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Complexities in the stream temperature regime of a small mixed-use watershed, Blacksburg, VA

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ABSTRACT

Stream temperature is a vital characteristic of stream ecosystems and has a strong control on chemical and biological processes. Water temperatures, particularly in small streams with low flows, can be affected by riparian vegetation and land cover. We designed a study using in situ temperature sensors to examine the annual thermal regime of Stroubles Creek, a small stream in Blacksburg, VA, across three land cover regions; urbanized, agricultural, and forested. During the warm sampling period, mean stream temperatures were: 17.8 °C (±3.5 °C) in the urban reaches; 20.0 °C (±3.0 °C) in the agricultural region; and 20.4 °C (±3.3 °C) in the forested area. Cold period daily stream temperatures were: 10.54 °C (±3.1 °C) in the urban reaches; 8.5 °C (±4.0 °C) in the agricultural region; and 7.7 °C (±4.1 °C) in the forested area. Linear regression analyses suggest that weekly mean stream and air temperatures have a significant linear relationship throughout the Stroubles Creek watershed, regardless of land cover or period. During the warm period, mean stream temperatures increased by 5.9 °C downstream along 9 km of the main stem from the headwater spring to the forested outflow as groundwater was exposed to air temperatures and environmental heat fluxes. Local cooling of stream water occurred in agricultural and forested reaches at sites with higher canopy, and possibly strong stream water–groundwater interactions. Stream temperatures decreased during the cold period by 4.5 °C from headwaters to outflow, with groundwater inputs producing areas of local warming. Although the stream water–groundwater relationship of Stroubles Creek was not quantified in this study, analyses suggest that groundwater and hyporheic flow, along with riparian vegetation and canopy cover, could be controls on stream temperatures. Identifying sources of cooling for stream temperatures in the Stroubles Creek watershed, such as riparian vegetation and groundwater, could be useful for restoring the natural thermal regime, which has important implications for restoration of water quality and aquatic organism diversity in this mixed land use watershed.

1. Introduction

Water temperature is a critical physical property of rivers and streams. Temperature has a major influence on the biological productivity and development of freshwater organisms, defines suitable habitat ranges, and controls chemical characteristics and processes of stream ecosystems (Blakey, 1966; Brown and Krygier, 1967; Cozzetto et al., 2006; Pedersen and Sand-Jensen, 2007; Webb et al., 2008). Stream temperature has been studied by many researchers due to its essential role in defining stream ecosystems. Stream temperatures can be affected by environmental factors including atmospheric and climatic conditions, physical characteristics of the watershed and stream, and hydrologic inputs (Brown and Krygier, 1970; Beschta et al., 1987; Rowe and Taylor, 1994; Bourque and Pomeroy, 2001; Poole and Berman, 2001; Younus et al., 2000; Caissie, 2006; Webb et al., 2008; Somers et al., 2013). In addition, human activity has an increasingly important effect on stream ecosystems and on stream temperature (Webb et al., 2008; Hester and Doyle, 2011).

Stream temperature changes as a result of heat fluxes between the stream and surrounding environment. Change in stream temperature is dependent on net heat fluxes and stream discharge, and is directly proportional to the stream surface area and inversely proportional to discharge (Brown and Krygier, 1967; Beschta et al., 1987; Poole and Berman, 2001; Webb et al., 2003; Moore et al., 2005a). The exchange of heat between the environment and the stream occurs primarily across the air–water boundary and the streambed-stream water interface through short- and long-wave

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radiation inputs, evaporation, convective heat transfer between the stream and atmosphere, conductive transfer between the steam water and bed, and advective energy transfer between water sources (Brown and Krygier, 1967; Brown, 1969; Beschta et al., 1987; Brown et al., 2005; Moore et al., 2005a). The thermal regime of small streams can vary widely depending on atmospheric and physical conditions. For example, shallow streams with low flows react to heat flux changes more dramatically than do larger rivers (Brown, 1969; Caissie, 2006; Webb et al., 2008). Water in headwater streams is generally close to a baseline temperature, which can be the temperature of groundwater, and increases as the water flows downstream towards equilibrium with atmospheric temperature (Poole and Berman, 2001; Caissie, 2006). Atmospheric conditions can include air temperature, vapor pressure, solar radiation, wind speed, cloud cover, and relative humidity (Evans et al., 1998; Webb and Zhang, 2004; Caissie, 2006). Physical characteristics of a watershed, such as topography and land cover, and those of a stream, such as stream orientation, streambed substrate, channel form, groundwater inputs, and canopy cover can also affect stream temperature and create varying microclimates and habitats (Ward, 1985; Beschta et al., 1987; Arscott et al., 2001; Moore et al., 2005a,b; Tague et al., 2007; Webb et al., 2008). At the streambed-stream water interface, heat can be exchanged through convection and advection from water passing through the hyporheic zone into the stream and vice versa (Brown et al., 2005; Hester et al., 2009). In karst regions, such as the New River Valley in Virginia, there may be springs from large underground aquifers that can discharge cold water into streams and have a significant effect on temperature regimes (Tague et al., 2007). Groundwater discharge into streams tends to moderate the water temperature of streams because the groundwater is typically cooler than stream water during the summer months and warmer than the stream water during the winter months (Alexander and Caissie, 2003).

