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Streambed temperature dynamics and corresponding heat fluxes in small streams experiencing seasonal ice cover

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SUMMARY

Streambed temperature and heat fluxes are important for aquatic habitats as well as in the development and improvement of water temperature models. In the present study, measured streambed temperatures at different depths were used as a tracer to predict the magnitude and direction of groundwater flow using an advection–conduction heat transport model. This analysis was carried out under different conditions, namely under natural surface water temperature conditions (i.e., as measured in the field), under steady-state conditions (e.g. under stream ice cover) and for conditions where the surface water temperatures followed a sinusoidal function. In Catamaran Brook, results from the advection–conduction numerical model showed good agreement between predicted and observed streambed temperatures with root-mean-square errors (RMSEs) ranging between 0.07 °C to 0.6 °C. A comparison of streambed fluxes showed that the heat flux by conduction was more important during the summer period for upwelling conditions (mean value 96 W m^{-2} at 25 °C), but was also present in winter (-20 W m^{-2}). Variability in heat flux by conduction was also greater when the diel surface water temperature variability was high (e.g. range of 6 °C). The heat flux by advection varied between -120 and 145 W m^{-2} (for typical water temperatures and vertical flow conditions within Catamaran Brook, 0–25 °C and ±0.005 m h^{-1}). Short-term heat exchange (diel) occurred within the thermally active depth, typically <0.7 m. The long-term annual streambed heat flux by conduction was also calculated and daily mean was generally less than ±11 W m^{-2}. Winter conditions provided a unique opportunity to analyse streambed heat fluxes under steady-state conditions when both conduction and advection fluxes were present.

1. Introduction

Water temperature influences many biotic and abiotic conditions within river systems. As such, it is considered one of the most important variables that determine the productive capacity of aquatic ecosystems. For example, water temperature influences the growth rate and development of aquatic organisms as well as their distribution within rivers (e.g. Hester and Doyle, 2011). Notably, most aquatic species have a specific range of water temperature that they can tolerate (Langford, 1990; Lund et al., 2002). In severe conditions, high temperatures can result in stress and even mortality in fish (Huntsman, 1942; Lee and Rinne, 1980). Stream or river water temperature can also impact chemical properties, dissolved oxygen concentrations and river pollution in general (Murdoch et al., 2000). Stream temperature is a major determinant of aquatic resources composition and distribution, and it is therefore imperative to understand the spatial and temporal variability of the underlying physical processes influencing stream temperature.

Most variations in stream water temperature (e.g., diel, daily and seasonal) occur as the result of heating and cooling of the river by outside sources. These processes are highly dependent on meteorological and geophysical conditions. For instance, water temperature is correlated to air temperature, and both regression and stochastic models have been used in the past to predict the thermal regime of a surface water body using air temperature as a predictor (Benyahya et al., 2007; Caissie et al., 1998, 2001;

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Mohseni et al., 1998; Stefan and Preud'homme, 1993). Deterministic models, which consider physical forcing and heat exchange processes, have also been employed as an alternative to regression and stochastic models (Benyahya et al., 2012; Brown, 1969; Caissie et al., 2007; Hebert et al., 2011; Morin and Couillard, 1990; Sinokrot and Stefan, 1993). When using deterministic models, the heat exchange can mostly be considered at two levels within the river, namely at the air/surface water interface and the water/streambed interface (Fig. 1). Historically, many studies have neglected the heat exchange at the streambed interface; however, recent studies of surface water/groundwater interactions have resulted in a better understanding of underlying processes, both from a modelling (Hondzo and Stefan, 1994; Leach and Moore, 2011; Prats et al., 2011; Sinokrot and Stefan, 1994; Younus et al., 2000) and aquatic habitat (Alexander and Caissie, 2003; Hendricks and White, 1991; Power et al., 1999) perspective. Neglecting the streambed heat flux is generally justified when the river is large, highly exposed to atmospheric conditions and has a relatively small groundwater component (Hebert et al., 2011). When the role of groundwater is significant, numerous methods have been used to study surface water/groundwater interactions, including isotopic and chemical hydrograph separation, stream gauging techniques, seepage metres, piezometers, tracer methods as well as thermal imagery (e.g., Boulton, 1993; Dugdale et al., 2013; Hooper and Shoemaker, 1986; Lee and Cherry, 1978; Malcolm et al., 2003). Studies have shown that using streambed water temperature as a tracer can be a very effective technique in studying surface water/groundwater interactions (Anibas et al., 2012; Anderson, 2005; Gordon et al., 2012; Goto et al., 2005; Hatch et al., 2006; Keery et al., 2007; Lapham, 1989; Luce et al., 2013; Silliman and Booth, 1993; Voytek et al., 2013). Some studies have also developed software packages for the analysis of water temperature time series within the streambed to infer the magnitude and direction of groundwater flow (e.g., Gordon et al., 2012; Voytek et al., 2013). Although many of these studies have used water temperature as a tracer to study surface water/groundwater interactions, few studies have actually quantified the corresponding streambed heat fluxes.

