Ecological Engineering 78 (2015) 101–111

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

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

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ARTICLE INFO

Article history:
Received 1 November 2013
Received in revised form 21 April 2014
Accepted 22 May 2014
Available online 28 June 2014

Keywords:
Stream temperature
Land use
Groundwater
Canopy cover
Stream restoration
Urban impacts

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.

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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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http://dx.doi.org/10.1016/j.ecoleng.2014.05.019
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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

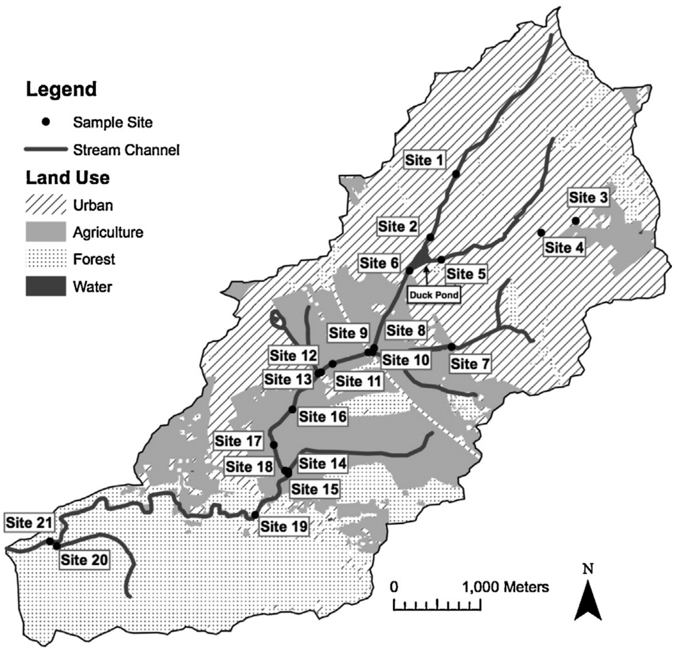

Fig. 1. Stroubles Creek watershed land cover and temperature sampling sites (1–21).

then through patchwork agricultural fields, finally flowing through forested cover near the outlet of our study watershed (Fig. 1). The Stroubles Creek headwaters are fed by natural springs in Blacksburg, forming two primary streams (Central Branch, Webb Branch) that flow through the town to converge in a pond in the middle of the campus of Virginia Polytechnic Institute and State University (Fig. 1). A third tributary flowing from the southeastern side of town converges with the main stem about 1000 m downstream from the pond. All of the urban land cover sites have some form of channel modification (channelization, buried stream reaches, pond) and add complexity to the Stroubles Creek watershed. The Stroubles Creek watershed is primarily forested (40%), with 29% agriculture, and 19% urban land cover (Younos and Walker, 2002).

The watershed is characterized by limestone and dolomite formations and the Stroubles Creek bed is alluvium-floodplain deposits of stratified unconsolidated sand, silt, and clay with beds and lenses of pebbles and cobbles (Mostaghimi et al., 2003). Annual mean precipitation for Blacksburg, VA is 103 cm. Stream temperature was measured from July 4, 2012 to June 30, 2013. The sampling period was split into a warm period (May–September) and cold period (October–April) based on when groundwater temperatures measured at site 3 were above or below mean air temperature to provide a consistent way to compare sampling years. The 2012 warm period (July 4, 2012–September 30, 2012) was drier and warmer than the 2013 warm period (May 1, 2013–June 30, 2013). During the 2012 warm period, rainfall events occurred on 30 out of 89 days, ranging from 0.025 cm to 1.45 cm, with a total of 12.8 cm, which is below average summer precipitation amounts. The mean discharge for Stroubles Creek during the 2012 warm period at site 16 was 0.122 $m^3 s^{-1}$ and due to the minimal precipitation events during this time, the stream was at baseflow, with groundwater the primary control of discharge. The 2013 warm period was much wetter with 32.5 cm total precipitation from May to June and a mean discharge of 0.318 $m^3 s^{-1}$. The 2012 warm period mean daily air temperature (19.69 °C ± 3.74 °C) was warmer than the 2013 warm period mean daily air temperature (17.2 °C ± 4.08 °C). Daily mean air temperature during the October 2012–April 2013 cold period was 4.55 °C (±5.96 °C), with 36.3 cm of precipitation and a mean cold period discharge of 0.167 $m^3 s^{-1}$.

2.2. Site selection

Twenty-one sites in the urban, agricultural, and forested land use areas were selected for temperature measurement (Fig. 1). The urban stream reaches are sites 1–7, with site 3 at the headwater spring on the southern branch of Stroubles Creek (Central Branch) and site 1 downstream of the headwater spring of the northern branch (Webb Branch). Temperatures measured at site 3 were assumed to represent the stream temperatures at the other headwater springs. Temperature sampling sites 8–18 are agricultural stream reaches, with sites 16–18 at sampling locations within the Virginia Tech Stream Restoration, Education, and Management (StREAM) Laboratory (www.bse.vt.edu/site/streamlab). The forest stream reaches are sites 19–21. HOBO Pendant Temperature Data Loggers (UA-022-64, Onset Computer Corporation) were deployed at sites 1–15 and 19–21, while YSI probes (Yellow Springs Instruments, Inc.) were already being used by the StREAM Lab to measure temperature at sites 16–18. At each sampling location, temperature probes were anchored in the stream thalweg approximately 5 cm above the streambed, except where bed substrate prevented the probe installation and then the probes were placed as close as possible to the thalweg. Temperature measurements with ±0.53 °C (HOBO data loggers) and ±0.15 °C (YSI probes) accuracy were taken at 15-min intervals to capture fine changes in temperature from July 4, 2012 to June 30, 2013.

2.2.1. Sampling site locations

From the headwater spring (site 3) the Central Branch flows through culverts and short underground channelized sections to site 4 where the stream is above ground for approximately 50 m in a channel that has been straightened with boulders (Fig. 2a) before flowing underground again towards site 5. Sampling sites 2, 5, and 7 are located directly downstream after the stream comes out from being channelized underground for major stretches. Site 1 is located about halfway from the headwaters of the Webb Branch to the confluence with the Central Branch at the Duck Pond. Much of Webb Branch upstream of site 1 is underground and at site 1 gabion walls 2-m high and culverts channelize the stream and are another example of the channel modifications in the Stroubles Creek watershed. Site 6 is located at the outlet of the Duck Pond, a feature that adds additional complexity to the urban stream sites.

