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A process-based stream temperature modelling approach for mountain regions

Ryan J. MacDonald *, Sarah Boon, James M. Byrne

University of Lethbridge, 4401 University Dr. W., Lethbridge, AB T1K 3M4, Canada

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SUMMARY

Mountain streams have thermal regimes that provide critical habitat for native aquatic organisms. However, understanding stream temperature response to environmental change in mountain regions is difficult because there is typically a lack of observations. This work aims to address this issue by coupling two process-based models to simulate stream temperature in a groundwater-dominated mountain catchment, Alberta, Canada, and using a reach-scale field study for model development and verification. Results suggest that it is possible to produce spatial simulations of hydrometeorological variables needed for process-based stream temperature modelling. Simulated stream energy budget estimates compare well with results from field-based studies, and errors in stream temperature simulations ($RMSE < 1.6$) are similar to other modelling studies, providing confidence in the methods developed. Model sensitivity analysis demonstrates the importance of incorporating meteorological, hydrological, and geomorphological controls on stream temperature in modelling studies. This study also demonstrates the current lack of process knowledge regarding in-stream ice cover and snowmelt effects on stream temperature, both of which can contribute substantially to stream thermal regimes. Future field-based and modelling studies should consider these processes in order to fully understand stream temperature response to environmental change.

1. Introduction

Stream temperature has been the focus of much recent research, primarily because temperature is a critical variable for aquatic ecosystem function (Buisson et al., 2008; Durance and Ormerod, 2009). The interactions between the surface (atmospheric) and subsurface (stream bed, hyporheic exchange, and groundwater flow) processes determining the thermal characteristics of streams are complex. Reach-scale studies continue to demonstrate that net radiation dominates the heat budget of most small streams (Brown, 1969; Brown and Krygier, 1970; Webb and Zhang, 1997; Johnson and Jones, 2000; Hannah et al., 2008; Leach and Moore, 2010; Hebert et al., 2011; Garner et al., 2012). Latent and sensible heat fluxes act as secondary atmospheric controls, accounting for a relatively small proportion of the heat budget (Webb and Zhang, 1997; Johnson, 2004; Leach and Moore, 2010). Hyporheic exchange flow can act to buffer stream temperature patterns (Poole and Berman, 2001; Story et al., 2003; Arrigoni et al., 2008; Leach and Moore, 2011). Collectively, reach-scale field studies have demonstrated that substantial spatial and temporal variation exists in both surface and subsurface processes controlling stream temperature (Webb et al., 2008). However, representing these processes in regions with limited data, and at scales applicable to environmental management-related questions presents a significant challenge.

Previous studies have applied statistical modelling methods, making use of correlations between stream temperature and variables such as stream discharge, air temperature, and physical catchment characteristics to quantify stream temperature response to environmental change at relatively large spatial scales (Mohseni et al., 2003; Isaak et al., 2010; Jones et al., 2013). While statistical models are useful due to their relatively low input data requirements and spatial applicability, it is important to recognize the difference between correlation and causation when assessing processes controlling stream temperature (Johnson, 2003). Therefore, modelling frameworks that incorporate the representation of key processes controlling stream temperature are necessary for understanding thermal response to environmental change (Norton and Bradford, 2009).

There are a number of process-based models available such as WET-Temp (Cox and Bolte, 2007) and SNTEMP (Theurer et al., 1984), later built upon to develop Heat Source (Boyd and Kasper, 2003) or models like SHADE-HSPF (Chen et al., 1998) and CEQUEAU (St-Hilaire et al., 2000) which integrate stream

* Corresponding author. Tel.: +1 403 892 4510.
E-mail address: ryan.macdonald@uleth.ca (R.J. MacDonald).

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temperature and catchment-scale hydrological modelling. These models and others are useful for assessing causal relationships because they represent key processes controlling stream temperature. However, a limitation of process-based models is they often have high input data requirements and can be difficult to apply in data-sparse regions (Benyahya et al., 2007).

To-date, the application of process-based stream temperature models in complex mountain catchments is limited, presenting a challenge for fully understanding the effects of anthropogenic and natural environmental disturbance on stream temperature. Most mountain regions lack the hydrometeorological and physiographic data required to simulate the stream energy and mass budget in process-based models. To help fill this gap, we developed a modelling approach that uses readily available hydrometeorological and physiographic data as spatial inputs to a process-based stream temperature model. This paper describes the application of the Generate Earth Systems Science input (GENESYS) hydrometeorological model (MacDonald et al., 2009) with spatial and temporal downscaling routines developed in a Geographical Information System (GIS) to simulate energy and mass budget variables important for process-based stream temperature modelling.

2. Study area

Data for model development and testing were collected in Star Creek in southern Alberta, Canada. The Star Creek catchment ranges in elevation from 1475 m to 2631 m with a mean slope of 44%. Glacial till and colluviums characterize the surficial geology below 1900 m above sea level (asl), and talus, cirque tills, and exposed bedrock are above 1900 m (Bayrock and Reimchen, 2007). The montane vegetative cover is dominated by lodgepole pine (*Pinus contorta*) and Engelmann spruce (*Picea engelmannii*), with some small stands of trembling aspen (*Populus tremuloides*). The subalpine vegetative cover is primarily subalpine fir (*Abies lasiocarpa*), Engelmann spruce, and white spruce (*Picea glauca*). The alpine portion of the catchment is characterized by meadows with low grasses and shrubs, talus slopes, and bare rock (Silins et al., 2009).

