henderson 2004; Cherkauer *et al.* 2005; Handcock *et al.* 2006). The spatial resolution of satellite imagery is too coarse to resolve any but the largest rivers. Airborne systems can resolve medium to large streams, and can give "snapshots" of spatial temperature patterns along extensive reaches, including the locations of local cool zones (thermal refugia) associated with groundwater discharge and inflow of cooler tributaries (Torgerson *et al.* 1999).

Calibration of Temperature Sensors

Though temperature sensors are generally reliable and accurate, and require little maintenance, they do require calibration. Thermometers and thermistors should be calibrated annually against an INMS (Institute for National Measurement Standards) calibration thermometer using a temperature-controlled water bath (Wagner *et al.* 2006). Calibration typically consists of an ice-point reading and calibrations at 3–5 temperatures within the range of the sensor. When practical, sensors should be checked more frequently using the "ice bucket" method (Dunham *et al.* 2005), whereby sensors are submerged in an insulated ice bath for 1 hour to verify that readings are 0°C.

In addition to the calibration procedures mentioned above, field meters or thermometers should be used to measure water temperature near the installed sensor during each field visit. After the recorded data have been downloaded, temperatures at the time of field visits can be extracted and compared with the manual measurements as a further calibration check. Such comparisons are particularly valuable where a sensor's calibration may have drifted during the field installation, as they can help to identify the appropriate segments of the data requiring drift corrections.

Verification and Correction of Stream Temperature Data

Before any analysis, data quality must be verified and any errors removed or

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corrected. Data should be plotted as time series and visually inspected for obvious outliers, such as values that differ substantially from preceding and following values. In many cases, the observations at the beginning and end of each data set need to be removed because the sensor would have been measuring air temperature while being programmed or downloaded in the office or at the field site. Similarly, any observations that were recorded when the water dropped below the sensor level (e.g., summer drought low flows, "de-watering") need to be removed. These measurements are usually relatively obvious, with sudden and substantial increases in daily oscillations and daily maximum values (Figure 3). When examining data to locate errors, it is helpful to compare stream temperature records with other nearby records, such as those from upstream or downstream stations, and local or regional climate stations.

When appropriate for project objectives, small data gaps can often be filled by using linear interpolation or modelling techniques. As a general guideline, interpolation should only be used on gaps that are less than 2 hours long, which is often sufficient for filling gaps created by removing air temperature data recorded during downloading. Modelling techniques can be used for longer gaps (hours to days); however, modelled data must be interpreted cautiously. Gap filling with models is possible when surrogate data are available, such as stream temperature from upstream or downstream sensors or nearby watersheds. Typically, a simple linear or multiple linear regression model is developed using several weeks of data immediately before and after the gap. Air temperature can also be used as a surrogate, though linear models may be unsuitable due to nonlinearities at high (25°C) and low (freezing) temperatures (Webb et al. 2003). In all cases, detailed notes on gap filling instances, methods, and rationale must be produced and kept with the data.

Recommendations for Monitoring Stream Temperature

The following general recommendations are based on experiences in measuring stream temperature at sites throughout British Columbia. Specific implementation may need to be varied to suit conditions at individual sites and/or project objectives.

Sensor Selection and Programming

Some manufacturers of temperature loggers, such as Vemco and Onset, produce units with different temperature ranges. It is important to purchase models that cover the range of stream temperatures that can occur within BC. Ideally, a logger should record temperatures ranging from below 0 and to at least 35°C.

Data loggers can be programmed to record either the individual measurements or to process the data and output summary statistics (e.g., mean, maximum, minimum) for a time interval. Where the immediate need is only for mean daily temperatures, it may seem simplest to program a logger to generate daily summaries. However, given the high temporal variability of stream temperatures, and the relative ease of use and reasonable costs of thermistors, high frequency monitoring (hourly or every 10–20 min) is now preferred, even if the immediate need for the data is to calculate daily means. This approach allows data to be used for various purposes beyond those for which the data may have been originally collected. This approach also allows field measurements of temperature using a standard instrument to be associated with a specific recorded value for comparison and calibration, as described earlier. Examination of the time series can also be valuable for interpreting data logger malfunctions or de-watering events (Figure 3).