Stroubles Creek flows from the outflow of the pond through agricultural land cover (Fig. 2b). Two small agricultural tributary reaches and the larger third tributary from the southeastern side of Blacksburg converge with the main stem of Stroubles Creek in the agricultural land cover area. A portion of Stroubles Creek flows through the Virginia Tech StREAM Lab where a stream restoration project took place in 2009 (Thompson et al., 2012). Finally, the stream flows out of the agricultural land cover to enter the forest at site 19. Upstream of the forest outflow (site 21) a forested tributary (site 20) converges with the main stem of Stroubles Creek. Examples of urban, agricultural, and forested land cover temperature sampling sites are shown in Fig. 2.

2.3. Climate, physical, and hydrologic measurements

In addition to water temperature, stream canopy cover was measured at each sampling site using a spherical convex densitometer (Convex Model A, Forestry Suppliers). Canopy cover was measured in four directions (upstream, downstream, left bank, right bank) in the center of the stream at each sampling location. Measurements were taken in October 2012 and estimates were

Fig. 2. Examples of the Stroubles Creek temperature sampling sites in (a) urban (site 4), (b) agricultural (site 18), and (c) forest (site 21) land cover regions.

made for trees that had already lost some leaves using photographs taken during July 2012. Meteorological data were collected at the Virginia Tech StREAM Lab meteorological station near site 17 (indicated on Fig. 1), including: precipitation (mm), air temperature (°C), solar radiation (MJ m^{-2}), wind speed (m s^{-1}), wind direction (degrees), and barometric pressure (mm Hg). Stroubles Creek stream stage (m) was measured at 10-min intervals at site 16 and discharge was calculated using a stage-discharge rating curve equation. ArcGIS (ArcGIS 9, ESRI, Redmond, CA) was used in conjunction with field observations to determine land cover throughout the Stroubles Creek watershed and within 50 m buffers around each temperature sampling probe, which was considered the sampling site land cover. The distances between each site as well as the length of the entire sampling reach were also measured using ArcGIS.

2.4. Statistical analysis

Boxplots were created to compare the mean, minimum, and maximum stream temperature measured each day during the warm and cold sampling periods among sites in the urban, agricultural, and forest stream reaches. Daily and weekly mean stream temperature, air temperature, solar radiation, precipitation, relative humidity, wind speed, and discharge values were calculated for use in the regression analyses.

Simple linear regression analyses were conducted to examine the relationship between air temperature and stream temperature at each sampling site (Erickson and Stefan, 2000; Caissie et al., 2004; Benyahya et al., 2007). The Durbin–Watson test for autocorrelation was used to determine the appropriateness of regression analyses on air and stream temperatures. Linear regressions were conducted only when the Durbin–Watson test statistic was between 1 and 3 for all sampling sites, reducing autocorrelation due to upstream influences on downstream samples within short sampling periods. Daily air and stream temperatures were not used for the linear regression analysis as the Durbin–Watson test statistic for many sites was <1, indicating that a linear regression was not appropriate at this time scale (Caissie, 2006). Multiple linear regression analyses were used to determine the relationship between meteorological conditions and stream temperature (Pedersen and Sand-Jensen, 2007; Webb et al., 2003). For all statistical analyses $\alpha = 0.05$ was used to determine statistical significance.

The spatial variation of stream temperatures was examined by creating a stream temperature contour plot from the headwater spring (site 3) downstream along the main stem to the forest outflow (site 21) over the summer sampling time period. For each temperature sampling site along the main stem the change in stream temperature from the upstream sampling site to the nearest downstream site was calculated. In addition, the change in temperature over the entire length of the main stem from the headwaters to the outflow was calculated. Statistical analysis was carried out using R (R Project) and MATLAB (MathWorks, Inc.).

3. Results

3.1. Daily stream temperatures

The daily mean stream temperatures along the main stem of Stroubles Creek during warm sampling periods (July–September 2012, May–June 2013) 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 (Table 1). Winter (October 2012–April 2013) daily mean 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 (Table 1). Daily average stream temperatures reflected daily air temperature patterns at every sampling site regardless of land cover and season. Warm period temperatures in the urban stream reaches varied widely depending on site, stream alterations, and local shading conditions, although warm period 2012 stream temperatures were consistently warmer than warm period 2013 temperatures. Stream temperatures at the headwater spring (site 3) had minimal variation throughout the year, with the coolest measured warm period temperatures of 14.6 °C (±0.3 °C) during 2013 and 13.5 °C (±0.27 °C) during 2013. At the outflow of the Duck Pond (site 6), stream temperatures were consistently the highest of all the urban sites (24.6 °C ± 2.8 °C in 2012, 20.4 °C ± 2.9 °C in 2013) (Fig. 3a). The stream temperature at the headwater spring is minimally influenced by the surrounding land cover, as the stream is entirely fed by groundwater at this location, while site 6 is at the outflow of the Duck Pond, where there is a large surface area for air–water interactions and volume of water for thermal storage.

The daily mean stream temperatures in the agricultural stream reaches were more uniform than the urban stream reaches during the warm sampling period with the coolest temperatures measured at site 12 (20.1 °C ± 2.6 °C in 2012, 15.8 °C ± 1.7 °C in 2013), downstream of a stream section shaded by riparian vegetation (Fig. 3a). Stream temperatures at site 16 and 17 were also cooler agricultural sites, although not outside the standard deviation range of the other agricultural sites. The mean temperature at the forest outflow site 21 (22.4 °C ± 1.9 °C in 2012, 18.0 °C ± 2.6 °C in 2013) was not cooler than the stream temperature at the beginning of the forested reach (site 19, 22.2 °C ± 2.9 °C in 2012, 18.1 °C ± 2.5 °C in 2013) in the warm sampling period (Fig. 3a).

During the warm period, the smaller tributaries to Stroubles Creek had periods of little or no discharge, leaving temperature probes in these sampling sites in standing pools of water or above the water for portions of the warm period, which can alter temperature measurements, therefore all tributary sites (sites 7, 8, 13, 14

Table 1
Stroubles Creek sampling sites and seasonal stream temperatures.