Land cover and riparian vegetation can influence stream temperature by altering how atmospheric, physical, and hydrologic factors control stream temperature. Riparian vegetation shading can have a stronger influence on the temperature of small streams compared to larger rivers. Brown and Krygier (1967) observed daily (diel) fluctuations of more than 10 °C in small streams (about $0.03\ m^3\ s^{-1}$) without canopy cover during the summer, while summer fluctuations of less than 1 °C occurred in the large Willamette River (approximately $140\ m^3\ s^{-1}$). Brown (1969) also observed that incoming net thermal radiation has a much stronger influence on the energy budget of a small stream ($<0.03\ m^3\ s^{-1}$) when there is no canopy cover to intercept the incoming solar radiation. An experimental shading experiment of a second-order stream in the Oregon Cascade Range showed that maximum stream temperatures significantly declined in the shaded reach, due to decreased incoming solar radiation (Johnson, 2004).

As in forested areas, loss of vegetation along streams in agricultural areas for livestock grazing or crop production can increase stream temperatures as more solar radiation reaches the stream (Belsky et al., 1999). Stream temperatures can also be altered by irrigation practices which can increase subsurface flow and tile drains that convey water directly to ditches or streams (Younus et al., 2000; Poole and Berman, 2001; Schilling et al., 2010). Additionally, the presence of ponds or lakes within the waterway may influence downstream water temperatures, although the evidence about this is conflicting. One study found that ponds used for irrigation or aesthetics had water temperature up to 4 °C higher than upstream or downstream reaches. Although the authors did not find significant increases in the temperature of water leaving the ponds, they did point out that logger placement might have influenced the results (Ham et al., 2006). In contrast, Booth et al. (2014) noted that streams downstream of a lake were 2–3 °C warmer than otherwise would be anticipated during summer months, and suggest that constructing ponds to improve water quality by reducing phosphorus or metals could lead to increased stream temperatures.

Urban development can also significantly impact stream temperatures as channelization, culverts, and impoundments alter the amount and timing of river flows and reduce connectivity between the stream water and groundwater (Poole and Berman, 2001; Krause et al., 2004). Surges of heated runoff from developed areas can alter natural stream thermal regimes and stress aquatic organisms (Hester and Bauman, 2013; Booth et al., 2014). Channel engineering can substantially alter the flow and energy of stream water and lead to a loss of ecological connectivity between the channel and the floodplain as well as the hyporheic zone (Brunke and Gonser, 1997; Poole and Berman, 2001; Hester and Gooseff, 2010; Booth et al., 2014). Reduced groundwater inflows can increase average or daily maximum surface stream temperatures in the summer and decrease temperatures in the winter as impervious cover and buildings alter natural precipitation, runoff, and infiltration patterns (Krause et al., 2004; Nelson and Palmer, 2007; Hester and Doyle, 2011). Somers et al. (2013) observed that at baseflow, five highly urbanized streams in North Carolina had mean temperatures of 21.1 °C compared to five streams in a forested area with mean temperatures of 19.5 °C. In addition, the baseflow temperature in the urbanized streams varied by as much as 10 °C over 1 km, compared to variation of 2 °C in the forested streams. After a storm event, urban stream temperatures increased by as much as 4 °C, while forested streams did not exhibit any temperature changes.

In our study of Stroubles Creek, a small, third-order stream in southwestern Virginia, we studied the thermal regime in three different land cover reaches – urban, agricultural, and forest – to explore the influence of land cover and canopy shading on stream temperature in warm (May–September) and cold (October–April) periods (2012–2013). In 1998, Stroubles Creek was listed as an impaired waterway due to high sediment loads and low aquatic diversity, based on the Clean Water Act standards (Mostaghimi et al., 2003). In 2009, restoration efforts began to reduce sediment loading to the stream, including improving connectivity between the channel and floodplain, and preventing livestock from entering the stream. However, the aquatic diversity of Stroubles Creek remains low (Roberts and Duncan, 2006), which may be due in part to water temperatures that are beyond the habitat threshold for many native species. Human activities, such as the removal of riparian vegetation and a shift from forested watersheds to agricultural and urban landscapes, can alter stream temperatures and reduce habitat ranges for aquatic species. The objective of this project was to characterize the thermal regime of Stroubles Creek throughout the watershed and identify the primary natural or anthropogenic controls on stream temperature; these findings can then be used to inform the design of remediation projects to improve the water quality and aquatic diversity of Stroubles Creek.

2. Materials and methods

2.1. Site description

Stroubles Creek is in the Town of Blacksburg in Montgomery County, VA and is a tributary of the New River in southwestern Virginia. Our study was conducted within the upper Stroubles Creek watershed where the stream is a third-order stream (1:24,000 USGS map scale) and has a watershed size of approximately $25\ km^2$ (Fig. 1). Unlike many headwater streams that begin in forest, Stroubles Creek flows through the urban center of the Town of Blacksburg, through the campus of Virginia Tech, and