The three sites used for model development in this study are Star West upper, Star East, and Star Main, located at elevations of 1691, 1597, and 1502 m asl, respectively (Fig. 1). Data from Star McLeran (1510 m) and Star East upper (1680 m) were used as model input (Fig. 1). Over the entire stream, the mean bankfull channel width is 3.0 m with a mean wetted width of 2.6 m, a mean bankfull depth of 0.34 m, and mean wetted depth of 0.21 m during a stream survey in August.

3. Methods

3.1. Stream morphology and riparian cover

The model parameterization used stream morphology data for Star Creek collected during stream surveys at the sub-reach (fall, cascade, chute, rapid, riffle, sheet, run, scour pool or plunge pool; Hawkins et al., 1993) and reach (colluvial, dune-ripple, pool-riffle, plan-bed, step-pool, cascade, or bedrock; Montgomery and Buffington, 1997) scales. These data were used to classify Star Creek as an intermediate between step-pool and pool-riffle channel types. An advantage to using stream classification is that as stream morphology data become available through sources like provincial governments (e.g., BC-MOE, 2012), classification systems can be used to define a set of model parameters that can be applied over a range of catchments. In this study, a Lidar Digital Elevation Model (DEM) with a 1 m cell size (ASRD, 2008) was used to calculate channel slope and aspect along the entire stream.

Canopy closure was estimated using hemispherical photographs taken with a Canon EOS 5D digital SLR camera with a full-frame sensor and a Sigma 180° true fisheye lens attached to a level tripod at 1.4 m above the stream surface. Hemispherical photographs were processed in Gap Light Analyzer v2.0 (GLA; Frazer et al., 1999). Closure estimates were 41%, 46%, and 37% at Star West upper, Star East, and Star Main, respectively. Canopy closure values were assigned for each of the riparian cover types (mixed pine-spruce, lodgepole pine, and trembling aspen in Star Creek based on the Alberta Vegetation Inventory (AVI) spatial vegetation polygon data (ASRD, 2010). The AVI data were also used to describe landcover types for the entire catchment. Soil characteristics were determined for each of the landcover types based on AVI polygon data. A total of 12 soil pits were dug (two per landcover type) to a depth of 1.5 m. Soil horizon depths and textures were measured *in situ* for each of the horizons (A, B, and C) identified in the pits (see Klute, 1986). Field capacity values were defined for each pit and landcover type based on texture as per Saxton and Rawls (2006).

3.2. Stream energy and mass balance data

Energy balance, mass balance, and stream temperature data used for this study were collected for the period between May 15 and December 31, 2010. Hydrometeorological stations located at Star West upper and Star Main (Fig. 1) were used to quantify the surface energy balance of the stream and to verify the model's ability to accurately represent stream temperature conditions (T_s; °C). At each station hourly and daily mean air temperature (T_a; °C), relative humidity (RH; %), and wind speed (u; m s^{-1}) were calculated from 10 second (s) measurements taken 2 m above the stream bankfull depth. Hourly mean net radiation (Q^*; W m^{-2}) was calculated from 10 s measurements taken directly over the stream surface at 1 m above bankfull depth. Hourly total precipitation (mm) was measured approximately 10 m from the stream bank at the Star Main site (MacDonald et al., 2014). Hourly mean T_s was calculated from 1 min measurements at the Star West upper, Star East upper, Star East, Star McLaren, and Star Main sites (Fig. 1).

Hourly mean stream discharge (Q; m^3 s^{-1}) was estimated using stage (cm) – discharge relationships at the Star Main, Star East, and Star West upper gauging stations, and at Star McLaren using a compound weir. Hourly mean stream stage was calculated from 10 s measurements taken in-stream at each site. Manual Q measurements were collected once per week over the study period at each site (MacDonald et al., 2014). Manual Q measurements were also collected once per month during June, July, August, and September at ten locations spaced approximately 100 m apart along Star Creek from Star Main to immediately upstream from the confluence of Star West and Star East (Fig. 1).

3.3. Hydrometeorological model

We used the GENESYS model to provide hydrometeorological inputs to a process-based stream temperature model. The advantage of using this modelling approach is that GENESYS uses readily available meteorological data to extrapolate hydrometeorological conditions over mountainous terrain (MacDonald et al., 2009). Daily maximum T_a, minimum T_a, average u, and total precipitation from the Star Main station were used as input to the GENESYS model for the period from January 1 to December 31, 2010.

The GENESYS model has been primarily used to simulate snow water equivalent (SWE) (Lapp et al., 2005; Larson et al., 2011; MacDonald et al., 2009) by integrating a GIS and a series of physical subroutines to estimate hydrometeorological variables for individual hydrological response units (HRUs). Using a combination of land cover from the AVI (ASRD, 2010), 100 m elevation bands,