Site	Land cover[a]	Canopy cover (%)	Distance downstream (m)[b]	Daily warm period temperature (°C)			Daily cold period temperature (°C)		
				Mean (±SD)	Min	Max	Mean (±SD)	Min	Max
1	U	79.2	0[c]	17.7 ± 2.3	12.1	22.1	9.4 ± 3.0	4.6	21.6
2	U	55.34	830	18.2 ± 2.3	12.4	22.1	10.2 ± 2.7	5.4	18.1
3	U	95.0	0[c]	14.1 ± 0.6	13.0	15.4	12.2 ± 1.0	9.6	14.5
4	U	95.0	375	16.5 ± 1.9	12.4	19.9	10.4 ± 2.4	4.7	16.7
5	U	95.0	1555	17.6 ± 2.1	13.3	22.2	12.0 ± 2.2	6.8	17.6
6	U	94.8	2160	22.9 ± 3.5	13.2	29.2	9.0 ± 4.6	2.2	19.7
7	U	21.0	0[c]	15.4 ± 0.1	13.2	18.2	12.4 ± 1.3	8.4	15.5
8	A	90.6	3010[d]	19.7 ± 2.7	12.8	24.8	9.5 ± 3.6	3.4	18.2
9	A	24.1	3005	20.7 ± 2.9	13.0	25.8	8.8 ± 4.0	2.4	18.7
10	A	94.8	3115	20.1 ± 2.7	13.0	24.8	9.4 ± 3.7	3.6	18.4
11	A	22.0	3540	20.3 ± 2.8	13.0	25.5	9.2 ± 3.7	3.1	18.5
12	A	0.16	3740	18.4 ± 3.1	12.0	24.2	8.1 ± 3.7	1.1	17.4
13	A	0.16	3743[d]	20.3 ± 2.8	12.9	25.6	9.1 ± 3.8	2.9	18.5
14	A	15.8	5145[d]	18.6 ± 3.0	10.7	23.6	NA	NA	NA
16	A	0.16	4260	19.8 ± 3.0	12.4	28.1	8.4 ± 4.1	0.6	18.3
17	A	0.16	4785	19.8 ± 3.1	12.5	26.5	7.7 ± 4.3	0	18.4
18	A	0.16	5180	20.1 ± 3.2	12.3	27.2	8.3 ± 4.0	1.9	18.5
15	A	0.16	5230	20.6 ± 3.2	12.7	28.1	8.6 ± 4.0	2.2	18.9
19	F	95.0	5925	20.5 ± 3.4	12.0	27.9	8.4 ± 4.0	1.9	19.1
20	F	95.0	9150[d]	16.7 ± 2.4	9.9	20.1	6.5 ± 3.9	0	15.4
21	F	95.0	9155	20.3 ± 3.2	11.8	25.4	6.7 ± 4.0	0.3	16.9

[a] U, urban; A, agricultural; F, forest.
[b] Distance downstream from site 3.
[c] Beginning of tributary.
[d] Tributary confluence.

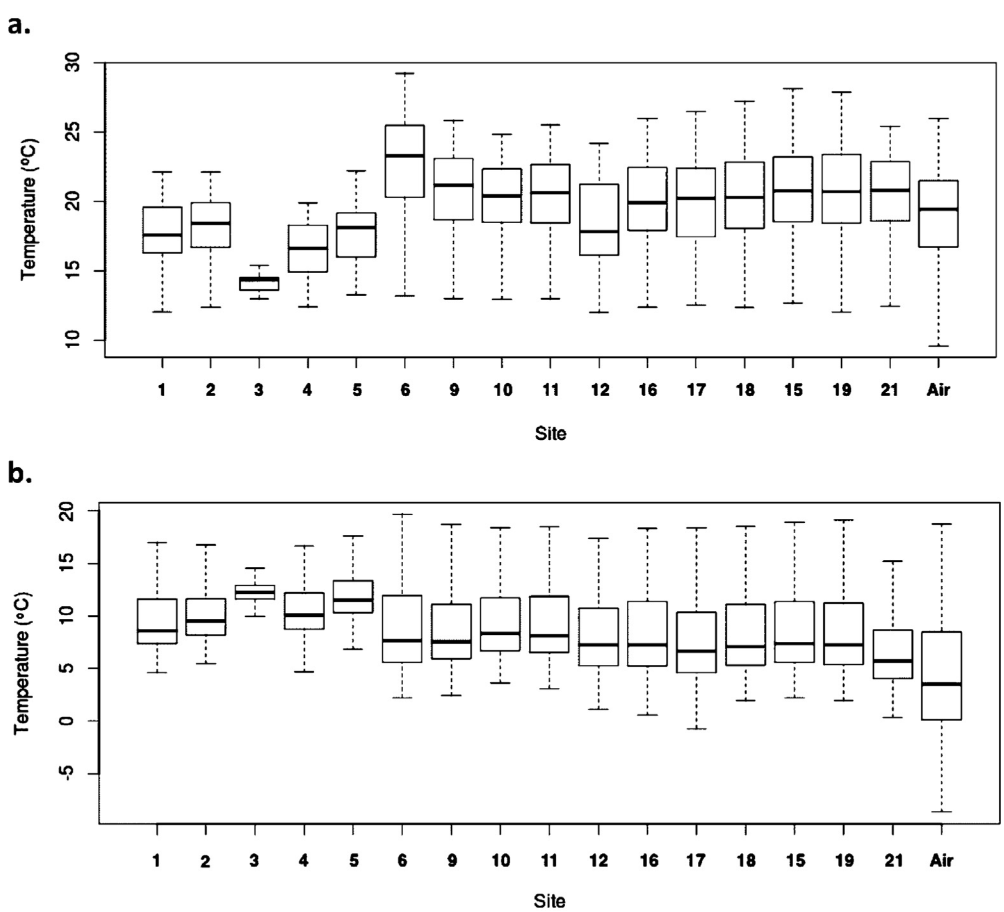

Fig. 3. Boxplots of mean warm period (a) and cold period (b) stream and air temperatures (°C) along the main stem of Stroubles Creek flowing from the urban region of Blacksburg (sites 1-6) through the agricultural region (Sites 9–12 and 15–18) and ending in the forested reaches (sites 19 and 21). The top and bottom of the box are first and third quartile temperatures, respectively, the center bar is median temperature, and the whiskers represent minimum and maximum mean temperatures.