Therefore, the aim of the present study is to examine surface water/groundwater interactions using an advection–conduction model under different thermal states (steady and transient) and for two different sites within Catamaran Brook (a tributary of the Little Southwest Miramichi River, NB, Canada, Fig. 2). These two sites within Catamaran Brook represent different size watercourses and groundwater flow conditions. The advection–conduction model will be used to better quantify vertical flow as well as conduction and advection fluxes over different time scales (diel and seasonal). Particular attention will be devoted to the winter regime where the stream and streambed can experience steady-state conditions in a northern climate. The specific objectives of the study are: (1) to examine the different boundary conditions of the advection–conduction model to better understand thermal and flow conditions within the streambed, (2) to observe streambed temperature variability at different depths, (3) to calculate different streambed heat fluxes based on temperature data and the groundwater flow rates obtained from the advection–conduction model, and (4) to compare the relative contribution of conductive and advective energy fluxes at both sites of Catamaran Brook (Site 1, a small tributary; Site 2 on the brook main stem).

2. Theory

2.1. General streambed advection–conduction model

Water temperature time series within a streambed have been used to study vertical water movements and to better understand surface water/groundwater interactions in streams and rivers (Anderson, 2005; Rau et al., 2014). For instance, times series analyses have been used to estimate vertical water fluxes within the streambed (Hatch et al., 2006; Keery et al., 2007; Luce et al., 2013; McCallum et al., 2012). These studies used variations in the phase and amplitude of water temperature time series measured at different depths within the stream substrate to estimate the vertical water flux in both space and time. Some studies have used simplified analytical solutions of the general one-dimensional heat transport equations, while others have used more general solutions obtained via numerical methods (Anderson, 2005; Lapham, 1989; Stallman, 1965).

The one-dimensional (i.e. vertical) advection–conduction heat transport equation is given by (Anderson, 2005):

$$k\frac{\partial^2 T}{\partial z^2} - v_z c_w \rho_w \frac{\partial T}{\partial z} = c\rho \frac{\partial T}{\partial t} \qquad (1)$$

where k is the effective thermal conductivity of the saturated sediment matrix (W m^{-1} °C^{-1}), T is the temperature at different depths (°C), z is the depth within the streambed (m), v_z is the vertical Darcy velocity (m s^{-1}, negative for upwelling water), c_w is the specific heat of the fluid (J kg^{-1} °C^{-1}), ρ_w is the density of the fluid (kg m^{-3}), c is

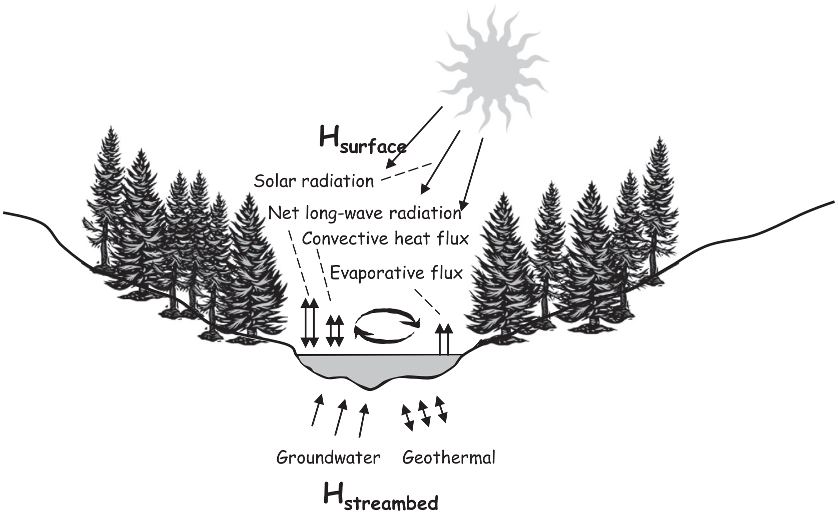

Fig. 1. Different heat fluxes at the stream surface and streambed.