Sensor Installation and Placement

Sensors should be shielded from solar radiation to avoid any possibility of anomalous heating, particularly during low-flow periods, when low flow velocities and high sun angles can cause the sensor temperature to rise above ambient water temperature. A number of investigators have placed sensors within short lengths (10–20 cm) of pipe. Emplacement in these shields also keeps the sensors out of direct contact with the stream bed, which may be cooler or warmer than ambient stream temperature in groundwater discharge zones, depending on season and time of day.

Sensors need to be placed where they will be protected from natural disturbances, such as substrate movement and debris during storm flows, and where they can be relocated easily. In small streams with low stream power, rebar hammered vertically into the bed can suitably anchor the sensors. In larger streams, sensors will usually be attached to a suitable weight which, in turn, will be leashed to an anchor point. The weights can be sand bags, blocks of concrete, exercising "dumbbells," or other object appropriate to a specific site. Heavy-duty clothesline is often an appropriate material for "leashing" thermistors to a streamside tree or other anchor. The anchor should, ideally, be fixed firmly in place, and not be movable during high flow. For example, large logs along the streambank may be stable at lower flows, but are prone to being swept away during high flows. Despite the best efforts, thermistor loss due to burial or significant channel erosion is always possible. For example, the second author installed a network of submersible temperature loggers in the southern Coast Mountains in summer 2003, and lost several during the October 2003 floods. One logger ended up buried under 2 m of gravel, while another was lost due to significant bank erosion that swept away the mature tree to which the instrument was leashed.

Sensor placement can be challenging, especially in streams with wide ranges of flow. The sensor should be placed in the stream where it will not become de-watered but will still experience water flow (i.e., not in stagnant pools). For streams that have not been viewed at a range of flows, it can be difficult to anticipate the patterns of depth and velocity during extreme conditions.

During installation, detailed hand-drawn maps, notes, and photos must be taken so that sensors can be relocated during various seasons and flows when sites can look quite different. Even though current temperature loggers may have sufficient memory to be left unattended for months, frequent field checks are recommended to ensure that the sensor is not lost, exposed to air, or placed in an isolated pool at low flows.

Other Comments

Streams that freeze or become covered with snow and ice present a range of challenges. It may be difficult to locate a logger within a snow-filled channel or to remove a logger from under a thick ice cover. Additional problems may occur in larger streams, where channel ice can remain intact through the early spring melt. In such cases, ice may be moved downstream with the flow, resulting in movement or loss of a logger. Ideally, loggers at such sites should be visited and downloaded in autumn to avoid possible data loss.

Another important issue is spatial heterogeneity of stream temperature within a reach, which tends to be greatest during periods of high stream temperature. Stream temperature variability should be measured with a manual instrument on warm summer days to assess how representative a monitoring site is relative to other locations within the reach.

Temperature loggers can collect tens of thousands of measurements each per year, making organization and storing of the data a challenge and data archiving paramount. Ideally, all data should be organized and stored in a relational database. At a minimum, each download file should be fully documented with metadata, such as site and deployment information and field notes, and be stored in at least two secure locations. ~

Summary

Stream temperature is an important water quality parameter. Despite the availability of accurate, robust temperature loggers at relatively low cost, monitoring stream temperature is not necessarily straightforward. Logger emplacement in a stream must consider spatial variability within a stream reach, which can be substantial; the possibility of logger loss during high flow periods; and the possibility of de-watering during low flows. In addition, the relative ease with which large data sets can be acquired makes it imperative to adopt strict protocols for documentation of metadata and data handling. A follow-up article will focus on monitoring protocols and analytical approaches for assessing stream thermal regimes and, in particular, the effects of forest harvesting and other human activity.

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For further information, contact:

Ed Quilty, PhD candidate, RPBio
Aquatic Informatics Inc.
1102-889 Homer Street
Vancouver BC V6B 5S3
Tel: (604) 873-2782
Email: ed@aquaticinformatics.com

or

Dan Moore, PhD, PGeo
Departments of Geography and
Forest Resources Management
University of British Columbia
1984 West Mall
Vancouver, BC V6T 1Z2
Tel: (604) 822-3538
Email: rdmoore@geog.ubc.ca

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