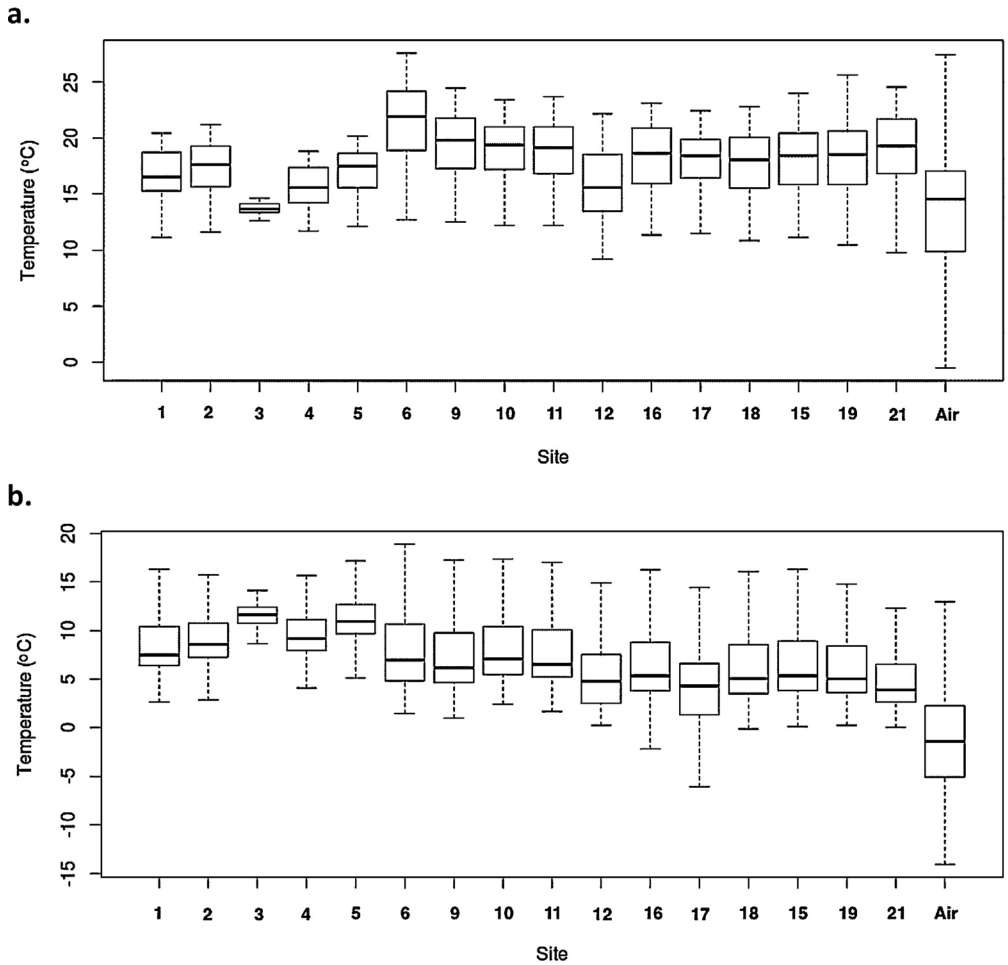

Fig. 4. Boxplots of minimum warm period (a) and cold period (b) stream and air temperatures (°C) along the main stem of Stroubles Creek flowing from the urban region of Blacksburg (sites 1–6) through the agricultural region (Sites 9–12 and 15–18) and ending in the forested reaches (sites 19. The top and bottom of the box are first and third quartile temperatures, respectively, the center bar is median temperature, and the whiskers represent minimum and maximum daily minimum temperatures.

and 20) were excluded from the stream temperature analyses in this paper.

During the cold sampling period (October 2012–April 2013), leaf fall reduced canopy cover to <5% at all sites. In contrast to the warm period temperatures, stream temperature was warmest at the urban sites and then cooled as Stroubles Creek flowed downstream through the agricultural and forested reaches. The mean stream temperature was warmest at site 3 (12.2 °C ± 1.0 °C) and site 5 (12.0 °C ± 2.2 °C) and coolest at site 6 (9.0 °C ± 4.6 °C), which is a reversal of warm period temperature trends (Fig. 3b). In the agricultural stream reaches, mean temperatures were lowest at site 12 (8.1 °C ± 3.7 °C) and site 17 (7.7 °C ± 4.3 °C), both of which were sites with cooler summer stream temperatures. As Stroubles Creek flowed out of the agricultural region into the forest, stream temperatures continued to decrease from 8.4 °C (±4.0 °C) at site 19 to 6.7 °C (±4.1 °C) at the outflow (site 12) (Fig. 3b).

3.2. Maximum and minimum stream temperatures

Maximum and minimum stream temperatures were measured to relate stream temperatures to fish and macroinvertebrate populations sampled throughout Stroubles Creek. Daily minimum stream temperatures measured during the warm period were similar across sampling sites, regardless of land use with the exception of site 6, where minimum temperatures (21.5 °C ± 4.4 °C) were consistently higher than minimum temperatures at other sites; this finding was most likely due to the thermal storage of the pond located upstream of site 6 (Fig. 4a). Minimum temperatures at urban sites 3 (13.7 °C ± 0.7 °C) and 4 (15.6 °C ± 2.3 °C) were cooler than other sites, most likely due to the groundwater influence at site 3 and site 4, downstream of site 3. In the agricultural area, the lowest minimum temperatures measured were at site 12 (15.8 °C ± 3.9 °C), which was also cooler than both the forested sites. Minimum stream temperatures during the cold period were highest in the urban region (11.5–8.1 °C) most likely due to groundwater and lack of interaction with air. The lowest minimum temperatures measured in the agricultural and forested regions were at site 17 (4.3 °C ± 3.9 °C) and site 21 (4.9 °C ± 2.2 °C) (Fig. 4b).

For many native species found in Stroubles Creek in a 2006 survey by Roberts and Duncan, stream temperatures measured above 30 °C during the 2012–2013 sampling period exceeded habitat thresholds for some species. The daily maximum stream temperatures measured reflected daily maximum air temperature patterns across all sampling sites, but more strongly in the agricultural and forested sites. During the warm sampling period, the maximum stream temperatures at site 6 were the warmest temperatures measured in the urban region (24.8 °C ± 4.6 °C), while maximum temperatures at site 3 only reached 15.2 °C (±1.5 °C) (Fig. 5a). Maximum temperatures were highest at site 15 (±24.3 °C 4.6 °C) in the agricultural region, with slight decreases in maximum

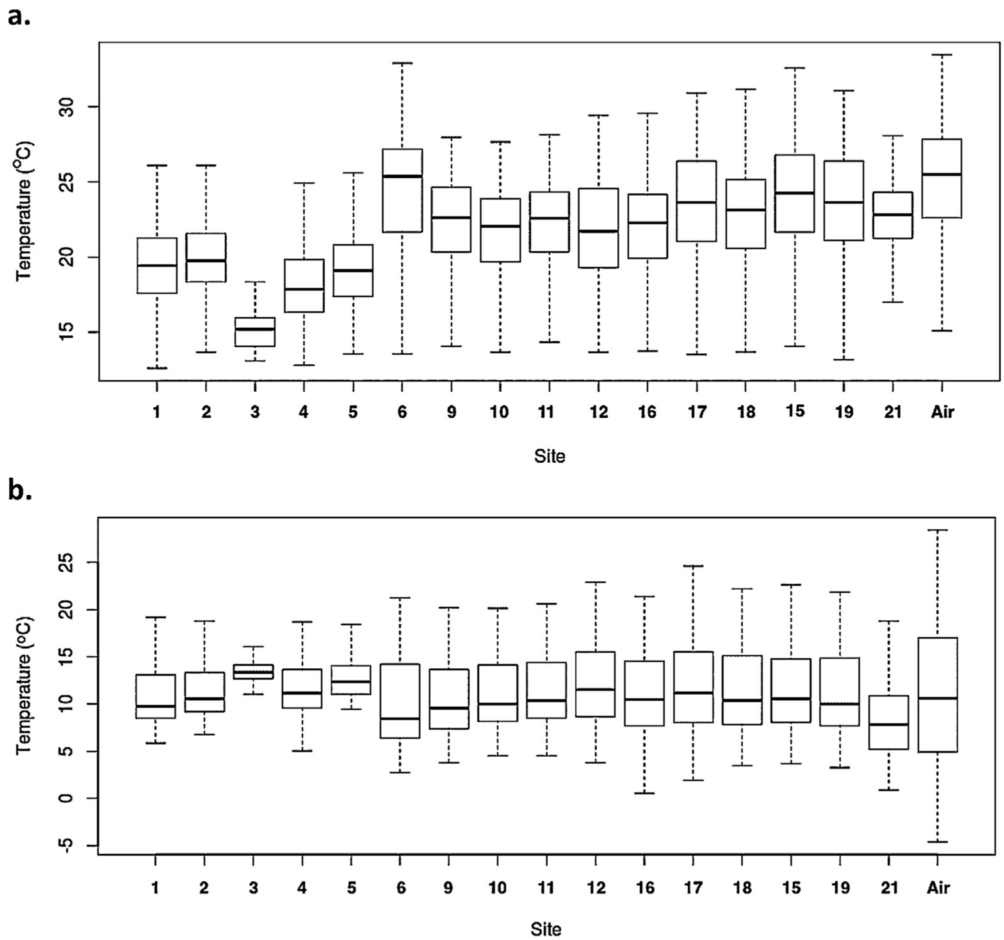

Fig. 5. Boxplots of maximum warm period (a) and cold period (b) stream and air temperatures (°C) along the main stem of Stroubles Creek flowing from the urban region of Blacksburg (sites 1–6) through the agricultural region (Sites 9–12 and 15–18) and ending in the forested reaches (sites 19 and 21). The top and bottom of the box are first and third quartile temperatures, respectively, the center bar is median temperature, and the whiskers represent minimum and maximum daily maximum temperatures.

temperatures compared to upstream temperatures observed at sites 10 and 18. The maximum temperatures at the forest outflow site 21 (22.5 °C ± 3.8 °C) were lower than the entrance to the forested stream reach (23.7 °C ± 4.4 °C). Stream temperatures above 30 °C were measured at several sampling points including site 6 (Maximum temperature measured = 32.9 °C) at the outflow of the Duck pond, open agricultural sites 15 (32.6 °C), 17 (30.9 °C), 18 (31.2 °C), and site 19 (31.1 °C) at the beginning of the forested reach during the warm sampling period. These maximum stream temperatures were measured from July 4, 2012 through August 2, 2012 when daily maximum air temperatures were above 29 °C. During the cold sampling period, the highest temperatures were measured at sites 3 and 5 (13.5 °C ± 1.2 °C; 12.8 °C ± 2.2 °C) where there was less stream-air interactions (Fig. 5b).

The diel fluctuations in stream temperature from minimum to maximum temperature were greatest during the warm sampling period at agricultural sites 12 (6.2 °C ± 2.4 °C) and 15 (6.3 °C ± 2.3 °C) were there was very little canopy shading. Daily temperature fluctuations were lowest at agricultural sites 9 (3.2 °C ± 1.2 °C), 10 (3.0 °C ± 1.2 °C), and 11 (3.8 °C ± 1.3 °C) where canopy shading was greater (22–95%). Of the urban sites, the diel fluctuations at site 6, the outflow of the pond, were greatest (3.36 °C ± 1.3 °C), with less fluctuations at the other urban sites, particularly those influenced by groundwater (site 3; 1.5 °C ± 1.2 °C) and buried underground (site 5; 2.2 °C ± 1.6 °C). The forest outflow site (site 21; 3.8 °C ± 1.9 °C) also had smaller diel fluctuations than the forest inflow site (19) or the agricultural sites. These trends were consistent through the cold season period.

3.3. Regression analysis

Linear regression analyses suggest that weekly mean stream and air temperatures had a significant linear relationship ($p < 0.05$) throughout the Stroubles Creek watershed, regardless of land cover or period (Fig. 6). The warm and cold period air-stream temperature linear relationship for the agricultural and forested stream reaches were stronger and less variable than the urban stream reach air-stream relationships, especially at site 5 where temperatures were measured as Stroubles Creek became daylighted. The slope of linear air-stream temperature equations along the main stem of Stroubles Creek increased downstream from 0.108 ($p < 0.001$) (site 3) at the stream headwaters to 0.853 ($p < 0.00001$) at the forested outflow (site 21), while intercepts decreased from site 3 (12.11) to site 21 (3.9) during the warm period. Regression analyses also suggest that weekly mean stream temperatures and solar radiation (MJ m^{-2}) had a weakly significant relationship ($p < 0.05$) for the majority of sampling sites. During the warm period, this relationship was strongest at sites 6, 10, and 11 ($p < 0.01$), although the relationship was significant at all agricultural and forest sites ($p < 0.05$). There was not a significant relationship between stream temperature and

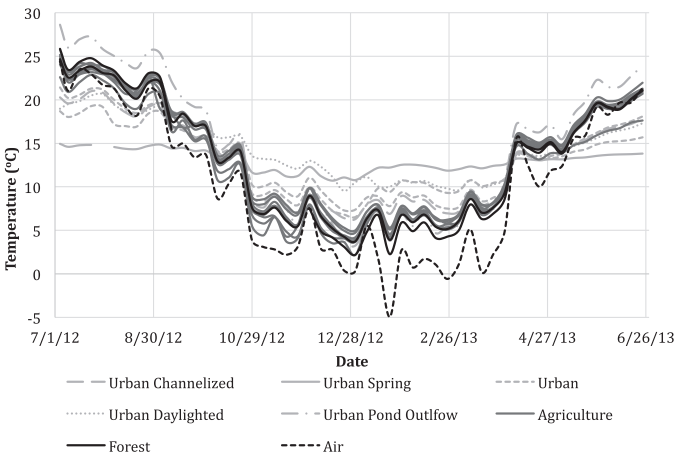

Fig. 6. Weekly mean stream temperatures (°C) along the main stem by land use region.

solar radiation at sites 3 and 5, which were not highly influenced by air temperature. The stream temperature-solar radiation relationship was stronger during the cold sampling period for all sites except site 5.

3.4. Spatial temperature changes

Over the warm sampling period, stream temperatures increased over approximately 9 km downstream along the main stem from the headwater spring (site 3) to the forested outflow (site 21) by 5.9 °C on average, although local cooling occurred in some reaches (Fig. 7). Warm period stream temperatures increased slightly from site 3 as the stream flowed downstream through culverts, channelized sections, and buried stream reaches to sites 4 and 5. After these underground sections, the stream entered the Duck Pond. Stream temperatures had increased substantially by 5.0 °C from the inflow (site 2 and site 5) to the outflow of the Duck Pond (site 6, 2005 m downstream). After flowing through agricultural stream reaches with patchy canopy cover shading, Stroubles Creek temperatures began cooling with respect to the maximum temperatures reached at site 6. Stream temperatures reached a local minimum between site 10 (3115 m downstream) and site 12 (3740 m). Canopy cover at site 10 was 94.8%, at site 11 was 22%, and at site 12 the canopy cover decreased to 0.16%. The stream temperatures increased again as Stroubles Creek flowed through the open agricultural reaches (sites 16–18), although local cooling was observed around 4785 m (site 17) on several days (Fig. 7). As this site is in an agricultural reach with no canopy cover, the cooling could possibly be attributed to groundwater inputs. During July 2012, stream temperatures

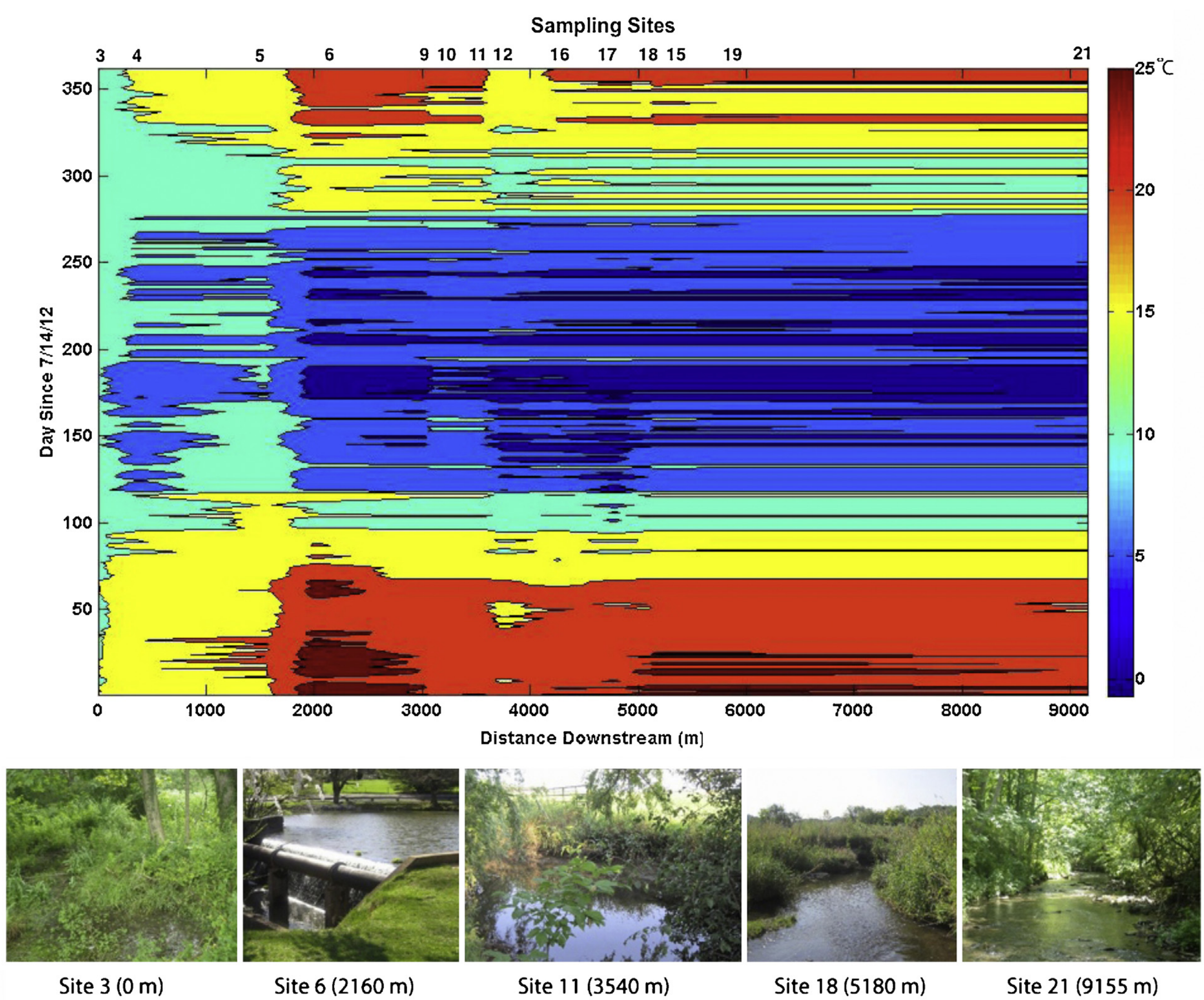

Fig. 7. Daily temperatures (°C), indicated by color bar, from Stroubles Creek headwater spring (site 3, 0 m) downstream along the main stem to forest outflow (site 21, 9155 m) from 7/4/12 to 6/30/13, excluding sites on Webb Branch tributary (site 1 and site 2).

increased to 28 °C as the stream flowed out of the agricultural land cover reaches to the beginning of the forest at site 19. From the beginning of the forested land cover to the forest outflow (site 21) stream temperatures had decreased to 20.4 °C. Beginning around September 9, 2012 the stream temperatures at the outflow (site 21) were within 4 °C of the headwater spring temperatures, and continued to cool throughout the fall and winter to a cold period mean of 6.7 °C. Headwater spring temperatures remained around 12 °C during the cold period, with stream temperatures falling as Stroubles Creek flowed downstream. Urban sites remained warmer than agricultural or forested sites, possibly due to groundwater sources or minimized air-stream interactions. In the agricultural stream reaches (3005–5100 m), local sites of warming appeared between sites 9 and 10, 12 and 16, and 17 and 18. With minimal to no canopy cover during the winter, groundwater inputs are the most likely source of warmer water.

4. Discussion

Our findings regarding stream temperature are in alignment with other observations that water in headwater streams is generally close to groundwater temperature and stream temperature increases or decreases as the water moves downstream and is in contact with the air and other energy sources (Borman and Larson, 2003; Caissie, 2006). During the warm sampling period, Stroubles Creek temperatures increased from the headwaters downstream to the outflow, while during the cold sampling period, stream temperatures decreased from the headwaters downstream. The mean warm period temperatures were lowest in the upper watershed urban reaches (17.8 °C), while stream temperatures were highest in the forested reach (20.4 °C) in the lower watershed. Generally during the warm sampling period, daily stream temperatures increased with distance from the source. The annual mean stream temperature measured at headwater site 3 (13.0 °C ± 1.3 °C) was a good estimate of the groundwater temperature and was consistent throughout the year.

There was more variation in the daily mean temperatures among the sites in the urban reaches than in the agricultural or forest reaches, despite the proximity of the urban sites to the stream headwaters. Channel constrictions and alterations, such as culverts, channelization, and buried stream reaches are most likely the cause of the wide variation in (up to 9.6 °C) in stream temperatures among urban sites in the warm period. The reasons for this may be complex, as channel engineering could be reducing the stream water–groundwater connectivity in some stream reaches thus decreasing the moderating effect of groundwater on stream temperatures. Buried stream reaches and culverts could also be limiting air-stream water energy fluxes. Warm period stream temperatures (mean, min, max) were consistently higher at site 6 than at any other site along Stroubles Creek. Site 6 is located at the outflow of the Duck Pond that Stroubles Creek flows through and the large surface area and volume of this pond increase the thermal capacity elevating maximum and minimum temperatures.

The maximum stream temperatures recorded along Stroubles Creek at sites 6, 15, 17–19 could be limiting the aquatic diversity by exceeding both the preferred habitat temperature and lethal temperature threshold for some native species. *Rhinichthys atratulus* (Blacknose dace), *Catostomus commersoni* (White sucker), and *Hypentelium nigricans* (Northern hogsucker) have lethal temperature thresholds around 30 °C, so stream temperatures above this value could be limiting their habitat range in Stroubles Creek (Roberts and Duncan, 2006; Hasnain et al., 2010). *Lepomis cyanellus* (Green sunfish), *Lepomis auritus* (redbreast sunfish), *Campostoma anomalum* (Central stonerollers), *Gambusia holbrooki* (Eastern mosquitofish) have higher lethal temperature ranges and are more prevalent throughout Stroubles Creek (Roberts and Duncan, 2006). All of these species have optimal growth temperature below 30 °C, but some (Blacknose dace, Longnose dace) could be severely impacted by these maximum temperatures (Hasnain et al., 2010). Although none of the field sites had mean maximum warm period temperatures above 21 °C, prolonged periods of stream temperatures reaching above species habitat thresholds occurred at several sites, with site 15 having 16 days above 30 °C.

In the agricultural stream reaches, the stream temperatures were more consistent than in the urban sites, even across a range of canopy shading values. During the warm period there was a slight decrease in daily mean temperature from site 9 to site 15 at the end of the agricultural region, suggesting that the high stream temperatures measured at site 6 decreased when flowing through stream reaches with a range of canopy shading. Within the agricultural region, the stream temperature continued to decrease, with the coolest temperatures in the agricultural area measured between site 10 (3115 m downstream) and site 12 (3740 m). Canopy cover at site 10 was 95%, at site 11 was 22%, and site 12 the canopy cover decreased to less than 1%. The low stream temperatures at sampling sites with higher canopy cover suggest that riparian vegetation is reducing daily stream temperatures, regardless of the broader land cover. In addition, diel warm period temperature fluctuations were greater in the agricultural sites with low canopy cover (sites 12, 17 and 18) than at the sites with higher canopy cover (sites 9, 10 and 11) suggesting that canopy cover shading is reducing energy inputs to the stream resulting in a smaller increase in stream temperature (Brown and Krygier, 1967; Brown, 1969; Beschta and Taylor, 1988; Rowe and Taylor, 1994; Johnson, 2004; Moore et al., 2005b; Webb et al., 2008). A slight decrease in temperatures between sampling sites 16 and 17, both of which have >1% shading, could be due to groundwater inputs. The groundwater system connection with Stroubles Creek has not yet been examined, but the karst aquifer system and the prevalence of springs in the watershed suggest that groundwater inputs could be a significant control on the stream temperature, as O'Driscoll and DeWalle (2006) and Tague et al. (2007) have observed in other karstic stream systems. During the cold period, the daily mean stream temperature also decreased as Stroubles Creek flowed from site 6 through the agricultural region to site 15. Canopy cover was <5% for the cold period and therefore did not have any influence on stream temperature. Slight increases in stream temperature between sites 12 and 16 and between sites 17 and 18 indicate that warmer groundwater inputs are increasing the stream temperature. The diel temperature fluctuations are reduced during the cold period, so inputs from groundwater into the stream are more apparent. The warm period stream temperature increases from site 15 to site 19 at the beginning of the forested reach; however, as the stream flows through the forested area, stream temperatures do not continue to increase (20.5 °C at site 19 to 20.3 °C at site 21), which suggests that either riparian vegetation or groundwater inputs, or both, are cooling the stream. During the cold period, decreasing stream temperature from 8.4 °C to at site 19 to 6.7 °C at the outflow site 21 suggests that winter air temperatures are cooling the stream as energy is exchanged between the warmer water and cooler atmosphere.

Air temperature appears to be a significant control on stream temperature based on the t-tests and regression analyses. Weekly mean air and stream temperatures had a significant linear relationship ($p < 0.05$) throughout the Stroubles Creek watershed, regardless of land cover or period. The linear relationship between maximum stream temperature and air temperature was strongest ($p < 0.001$) in agricultural sites (9–12 and 15–18), forest stream reaches (19 and 21), and urban site 6. The weaker air-stream temperature relationship observed in the urban reaches could be due to the various channel engineering structures and buried stream reaches that reduce energy fluxes at the air–water boundary. It is also possible that the sites further downstream have a stronger linear air–water relationship because the stream has been exposed to the air for a longer period of time. The slope and y-intercept values for the Stroubles Creek warm period air-stream temperature linear regressions are similar to values found by other researchers (Jeppesen and Iversen, 1987; Pedersen and Sand-Jensen, 2007). Jeppesen and Iversen (1987) calculated slope values of 1.047 and 0.865 with intercepts of 0.01 and 2.09 for two low gradient stream reaches. Pedersen and Sand-Jensen (2007) studied 11 stream sites and found a range of air-stream relationships with slopes from 0.28 to 0.1 and intercepts from 5.46 to 0.86. The warm period slopes for the Stroubles Creek relationships range from 0.108 to 0.86 with intercepts from 12.1 to 3.9. The shallow slopes and high intercepts suggest that Stroubles Creek has areas of strong groundwater inputs, similar to streams observed by Erickson and Stefan (2000), Caissie et al. (2004), and O'Driscoll and DeWalle (2006). The air-stream temperature relationship is consistent throughout the year, although the linear relationship is stronger during the warm period than the cold period. As regression analyses were conducted on weekly data these trends can describe the relationship between Stroubles Creek temperatures and surrounding environmental inputs; however, daily maximum and minimum stream temperatures most likely are stronger controls on aquatic species habitat ranges and thresholds.

In the multiple linear regression analyses only air temperature and solar radiation were significant predictors of stream temperature. Solar radiation was a weak predictor of stream temperature at the urban sites where channel alterations may have reduced the amount of solar radiation received by the stream. In the agricultural and forested reaches stream temperatures decreased at sites with higher canopy cover (site 10 and site 21). Other studies examining stream temperature, energy fluxes, and canopy cover have observed an increase in temperatures when canopy is reduced and many have concluded that the observed results are due to a decrease in incoming radiation (Brown and Krygier, 1967; Brown, 1969; Beschta and Taylor, 1988; Johnson, 2004). The weaker relationship between stream temperature and solar radiation compared with the air-stream temperature relationship observed at Stroubles Creek could be due to a stronger influence of groundwater and air temperature on stream temperature than net radiation. It is also possible that the measurements of incoming solar radiation and air temperature from the meteorological station in the StREAM Lab do not accurately represent the direct solar radiation reaching local stream sites or micro-climates that might differ based on riparian vegetation and shading. In future, individual site measurements of meteorological conditions, including air temperature, solar radiation, and groundwater inputs would provide a stronger dataset to use to explore the relationship between Stroubles Creek temperatures and energy fluxes. A portion of the variation in stream temperature is explained by the air-stream temperature linear relationship, but the remaining variation in temperature could be explained by solar radiation influences, riparian vegetation shading, and groundwater inputs. This research could be expanded by measuring meteorological conditions, groundwater inputs, and aquatic species at each site along Stroubles Creek.

The spatial analysis of stream temperatures indicates there was an increase downstream from the headwater spring (site 3) to the forested outflow (site 21) during the warm period; however, in some stream reaches (sites 10, 12 and 17) there was local cooling occurring. There were also sites of local warming, such as sites 6, 16, and 19 where temperatures increased to the warmest measured along the main stem (Fig. 7). The sites where local cooling occurs along Stroubles Creek have dense riparian vegetation and canopy cover greater than 50% or possibly groundwater inputs, while the local warming occurs along portions of the stream without dense riparian vegetation shading the stream. In addition, the data collected during the warm period indicate that when Stroubles Creek flows through the forested region, stream temperatures are lowered and there is the possibility that the forested cover could reduce stream temperatures close to the temperatures measured at the headwater spring. Other researchers have also observed that riparian vegetation can significantly reduce stream temperatures when compared with an open stream (Brown and Krygier, 1970; Burton and Likens, 1973; Beschta and Taylor, 1988). Gomi et al. (2006) found that riparian vegetation buffers of 10-30 m were effective at minimizing stream temperature increases. These results imply that riparian vegetation shading, even by shrubs and small trees bordering agricultural fields, has the ability to mitigate stream temperature increases when compared to sites with minimal vegetation and could be an important consideration for restoration efforts.

5. Conclusions

In this study, we observed that the maximum stream temperatures reached during warm periods could be the primary limitation to aquatic diversity and suitable habitat in Stroubles Creek. The variety of impoundments, channelization, and other alterations along urban reaches of Stroubles Creek affect stream temperatures in different ways. Buried sections of the stream and culverts reduce stream temperatures during warm periods, while ponds and lack of vegetation shading increase stream temperatures. These alterations to natural stream water–groundwater and stream-air interactions lead to complex temperature patterns and can disrupt habitat for aquatic organisms. We recommend restoration projects that increase riparian vegetation and shading in the urban and agricultural land use regions to provide local cooling. This could be particularly beneficial downstream of the Duck Pond to reduce maximum temperatures below the critical thresholds for aquatic organisms. In conjunction with efforts to reduce sediment and nutrient inputs into the stream and improve water quality, these targeted restoration efforts could increase the aquatic diversity of Stroubles Creek. In addition, we recommend that the potential impact on stream temperature should be considered in future development plans along Stroubles Creek.

Acknowledgments

Research support provided by the Hampshire College MacArthur Foundation Faculty Development Grant and Summer Dean's Fund, as well as Institute for Critical Technology and Applied Sciences (ICTAS) at Virginia Tech Project Water Thrust and NSF-EEC-REU Grant no. 1156688 funding to VT. We would also like to acknowledge Sarah Hews (Hampshire College) for her data analysis assistance, Virginia Tech StREAM Lab NSF-REU 2012 fellows, Siavash Hoomehr, and Laura Lehman for their field and laboratory assistance, and C. Nathan Jones (Virginia Tech) for his field sampling assistance.

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